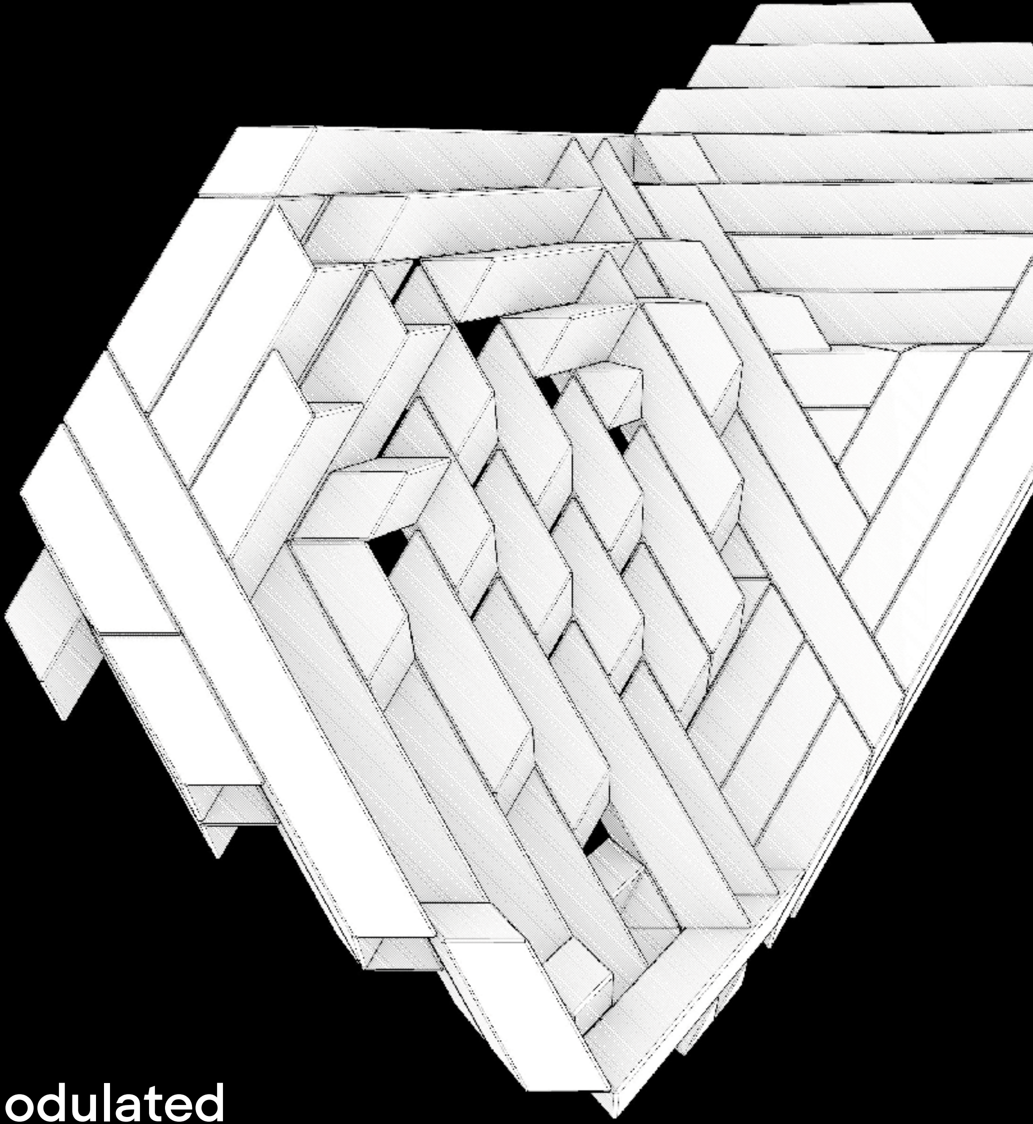
Siim Tuksam

Dissertationes Academiae
Artium Estoniae 33



Modulated Modularity — from mass customisation to custom mass production

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Moduleeritud modulaarsus – masskohandamisest kohandatud masstootmiseni

doctoral thesis

Estonian Academy of Arts 2020

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from mass customisation to custom mass production

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Preface

This thesis reports on original research based on the work of my office PART – Practice for Architecture, Research and Theory. PART was founded together with Sille Pihlak in 2015, and we both started our PhD studies in 2016. All of PART's projects have shared authorship between the two of us and often other collaborators. Within this text, whenever I refer to us, it means PART, that is Sille Pihlak and me. Although all PART projects have shared authorship, the theoretical framework and algorithmic design methods presented in this dissertation are my original contribution.

As the name of the office states, the work that we do combines the three aspects of architectural production into a unified practice. Architecture here refers to the practice of designing buildings and getting them built, research means experimental projects for testing ideas, often in a mixed academic-professional framework, and theory refers to the investigation, evaluation and communication of ideas and discoveries through text. This publication is the documentation of my main concerns within the practice over the last four years, since the founding of the office, culminating in a theoretical work, where the other two parts of the practice serve as testing ground and demonstrators.

Acknowledgements

A lot of this work would not have been possible without clients and partners like Tallinn Architecture Biennale, Tallinn Music Week, the Faculty of Architecture at the Estonian Academy of Arts and others. Marten Kaevats, head curator of the 2015 Tallinn Architecture Biennale, invited Sille Pihlak and me to curate the main exhibition of TAB 2015, which was the critical impetus for founding PART. Veronika Valk-Siska invited us to curate the Open Lecture Series and to start junior researcher positions and PhD studies at the EKA Faculty of Architecture and has been a catalyst and supporter in many other professional endeavours. Thank you!

The thesis has been tested in biannual RMIT Europe Practice Research Symposia, where a number of peers and colleagues have given critical advice and guidance over the years. I am especially grateful to Roland Snooks for being critical and supportive at the same time but of course many others, who have given feedback in the panels and helped me wind down after hours.

I would like to thank my supervisors: Antoine Picon, whose writings have greatly influenced my thinking and whose advice has guided me towards a more coherent theoretical framework within this thesis; and Renee Puusepp for checking up on the proper scientific nature of this creative research.

None of the accomplishments of PART would have been possible without Sille Pihlak, who is the other half of PART and co-author of all PART projects and whose incredible persistence and determination is the key ingredient in our experimental practice.

The thesis has been supported by Riigi Kinnisvara AS and Tallinn city Raestipendium.

Introduction

The construction industry today is facing enormous challenges – climate change and the resulting regulations in construction (Directive 2010) create unprecedented pressure to achieve cost-cutting, efficiency, standardisation and automation (McKinsey 2017). Although technological development is increasing productivity and overall wealth, it is one of the main reasons for rising inequality in many countries (UNDESA 2020). The rise of conservatism is understandable in the given circumstances; however, it is not going to solve the issue. Automation is too efficient to be stopped. The construction industry is heading towards complete digitalisation. For architects, the only way to influence the process is to become a part of it.

The computational mindset is playing an increasingly important role in our lives. The question is how people can remain human in such an automated dark age (Bridle 2018). Is there still room for architecture as an autonomous discipline within this highly restricted and regulated field? And how can we understand autonomy at all in a hyper-networked world? Of course these questions are not new. As Antoine Picon writes in the introduction to Jean-Nicolas-Louis Durand's "Précis of the Lectures on Architecture":

> *What has not changed … is the nature of the challenge that Durand confronted: the possibility of maintaining architecture as an autonomous discipline on the threshold of a world increasingly dominated by scientific and technological rationality.* (Picon 2000: 3)

Computation has influenced architecture since the beginning of computational thought (Caetano 2020), and as a term is too wide to categorise the focus of this thesis. This thesis reports on original research into how design thought has developed within the critical discourse of digital architecture. From overcoming complexity and contradiction by translating smooth topology into variable tectonics (Lynn 1996) to using ever more complex algorithms to handle complexity (Sakamoto 2008, Schumacher 2012) and in parallel using other algorithms to create complexity and emergence (Aranda/Lasch 2006, Terzidis 2006, Snooks 2017, Andrasek 2018), developing more and more intricate ways of fabrication to integrate physical processes into the creation of exuberant form and materiality (Gramazio/Koehler 2010, Menges 2012) and eventually reconcile this discourse with the realities of the digitally augmented construction industry – breaking out of the research lab.

This is where the research turns experimental, testing design approaches of the digital within the Estonian timber house manufacturing industry and eventually expanding to a more general understanding of contemporary industrial fabrication and construction practices. One of the most significant recent changes in digital architecture thinking, led by a growing will to construct buildings rather than research pavilions or high-end museums, has been to take contemporary industrial production processes as a given and using algorithmic design to tackle these and other environmental, economic and societal realities, while still building on the established discourse of digital architecture. This notion of a certain pragmatism has been part of the discourse with varying degrees of prominence. Digital tools in architecture have foremost been used to optimise existing processes. The digital drafting tool AutoCAD was released in 1982 (Caetano 2020: 168). What is different is that digital technology and culture has come a long way since, and that allows the critical discourse of the digital to be reconciled with the more pragmatic computational discourse. I would argue that the discourse on digital architecture has resisted the scientific and technological rationality of computation to avoid losing its autonomy. Through the experiments made within the scope of my research, in collaboration with industry partners, it is evident that the postulates of digital architecture must be reconsidered – infinitesimal variation needs to be questioned and modularity introduced. Like the renewed interest and extensive recent developments in the once forgotten artificial intelligence and virtual reality, the sensibilities of early computational art from the post-war heyday of cybernetics also seem to be creeping into the design language of current architectural design connected to automation and machine intelligence. Through the notion of this revival and the reading of Reyner Banham's "The New Brutalism" (Banham 1955) and Todd Gannon's interpretation of Banham's work (Gannon 2017), the striking similarities between the description of new brutalism and the aforementioned current trends in digital architecture, are a good reason to categorise them as computational brutalism.

The ambition of this research is, in the current context and moment in time, to develop an original design method that operates within a defined discourse of digital architecture and, by entangling the underlying motivations and considerations in developing this method, to contribute to the discourse. What this discourse is, is the subject of the first chapter. The method is based on non-speculative modes of construction – not something that will be possible in the future, but something that is applicable here and now. By testing this approach in a series of experiments the developed design method has reached a level of maturity that has been demonstrated in various structures built within the scope of this research. Looking back at the work, it is evident that on an abstract level, some of the discoveries made during this process are generally applicable beyond the discourse of digital architecture, in design for the automated industrial production of buildings.

Investigating modularity in digital architecture, I arrive at modulation, which is the negotiation between the utilitarian method of dynamic geometric systems based on conditioning circumstances and the architectural expression of the otherness of the real, through the emergent qualities of these geometric systems. Or to put it more simply: modulation is the negotiation between rules (nature and society) and expression (user, author and discipline). Or to draw a parallel to an over-used expression about architecture, in Old French modulation, coincidentally, stands for the act of making music.

Dynamic geometric systems are computationally constructed geometries that can be manipulated and constructed with precise interdependencies so as to make them adaptable to various needs (Aranda/Lasch 2006: 9). The conditioning circumstances include all the codes, regulations and laws of both nature and society (like wind load, maximum buildable area, or dimensions of timber). Emergence (Holland 2000) is a quality found in both natural and social systems and is characterised by otherness, the non-human quality of self-organising systems. The real is a term I borrow from Picon, meaning the underlying structure, "that enables reality to unfold, or as a virtuality that triggers the unfolding of reality" (Picon 2010: 212). Similarly, the German term *Raumstruktur* refers to the idea of spatial potential conditioned by nature and society; it has been used by the German architect Eckhardt Schulze-Fielitz, who referred to it as a macro material, capable of modulation (*Modulationsfähige Makromaterie)* (Schulze-Fielitz 1960: 168).

The term modulation (from Latin *modus* – proper measure) in this context refers to carefully measured dynamic change, variation or play on modularity. The real as an abstract idea is too complex to be the basis for any actual spatial structure. Modulation therefore helps us decide which aspects of the real are essential and which are not – which of them to include in the computational model of the real and what is their proper measure. My aim with modulated modularity is to describe an algorithmic approach to modular architecture that connects rule-based emergence with subjective manipulation, while keeping in mind contemporary industrial methods of (pre-)fabrication for modular architecture, most often dealing with timber materials, like cross-laminated timber (CLT), plywood or glued laminated timber (glulam).

I am interested in the intersection between contemporary (non-speculative) means of construction and digital design as heterogeneous, emergent and non-deterministic. Is this algorithmic indeterminacy applicable in design for construction in the current context considering also cost and sustainability? What are the strategies for maintaining algorithmic sensibilities, while optimising for the realities of economics and construction? In order to answer these questions modulated modularity proposes a rethinking of one of the fundamentals of modern architecture – the grid. Creating non-standard modulated grids (*Raumstruktur)* results in non-standard modularity that is based on custom mass production as opposed to standard mass production or mass customisation.

Research questions

When starting this investigation in 2016 we were working on how to build on the experience of curating *Body Building,* the main exhibition of the Tallinn Architecture Biennale in 2015 (Fig. 1), and our first installation, built as an extension of the exhibition in front of the venue (Fig. 2). The aim of the Body Building exhibition and installation was to map the current state of digital architecture.

> *Body Building, the main exhibition of Tallinn Architecture Biennale TAB 2015 is looking at hybrid forms of construction where cutting-edge technology and science meet the self-driven variability of material systems and where the degrees of freedom and control define an outcome of multiplicity within tolerance, trying to find a balance between the unruly and the predictable – body and building*. (Pihlak/Tuksam 2015: 3)

The exhibition was organised on a two-dimensional field of digital–physical and control–autonomy. The four corners of the field describe extremes of genesis: digital/controlled (abstract geometry), physical/controlled (material informed geometry), physical/autonomous (material computing), digital/autonomous (generative algorithms). Our installation was trying to combine these extremes into a coherent body-building. From this process, trying to bring our ideas of digital design into contemporary construction, many shortcomings in our thinking and in the processes of moving from design to construction surfaced.

From my earlier experience, as an intern at Gehry Technologies in 2010, I had been concerned with the duality of the technical vs the artistic. The job at Gehry Tech was to post-rationalise architectural projects: breaking down design surfaces into architectural elements and detailing them. (Fig. 3) The people working there were mainly architects. It is clear that specialisation is needed and architects with different skill-sets work at different stages of projects. At the same time, the digital is an enabler of collective intelligence (Hight/Perry 2006), meaning these different know-hows could be utilised almost simultaneously and horizontally or at least in a feedback loop. The initial question for me was then how to combine the conditioning circumstances with architectural expression without compromising one for the other? Based on the experience from the Body Building installation, further investigation was needed on how

Fig. 1. Body Building exhibition, Tallinn Architecture Biennale 2015, PART Architects.

Fig. 2. Body Building installation, Tallinn Architecture Biennale 2015, PART Architects.

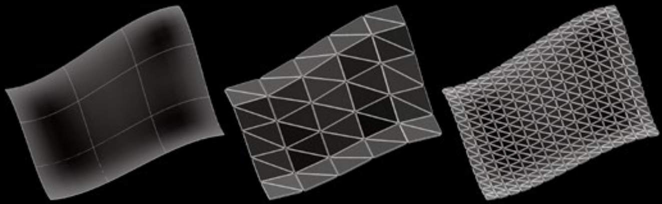

Fig. 3. Surface panelisation.

the way things are built could be changed. We saw shortcomings in the implementation of integrated design (incorporating structural and environmental analysis), the transition from file to factory, and the complexity of the on-site construction process. Which brought me to question why we do these things at all, if there is this much resistance to change. What is the cultural relevance of doing the things we do? What is the role of the architect in a data driven algorithmic process of creating architecture? At this point I would rephrase these questions:

1. How is it possible to maintain the autonomy, or even authority, of the discipline, facing the realities of extensive standardisation, automation and artificial intelligence?

