SUBSTANTIATING LINES: THREADS, FOLDS & TRACES

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> *"Threads may be transformed into traces, and traces into threads. It is in through the transformation of threads into traces, I argue, that surfaces are brought into being. And conversely, it is through the transformation of traces into threads that surfaces are dissolved".*[1]

Abstract

The adoption of digital fabrication technologies in architecture allows for novel ways of translations between designing and making, between idea and materialization, a role that since the emergence of the profession has been fulfilled by architectural drawings. This paper reflects on the role of drawing in architectural practice mediated through digital fabrication, and its impact on the allocation of authorship. Based on three design explorations from architectural practice and teaching, using computation and digital fabrication, the paper looks into different types of lines emerging from those processes: threads, traces & folds. This tentative, not exhaustive, categorization of lines is based on their agency in the translation between design idea and material artifact. The paper proposes *substantiating lines* as a way of researching processes mediated through computation and digital fabrication. This approach is situated them within the lineage of architectural exploration of the gap between drawing and making, instead of approaching digital fabrication as closure, where digital models provide complete determinacy of the material artifact.

Between Designing and Making

In architecture, there tends to be a distance between the acts of designing and making; architects do not work with the object of their thought directly, but do so through intervening media. This distance can be traced back to the origin of architecture as a profession[2] and the establishing of drawing as its principal means for exploring, communicating and materializing design ideas.[3] Throughout the multiple developments in theories of perspective and projection, descriptive geometry, drawing tools and media and technologies of reproduction, drawing has remained central in how we conceive of and practice architecture. Architectural drawing is not a mere tool for capturing and notating design ideas, it contributes to uncovering novel design ideas, in other words, 'drawing is a form of thinking'[4].

In his influential essay *'Translations from Drawing to Building'* Robin Evans argues that the power of drawing as a medium relies on its *'distinctness from and unlikeness to the thing that is represented, rather than its likeness to it.*[5]' The architectural drawing is different from the building and its functioning as a design medium relies on understanding that difference. Rather than providing complete determination in advance the role of the drawing is transitive: translating between idea and materialization drawing allows linking the abstract and the corporeal, leaves room for the emergence of design ideas and extends the journey of design exploration, and has the potential to reach destinations further than intended.[6]

Autographic and Allographic Practices

The distance between designing and making has led to different understandings of where authorship can be located in architectural work. One could locate authorship in the drawing, as it captures the design intent of the architect without being constrained by the contingencies of building practice[7]; or you could locate the authorship in the building, reducing the drawing to a mere instrument to arrive at its construction. In practice, these extreme positions[8] are hard to maintain and authorship lies somewhere in-between and is never absolute. The drawing only partially reflects design intent; it introduces its own qualities, and cannot completely control the process of building that depends on many parameters and external influences[9]. As Stan Allen states: "*architectural drawing is in some basic way impure, unclassifiable. Its link to the reality it designates is complex and changeable*"[10].

In his classification of different art forms, Nelson Goodman makes a distinction between autographic and allographic practices.[11] In autographic arts, such as painting and sculpture, the authenticity of the work depends on it being executed by the artist; in other words, it bears the traces of the hand of the artist.[12] In allographic arts, such as music or poetry, the work can be executed without the direct presence of the author. Where autographic arts work directly with the matter at hand, allographic arts work through notation, usually

leaving the execution to others. Allographic arts are often temporal and ephemeral, as in music, or need coordinated execution by many people, as in a theatre or in an orchestra.

Nelson Goodman considers architecture to be a "curious mixture" of autographic and allographic practices. Like other arts, architecture started out as the autographic practice of making and building but has acquired allographic elements through the introduction of notation in the form of the drawing. Unlike other allographic practices, architecture deals with concrete material and is not purely ephemeral, but its construction needs the coordinated execution by many people. Architectural drawings cannot be reduced to "pictures" of a future building, according to Goodman; he compares architectural drawing with a musical score, an instruction that combines graphic notations with texts and symbols. The instructions captured in an architectural drawing are not complete and need to be complemented through other documents, the process of building involves many decisions to be made, often requiring the architect to visit the construction site.[13]

Introducing the Machines

Over the last four decades, digital technologies have had an increasing impact on architecture to the extent that almost all design processes are mediated through digital technologies. In more conventional architectural practice[14] the impact was initially limited to the hardware and software architects use for drawing, resulting in mimicking analogue predecessors of drafting, modeling and rendering. Only more recently through the increased accessibility of computation, the development of building information modeling and the adoption of digital fabrication, have digital technologies also affected the translation between designing and making.[15] Digital fabrication has allowed for the production of designs that go beyond standardization, and inspired architect to develop new theoretical understandings and material sensibilities.[16]

The adoption of digital fabrication has once again brought materiality and making to the center of attention in architectural design, both in academia and in practice. This shift requires us to rethink the transfer between designing and making, between drawing and building, and the allocation of authorship within architectural work. A number of researchers, most prominently Branko Kolarevic[17], have argued that the adoption of digital fabrication technologies could lead to a more central position in making and construction for the architect. Suggesting a return to the role of the master-builder, shifting architecture back to its autographic origins. In contrast, Mario Carpo sees the adoption of digital fabrication technologies in architecture as the final emancipation of architecture into a fully allographic practice. *[18]*

These positions are opposed in where they allocate authorship and how they interpret the nature of transfer between design and making as affected by digital fabrication. Kolarevic[19] stresses the importance of collaboration and shared digital models and positions the architect central in this shared digital environment. Carpo[20] gives the architect full authorial control over both drawing and building by describing the cad file as an absolute and unequivocal form of representation that can be materialized regardless of place and time. While they differ in nuance, they both propose that the adoption of digital fabrication in architecture offers the potential for an increased authorship for architects, an increased control over materiality and making.