2. What can we learn from computational design thinking that would help us develop design methods that are in line with both the realities of the contemporary construction industry and with the critical discourse of the digital?

3. What is the aesthetic, political or cultural relevance of these design methods?

The need to maintain autonomy is the need to maintain the freedom of expression that makes architecture part of cultural production. Considering the rising concerns about the environment and an ever increasing population, this needs to be achieved in a sustainable and efficient way. Automation and standardisation is in that sense inevitable in the architecture, engineering and construction (AEC) industry. Algorithmic design and industrial computer aided manufacturing (CAM) are under-utilised (McKinsey 2017). In PART's case-studies we saw that often the computer numeric controlled (CNC) machinery is there, but in industrial settings it is not used as in the academic environment as a universal tool for mass customisation, but rather as a tool for serial mass production, meaning once they're programmed and checked for errors they need to run uninterrupted for a while to be cost-effective. The added value of a customised product needs to meet the added cost of changing production setups (Piller 2004). Not to mention that fabrication is just the first step in the production of buildings. The construction process, but also modifications, repairs and demolition – the whole life-cycle – should be considered. The question of maintaining the autonomy is therefore seen here as how to turn the increasing amount of requirements, regulations and codes into a generative component of design. How does this influence the modulation of the *Raumstruktur* and the expression there of? I try to answer this question by investigating the relationship between standardisation and creativity – analysis and synthesis.

Assuming that in the future mass customisation would be the norm was probably the biggest misconception of the vanguard architects of the 1990s – the early digitals – who therefore disregarded modularity and repetition as repressive. Automation relies on standardisation. Robust standardisation is the basis of digital variation – hence we have concepts like pixel (picture element), voxel (volumetric pixel) and resolution (pixel density). Now, that we have reached retina resolution (higher than the human eye can distinguish), lower resolution can be explored as an aesthetic domain, where granularity, discontinuity and discreteness become qualities rather than a lack of resolution. (Fig. 4) In this context, standardisation can be seen as an enabler of variation, the creation of an open tool, rather than a restrictive set of rules. The elements of architecture need to be rethought within this framework. Computational design thinking in the middle of the last century was ahead of its time; many of the ideas of that time are starting to find application just now, most prominently artificial intelligence, which has seen rapid development in the last few years. Within this thesis the idea of the *Raumstruktur* is investigated making use of the tools of digital architecture developed over the last few decades. The real-time manipulation and simulation of these spatial structures creates an opportunity for creating bespoke designs from standardised elements. Analysis thus becomes inseparable from synthesis – an idea that can be traced through the analytical method of the Age of Enlightenment in Durand's work (Picon 2000: 42), the prefabricated structures of the middle of the last century inspired by system theory (von Bertalanffy 1968) or the flat ontology of the digital architecture of the 90s (DeLanda 2002: 47).

Once we have enabled variation, the questions of politics and aesthetics arise, which are of course related, as the distribution of the sensible, as Jacques Rancière explains (Rancière 2009). What kinds of politics do technological paradigms enable?[1] I will try to give an answer to this question; in the last chapter I will look at modulation and control through the ideas of Gilbert Simondon and Gilles Deleuze. Within architecture, technology has an immense impact on spatial organisation. What is under investigation in this research is the changing qualities of tectonic and formal articulation – how matter is organised in space to form architectural spaces and experiences. Spatial organisation and its sensibility have been studied throughout architectural history through proportion and rhythm – the human relation to artificial and natural objects. The changing perception of the body, and therefore any corpus – natural, textual, artefactual, social etc. has changed from a Vitruvian centralised hierarchical organism (McEwen 2002) to an open complex system composed

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[1] A question asked by Roemer van Toorn at the Space and Digital Reality conference at the Estonian Academy of Arts on 11.09.2019 (Tuksam 2020).

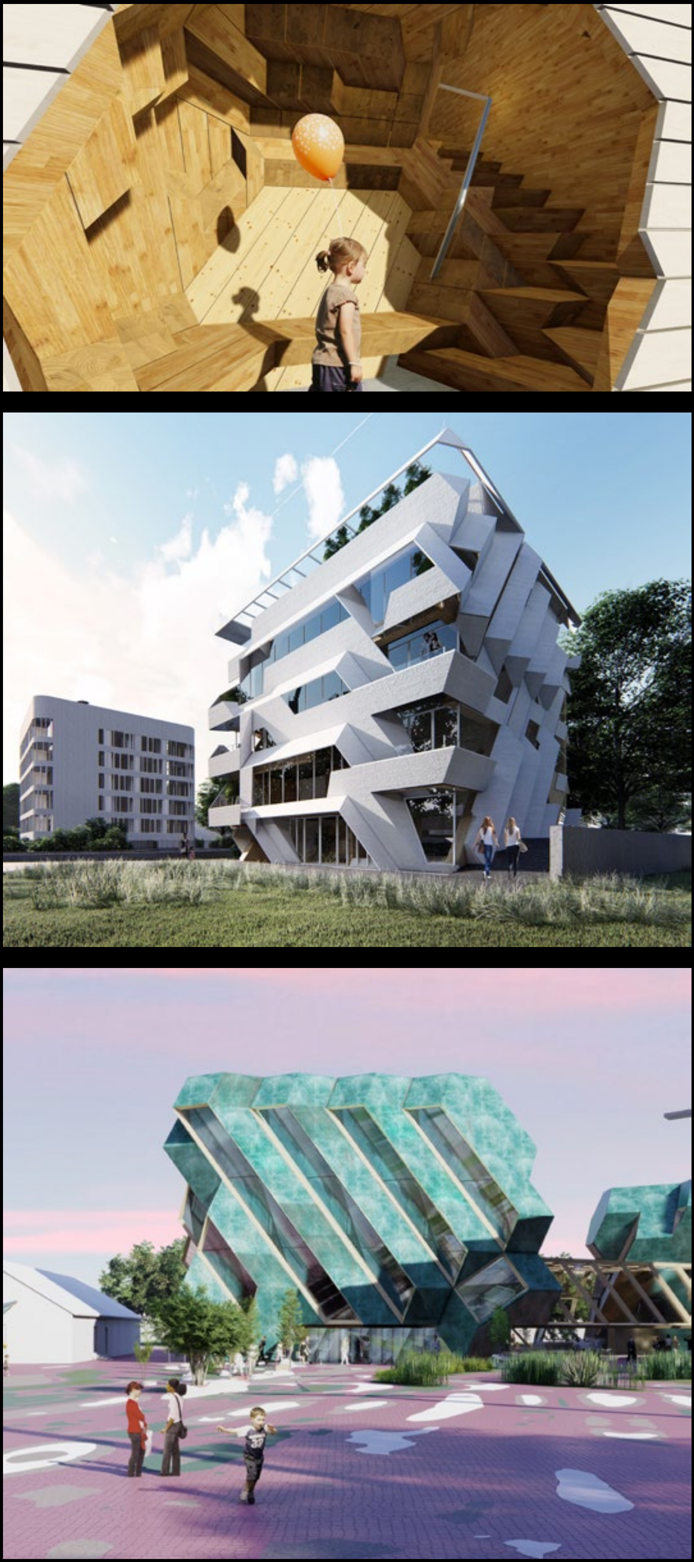

Fig. 4. Resolution in PART projects ranging from step to floor height.

of a multitude of agents and understood through computational models (Monteiro 2011). (Fig. 5) Technology changes the way we see the world, how we create it and how we want to live in it. In this sense formal and tectonic qualities are also a matter of access, access to the expressed formative forces, and therefore have a social dimension. This emergence of a communicative dimension, one of the aspects suggesting a return of the ornamental (Picon 2013) is what I assume is what Banham calls memorable image (Banham 1955, Gannon 2017). Autonomy means that the discourse of architecture develops as an intellectual discourse separate from construction. As Rancière says, "Just as there is not always art (though there is always music, sculpture, dance, and so on), there is not always politics (though there are always forms of power and consent)" (Rancière 2009: 32). Architecture needs to be different from construction. There must be an ornamental quality that ties together aesthetics and politics, the subjective and the collective. We are not just developing methods to replace concrete with timber in architecture; for instance, we are looking for a new timber architecture, one that expresses its materiality and its means of creation and production as a statement about the kind of world that we want to live in.

To study and create proportion one cannot overlook the topic of grids. Grids and regulating lines have been classically used as two-dimensional drawing aids roughly correlating with the invention of projective geometry in the 15th century (Carpo 2011: 58). At the end of the '50s, when architecture turned from object to environment (Vardouli 2011), spatial grids started to organise the emergent Spatial City (Schulze-Fielitz 1960). Bringing this idea to the 21st century, computational geometry and constraint modelling (Clayton 2014: 30), grids and regulating lines become non-cartesian coordinate spaces allowing for continuous topological transformations and nesting – spaces within spaces. Within this research these spaces have been studied for the generation of adaptive details, structural lattice systems and volumetric subdivision. (Fig. 6)

The modulation of spatial grids is among others a political and aesthetic device – a way of communication, with its own syntax. Is there then a language of computer enabled design? I would say that two main distinguished strands in construction-oriented digital architecture are currently established – the practitioners and the researchers. The practitioners, backed by big business and governments in fast developing regions, express the calculus-based sensibilities of early digital architecture. The most prominent of those, just to give one example, is probably Zaha Hadid Architects and Patrick Schumacher, the latter advocating almost a totalitarian coherence and continuity with his parametricism (Schumacher 2012). (Fig. 7) The researchers are concerned with developing digital

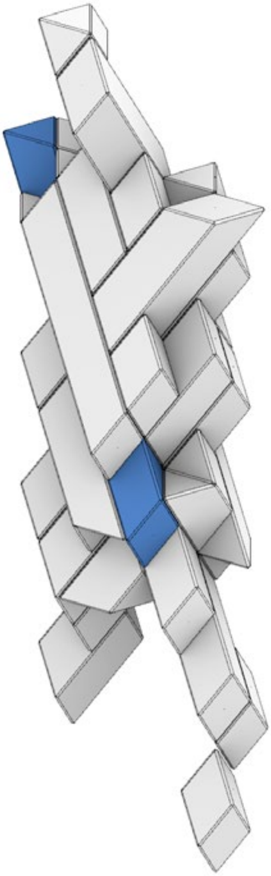

Fig. 5. The Modulated Man.

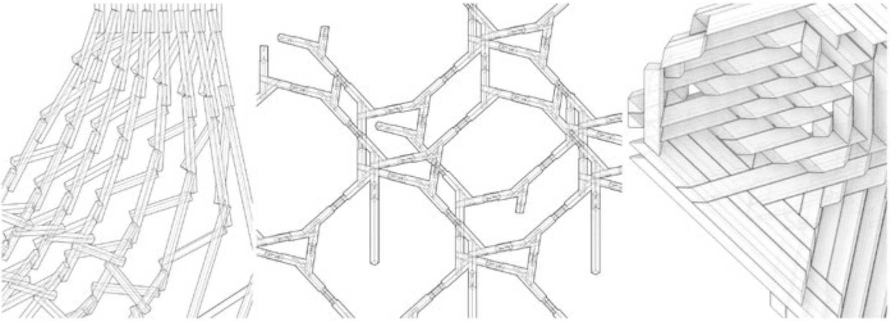

Fig. 6. Geometry samples from the Body Building installation and the Digital Thicket structure by PART Architects and the modulated modularity algorithm for generating linear elements following a base geometry.

Fig. 7. Beijing Daxing International Airport 2019, Zaha Hadid Architects.

Fig. 8. Complex Timber Structures 2013, Gramazio Kohler Research, ETH Zurich.
Photo: Gramazio Kohler FResearch, ETH Zurich.

Fig. 9. ICD/ITKE Research Pavilion 2011, University of Stuttgart.

fabrication techniques that thrive on academic research into innovative ways of design and fabrication, backed by public and industry funding. The most prominent here being ETH's Gramazio Kohler Research, led by Fabio Gramazio and Matthias Köhler (Fig. 8) and Stuttgart University's Institute for Computational Design and Construction (ICD) led by Achim Menges (Fig. 9), for example. This is not to say that they would be completely divided, but there is a definitive focus. However, there is also a branch devoted to bringing digital architecture out of the research lab and down from the ivory tower of flagship architecture, while being critical of the status quo and still developing autonomous architectural discourse, connecting practice and research. All these branches establish a different kind of language and politics yet share an underlying computational logic and are therefore subject to modulation.

Modulation is a process of optimisation. As always with optimisation processes one needs to know exactly what the parameters to be optimised are. Essentially the quest is about finding a good balance between what can be done and what is desirable. The paradox here is that limitations can be more creative than freedoms, and new qualities, the unexpected, most often arise from optimising for contradictory objectives and constraints. Modulation in this sense is not a process of finding a compromise but rather finding the perfect mixture of the right ingredients. For successful modulation, the ingredients should remain distinguished parts of the whole, not dissolve into the mix. Modulation, therefore, is a process of optimisation, where the inputs are not the ideal vs the real but rather a myriad of conditioning circumstances, some of them being structural, material, economic, social but also purely architectural, aesthetic and subjective. It is all those and other criteria that define the eventual outcome that in the end is evaluated subjectively weighing the quantitative against the qualitative. To accommodate these various inputs in a meaningful way, a certain level of complexity is needed. Ultimately modulation is about enabling an architectural language of computational emergence. Architecture has always been a combination of human and non-human affecters, a duality of nature vs culture. More recently this duality has become technology vs culture as computational (and bureaucratic) emergence has become a new non-human component of our environment. This non-human other is the locus of what is called the creative friction. In computational design this otherness is evoked through the emergent nature of the digitally automated. This creates a new duality of imposed order vs self-organisation, top-down vs bottom-up, complex simplicity vs simple complexity. Within this work I am trying to modulate these opposites.

Methodology

The work is set up as open-ended research by design, where the creative driver is the friction between the legacy of digital architecture – based on mass customisation – and the realities of working together with industrial manufacturers, standard materials, construction workers and the constraints of structural integrity, safety, sustainability, budget etc. Through a series of experiments this design research has evolved from looking at mimetic algorithms and variable tectonics towards a pre-rationalised design approach, where algorithmic tools of simulation, analysis and optimisation are created, combined and incorporated into the design algorithm. The work is projective and reflective at the same time – research by design, using experiments that turn into practice research and theoretical research. It involves the critical analysis and constant recalibration of past and ongoing projects developed by PART Architects.

The research encompasses four years of design projects that deal with algorithmic design and fabrication in Estonia, where instead of research and development within the safe space of a university laboratory, we have been using commercial projects and local industry as our testing ground. On the one hand, this is an empirical experimental study. At the same time, the work is bound by the discursive setting within the evolving discourse of digital architecture. The projects show an evolution of ideas about where digital architecture should be heading. Assumptions are tested, evaluated and rethought in a continuous loop. This thesis, therefore, is a snapshot of current ideas and topics in our practice put into the context of the current architectural field, defining our community of practice and eventually drawing out our positions and the unique contributions of the two partners of PART: Sille Pihlak and me, resulting in two dissertations looking at the same work from two different perspectives. Mine is focused on questions regarding the relation between technology and design. I am looking for ways of modulating emergence and subjectivity to flatten existing hierarchies into a field of possibilities for quantitative and qualitative optimisation[2]. The goal is to develop a hybrid design method that combines automated and subjective decision-making. At the onset of extensive algorithmic automation and artificial intelligence in the AEC industry, instruments of political intervention are a question of architectural design – computational technologies have blurred the distinction between immanence and transcendence.

In “Intensive Science and Virtual Philosophy” Manuel DeLanda describes flat ontology thus:

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[2] Qualitative optimisation in architecture is here understood as subjective intervention by stakeholders based on non-quantifiable qualities. This can be achieved by changing the weights of the objectives within the fitness function or by selecting quantitatively sub-optimum solutions.

Fig. 10. Modulation of an undulating surface in two different resolutions.

Fig. 11. The milestone projects, from left to right: the Body Building installation, Urban Jungle vertical garden and Shift Lofts timber apartment building.

> *…while an ontology based on relations between general types and particular instances is hierarchical, each level representing a different ontological category (organism, species, genera), an approach in terms of interacting parts and emergent wholes leads to a flat ontology, one made exclusively of unique, singular individuals, differing in spatio-temporal scale but not in ontological status*. (DeLanda 2002: 47)

Modulated modularity is a method where this collapse of hierarchy is explored in the creation of architectural composition, creating systems where the part and whole can exist in simultaneous change. Within this method, emergence is used as a kind of search engine – changing the properties of the parts results in sometimes unforeseen changes in the whole.[3] Within folding (Lynn 2004) populating details over a curved surface is called intricacy, where tectonics adapt to topology in a hierarchical manner. The manipulation of the design surface results in a manipulation of the generated elements. In modulation this adaptation is regulated, creating a negotiation between elements and the massing. The manipulation of the design surface results in the reconfiguration of pre-defined elements. In later PART projects the variation of elements is limited to combinatorics and subdivisions within the modulated *Raumstruktur*, most often the tetrahedral-octahedral honeycomb (Tetrahedral... 2020). (Fig. 10)

Throughout this research I am working towards a more generally applicable design method that would allow bespoke designs to be constructed out of repetitive elements. The actual standardised parts or construction elements are in constant development, meaning the objective is not to come up with one standardised building block but rather a system for developing new construction elements for each project that are then used for that project. The elements should be easily fabricated and assembled and designed using zero-waste and lean construction principles, while allowing for maximum flexibility in the design of the whole. This is achieved through real-time simulation of the effects that part-level design decisions have on the aggregation of the whole.

Structure

There are three stages clearly defined within this research that test distinct theoretical approaches and result in distinctly different architectural language. (Fig. 11) These three major steps in the development of my research are represented through three milestone projects: Body Building – object-based design, Digital Thicket – generative modularity, and modulated modularity – a negotiation between structure and image.

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[3] For example, the Digital Thicket structure is the result of exploring rotational change between elements. (Fig. 42)

The dissertation is structured around these three topics:

1. Variation – early digital architecture, characterised by curvilinearity, variation, mass customisation. The computer offers superior control over authorial creation – the elegant calculus-based manipulation of the whole drives the generation of parts. These ideas are tested in our earliest projects: Body Building, Sound Waves and Rheological Formation.

2. Repetition – system building, looking at generative methods of modular systems; characterised by emergence, complexity, self-organisation. The process of creation becomes one of search and curation – defining geometric and behavioural rules for parts generates a complex whole. These ideas are tested in a modular approach where simple elements can generate heterogeneous wholes: Digital Thicket, Here and Elsewhere, Urban Jungle.

3. Modulation – computational brutalism, an attempt to reconcile folding and modularity and rethinking digital architecture around the modulation of the *Raumstruktur*. Modulation collapses the hierarchy between part and whole to a horizontal process where the local and the global are simultaneously created, modified and analysed – enabling parallel quantitative and qualitative optimisation.

The Body Building installation, our first timber installation as PART, in its reasoning is indistinguishable from Versioning (SHoP 2002) – differentiated from Folding (Lynn 2004) only by an immediate commitment to constructability. It was produced in the local timber house manufacturing industry but was designed without any previous knowledge about working in this context. Although in terms of design language this design approach has been discarded, on a deeper level, the workflows and ideas about adaptive joinery, tolerances, types etc. have been the basis for the subsequent projects. The 1990s vision of mass customisation and endless variation have proved cumbersome to say the least, but the ideas about algorithmic principles and topology, like the computational relation between a blob and a sphere being an instance of the same, for me, are still highly relevant. The idea of multiplicity is one of the core principles of modulation: computational geometry is not static or fixed, the same logic that in one instance produces a cube, or a sphere, in another can produce a blob. (Fig. 12) It is a question of modulating these relationships to reach viable results.

These ideas were tested in the Digital Thicket project, whereby combining generative algorithms with controllable variables, the behaviour of the system could be studied to find effective patterns. (Fig. 13) The Digital Thicket series is reinterpreted by investigating the digitalisation

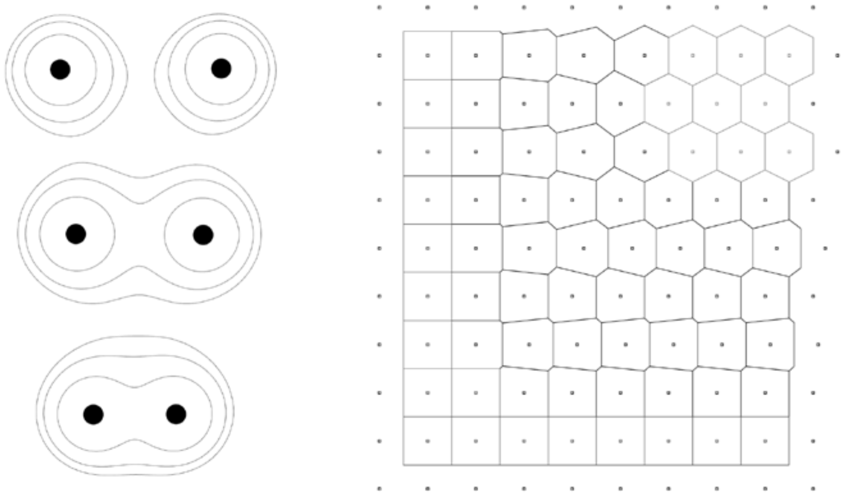

Fig. 12. Transformations in computational geometry. A sphere is a blob, a square and a hexagon are both Voronoi cells.

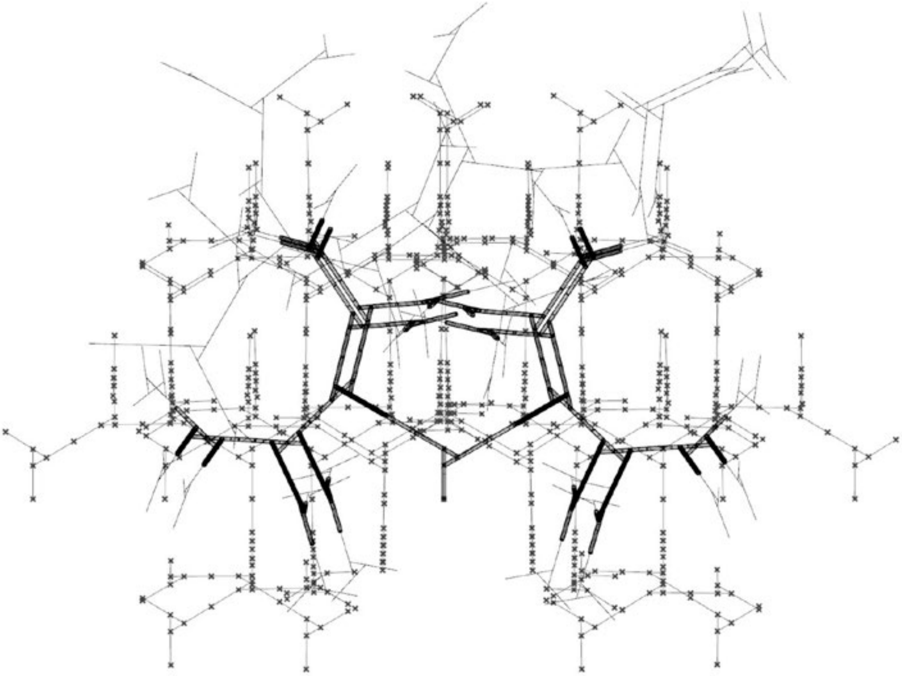

Fig. 13. Digital Thicket, early sketch. The parametric model was used as a search engine to find the final cellular lattice structure geometry.

of architecture from Jean-Nicolas-Louis Durand (Picon 2000) to Konrad Wachsmann (Imperale 2012) to Eckhardt Schulze-Fielitz (Schulze-Fielitz 1965).

The idea of multiple optimums within a field of possibilities led to modulated modularity – combining variation and repetition within a coherent but dynamic geometric system allowing for a system that combines different modules and bespoke elements in systemic continuity, an idea first tested in Sift Lofts, a multi-storey apartment building. The modulated modularity projects, while seen as part of digital architecture, are looked at in the light of mid-20th century tendencies in European architecture, through Reyner Banham's definition of new brutalism arriving at defining architectural qualities of modulated modularity as part of a wider movement of computational brutalism. This research focuses on automating the conditioning circumstances of the real into a design tool. The method developed for this end is called modulated modularity. Post-rationalisation is always an approximation of the actual design. Modulated modularity is aestheticising the discrepancy between the ideal and the actual or the ideal and the model. In reconciling heterogeneity and standardisation the question is – where do they meet? – and this is a parametric balancing act. Bringing in tools from design automation, like structural evaluation and evolutionary optimisation, creates virtual fields of possible architectures, constrained by a model of the realities of contemporary construction. Exploring these possibilities using algorithmic simulation combined with subjective design methods like drafting or modelling allows for unprecedented design solutions to be discovered. Modulation not only reconciles variation and repetition (Folding and modularity) but the emergent and the expressive – writing the cultural practice of architecture into the code of the technical field of construction. The aim of this dissertation is to describe modulated modularity as an original holistic design method, subscribing to computational brutalism, to reconcile standardisation and automation with the emergence in algorithmic architectural design – to be part of determining the form standard architecture will take – constructing the new normal.

In the following chapter, I will give my view of digital architecture as a critical discourse and show how discarding modularity and repetition argued by an idealised vision of mass customisation has turned out to be its biggest flaw.

1.

Variation – the fallacy of mass customisation

In this chapter, I will present my view of the discourse of digital architecture, within which my work operates. This is not a historical review, but rather a viewpoint on this discourse as it is understood within the scope of this thesis and the argumentation for the experimental architectural projects developed. The story begins with a promise. Computer aided design (CAD) and computer aided manufacturing (CAM) will make mass customisation possible, where not just every building but also every part of every building can be unique. Anything that is produced using digital means of design and production (CAD and CAM) can be customised and still be produced at no extra time or cost (Carpo 2011: 57). We do not need to come up with a standard solution that suits every situation, instead using computational methods, we can design objects that have variable input parameters and are thereby adaptable to each occasion. In digital architecture, this is seen as an opportunity to have each element of the building customised – to create infinitesimal variation.

1.1. The discourse of digital architecture

It is generally agreed that what is called digital architecture is what started at the end of the 80s and beginning of the 90s. It is not just architecture created using digital tools, it is architecture that could not be created without them. I use the term digital architecture as the critical discourse that evolved as a part of a broader digital culture. In 1992, the Paperless Studio at Columbia University was the first fully digital course. In 1993, Folding in Architecture is published and Greg Lynn defines digital architecture through the Deleuzian fold. In 1991, Frank Gehry won the competition for the Bilbao Guggenheim museum; in 1994, Lars Spuybroek and NOX designed the HtwoOexpo, and in 1995, Foreign Office Architects designed the Yokohama Port Terminal – three of the most prominent built examples of early digital architecture. A differentiation must be made between technically digital design; that is, design processes that make use of digital tools, and the discourse of digital architecture; that is, a stage in the evolution of architectural design, influenced by both societal and technological changes (philosophy and science) brought on by digital computation and made possible by the widespread adoption of personal computers. The use of CAD software in architecture has its roots in a much earlier time and can definitely be traced back to the 60s (Caetano/Leitão 2020). Ideas of computational design go back even farther. Based on my literature review, the discourse on digital architecture seems to have resisted the scientific and technological rationality of computation and generative design in favour of a more speculative and philosophical approach to digital tools. As the sophistication of the tools, and the designers using them, grew with time, more computational strategies were incorporated in the design process, which is why these topics are looked at in the later chapters.

Digital architecture as a term is somewhat misleading, as what is generally considered digital architecture preceded the actual use of digital tools and is based on calculus, the mathematical study of continuous change (Lynn 2004: 9), while digital, numeric, refers to discreteness. In 2004, Greg Lynn writes in the introduction to the reprint of the 1993 Architectural Design (AD) special issue:

> *For me, it is calculus that was the subject of the issue and it is the discovery and implementation of calculus by architects that continues to drive the field in terms of formal and constructed complexity. The loss of the module in favour of the infinitesimal component and the displacement of the fragmentary collage by the intensive whole are the legacy of the introduction of calculus*. (Lynn 2004: 11)

Greg Lynn describes folding with terms like voluptuous form, stochastic emergence, intricate assembly – the ideas influenced by Gilles Deleuze, Gottfried Wilhelm Leibniz or Rene Thom are still relevant. Adopting computational tools used in character animation brought a new vocabulary into the language of architecture. Using mainly default algorithms, like the Catmull-Clark subdivision,[4] Laplacian smoothing[5] and others, created a distinctively blobby design language, often detailed with the same mesh subdivision patterns. Spline modelling[6] allows for the intuitive modelling of complex shapes while smoothing out any kinks. Scripting makes it possible to define relationships, systemic thinking – constraints, relationships, tolerances, if-then statements – making it possible to go from fixed details to the parametric resolution of joinery. Simulation of forces and agents makes it possible to create formal adaptations and behavioural systems that can be analysed and optimised. All of this speaks of a desire to effortlessly manipulate materials and forces to produce elegant forms.

The early digital architects were largely influenced by Gilles Deleuze and his “The Fold: Leibniz and the Baroque” (Deleuze 1993). Leibniz as an inventor of calculus was the hero of early digital architecture.

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[4] Catmull-Clark subdivision is a technique used in subdivision surface modelling to achieve smooth continuous surfaces.

[5] Laplacian smoothing is an algorithm for smoothing a polygonal mesh, a computational surface defined by a finite number of points called vertices, connecting edges and the resulting planar triangular faces.

[6] The term spline comes from the flexible spline devices used by shipbuilders and draftsmen to draw smooth shapes. Splines are popular curves in these subfields because of the simplicity of their construction, their ease and accuracy of evaluation, and their capacity to approximate complex shapes through curve fitting and interactive curve design. (Spline… 2020).

His potential fields and monads perfectly resonated with digital architecture – rather than creating objects, the result was building systems that allow the instantiation of adapted objects, appropriate for the present situation. The early digital architects also saw an opportunity here to take the next step from deconstructivism. The form of an architectural object is indeed influenced by highly different and conflicting forces (not only physical but also historical, cultural, urban etc.), but with calculus one can fold the given forces into a coherent, continuous system. This, in turn, allows for a combination of topology and tectonics – animated form populated with adaptive components. Every design becomes a mathematical function, where the end result is calculated based on input parameters. (Fig. 14)

With regard to the realisation of such smooth forms, the question of geometry became once again an important issue. Classical and Baroque architecture came to be held in high esteem once again for their rigorous geometric construction. (Fig. 15) The study of the relationships between geometry and construction were similarly given a new boost. It was clear that with the new tools, the given relationships could be automated. The regulating lines of classical architecture have made it into today's Building Information Modelling (BIM) as geometric constraints and interdependencies, so-called construction geometry or base geometry, that 'drives' the rest of geometry (Clayton 2014: 30). These rigorously animated relationships at a certain level of complexity give computational geometry a behavioural quality, evoking the notion of emergence, where the whole has qualities that cannot be traced back to its individual parts.