In both positions, we can read an assumption that technologies, in particular, digital modeling and digital fabrication, are neutral and transparent, collapsing the gap between designing and making. In his book "*The Death of Drawing, Architecture in the Age of Simulation",* David Scheer argues that this is part of a larger cultural shift from representation to simulation, finally catching up with architectural practice. Whereas architectural representation operates through understanding the difference between the drawn and the build, a simulation collapses this difference and *performs or behaves as* the build, at least partially and temporarily. According to Sheer, the adoption of building information modeling and digital fabrication technologies renders architectural drawing obsolete, as these technologies rely on simulation rather than representation. [21]

Extending the Journey

Based on the experience of using digital fabrication in practice and teaching, it is my assumption that there remains a role for drawing and representation, i.e. that digital models do not provide complete determination of the materialized artifact. The research project takes a close look at what happens in the transfer between file and artifact, it approaches digital fabrication not as neutral means of closing the gap between designing and making, but as a set of technologies that allow for specific ways of transferring and bridging this gap. This research questions whether digital models work only as simulation providing complete determinacy in advance or that some of the transitive properties of drawing remain, taking Robin Evans advice to extend the journey between designing and making, which might lead to novel design outcomes.

This paper is based on three design explorations that report on such journeys of going from design intent to fabricated artifact. In that sense, in this paper, I use the term allographic in its literal translation from Greek, which means “other writing”, as opposed to autographic, which means “own writing”, or “handwriting”. Rather than using digital fabrication as a technology that allows uninterrupted translation of intent into matter, it is exactly the traces of this otherness, the *allo*,[22] which interested me while undertaking these design explorations. Instead of striving for complete control over the fabrication process, the research project looks into how materials, code and fabrication machines contribute to the design outcome. How drawings, more particularly lines, have agency in the translation from idea to artifact, and allow for reaching destinations further than foreseen in either the technology or the design intent.

Lines, Threads, and Traces

Materials go through a number of transformations before being applied in architecture: processes of growth, sedimentation, synthesis. Raw matter is harvested and worked into materials, components, and products for building. Material transformations continue during construction and after, through use, aging, weathering and repair. All of these processes leave traces in the materials and the artefacts constructed from them, designing with these traces has a long history in architecture.[23]

The traces found in designed artifacts are as much the result of natural processes as they are of disciplining material through industrial processes into sheets, beams, and building components. Tim Ingold argues that the conception of architecture as being built up from geometric components, like a giant jigsaw puzzle, is only relatively recent; he locates the origins of architecture in practices of weaving, basket making, carpentry and other crafts. In these practices, form is not predefined as a kit of parts but emerges out of the gradual process of weaving of threads, or gradual shaping of materials through an understanding of their intensive makeup, as in stone- and woodworking.[24]

The use of materials in digital fabrication can be understood from the ideas outlined above: materials used for digital fabrication tend to be highly standardized and industrial[25] - sheet and block materials for cutting and milling, filament or powder for additive manufacturing - but fabricated artifacts tend to be highly specific, non-standard and unique. This has typically led to an even more complex kit of parts, where every component that makes up a structure is unique and can be described geometrically and exactly fabricated. Digital fabrication processes leave traces of their own: the trace followed by a cutting mill, the burned edges of a laser cut sheet or the layered build-up of additive manufacturing. Instead of using digital fabrication for precision and exactly replicating digital models, *substantiating lines* proposes an alternative use of digital fabrication, exploring and embracing these traces.

Design Explorations

The argument of this paper is based on my doctoral research conducted at the MMlab, Faculty of Architecture, KU Leuven, and work done as a guest researcher at the Architectural Robotics and Computation Lab of the Aarhus School of Architecture, where some of the work discussed was exhibited.[26] While the projects are different in scale, context, and focus, they emerged from an interest in digital fabrication technologies and explores their potential and limitations for design. It is only through conducting these explorations that the focus on the role of drawing in digital fabrication processes emerged and was further developed.

Encoded Matter

The *Encoded Matter* project consists of a series of design experiments that look into inexpensive, open-source and self-built, additive manufacturing as a specific fabrication technology, explores its potential and limitations. The project aimed to uncover how the materials, the fabrication machines, and the code that runs them influence the materiality of the fabricated artifacts. Important to this project is the accessible, open and hackable nature of the technology both in hardware and in software. This allows for a close inspection of how the fabrication processes leave traces and unfold in time, and how this performance can be hacked in order to achieve specific material qualities in the fabricated artifacts. During the design exploration, different series of artifacts were designed and fabricated, and a specific design tool for each of these series was developed.

Series 1: Objects Without Skins (Fig 1-4) - Going from file to artefact requires processing a digital model through a machine specific software. In additive manufacturing this means going from a digital model describing the outer shape of an artefact – as a triangulated mesh – to a file that encoded the movement of the tool head and describes the fabrication process and how it unfolds in time – a g-code file. The starting point of this series was to go beyond the volumetric description of the artifact as a mesh and directly generate

the g-code from within a custom developed design tool, written in Processing[27] and Grasshopper[28]. This results in material qualities that are radically different from what the fabrication technology normally produces, and actually exploits the difference between the encoded file and the materialised artefact, not as a failure but as design potential.

Series 2: Hatching with Matter (Fig 5-7) - In architectural drawing, hatches and line-weights operate as symbolic notations of materiality, some properties of the represented material are reflected in how the hatches and lines are drawn, e.g. thicker lines and denser hatches tend to represent heavier and denser materials. The series of artefacts explore digital fabrication as drawing with matter. Instead of approaching hatches and lines as a symbolic notation, they are used directly to control translucency and density of the material. The same algorithms used for generating the fabrication files are used for making drawings through a pen plotter. These drawings are themselves outcomes of the same processes, they are not made as notations prior to fabrication, and the process of making them enacts a performance similar to the movement of the tool head of the fabrication machine.

Series 3: Pushing Material and Machine Limits (Fig. 8-9) **-** Like all digital fabrication machines, the 3D printer used had limitations[29]: the size of the print was limited, shapes with overhangs cannot be printed, it has a relatively slow speed and only specific material can be used. The resulting prints clearly show material traces of the printing process: the flat bottom due to the heated bed, the visible layers and threading where unsupported overhangs occur in the model. Instead of printing finished objects panels were printed that could be assembled into larger objects afterward. The panels were kept flat, so printing times were greatly reduced. Because of the heated bed, the panels had a flat side and a more articulated side. While assembling, both of those sides could be used as an outside of the object, resulting in radically different artifacts with a materiality and scale that went beyond what normally can be produced with these machines.