Animation opens up the possibility to explore emergence as a design tool. Calculus and topological relationships enable the animation of form (Lynn 1999: 10). Lynn describes how boats are designed in a design space, where flow, drag and turbulence exist. It is a computational model of an environment, acting upon the design in its formation. In the early 2000s, a lot of simulation and animation software was explored to produce geometries relating to natural phenomena like liquid flow for instance. From there it is not a big step to agent-based systems, where elements are given rules on how to behave. These systems can then only be simulated with velocity, mass, various forces, fields of vision and attractors. These systems, initially developed to simulate real-world complex multi-agent systems, like flocks of birds or economic behaviour, made their way into architecture and started to be modelled to perform architecturally, creating space, pattern, volume. One of the most prominent architects in this line of inquiry within the digital architecture discourse has been Roland Snooks (Fig. 16) and Kokkugia, with his agent bodies being used to create fibrous assemblages and structural ornamentation (Snooks 2014). This method, however, is not just a tool for speculation.

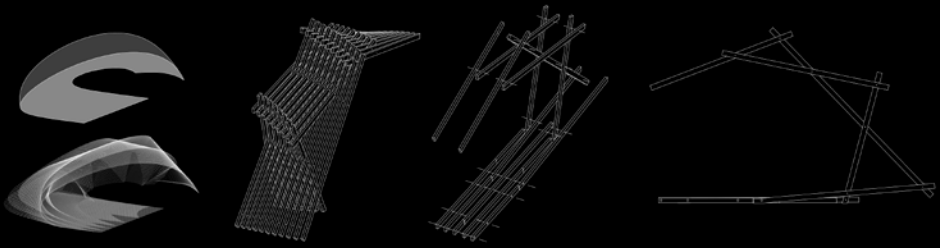

Fig. 14. Rheological Formation 2017. The smooth surface is populated with adaptive timber frames using a simple technique called contouring. Each contour is then the base for the timber frame to adapt to.

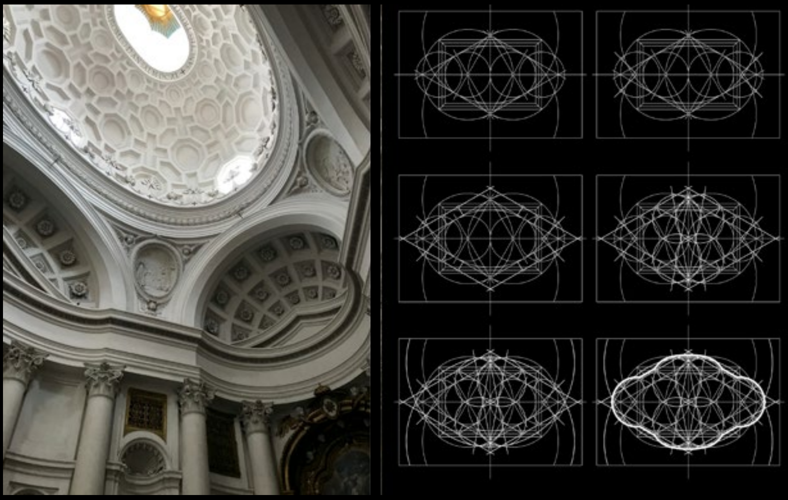

Fig. 15. The San Carlo alle Quattro Fontane church by Francesco Borromini is known for its rigorous geometric construction.

Fig. 16. SwarmRelief prototype by Roland Snooks at the TAB 2015 Body Building exhibition.

Many real-world applications are used in the study of complex systems like cities, economies etc. Similarly, this method can be used in less speculative ways within architecture.

With the rising sophistication in architectural computation and scripting, history and theory is replaced by code. The automation of architectural knowledge within CAD software and script libraries makes designers oblivious to precedent. In the evolution of digital architecture, with its hype and explosive spread, a lot of less-informed, dilettante experimentation started to occur.

> *The myth of happy accidents and unmotivated experiments could have been the product of a knowledge gap between designers and theorists or it might have had other causes. The net result was a shift from critical disciplinary use of technology to a more vocational and tool-driven approach that celebrated mindless variation without intellectual or cultural relevance.* (Lynn 2013: 14)

The novelty of character animation, fluid simulation and other trends, that resulted in many of those "unmotivated experiments", have by now fallen out of fashion. Benjamin Bratton has a slightly more positive view on the end of theory, where it is replaced by software:

> *For design, theory and computation have been intertwined for decades. One might even suspect a direct correlation between the end of theory and the rise of software (software being a form of technology that is linguistic as well as a form of language that is technological). Sometime from 1995 to 1997 or so, especially in academic design programs, software seemed to displace theory as a tool for thought. Many students interested in asking essential questions about how things work turned to software, not just to describe those things but also to make them, and not just to make them, but also to think through them. This shift came with trade-offs. Thinking with tools, and in this case, working with the fixed capital of advanced technologies, is a good thing. It is part of the genesis of our species. It is how we mediate the world and are mediated by it; we become what we are by making that which in turn makes us.* (Bratton 2015: 18)

The important part here is that to replace theory with software one needs to think through software – meaning, not just using it, but being critical about it and its use.

In "Archaeology of the Digital" (Lynn 2013), Lynn has picked four projects that illustrate four different approaches to the digital in architecture: Frank O. Gehry as a virtuoso of digital geometry, especially surface modelling and panelisation (digital construction); Peter Eisenman as the father of the procedural generative approach (emergent), Shoei Yoh using environmental forces to define variations in structural systems (morphogenetic) and Chuck Hoberman developing animation algorithms to determine collisions in dynamic geometric systems (analytic). Everything that comes after is a development and permutation of these concepts in architectural design.

> *In each and every case Hoberman, Yoh, Eisenman and Gehry approached the digital medium with insight and intelligence, treating the digital not merely as a tool but as a new creative medium that is integral to and an extension of their design process.* (Lynn 2013: 12)

It is remarkable that for the last three decades nothing really new has emerged from this lineage of experimentation that was not to some extent anticipated in 1993. As the ideas for computational design emerged ahead of widespread easy access computational technology, they were too difficult to adapt to practice as the user interface and computation power had not yet sufficiently developed. With the boom of personal computing during the dot-com bubble these ideas spread explosively and produced a hype creating a lot of open experimentation. Thirty years later one could say that digital design has reached a level of maturity as both the conceptual framework and the tools have been around for long enough. Still the last step is missing. All the components are there, but full-scale application in construction is still lacking. It is now the moment where the next crazy computationally generated image or virtual environment does not excite anyone anymore. Not even the most amazing physically constructed pavilion. The next frontier is disrupting large-scale, sustainable and affordable construction and a generation of architects is trying to do just that – develop a new way of designing and constructing that actually delivers on the promises of the folded, the parametric, the emergent, the morphogenetic – maximising creative freedom at no extra cost.[7]

1.2. Politics of the digital

When replacing theory with software, translating it into codes and models, which are always a convention, there is no way of avoiding the topic

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[7] This is not the first time this agenda has been topical. See Versioning (SHoP 2002).

of the politics of the digital. Coming back to one of the main research questions about the autonomy and authority of the architectural profession, this is a political question. But the question of politics is multifaceted: there are questions of agency, authorship, aesthetics, the collective, negotiation and optimisation.

> *[I]nformation processing acts both as a force outside a form, so to speak (that is, the new habits of perception, behavior, work, and play), as well as being the very method through which the forms are designed.* (Manovich 2008: 336)

Next to the technological arguments about what is possible, and how it affects architectural design as a tool, there is also the question of how to put these tools to best use. As the philosopher and cognitive scientist Daniel Dennett says, looking at evolution and asking the question "Why?" we need to split this question into two: "How come?" and "What for?" The first gives an answer to why something happened. Without a reason. The second, why it prevailed. At the advent of artificial intelligence (AI), we have to make sure we ask the second question about any code or model that we create. By thinking algorithmically we are not creating only one specific type of future, but establishing systems that govern the way events unfold. This does not mean everything will be predetermined. No software can ever be finite. In addition, it is always possible to integrate public opinion, polls etc. – politics as a software upgrade.

Christopher Hight and Chris Perry, the editors of the autumn 2006 edition of AD titled "Collective Intelligence in Design" discuss the issue of collective creation, using Michael Hardt and Antonio Negri's vision of the 'multitude' as an example. Hight and Perry interpret it as follows:

> *...the 'Multitude' is a way of imagining the emergence of new forms of social, economic and political power enabled by the very same communication and information technologies, wherein a common space is constructed by linking an infinitely diverse set of individual interests […]* (Hight/Perry 2006: 6)

In this vision, the possibility not to generalise is significant. 'Multitude' is not a simplification like 'people', signifying a unified social body; multitude takes into account each individual. A theory like this fits well when describing the possibilities of design in a networked society. Why is this data-based dispersion of agency good news for architects one might ask? Architecture has always been political, about convincing people, that doing things in a certain way is better than another. So similarly, as we have seen with big data being used to meddle with recent elections, the political will of the multitude is still very much influenced by the same media that gives this multitude its voice. This knowledge was used in election campaigns just as much by Barack Obama as it was by Donald Trump. As much as digital technologies have liberated us as individuals, we, as the digitally enabled multitude, have also become bodies of data in a global network. This makes it possible to analyse and simulate the behaviour of the masses with unprecedented precision and creates the possibility of manipulation on a global scale. Considering this, is the digital really an enabler of endless variation, as proposed by the first generation of digital architects, or rather a contingent system of standardisation?

Today, we perceive with increasing clarity how complicated our society really is. Political crises of recent years show how impossible it is to subordinate diversity to an ideal system. Different images of what is happening in the world reach us through diverse information channels. During the Arab Spring, social media was claimed to have helped justice prevail, but it is increasingly clear that in one way or another all media is corruptible. The fantasy of an ideal metaphysical social order has been shattered. Instead we are putting our hopes on big data – data collected automatically in real-time promises to show the world as it really is. We should not slip into idealist generalisations, but the analysis of enormous quantities of data seems to be the final promise for identifying patterns in chaos – without generalisation. Digital technology reaches everywhere. In commerce, it goes without saying that statistics are gathered about how much, where and why something is bought, and design, production and logistics are then optimised by analysing this data. Nowadays all objects to which enough data collecting technology is attached, are linked to the internet of things. In this way, our environment and the people and objects moving within it have become agents in large computational models. Collectable data is limitless and increasingly influencing every aspect of our lives. We could say that data-based adaptability, diversity, and variability have become the typical features of the ruling ideology. At the same time broad generalisations can be made as we see we are more alike than we would like to think. Economically and politically these generalisations are exploited and speak in favour of a sort of standardisation rather than infinitesimal variation. Antoinette Rouvroy speaks even of the evacuation of the subject, where the speed of digital technology is used to shut down reflexivity and to tap directly into impulses (Rouvroy 2020). By evacuating the subject, the noise is removed from the signal and turned into information, we are digitised.

At least to the same extent that it is possible to see positive solutions from data analysis, there are also dangers; big data is accompanied by the myth of truth. Information is one of the most powerful tools for manipulation and when it is backed by large amounts of data, it is difficult to argue against. Errors accumulate during collecting, recording, reading and processing – data has tolerances. A certain level of caution is necessary when working with it. In data-based architecture it is important to consider the aforementioned tolerances and maintain a critical attitude towards the resulting design. The architect as author is not going to disappear, even if there are hundreds of co-authors. Making sense of the reality made visible to us through data still requires human interpretation.

In the epilogue of his book “The Alphabet and the Algorithm”, Carpo talks about split agency and differentiates between designers who design objects and are digital interactors and those who create objectiles and are digital designers (Carpo 2011: 126). It is no longer enough for designers who use digital tools to use prewritten programs, because the program as a tool – stylus – has a stylistic limitation written into it. In the digital age, the author is the one who creates the system, the final form of it is defined by the user. The division is not that simple. As the computational design models meet the chaos of the real life context, unforeseen applications can emerge. The architect role cannot be divided into either design or interaction, it is about teasing out design solutions from complex systems. Algorithmic simulation allows us to do that with growing precision and inventiveness.

Architects will need to find ways to maintain both the autonomy and authority of the discipline in order not to be dissolved by technology and policy. Technology is increasing overall wealth, but without political intervention it is also increasing social inequality and accumulation of capital (UNDESA 2020). The problem is not technology, but the way it is used. With increasing digitalisation and automation of the AEC industry this autonomous agency of architecture needs to be coded in.

1.3. Mass customisation and the return of detail

One of the underlying causes ushering the advent of modernism was the poor quality of the first industrially produced products – mass production of ornament without meaning. The principles of efficiency, minimalism and form following function were set to bring order to a world full of clutter (Banham 1960: 9). A century later, our cities are cluttered with what the market economy has turned modernism into. The means of industrial production proved so efficient that they became ubiquitous and are used for absolutely all purposes, not just for achieving the elegant utopia. Even early digital architecture was (and still is) constructed with the same means. Ever more complicated software solutions have been developed to post-rationalise the desire for “homogeneity at a distance and near formal incoherence in detail" (Lynn 2004: 11), while the construction methods and materials have not really changed – we are still producing linear profiles and plate materials that are offered in standard measurements.

Yet, the early digitals saw digital fabrication as an opportunity for mass customisation and hence the return of the detail. Greg Lynn in "Folding in Architecture" describes this through the term intricacy.

> *Intricacy is the fusion of disparate elements into continuity, the becoming whole of components that retain their status as pieces in a larger composition. Unlike simple hierarchy, subdivision, compartmentalisation or modularity, intricacy involves a variation of the parts that is not reducible to the structure of the whole. The term intricacy is intended to move away from this understanding of the architectural detail as an isolated fetishized instance within an otherwise minimal framework. Detail need not be the reduction or concentration of architectural design into a discrete moment. In an intricate network, there are no details per se. Detail is everywhere, ubiquitously distributed and continuously variegated in collaboration with formal and spatial effects. Instead of punctuating volumetric minimalism with discrete details, intricacy implies complexity all over without recourse to compositional contrast. Intricacy occurs where macro- and micro-scales of components are interwoven and intertwined. The major connection of the term intricacy to the concepts present in Folding in Architecture is that the term is a derivative of "pli", much like the other terms – complex, complicated, pliant – all of which imply compositional practices of weaving, folding and joining.* (Lynn 2004: 9)

One of the arguments in folding was that digital tools let us combine topology with tectonics. Meaning architectural elements and their connection details need no longer be solved with standardised details, drawn up in a sectional drawing, but could be conditionally modelled or scripted with calculus-based trigonometric relationships rather than fixed standard measurements. Taking into consideration all the tolerances and limitations. (Fig. 17) Standardisation and automation follow the path of least resistance. Problems are broken down to subproblems and dealt with separately – the analytic method. This has been the case until very recently – one can take standard elements and combine them to create assemblies. You take some lumber and use nails, screws and stainless steel elements to join them together. Something that in premodern times might have

Fig. 17. Body Building installation 2015. All the pieces are unique, robotically machined with three types of algorithmically generated half lap joints.

Fig. 18. Aluminium facade panelisation of the Galaxy Soho (completed 2012) by Zaha Hadid Architects.

been done out of one piece or a single material is now a hybrid structure of material mined all over the globe, and made into products in other parts of the globe, calculated by a global army of engineers and shipped in, to anywhere in the world. With the rise of CNC some of these global production chains could be collapsed once again, using CNC-machined joinery, carving or printing.

The rise of digital architecture was accompanied by the adoption of CNC milling, laser-cutting and 3D-printing or what is also known as rapid prototyping technology. The unprecedented ease of producing precise complex geometry digitally and instantly materialising it with the help of digital fabrication tools spurred the idea that endless variation is possible at no extra cost. As Carpo explains, digitally mass customised objects all individually different should cost no more than identical mass produced copies (Carpo 2017: 57). This idea is supposed to enable intricacy – as there is seemingly no limit to the complexity of the produced elements, custom joints and details can be machined into the part itself.

The standard joints and standard calculation models, favoured in industrial production, could be made parametric, resulting in adaptive joinery and flexible standards. Our Tallinn Architecture Biennale 2015 Body Building installation was testing exactly this idea. Is it possible to develop adaptive joints and produce them, all unique, within the local timber house manufacturing industry? Christoph Schindler describes in his PhD (Schindler 2009) how often wood to wood joints are more economical and stronger than using industrially produced products. This is not only changing the production chain and making construction more sustainable, but is also changing the way things look. In contemporary timber construction, this means the reappearance of dovetail joinery and finger-joints for instance (Schindler 2009: 208). Using non-standard joinery that can be produced in any advanced log milling company, enables non-standard geometries at a competitive cost. There is no more need to use standard elements to drive price down by competition. With flexible digital fabrication, a bespoke design can be produced at any factory with the necessary equipment, rather than relying on specialist producers.

Moving into construction, digital design and the search for new forms brings the question of materiality ever more sharply into focus. The physical model and prototype are the primary tools of the digital designer. However, the persistence of industrial production is the main obstacle to material experimentation infiltrating construction: abandoning tried-and-true technologies in favour of innovative and untested methods does not pay off. Most common building elements, such as the I-beam, are already included automatically in the toolbars of CAD and BIM programmes, and thus spur a deficit of choice. In order to construct complex architecture on a large scale, its design process must be optimised – designers need to progress quickly from idea to blueprints. Ideally, though, innovative solutions that enable a simple and economical building process could arise as a result of an intense and time-consuming design phase. This is indeed what distinguishes academic architecture from practice.

In practice, the development of parametric tools has increased the potential for the simulation and modelling the qualities and restrictions of materials in production. In a 2014 Sliver lecture at the University of Applied Arts Vienna, Cristiano Ceccato of Zaha Hadid Architects introduced solutions that the office had created (Ceccato 2014). Among architects, BIM (Building Information Modelling) has become a swear word to some extent, tinged by standardisation and regulation. Ceccato prefers to use the terms ‘parametric’ or ‘automated working method’, which may perhaps leave the impression of greater freedom – it is possible for the architects to determine more on their own. The secrets of the success of Zaha Hadid Architects are complicated adaptive systems, which take the production factory’s possibilities as input parameters. One of the most colourful of Ceccato’s examples of material inclusion was the Galaxy Soho aluminium-facade saga, over the course of which the architects visited most of China’s aluminium producers in search of a suitable facility. The facade’s ultimate appearance was the result of the standard size of rolls of aluminium sheet, the work-space of CNC benches, and the particular attributes of the aluminium’s flexibility. (Fig. 18) No matter how much architects may want to familiarise themselves with the nature of a material and come up with new ways of using it, in a practice that yearns for immediate yield, building models must still mainly adhere to the opportunities provided by production lines.

While interning at the Gehry Technologies office in 2011, I worked on optimising a building’s glass facade. The project foresaw massive double curved glass surfaces that had to be made producible. In order for this to happen, an optimisation tool was developed in Paris for a Belgian facade-maker according to the parameters supplied by an Italian glass manufacturer. Taking into account the parameters of a CNC bending furnace that was to be used to shape cylindrical and conical glass panels with a certain maximum size, my internship supervisor Andrew Witt created a virtual smart-panel that could adapt the most exact producible shape according to the given design surface.

This kind of post-rationalisation process takes material qualities directly into account, but is nevertheless a compromise – ultimately, the producer’s machines dictate the types of elements into which the designed surface will be divided. In Ceccato’s opinion, designers could be more involved in pre-rationalisation; that is, already taking into account the limitations derived from the materials and production in the initial design phase. The speculative spirit of the digital would suggest, however, that entirely new methods of production could be created, and only the limitations that stem from the material's qualities taken into account. Or, if a material that possesses the necessary qualities is lacking, why not design a new one?

As of today, materiality has become an integral part of digital models, although the complicated process of translating the digital into the physical remains apparent, especially in large-scale projects. New production methods that attempt to resolve these discrepancies take root more often in the workshops of designers and small-scale manufacturers. Marjan Colletti refers to the new approach to materiality inspired by digital means as 'neomaterialism': "Nowadays, we are entering a post-digital age of what may be called New Materialism, focused mostly on finding ways of translating digital design into real-life prototyping" (Colletti 2014: 203). (Fig. 19)

The pioneers of digital design knew from the very beginning that the execution of new forms in today's pace of life while remaining true to new tools requires the implementation of new technology in construction. The three-axis CNC milling machine was the first 'new' technology (dating back to the mid-20th century) used to start creating new forms. For a designer working on CAD programmes, operating a milling machine is not especially difficult either. This type of immediate CAD-CAM connection has placed the designer into the role of the craftsman once again. Just as with every tool, the machine leaves its own mark on the material, which can be used to achieve various kinds of surface finishes. Designing the tooling path is just as important as the form itself, in addition to a connection with the material, of course: the feasibility or suitability of various millable forms with the structure of the wood or other materials. The implementation of CNC milling enabled almost immediate feedback between the digital and the material. By performing these experiments over and over, one's understanding of the material's behaviour, tolerances, and aesthetics also grows.

Exploring the range in adaptive detailing has become a fascination in itself. According to folding, as these details are driven by calculus-based curves, force fields and local relationships, each instance of an algorithmic detail becomes a unique moment in an intensive whole of an undulating gradient field of parts. Ornament was considered a crime because it was wasteful, labour-intensive and expensive. With automated fabrication and renewable materials, this is seemingly no longer the case. Furthermore, a century of anonymous concrete, steel and glass surfaces has created the demand for the adornment and expression of a new digital age. Not ornament in its original sense though, as something that is added to the actual body of a building, but rather as a constructional detail that accentuates the logic of design and assembly. When considering the

Fig. 19. FrAgile 2: Porous Cast at the Body Building exhibition 2015 by REX|Lab, Marjan Colletti and Kadri Tamre.

Fig. 20. The Body Building installation, while exhibiting the expressive range of contemporary timber structures, becomes an urban ornament – being simultaneously a way-finding device, pointing at the three main venues of TAB 2015 and a pergola.

etymology of the word, ornament is derived from the Latin word *ordinare* meaning to put in order. The aim of ornament in the classic sense was to organise the elements of the building, to make them clearly readable and draw attention to them. Therefore, ornament is concerned with understanding and meaning (Picon 2013: 50). This previously non-essential addition, the expression of the underlying reasoning, is now folded into the structure itself. (Fig. 20)

1.4. Robots and fabrication design

As dealing with new production methods is risky in practice, knowledge and experience must come from somewhere else. This 'somewhere' is most often the academic research environment. Most architecture schools by now have fabrication labs: 3D milling machines, laser cutters, 3D printers, and industrial robots. These tools have brought an abundance of new materials (plastics, composite materials, even natural silk) to the architect's desk, materials which have been impossible to work with in the creative process on such a level before. The precision with which prototypes can be built gives architects a much better idea of how the final component, product, or building will behave. 3D printers nowadays enable the combination of different materials with various physical properties. The 3D printer itself has become an end-of-arm tool for industrial robotic arms. (Fig. 21)

Academic research in architecture schools has strongly relied on open-ended experiments. In 2011, I had the opportunity to take part in Peter Testa's Real-Time-Robotics course at the brand new SCI-Arc Robot House, where our task was to become familiar with the tool instead of designing for or fabricating with it. Robots enable a direct link between the virtual reality of a CAD programme and physical space; however, the connecting is not the translation of form from the digital to the physical, but rather motion. The precision and control that robotics makes possible allows us to work with material in unprecedented ways. Skills that only experts with generations of experience have previously been able to master can now be translated into a few rows of code and repeated ad nauseam, with super-human patience and precision.

In the studio project sPhysical (Fig. 22) at SCI-Arc, our team attempted to combine the characteristic precision and repeatability of the movements of the robotic arm with hard-to-control material processes, such as melting or expanding. To translate motion into form, we came up with a simplified version of glassblowing. Using robotically controlled heat guns, we created non-uniform structural properties within the material of plastic containers that we then inflated using digitally controlled air pressure. This very primitive and clumsy experiment produced beautiful

Fig. 21. A regular heat gun used as an end of arm tool for the sPhysical project. Team: Erin Besler, Eugen Kosgoron, Siim Tuksam and Peter Vikar. 2011 winter term in Studio Testa, Sci-Arc, Los Angeles.

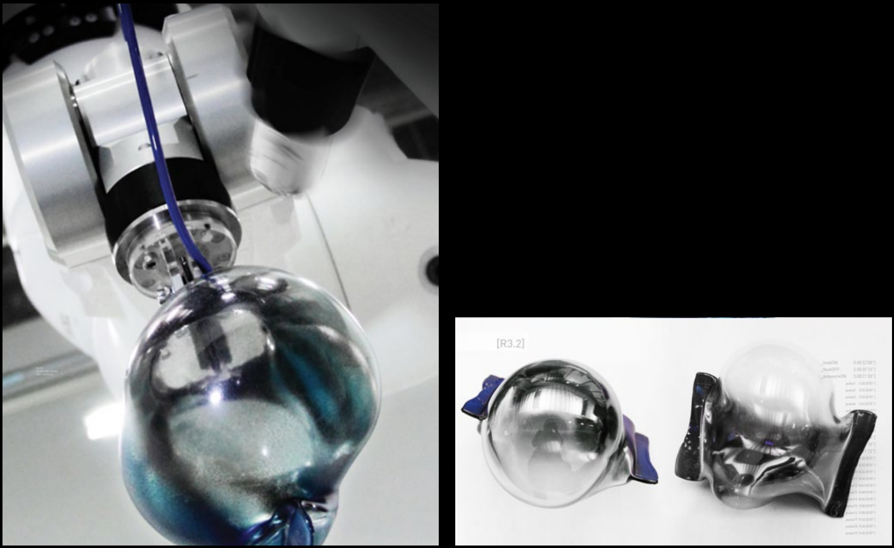


Fig. 22. sPhysical 2011. The project subsists on the translational discrepancies that arise during the interplay between an excessively controlled but exceedingly irresolute digital environment and its materialisation into the reality of physical space. sPhysical seeks the epitome of synthesising digital tools with physical expression by re-conceptualising material design processes and applications in the field of architecture. The problem of materialisation exists as the limitation of digital control and resolution. Matter and form are subjugated through a logic of rigging, a concept derived from and informed by robotic motion-control, and embedded with a certain propensity and agency. A design methodology, one that realises the potential of designed properties, will be achieved through the conceptualisation of rigging matter and form. Team: Erin Besler, Eugen Kosgoron, Siim Tuksam and Peter Vikar. 2011 winter term in Studio Testa, Sci-Arc, Los Angeles.

aesthetic results, but also enabled us to form conclusions about what could be created using such technology in the future. It is an exceptionally effective production process for zero-waste, double curved surfaces. Testa called this approach material rigging, referring to the character animation technique used in animation software. I will come back to this idea of rigged materiality in the last chapter, where I talk about the quality of precisely defined dynamic geometric systems – formality.

The triumph of early digital architecture started to give with the burst of the dot-com bubble in 2000, and received a final blow with the economic crisis of 2008. The result – digital architecture moved into research laboratories. Design research got a boost and in addition to large technical universities such as the ETH, industrial robots and 3D printers came to conquer increasingly more research institutions. Research in digital architecture became both more computational and more engaged with its materialisation, studying the qualities of various materials and the possibilities of machines, combining them in all imaginable ways (see the main exhibition of TAB 2015 "Body Building"). "About 16 key patents relating to 3D printing processes called Material Extrusion, Powder Bed Fusion, and Vat Photopolymerization expired in 2013–14" (Hornick 2016). All of this meant robotisation and rapid development in 3D printing technology proved a fertile ground for computational design innovation. News of ever bigger and more complex 3D printed buildings went around the world one after the other. In 2013, Michael Hansmayer and Benjamin Dillenburger published their Digital Grotesque I, a room scale 3D sand printed grotto (Dillenburger 2017).

At about the same time, in 2007, parametric architecture also took off, as scripting no longer required the writing of complicated code and the most widely used visual programming environment today – Grasshopper – emerged, allowing the intuitive stacking and joining of algorithms as needed. Panelisation was one of the tool's first main functions, as the smooth surfaces were divided into producible elements. Parametric design is at the core of Grasshopper with the number slider, probably one of the most essential components, making it possible to animate change in the algorithm and the resulting geometry.

Algorithmic design, however, does not end with writing code. In the 2011 autumn issue of Log, Andrew Witt states, "design has reached a new era of technical invention" (Witt 2011: 17). The limitations of CAD-CAM machines have been overcome – they are being modified to create new aesthetics by reconstructing the mechanics or by creating completely new machines, using mini controllers and computers like Arduino or Raspberry Pi. When it comes to industrial robots, building one's own tools is inevitable, since it is a universal machine tasked only with positioning the tool connected to it. Although the way designers and artists hack machines is nothing new. One of the most memorable examples Witt gives is how artists used the machines designed to calculate the trajectories of ballistic missiles to create drawings of complex periodic curves. A new aesthetics that appeared was soon used in special effects in the film industry (Witt 2011: 20).

With the development of technology and ease of access, architects over the last decade have made increasing use of robotics. The first fascination with them seems to be fading and for some time these tools have been moving from showrooms back to workshops. By using industrial robots, some hope of achieving greater precision and capability, others hope for greater integration between digital design and the end product, while some see it as a platform for experimentation and speculation. There are numerous different directions in this field. On one hand, robotic arms allow unprecedented precision, control and automation. The initial reflex was to start using them for the fabrication and automation of simple construction techniques. This strategy yielded some fascinating results by sheer precision and determination. ETH Zurich was one of the first universities where architects started experimenting with industrial robots for brick-laying – Fabio Gramazio and Köhler's Pike Loop represented Switzerland at the Venice Biennale in 2008. (Fig. 23) At SCI-Arc as I mentioned above, we were deterred from thinking about fabrication and encouraged to speculate on how robotic motion could enter at any point in architectural design from drawing and representation to construction and demolition. The neo-materialist direction of Marjan Colletti, or post-digital, the term used by Matias del Campo, suggest a split agency between the precise control of the robot and unpredictable material processes similar to the approach of the sPhysical project, Colletti's FrAgile 2: Porous Cast (Pihlak/Tuksam 2015: 47) at the Body Building exhibition or del Campos Plato's Columns (del Campo 2018: 247), where materiality is approached in an experimental way to explore its self-organisational properties.

Robotic design was supposed to be closing the gap between digital and physical production. This technology makes it possible to overcome the problem of discrete translation between the digital and the physical and instead use continuous motion to form matter. The bluntly determined precision of non-responsive robotic motion, however, reveals the inherent flaw of the modernist idea that the world could be engineered. AI Build is suggesting that machine learning could overcome this shortcoming. As of now, this is not really the case, and larger 3D prints need to take into account physical restrictions as well as a certain percentage of failure if we want the precision and reliability needed in construction rather than open-ended experimentation for design – even 3D prints need to be broken down into parts that have very physical limitations.