The main contribution of this project lies in the shift of describing the form of an artifact to encoding the process of fabrication in time, and the material qualities that are afforded by this shift. The digital drawing encodes the movement and material deposition of the printer as a series of lines. However, these do not completely determine the artifacts; it is only through the actual performing of the act of making, substantiating these lines, that the materiality of the artifacts is achieved.

Hybrid Territories.

Robotic hotwire cutting (RHWC) has been pioneered by Asbjørn Søndergaard, Jelle Feringa, and Wes McGee at the Aarhus School of Architecture, TU Delft and Taubman College of Architecture[30]. The most common use of the technology is to use a heated nichrome wire mounted on an industrial robot arm to cut blocks of eps foam. The resulting blocks are mostly used as molds for casting concrete, but can also be used as positive pieces in prototypes and installations. The main advantage of this technology is that it is fast compared to milling of eps foam, where materially is gradually milled away.[31] I have participated in the Soft Structures workshop taught by Anders Kruse Aagaard and Ryan Hughes[32], introducing participants to the design, the programming of a robotic arm, the cutting and casting process. In order for the concrete not to adhere to the mold we experimented with various textiles, demolding and retarding agents, resulting in different surface finishes.

As a continuation of the Soft Structures workshop, Ryan Hughes and the author developed a hybrid fabrication approach that combines hotwire cutting with milling. Instead of mounting a fabrication tool on a robotic arm (tool-to-part), the robot arm picks up a block of foam and moves it to several tools positioned around the robotic arm (part-to-tool). The resulting process combines the speed of hotwire-cutting with the precision of milling; geometrically the parts combine the ruled surfaces of hotwire cutting and the lines of the tool paths of the milling. The casting process was further developed so that both pieces of foam cut-off by the hotwire were used as a mold. The resulting pieces on one side had a milled surface and on the other, a hotwire cut ruled surface.

In total nine pieces were produced, to be assembled into a wall or screen, gradually becoming rougher towards the top, this effect was produced through increasingly distorting the toolpaths. While the instructions for milling the foam are, only a list of targets the robots move the block towards, the shape and size of the milling bit determine the thickness of the line this produces. The materiality of the parts is further influenced by the material composition of concrete, the process of casting and demoulding. From each step of the process: the foam block, the mold and the final cast piece, high-resolution 3D scans were made. These scans were combined and overlaid with the machining instructions in a piece of software, which slowly panned and

zoomed through these hybrid territories (Fig. 10-12), revealing the negotiation between toolpath and materiality, between mould and casted surface, between lines and substance.

Timber Roof Structure
This project was made as a continuation of the modeling process for a renovation project of a single-family house by Perneel Osten architecten[33] (www.perneelosten.be), in collaboration with the author. During the architectural design and development process a number of material and digital design models were produced: sketch models, scale models, explicit digital models, parametric models, presentation models and mock-ups[34]. The parametric models allow for variations in design to be explored differently than other types of design models and have the ability to inform design decisions and their flexibility to respond to local changes.

The central element of the architectural project consists of a timber roof structure (Fig 14-17) that covers the existing part of the house, is folded over the new extension and comes down to demarcate the entrance and exterior functions. For the largest part of the project, the timber roof structure is visible, both on the inside and on the outside. The roof structure is supported by new and existing brick walls and three concrete volumes. It unites different spaces, providing a similar architectural articulation throughout the project while adapting to the new and existing support structures, and articulating local spatial conditions.

Three parametric models were made during the design of the roof structure and its support structure, encoding geometric and material constraints, allowing for exploring design variations and providing feedback: (Fig. 13) a model for designing the overall shape of the roof folded over the existing building and the extension, and defining the material articulations of the primary and secondary beams, (Fig 18-19) a model for designing the concrete volumes and the necessary formwork for construction and (3) a model resolving complex timber joints where varying numbers of the main beams meet. Instead of making one master mode aiming to control the overall geometry, this agile modeling approach is developed to tackle specific design issues when they arise during the design process.

The first two models are mainly concerned with geometric and structural issues, folding the roof and keeping it planar, and providing control over the distancing of the primary and secondary structures, their result is a clear structural diagram, consisting of the axis-lines for the beams meeting in a single point in space. The third model (Fig. 20-23) looked into the challenges that arise from materializing these structural axes, incorporating geometric, structural and fabrication constraints in a parametric model of each of the joints of the timber structure. The axis lines negotiate between several scales of the structure: while they resolving structural issues on the larger scale, thickening them and fitting timber beams to them provides a whole new set of design challenges. The main design issue here is geometric: given that all the beams are rotated at different angles, they have different heights when they meet in the joint.

During my research stay in Aarhus I fabricated two prototypes as a possible solution for those joints. The prototype combines steel fins which have been cut with a waterjet and wood that has been milled with a 5 axes CNC, the whole is bolted together. In going from the axis-lines to a materialised artefacts, tolerances and fabrication constraints, and material behaviours had to be taken into account: a pocket was milled in the wood to make place for the material of the weld, tolerances where introduced for the countersinks and whole for bolting, laser-cut jigs were used as support while welding the steel. The timber and steel joint demonstrates that material behaves, wood warps when drying, steel deforms when welding and diverges from the geometries describing them, but also that the precise and carefull use of digital fabrication machinery allows for designing anticipating these behaviours through tolerances.

Conclusion

The design explorations are different in their origin in practice and teaching, their scale and the kinds of research they give rise to: The *Timber Roof Structure* design exploration is clearly project driven; the questions emerge from resolving issues of structure and fabrication in order to achieve a structure that negotiates spatial experience and material articulation. The *Hybrid Territories* project can be described as technology-driven research, where a specific technology is scrutinised to uncover what material qualities can be achieved in the application of this technology. Whereas the *Encoded Matter* project started out as technology driven, it evolved into a more process-driven research, directly addressing the role of drawing in a design process mediated through digital fabrication, without necessarily working towards a direct application. All three, however, demonstrate how substantiating lines might be used as a way of researching design processes

mediated through computation and digital fabrication.