Robots as universal tools have made it possible not only to create

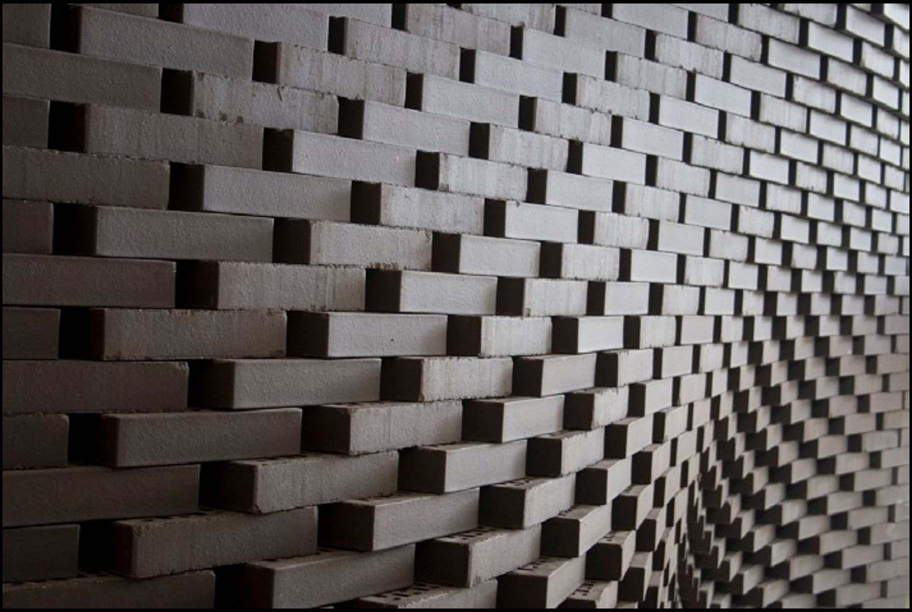


Fig. 23. Structural Oscillations 2008 by Gramazio Kohler Research, ETH Zurich.

Fig. 24. Digital Thicket 2017, assembled by volunteers.

material prototypes but also prototype fabrication processes. For example, the ICD/ITKE Research Pavilion 2014–15 (Doerstelmann et. al. 2015) was produced using a highly sophisticated end-of-arm tool to laminate carbon fibres onto a pneumatic lost formwork. Robots have sparked our imagination, but similarly to the pre-90s, during the so-called embryonic phase of computational design (Caetano 2020: 166) the use of technology often becomes overly complicated and is rather replaced by manual labour.

Industrial robots have been used for decades, but contrary to the assumptions of the earliest architects to adopt them, they are not really meant to be universal tools in the sense that most of them are programmed once to perform the same task for their whole life-span. Most CNC-machinery quite often still requires a trial-and-error phase in their programming to perform a new task perfectly. Therefore, going into industrial production that goes beyond two-dimensional cutting, endless variation is still not really viable. "With the rise of robotics, a return to simple, discrete, repetitive elements can be predicted," argues Picon in his 2010 book "Digital Culture in Architecture" (Picon 2010: 166). He emphasises Lynn's BlobWall and Gramazio and Koehler's robotically laid brick walls. The automation of the construction process points towards the rise of discrete parts. But this is not only true for robotic construction. According to our experience, a certain level of automatism is also beneficial with regular human construction workers. (Fig. 24) Paradoxically, the rigour of designing for robotic assembly often makes it easier to do it by hand.

1.5. Facing the realities of construction

Over the last four subsections, I have looked at the discourse of digital architecture and opened up some of the topics relevant for this thesis. In the 90s, folding replaced complexity and contradiction. Folding removed contradiction from deconstructivist architecture, pliantly adapting to the forces informing architecture. Digital tools and digital culture raised questions of politics, agency and collective intelligence ultimately challenging the established role of the author. Digital fabrication at the same time enabled complexity, intricacy, mass customisation and the return of the detail evoking the notion of craftsmanship and collapsing the production chain, apparently removing the need for a collective practice. Moving to robotic production and fabrication design, we are not creating the simple complexity of computation, where the simplest of rules can produce patterns of chaos and order, but the complex simplicity of the early modernists, where an enormous amount of effort is put into the appearance of elegance.

> *The loss of the module in favour of the infinitesimal component and the displacement of the fragmentary collage by the intensive whole are the legacy of the introduction of calculus. […] A multifaceted approach between complex interconnectedness and singularity, between homogeneity at a distance and near formal incoherence in detail, between disparate interacting systems and monolithic wholes, and finally between mechanical components and voluptuous organic surfaces, is all part and parcel of the shift from whole number and fractional dimensions to formal and material sensibilities of the infinitesimal.* (Lynn 2004: 11)

If this is considered the beginning of digital architecture – shifting from the discreteness of integers to the continuity of real numbers – digital architecture is really an oxymoron. Still, intensive wholes, complex interconnectedness, homogeneity at a distance and even voluptuous organic surfaces, are achievable using discrete modular elements – this is the way the singular is wrought out of the standardised and the digitised – bits, pixels and voxels. Digital cameras used to compete in pixel count. Every new camera had to have more pixels than the previous. At one point this race stopped – we reached retina resolution. There is no further qualitative gain from raising the quantity of pixels. Digital architecture has reached a similar maturity – once we have managed to produce perfect smoothness, the fascinating complexity and intricacy vanishes. We have arguably arrived in the post-digital age where we do not look at digital technology for answers but merely use it, in its full potential to answer questions autonomous from the digital regime.

The politics of the digital is important on two levels: mainly the agency of architects and the discipline within spatial production, especially in construction, and our role within the process of digitalisation and the accompanying standardisation. The construction industry at large is now concerned with its low productivity rate. Within the process of digitalisation and writing up digital standards for productivity, architects need to be extremely vigilant and engaged. The question remains how to write non-standard standards to enable the openness, adaptability, diversity and heterogeneity inherent to the digital culture.

Mass customisation is the bearer of this kind of heterogeneity or complexity sought after by digital architects. Yet looking at what is considered mass customisation in manufacturing, it is customisation in configuration not in elements. Within the discourse of digital architecture, the term mass customisation is mostly used in its idealised meaning – custom objects produced at the scale and efficiency of mass production. Reading into mass customisation research in contemporary manufacturing, the picture is a little different. As Frank Piller points out, in mass customisation the emphasis is on the term mass. Mass customisation is a version of mass production, making use of flexible manufacturing systems (Piller et al. 2004). The use of mass customisation in digital architecture is best described by the Embryologic Houses by Greg Lynn (Lynn 2000) – an endless variety of unique blobs. Mass customisation in the manufacturing industry today is more like choosing a unique colour combination for your NikeID shoes.

SHoP/Sharples Holden Pasquarelli with their idea of versioning (SHoP 2002) were going one step closer to manufacturing, arguing for constructability, but were far from trying to compete with the status quo efficiency of standard construction. According to Carpo, versioning was trying to 'erode the barriers' between construction and design. As he also states, the architectural definition of versioning to this day is unclear. "The featured buildings often look angular, not curvilinear, and follow simplified geometries; the final recommendation to use digital tools to facilitate the early involvement of and collaboration between participants in the design and construction process anticipates the agenda of Building Information Modelling software, which was in development at the time" (Carpo 2013: 131). Here the discrepancy between design intent and the produced outcome becomes evident through qualitative statements like simplified and angular, as it clearly tried to be a next step in digital architecture, visually moving backward towards deconstructivism.

With robots conquering fabrication facilities a lot of fabrication projects emerged. Recently, this type of pavilion architecture has raised a lot of discussion around their productivity for the discipline. Are they a demonstrator for a wider architectural approach, like Mies van der Rohe's Barcelona Pavilion? Or an end in themselves – a funding and marketing device for research institutions? At the same time, the robot arm is starting to lose its charm and recede from the showroom back to the workshops, where it is mainly used as a six-axis milling machine or large-scale 3D printer. The robotisation of construction is not happening yet, or any time soon. Interestingly, some of the discrete assembly systems developed for robots work just as well in making manual labour more efficient and reliable due to algorithmic thinking. Is the robot arm really the universal tool for mass customisation at no extra cost, or rather a simulation platform for testing possible industrial methods and the automation of more complex but repetitive tasks?

After a short fling with postmodernism, the digital architecture of the early 1990s with its smooth, seamless surfaces, could be considered a return to modernist aesthetics. With the help of calculus, it is possible to express postmodernist ideas through ideal forms. Contradictory external forces were smoothly folded into mathematical surfaces. Spline constructed surfaces are defined by algorithms that interpolate smooth curves between sets of points. Smooth curves can be fitted through the coarsest of datasets. The appearance of cloud computation, the internet of things and big data are taking their place in digital postmodernism, characterised by fragmentation, plurality and density. Rem Koolhaas wrote about a similar tendency in "Junkspace", "At the exact moment that our culture has abandoned repetition and regularity as repressive, building materials have become more and more modular, unitary, and standardised; substance now comes predigitised [...] Instead of trying to wrest order out of chaos, the picturesque is now wrested from the homogenised, the singular liberated from the standardised" (Koolhaas 2002: 178). The ideological conflict here lies in the fact that attempts are made to build calculus-based curvilinear forms from standard building materials. The answer could be either developing construction methods more in line with continuity, utilising material computation (Menges 2012), or on the contrary, embracing the digital, discreteness of matter, and calculus-based algorithms to make best use of them.

To physically produce seamless computer generated surfaces today, they need to be divided into infinitely small parts – the resolution needs to be increased. 3D printers only recognise straight lines, meaning that in order to achieve continuity and to make the end result look similar to the actual curvilinear design, it is necessary to calculate as many points as possible on a surface and then print the thinnest layers possible. By exploiting material properties such as plasticity or flexibility, it becomes possible to create "pure forms" in the way a glassblower or sculptor does, and therefore to abolish the issue of resolution. The material itself becomes a part of the digital model; its properties become variables in the algorithm. In speculative practice, this is a valid option being explored by the ICD at Stuttgart University, in the spirit of Frei Otto, or CITA – Centre for Information Technology and Architecture at KADK. Only time will tell whether such methods will ever find widespread practical application or not.

Digital architecture initially included a lot of post-rationalisation, meaning making the designed geometry constructible. This was pioneered most prominently by Frank O. Gehry who, in addition to his architecture office, established his own software company Gehry Technologies. They provided their software and services to many well-known offices such as Zaha Hadid Architects, Coop Himmelb(l)au or UNStudio. At present, the company has been sold to Trimble, a huge corporation whose tag-line is "transforming the way the world works". When I worked there as an intern in 2011, it was a highly exciting company employing numerous people with a background in architecture. Ever since the two-month internship, I have firmly believed that the knowledge of architecture, engineering and manufacturing should be integrated in the design from the very beginning. With algorithmic means, it is possible to achieve the same kind of freedom in the creation of form as digital architects had done before the crisis, while also considering the constructional and geometric restrictions right from the outset. (Fig. 25) Furthermore, the given constraints can be used creatively. This, in turn, marks an essential difference from the early digital architecture. If the latter was mostly concerned with the building surface that can be experienced, somewhat ignoring the construction, then the present methods allow the designer to regard the building as a comprehensive whole consisting of volumetric elements and consider their geometry as well as their structural and other physical qualities.

Non-standard architecture and customisation enjoyed a high tide around the turn of the century. The early digital architects were using digital tools mostly as-is, meaning in the early days there was little scripting or programming and rather the idea that the tools developed for modelling cars and planes could be used to produce curvy smooth architecture. From the very beginning it was clear that these curvy forms needed to be broken down into parts. Greg Lynn saw in calculus and digital computer aided design (CAD) and computer aided manufacturing (CAM) an opportunity to fold together topology and tectonics. In a way my research is still trying to do the same thing, but in a non-speculative way, where the CAM-tools have reached the mainstream and we can actually see how the industry has adapted and is using the tools in their day to day processes. In my experience, infinitesimal variation is not viable in even the most advanced industrial mass production.

Reading the theory of non-standard by Patrick Beaucé and Bernard Cache from 2003, the ideas that are the basis of my research are already mostly there. (The design output is at the same time completely different.) “Writing of software programs is at once the major genre of contemporary culture and at the same time the privileged terrain of a confrontation of the forces which organise production in our societies” (Beaucé/Cache 2003: 123). Today, writing software is the main mode of automation and as such an essential part of the developments in the construction industry. To keep construction part of architectural culture, algorithmic automation needs to be part of the toolset for architects creating it. Beaucé and Cache carry on describing associativeness as a strategic concept that will determine the form standard architecture will take – a new normal in the making. They describe associativeness as “the software method of constituting the architectural project in a long sequence of relationships from the first conceptual hypotheses to the driving of the machines that prefabricate the components that will be assembled on site” (Beaucé/Cache 2003: 123). This is a clear description of