The fabrication machines used in these design projects, and the fabrication processes they afford, leave their own marks in the fabricated artefacts: the visible layered structure, limits in size, and the flat bottom of the prints due to the heated bed, the impossibility of printing overhangs and the visible material threads in the *Encoded Matter* project. The traces of the mill and the ruled surfaces in the *Hybrid Territories* project, as well as the material traces of moulding and casting concrete. The various textures resulting from milling the timber beams in the *Timber Roof Structure* project. The machines, being material contraptions driven by code, inherit aspects and qualities from both the material they work with and the code that runs them. Moreover, taking digital code as an input and generating material objects as an output makes traces of the code apparent in the material world. Instead of seeing the grain, the resolution and visible traces of the technology as a problem, something to be resolved through a better, newer version of the technology, we can design for and with these qualities, it is these qualities I describe as being allographic, thus extending the notion to include agency of code, matter and machine.[35]

This paper questioned whether the introduction of digital design technologies leads to a shift toward an allographic design practice, or allows a more autographic role to be reclaimed. While the scale, scope and nature of these projects leave many questions unanswered, from a distance, these projects look very similar to an autographic, crafts-like endeavour; but that fails to notice the allographic qualities that drive this work. The design projects described in this paper started from wonder for and an interest in making material things, and the pleasure I find in unravelling and understanding the inner workings of both code and machines. The source of this wonder and pleasure lie in the allographic qualities found in material, code and machine. I do consider myself the author of these works, but their specific qualities could only emerge in the mangle[36] of a design process that operates between the material and digital world, and negotiates with agencies external to those of the designer.

The paper demonstrates that there remains a distinction between the digital file and the resulting material artefact, that our material world is not made up of vectors, pixels and meshes, albeit informed by them[37]. In that sense digital models, although they might be intended as simulations that provide complete determinacy in advance, retain the transitive qualities that characterise architectural drawings. The paper described different kinds of lines and their agency in the design process mediated through digital fabrication: (1) the trace, a line resulting from an act of fabrication, the trace of a mill or a hotwire cutting through foam as demonstrated in the *Hybrid Territories* project; (2) the thread, or the gradual build-up of the artefacts in the *Encoded Matter* project, directly drawing or hatching with matter; (3) the folded line of a triangulated roof that becomes an structural axis line in the *Timber Roof Structure* project, that negotiates between structural scheme and its materialisation. These kind of lines produced during the design explorations, while far from being an exhaustive list, demonstrate that designing mediated through digital fabrication can be approached as *substantiating lines,* and that such an approach can lead to novel material outcomes.

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[1] Tim Ingold*, Lines: A Brief History* (2007). p.52.

[2] This can be traced back to the Renaissance, more particular Alberti, see Perez-Gomez, Alberto, and Louise Pelletier. *Architectural Representation and the Perspective Hinge*. The MIT Press, 2000.

[3] Models also play an important role, but are not as extensively studied. see Bradley Starkey, Post-Secular Architecture, Material, Intellectual, Spiritual Models, in Marco Frascari, Jonathan Hale and Bradley Starkey, *From Models to Drawings: Imagination and Representation in Architecture* (2007). p.231.

[4] Steven Groák, *The Idea of Building: Thought and Action in the Design and Production of Buildings* (1992), p. 150

[5] Robin Evans, *Translations from Drawing to Building and Other Essays* (1997). p. 154.

[6] Robin Evans, *Translations from Drawing to Building and Other Essays* (1997). p. 156.

[7] Jeremy Till, *Architecture Depends* (2009), pp. 44-56.

[8] For an interesting discussion outlining different contemporary positions, see Riedijk, Michiel, *Architecture as a Craft: Architecture, Drawing, Model and Position* (2010).

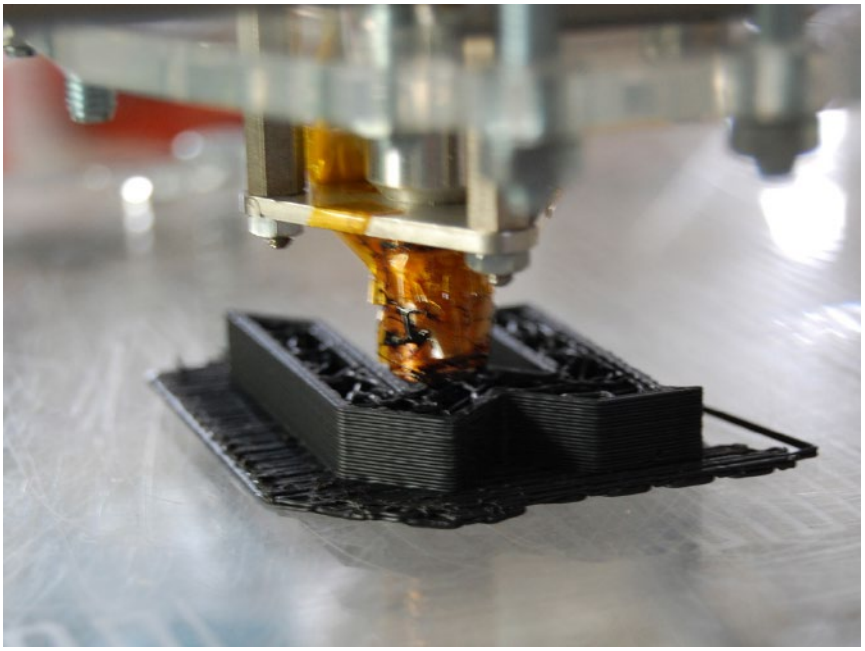
[9] Jeremy *Till, Architecture Depends* (2009), p. 45-63.

[10] Stan Allen, Mapping the Un-mappable, in *Practice: Architecture, Technique + Representation* (2009). p.41

[11] Nelson Goodman, *Languages of Art (*1976). pp. 99-174

[12] This is obviously a generalization, many examples of sculpture and painting can be found that are partly executed by other hands than that of the artist.

[13] Stan Allen, Mapping the Un-mappable, *in Practice: Architecture, Technique + Representation* (2009). pp. 48-49.
[14] Ever since the late '60 computation has inspired more avant-garde architects, see for example the early work of John Frazer, Frazer, John. *An Evolutionary Architecture*. London: Architectural Association, 1995.
[15] See Stephen Kieran and James Timberlake, *Refabricating Architecture: How Manufacturing Methodologies Are Poised to Transform Building Construction* (2004) and Neil Leach, David Turnbull and Chris Williams (eds.), *Digital Tectonics* (2004).
[16] See Gramazio & Kohler. Digital Materiality in Architecture. Baden: Lars Müller Publishers (2008)
[17] See Stephen Kieran and James Timberlake, Refabricating Architecture: How Manufacturing Methodologies Are Poised to Transform Building Construction (2004), pp.27-31. and Branko Kolarevic, "Information Master Builders" in Branko Kolarevic, Architecture in the Digital Age: Design and Manufacturing (2005). pp. 55-62.
[18] Mario Carpo, *The Alphabet and the Algorithm*, Writing Architecture (2011), p. 78.
[19] Branko Kolarevic, "Information Master Builders" in Branko Kolarevic, Architecture in the Digital Age: Design and Manufacturing (2005). pp. 55-62
[20] Mario Carpo, *The Alphabet and the Algorithm*, Writing Architecture (2011), p. 78.
[21] Scheer, David R. The Death of Drawing: Architecture in the Age of Simulation. (2014).
[22] Allo or otherness is used by Kostas Terzidis to describe the contribution of algorithms to a design process, see Kostas Terzidis*, Algorithmic Architecture* (2006), p. 27.
[23] While many examples could be given of architects and designers with a particular attention for these traces, I refer here to the books by Jonathan Hill, *Actions of Architecture: Architects and Creative Users* (2003) and *Immaterial Architecture* (2006), see also Ingold, Tim. *Making: Anthropology, Archaeology, Art and Architecture* (London, New York, Routledge, 2013).
[24] Tim Ingold, *Making: Anthropology, Archaeology, Art and Architecture* (2013).). pp. 47-48.
[25] There as been research into scanning natural materials for later use in digital fabrication, example the Woodchip Barn developed by AA at Hooke Park. See http://designandmake.aaschool.ac.uk/woodchip-barn/, consulted on 20/06/2017.
[26] See http://aarch.dk/info/updates/exhibitions/corneel-cannaerts-exhibition/, consulted on 01/03/2018
[27] Processing is an open source creative coding platform, developed at MIT Media Lab, see www.processing.org (consulted on 10/10/2017).
[28] Grasshopper is a parametric modelling environment for Rhinoceros, see www.grasshopper3d.com (consulted on 10/10/2017).
[29] Several printers were used: A Makerbot and an Ultimaker.
[30] Wes McGee, Jelle Feringa and Asbjørn Søndergaard, 'Processes for an Architecture of Volume', in Proceedings of Rob|Arch 2012:Robotic Fabrication for Architecture, Art, and Design (Vienna: Springer, 2012), pp. 62–71. And Jelle Feringa and Asbjørn Søndergaard, Fabricating Architectural Volume: Stereotomic investigations in robotic craft in, Gramazio, Fabio, e.a. Fabricate: Negotiating Design et Making. 2014.
[31] Anders, Jelle and ODICO reference.
[32] See http://aarch.dk/info/updates/exhibitions/soft-structures-exhibition/, consulted on 01/03/2018.
[33] See www.perneelosten.be, consulted on 01/03/2018.
[34] This project was part of the exhibition *Maatwerk \ Massarbeit: Architektur Aus Flandern Und Den Niederlanden*, 2016-2017 at the Deutches Architecturmuseum, Frankfurt.
[35] My understanding of agency has been developed by undertaking this research and is aligned with Andrew Pickerings notion of non-human agency, see Pickering, Andrew*. The Mangle of Practice: Time, Agency, and Science* (1995) and Knappert and Malafouris argument for material agency, see Knappett, Carl, and Malafouris, Lambros (eds.), *Material Agency: Towards a Non-Anthropocentric Approach* (2008).
[36] See Pickering, Andrew*. The Mangle of Practice: Time, Agency, and Science* (1995). pp. 21-26.
[37] Sheil, Bob, Distinguishing between the Drawn and the Made in Menges, Achim. *Material Computation: Higher Integration in Morphogenetic Design* Architectural Design. (2012).