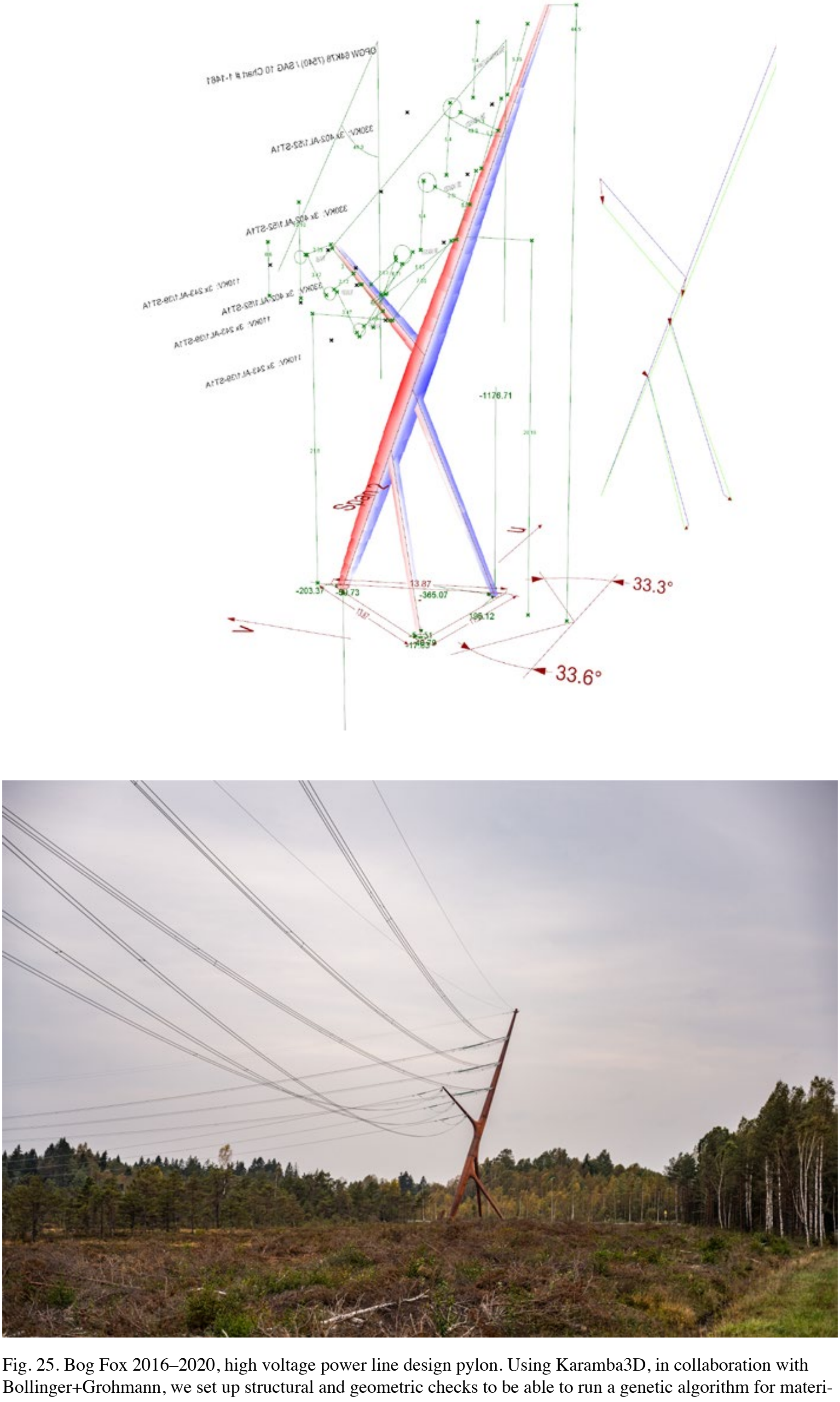
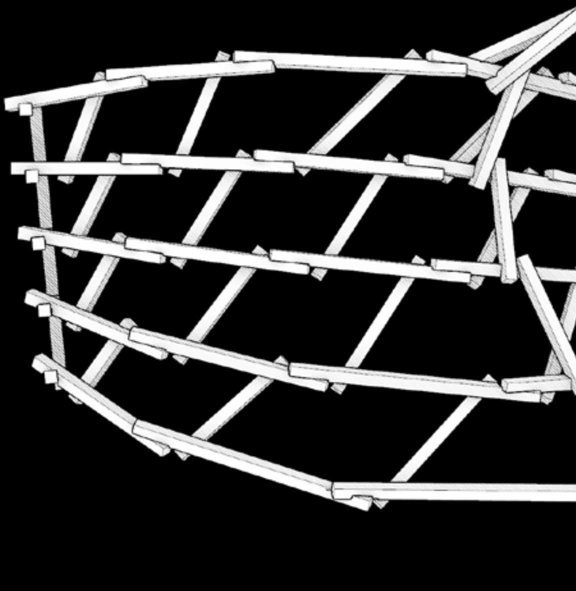
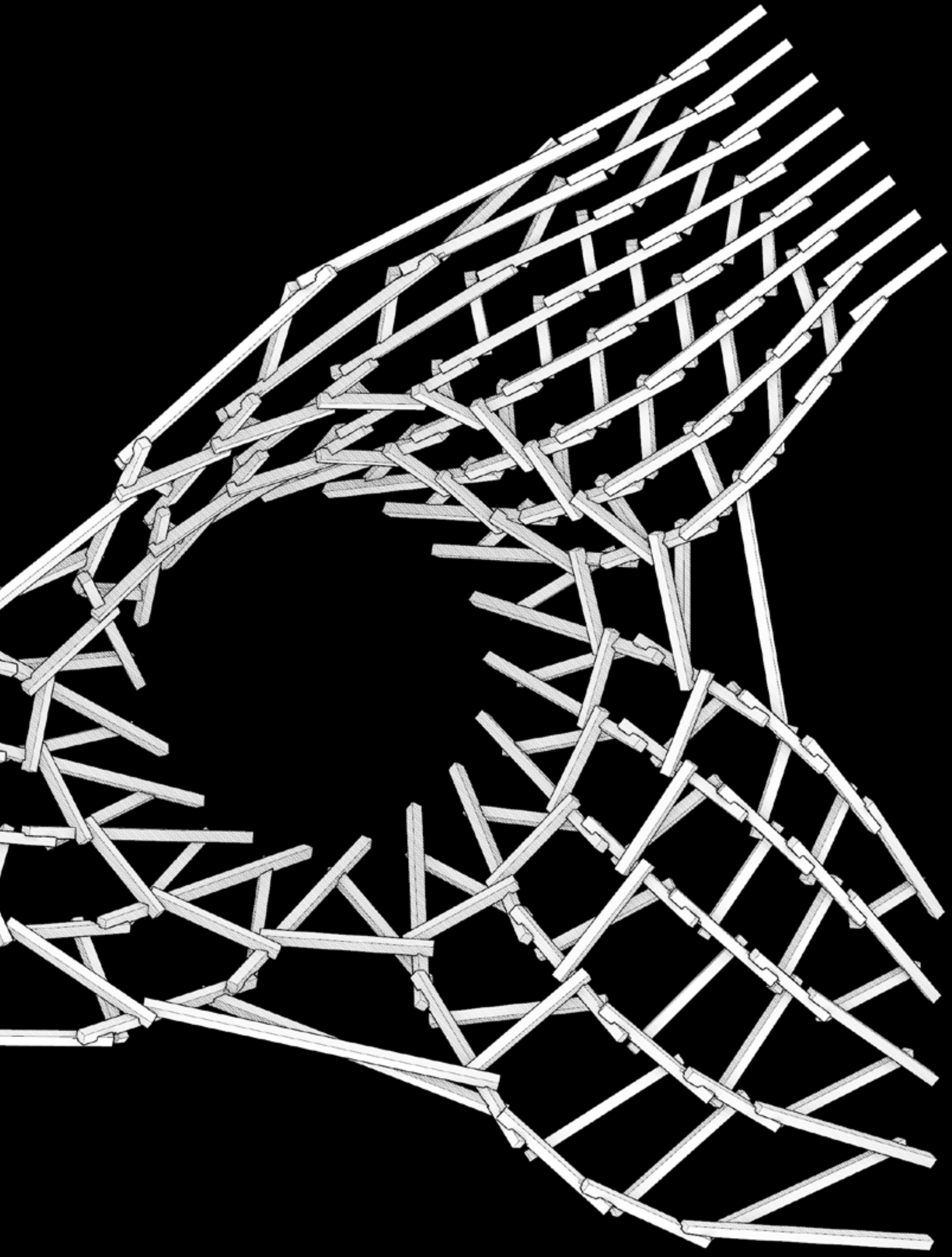


Fig. 25. Bog Fox 2016–2020, high voltage power line design pylon. Using Karamba3D, in collaboration with Bollinger+Grohmann, we set up structural and geometric checks to be able to run a genetic algorithm for material weight minimisation. Manual adjustments were made afterwards to balance additional weight versus aesthetic preferences.

the CAD-CAM mentality that whatever we design, we can translate into machine code and produce it, whether by CNC milling, the preferred tool of the early digitals, or by 3D printing, as nowadays. The problem is that this approach, seen as a reasoning in favour of curvaceous non-standard designs and infinitesimal variation, does not scale very well, neither technically nor financially. Today, when robotic fabrication is part of any contemporary timber house factory, we can study the real possibilities and economics of the process much more closely and bring this knowledge into our associative design process, making more informed decisions. This is not to say that the blobs of the early digitals were misinformed, but that the aim or goal has changed. With any new technology the newly created design space has to be explored in its full potential. This research is interested in how the same approach of associative design can be applied in an industrial setting today and meet the demands of our current construction industry. With the financial crisis of 2008 and rising environmental concerns nowadays, standardisation, automation, optimisation towards sustainability and efficiency are on the rise and more topical than ever. At the same time, the desire for heterogeneous environments is just as prominent – the current green wave is asking not only for a halt to global warming but also protecting and supporting biodiversity and heterogeneity.



1.6.
Milestone project: Body Building



Year:	*2015*
Client:	*Tallinn Architecture Biennale 2015*
Location:	*Ahtri 2, Tallinn, Estonia*
Scale:	*80 m^2*
Elements:	*225 unique pieces*
Material:	*95x95 mm lumber, 2.7 m^3*

With our first project, the Body Building installation, we aimed to demonstrate the capabilities of the local wooden house manufacturers and by that, hopefully, create a discussion moving further from apparent sustainability and the financial gains from exports. We found a local factory in south Estonia who owned a Hundegger K2i with a 5-axis universal tool. Using their machine, we could demonstrate an algorithmic approach to timber lattice structures. The idea was to use standard materials and industrial production to test the real-world applicability of calculus-based continuity and infinitesimal variation. (Fig. 26)

The Body Building installation was an urban extension of the 2015 Tallinn Architecture Biennale's main exhibition "Body Building" at the Museum of Estonian Architecture. The exhibition explored "hybrid forms of construction where cutting-edge technology and science meet the self-driven variability of material systems, and degrees of freedom and control define an outcome of multiplicity within tolerance, trying to find a balance between the unruly and the predictable – body and building" (Pihlak/Tuksam 2015). The installation is an attempt to contextualise these ideas by using local resources and capabilities.

The installation, located on a major artery in the city of Tallinn, was a conceptual beacon and guide for the three main venues of TAB – the Estonian Centre of Architecture, Viru Square and the Museum of Estonian Architecture. The freeform structure (body) is the result of algorithmic negotiations between ideal geometries; for example, lines, planes, circles and cuboids (building). (Fig. 27) By using computational methods, the installation brings pliant forms and vegetal materials into the otherwise rigid and mineral based city centre. The structure was intended to show a transition between primitive geometric shapes: circle, horizontal plane, vertical plane and arch. The base geometry was generated using magnetic field simulation, to create a twisted blend between the four edge conditions. (Fig. 27: a) The resulting field lines were divided into segments that would become the axis for the timber pieces. (Fig. 27: b, d) As the curves were not planar, all the elements had to be individually adjusted to create a smooth transition between them. (Fig. 27: g) The negotiations between the rectilinear timber and smooth geometric transitions formed a gradient field of varying joints – every element unique.

The project combines many algorithmic tools to arrive at the end result. The magnetic field creates a virtual environment that creates a coherent relationship between the pieces of timber. The form was achieved playing with a combination of various forces and distinct edge conditions, while computing magnetic field lines through specific starting points. A number of geometric manipulations were then performed. The physics simulation plugin Kangaroo was used to average kinks in order to maximise contact area for all joints. Simultaneously, Karamba3D was

Fig. 26. Body Building installation, Tallinn Architecture Biennale 2015.

used to evaluate structural performance. (Fig. 27: c, f) By manipulating the magnetic field, the overall geometry was optimised to perform better structurally.

The pavilion is a contemporary take on wooden post and beam construction, manufactured on a fully automatic wooden house production line, where traditional log houses are produced on a daily basis. The project aimed to promote the use of algorithmic design in industrial production and spark a discussion on the future of wooden architecture between the local wood industry, engineers and architects.

The 225 unique elements of the installation were generated using popular algorithmic design and engineering software (Rhinoceros, Grasshopper, Karamba3D, Kangaroo). The 95x95 mm timber elements with 450 different joints were 5-axis CNC-milled on a Hundegger 2Ki over 10 hours and assembled with 2,000 screws over 5 days by volunteers. (Fig. 28) The fully algorithmic 3D-model was developed over a period of 6 months, resulting in a design tool where the base geometry is interchangeable within a few moments and various parameters of the design are controlled by numeric input. Using the Karamba3D structural analysis plugin, all the structural changes are constantly recalculated and optimised.

With the project we developed a strategy for constructing freeform structures out of standard timber using variable half lap joints that were optimised within the limits of production and structural tolerances. (Fig. 29) The design had to be adjusted to hsb-cad restrictions as we did not have access to a software that would have bridged Rhinoceros and hsb-cad. Many of the conversions failed to work properly, meaning we had to delete and add treatments by hand by also exporting the boolean geometry. Smaller manufacturers often lack the know-how and will to use their robotic fabrication lines as flexible tools. Repetition and standardisation in materials geometry and tooling is strongly preferred. In our case, I visited the manufacturer to produce fabrication files for the Hundegger and ended up simplifying the geometry of the joints as well as creating custom boolean geometry to manually apply treatments in hsb-cad when the automatic conversion failed.

A few weeks after the opening, we were contacted by the city officials who asked whether we agreed to leave the temporary structure in its location for another year. (Fig. 30) The project was a discussion starter among local architects, engineers and manufacturers, hoping to start working together on more experimental projects and to develop more productive, innovative workflows by incorporating academic research. Many of the discussion focused on the inefficiencies and risk of industrially producing infinitesimal variation.

What we have later learned from experimental projects with

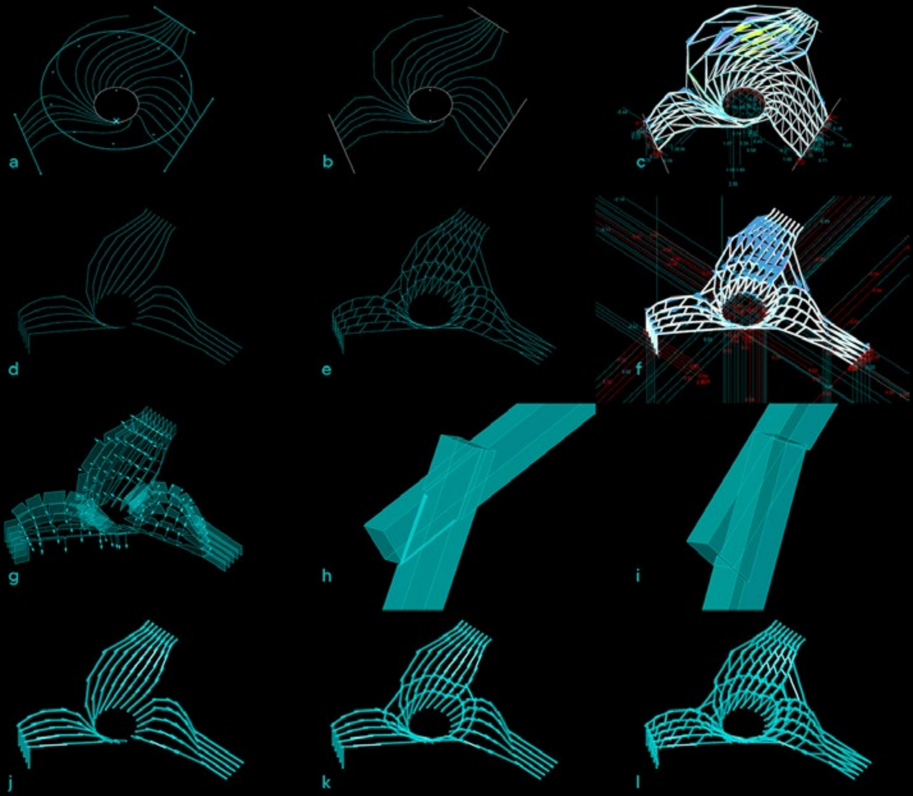


Fig. 27. Body Building installation 2015: a – magnetic field simulation for formal control, b – linear segmentation of the main axes, c – initial Karamba3D analysis, d – geometrically and structurally optimised main axes, e – added cross bracing, secondary axes, f – Karamba3D analysis after optimisation, g – element orientation optimisation for equal transition angles along main axes, h and i – as internal corners were not possible to be milled, cuts had to go through, creating the need to choose which direction to cut away to minimise cut-away material based on the angle between the axes of two consecutive elements along the main axes, j – main axes elements, k – added horizontal ‘belt’, l – added secondary elements.

industrial partners, is that even though they have robotic log and plate milling lines that can cut every piece differently, it just does not pay off. (Fig. 31–34) Machining files still need to be generated and errors checked for every new piece. If we are talking about going beyond the pavilion scale, the produced elements need to be constrained in variation and geometry. Even 3D printing has its structural limits. AI is starting to handle the unexpectedness of material processes, but cannot handle the catastrophe of structural failure during fabrication, or the economy of replacing a single custom element, when even in mass customisation economies of scale still apply, as by the time one needs a replacement, the production line is already set up to produce something different. Every unnecessary tool change, repositioning, needless cut will amount to big changes in overall cost and reliability. Not to mention the fact that industrial production is never without its defects. For standard elements, the problem is easily fixed by compensating the statistical error with more elements produced for example. In the case of unique elements, it needs to be produced separately often creating disproportionate effort and cost.

Standardisation and modularity create resilience, and more robust error proof systems. Still, CNC technology allows for custom mass production. There is no need to rely solely on mass produced products when custom mass production is readily available. As the process is based on timber house manufacturing, there is reason to assume that custom mass production is scalable. Having learned this through our first installation projects and presenting them at timber construction conferences, we decided to give modularity a chance. Although this is a fundamental conceptual change, there are many parts of the project that continue to be developed. One of the fundamental common threads is the underlying spatial structure. Even the folding based projects are based on structuring space, the difference is in the way it is done – topological variation vs discrete subdivision.