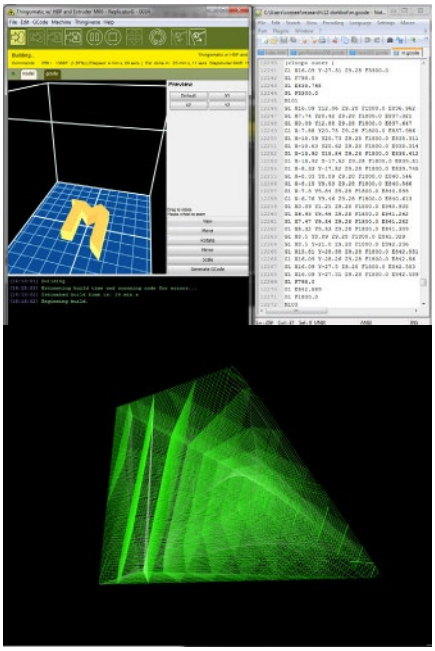


Fig. 1-2. Encoded Matter: Pushing Machine Limits

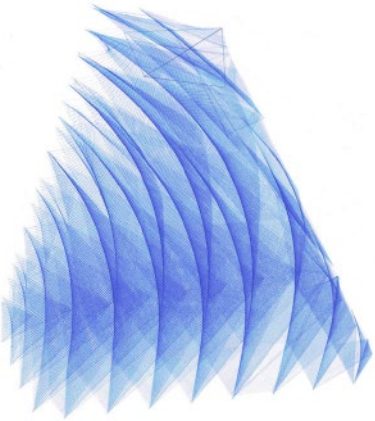
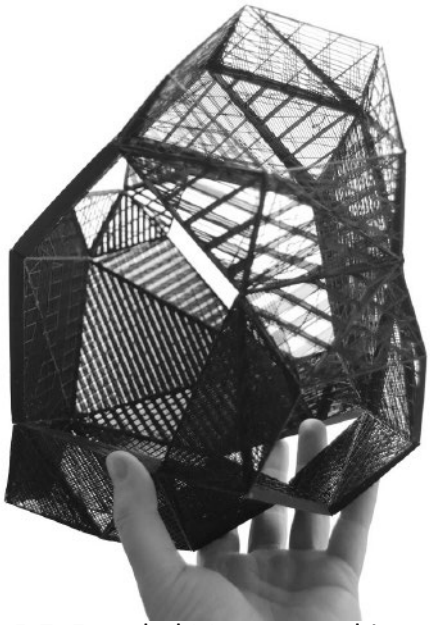


Fig. 3-4: Encoded Matter: Objects Without Skins, Artefact and Drawing



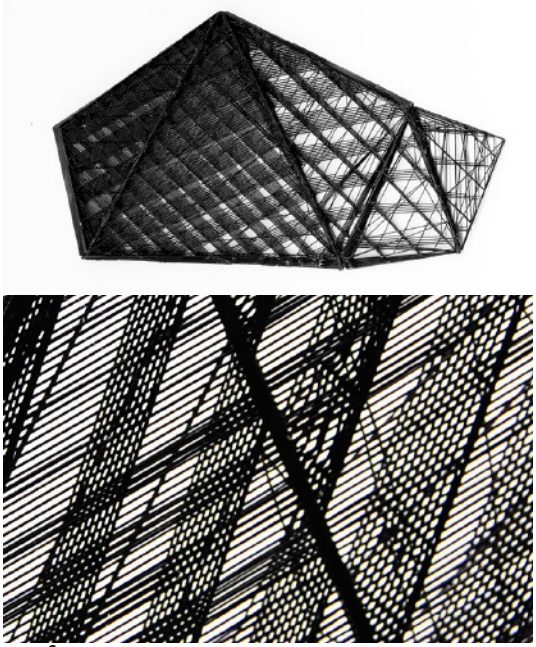


Fig. 5-7. Encoded Matter: Hatching with Matter, Artefact.

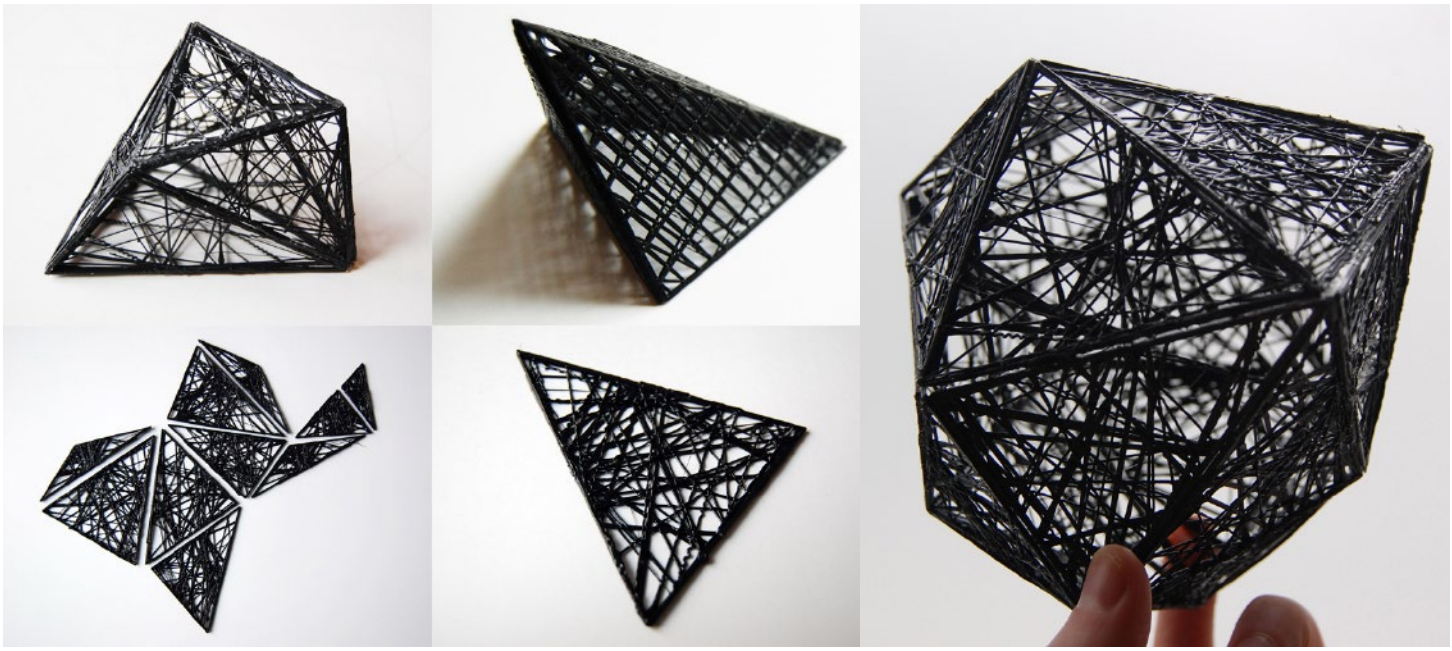


Fig. 8-9: Encoded Matter: Pushing Machine Limits

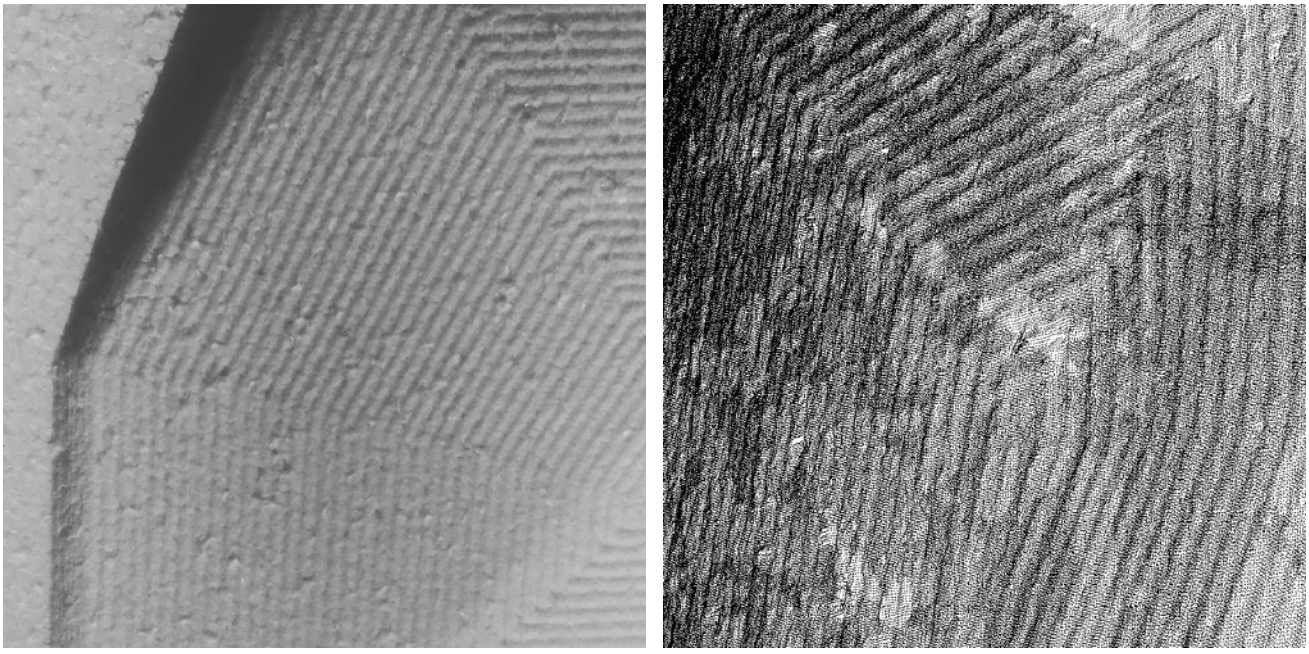


Fig. 10-11. Hybrid Territories: Photograph and Scan of Milling Toolpath.

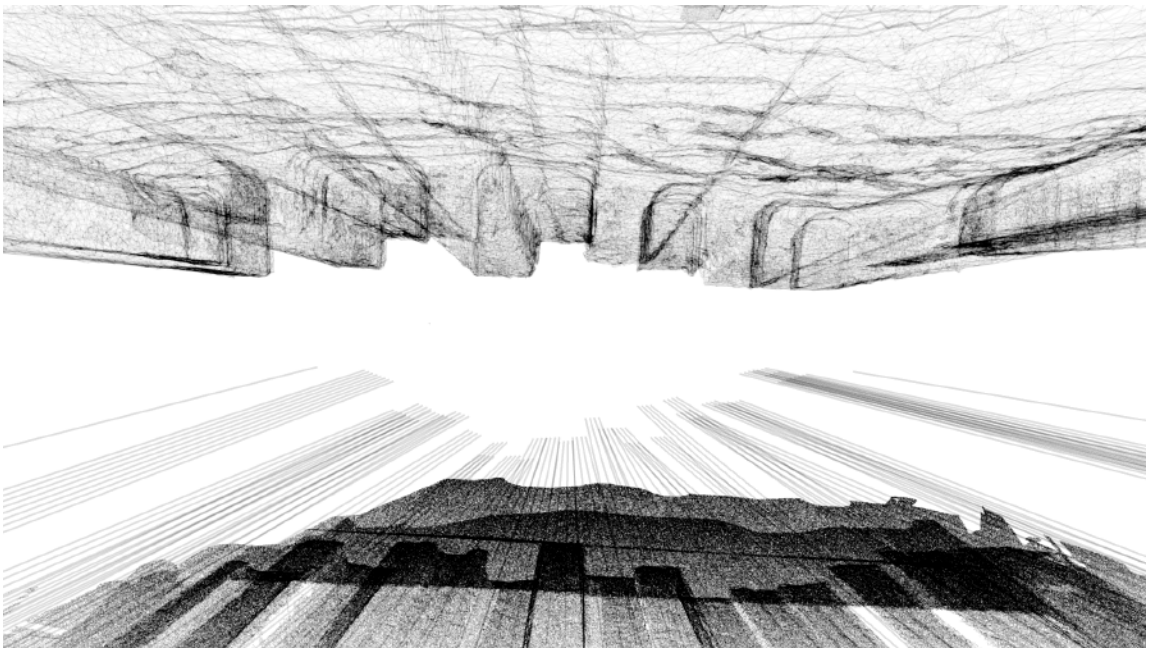


Fig. 12. Hybrid Territories: Software displaying lines and scanned surface.

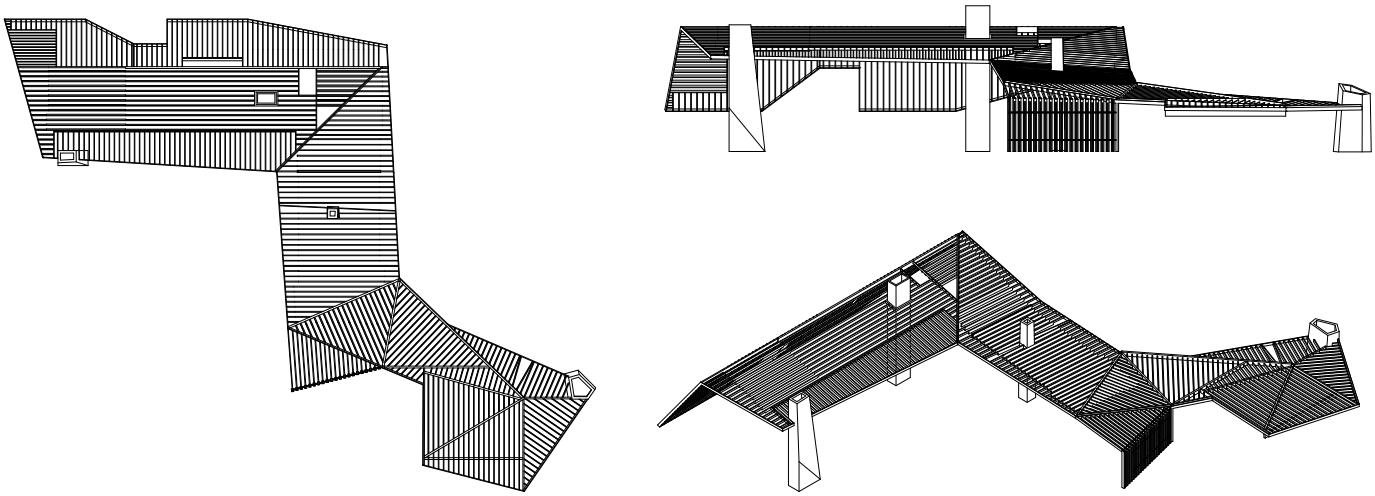


Fig. 13. Paramaetric Model 1: defining overall shape of the roof and the material articulations of the beams

Fig. 14-17. Interior photogaph of the built roof structure

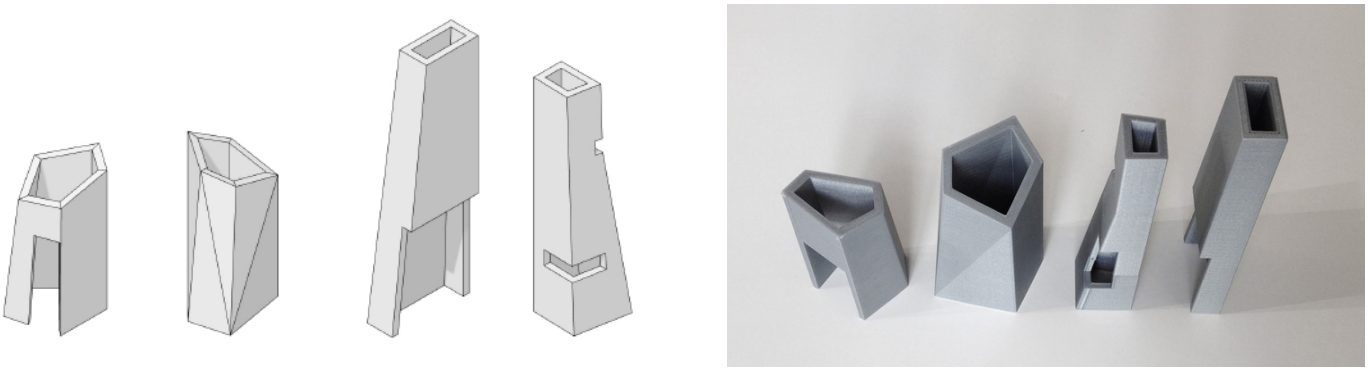


Fig. 18-19. Parametric Model 2: variations in concrete volumes and physical models

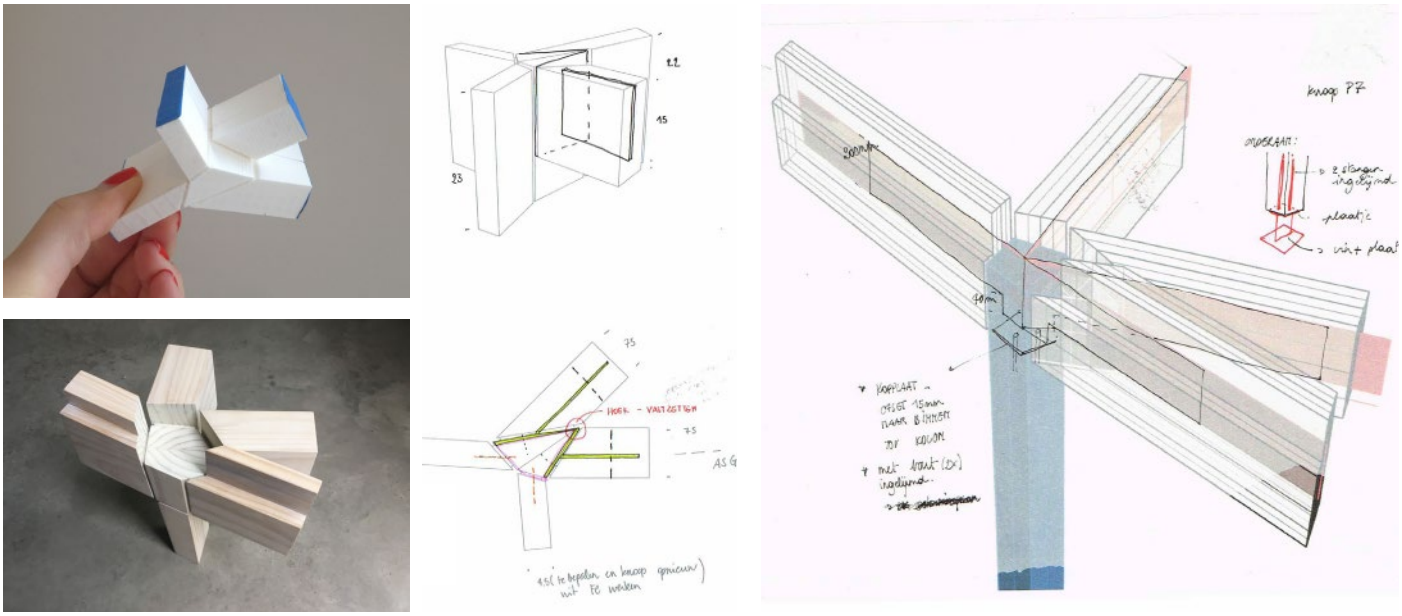


Fig. 20-23. Parametric Model 3: desinging and refining joints of main beams and physical model & mock-up.