Within the Body Building project the question of resolution already comes up: how many points is the magnetic field evaluated at? How many segments are the resulting field lines divided into? Using continuous functions in calculation ends up being represented or materialised in discrete instances. In computational geometry, field evaluation is often done in an orthogonal spatial grid and visualised, for instance, using voxels or meshes generated using the marching cubes algorithm. Within Body Building, once the field is evaluated, based on scalar values a point grid is obtained. Based on the methods used for this evaluation, the point grid can be regular or irregular, ordered or random. In the Body Building project, the resulting point grid is irregular yet ordered (Fig. 35), meaning nodes can be predictably connected using list operations. The manipula-

Fig. 28. Body Building installation 2015 construction process.

Fig. 29. Body Building installation 2015 close up – “homogeneity at a distance and near formal incoherence in detail” (Lynn 2004: 11) – the machined elements fit perfectly at seemingly random angles.

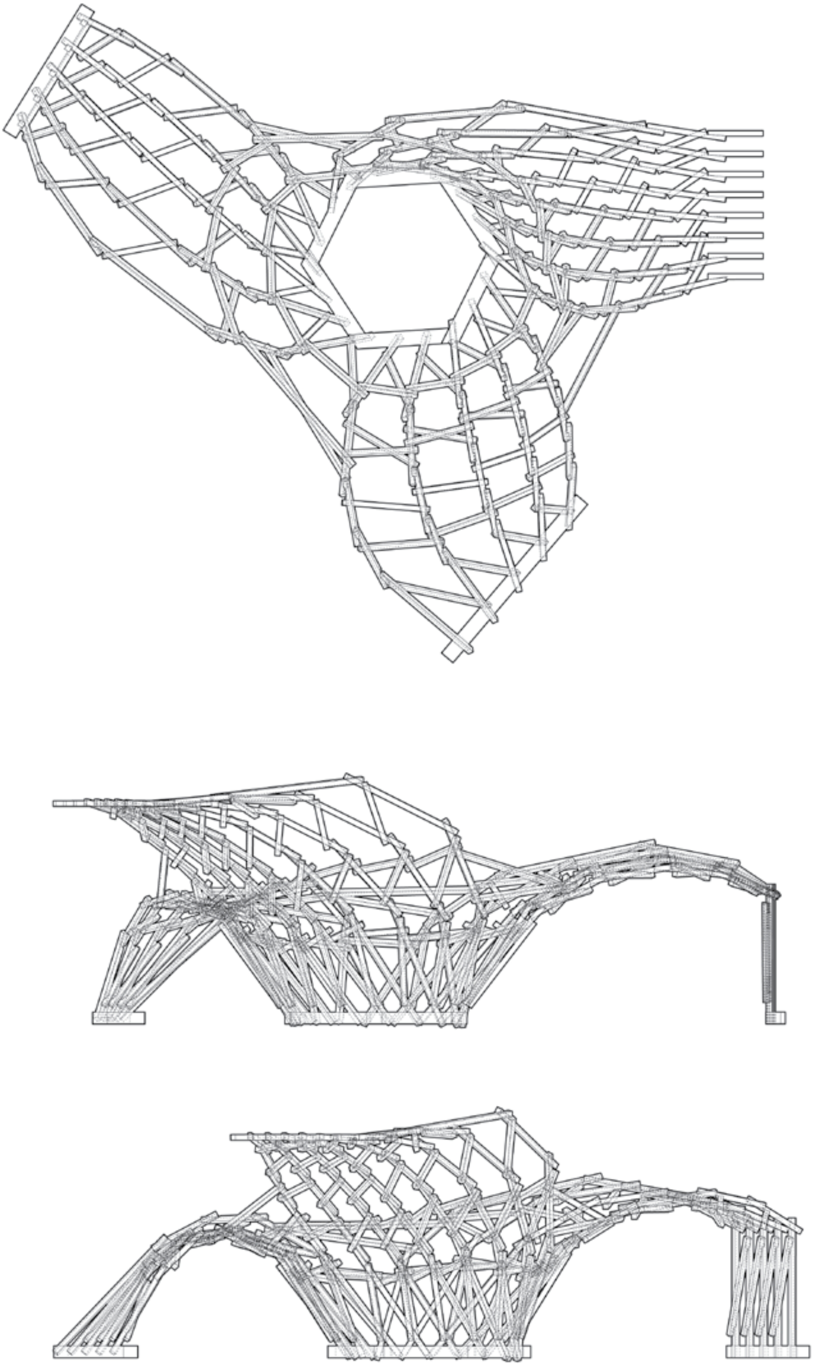


Fig. 30. The drawings of the Body Building installation 2015 were generated for purely documentation purposes. Fabrication files were generated directly from the 3D model, which was also used as a guide for assembly.

Fig. 31. SoundWave I. 2016 Tallinn Music Week City Stage at Musumägi, in collaboration with 2nd year students from the Interior Architecture department at the Estonian Academy of Arts. Team: Mariann Drell, Ardo Hiiuväin, Lennart Lind, Henri Kaarel Luht, Andrea Miku, Mariette Nõmm, Johanna Sepp, Kertti Soots, Sabine Suuster, Teele Tomson, Birgit Õigus.

Fig. 32. SoundWave II. 2016 Tallinn Music Week City Stage at Musumägi, in collaboration with 2nd year students from the Interior Architecture department at the Estonian Academy of Arts. Team: Mariann Drell, Ardo Hiiuväin, Lennart Lind, Henri Kaarel Luht, Andrea Miku, Mariette Nõmm, Johanna Sepp, Kertti Soots, Sabine Suuster, Teele Tomson, Birgit Õigus.

Fig. 33. SoundWave III. 2016 Tallinn Music Week City Stage at Musumägi, in collaboration with 2nd year students from the Interior Architecture department at the Estonian Academy of Arts. Team: Mariann Drell, Ardo Hiiuväin, Lennart Lind, Henri Kaarel Luht, Andrea Miku, Mariette Nõmm, Johanna Sepp, Kertti Soots, Sabine Suuster, Teele Tomson, Birgit Õigus.

Fig. 34. Rheological Formation 2017. Installation by PART Architects for the Into the Valley music festival.

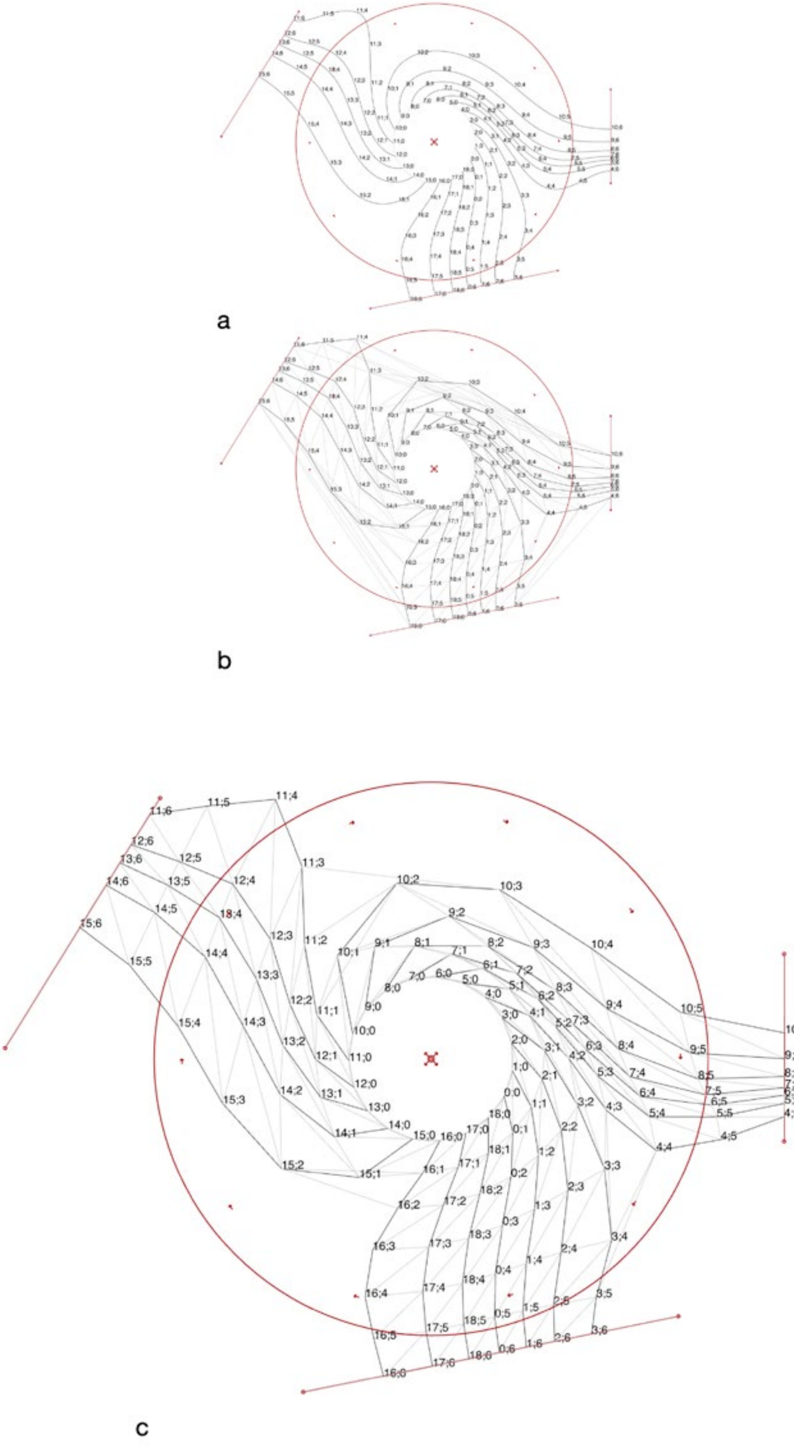


Fig. 35. Body Building installation 2015. The magnetic field lines are evaluated at 19 points and divided into 6 segments.

tion and evaluation of grids and fields will be a returning topic through many other projects.

As our goal has been efficient fabrication and assembly using standard (timber) materials, the Body Building installation was only possible as a lattice structure. The only waste is the material milled out of the lap joints. Once surfaces and volumes come into play variable structures get more difficult to fabricate and construct. Producing enclosure with surfaces would have yielded larger amounts of waste material.

From a designer's point of view, the biggest disappointment was the way the structure was perceived as random or whimsical, as if constructed by hand – the algorithmic precision is lost in the final object, at least for the untrained eye. Considering the ornamental quality of the work and its supposed communicative dimension, this can be considered a failure.

Considering the problematics of fabricating infinitesimally variable parts and learning from mass customisation in industrial products created a shift in the research towards studying variation in configuration rather than fabrication. The next chapter will look at modularity, standardisation and computational design in architecture and at a body of work in the practice of PART I call the Digital Thicket series.

2.

Repetition – from standardisation to emergence

In 2017, having produced a series of small-scale timber installations exploring the capabilities of the local timber house manufacturing industry, PART Architects was asked to design and build a spatial identity for the 2017 Estonian presidency of the Council of the European Union opening ceremony on Freedom Square in Tallinn, on an area of around 3,000 square meters for about 15,000 people. The installation had to be erected in two days and taken down in one night. With the project called Digital Thicket a new topic entered my research – modularity. (Fig. 36)

The following chapter will trace the emergence of standardisation and modularity in architecture by looking at precedents from Jean-Nicolas-Louis Durand (Picon 2000) to Wachsmann's Packaged House system (Imperale 2012) and Eckhardt Schulze-Fielitz (ESF) (Schulze-Fielitz 1960). Digital standardisation is looking for the elementary building blocks in architecture. I draw a parallel between building construction and geometric construction and show how the changes made possible by digital computation in geometric construction could influence the construction of buildings. System building explores an interest in developing universal methods for the creation of architecture, based on digital standardisation, eventually arriving at the possibility of integrated design and through that at the emergence of otherness in the modulated models of the *Raumstruktur*.

The other half of this chapter will look at how these models can integrate conditioning circumstances and computational analysis to arrive at the possibility of the instant evaluation and modulation of emergent systems. The complicated simplicity of modernity is replaced by the simple complexity of the computational age.

2.1. Digital standardisation – looking for elements

> *The elements of science are not founded on the rock of identity but on the shifting sand of their relationship with humanity.*
> (Picon 2000: 39)

At the beginning of the 19th century, Durand developed an analytical method for architecture. In the spirit of Condillac, objects of study must be completely disassembled so that their reassembly becomes easy (Picon 2000: 18). This means that first we need to define the elements or components that can be used to create new architectural compositions. What could these elements be? Element itself is a complex term. In the natural sciences elements as the basic building blocks are constantly redefined as new discoveries are made. The element then becomes a matter of productivity – to what level is it appropriate to divide something in order

Fig. 36. Digital Thicket 2017 by PART Architects.

to operate with it. In current day construction of prefabricated modular architecture this decision is mainly driven by logistics. Architecture is defined by the size of the shipping container. Looking at architectural precedents, could architectural elements be based on autonomous grounds?

Standardisation is one of the foundations of modern architecture. In the spirit of Durand, the early modernists, like Walter Gropius, Adolf Loos, le Corbusier and others, started cleansing architecture of the chaos and clutter accommodated by industrial production (Banham 1960: 9). Since Durand's time, standardisation has been seen by some as restrictive and reductionist – killing the soul of architecture – but also as a means of providing the best for the most for the least by others. Durand used the analytical method to break architecture down into elements and modules that could be easily reassembled according to circulation flows and programmatic needs. In this way, standardisation and modularisation actually enables creativity in the composition of architectural elements, as known architectural elements are turned into proto-pixels. Standardisation is the foundation of automation – as certain parts of the design are already taken care of, we don't need to rethink all the parts every time. The question then really becomes, what parts and to what level do we standardise. What defines the productive element of architecture considering the contemporary computational means of design and automated production?

Durand created a catalogue of building parts to be used in composing new buildings, others have used the human body as a standard measure for size and proportion – the Vitruvian man, the Modulor. Ernst Neufert's "Architect's Data" is still referred to in architectural education for the correct scale and proportion of spaces. Technology has been a major driver for 'how' (catalogues, restrictions, models, methods) and 'for what' we standardise (design, fabrication, construction etc). Nowadays, the construction industry is in the process of adopting Building Information Modelling (BIM) with embedded catalogues of standard materials, elements, products etc. Creating the standard for BIM models in national tenders is currently in development in Estonia. Again, similar to Durand's opponents, architects, even early advocates of BIM, have long started to see it as a straitjacket. Standardisation in itself is not the enemy. One of the biggest protagonists of BIM has been Frank Gehry with his project delivery company Gehry Technologies and their own software packet Digital Project. At Gehry Tech standards were used creatively – creating components (scripts called Knowledge Patterns and adaptive geometric components called Power Copies) so that they can be easily reassembled in an adaptive and creative rather than reductionist and generic way. In this way they could deliver Bilbao Guggenheim, a building of precedent complexity, on budget and on time. As Charles Jencks notes, this is due to "the same size titanium panel throughout, a rigidity which is criticized elsewhere …, because it is out of keeping with the general approach – that is … varying the module to suit the curve and function" (Jencks 1997: 106). In the 90s, one got shamed for creating repetitive components. One could say though that repetition was the result of computational optimisation, where variation was optimised to zero.

A perfect example of a computational standard is the Delaunay triangulation and its dual the Voronoi diagram. The Delaunay triangulation has a single solution for any set of points as its rules state that no point of the set is inside the circumcircle of any drawn triangle. The centres of these circumcircles form the corner points or vertices for the cells of the Voronoi diagram. The robustness of the method – it works with almost any set of points – has resulted in extensive use in computational design. Apart from the organic-looking cellular aesthetic, there are numerous qualities that make it a useful tool in computational design. (Fig. 37) Say you wanted to design a roof with a constant pitch for a house with a complex, irregular floor plan. The Voronoi diagram can be used to find the equidistance curve, showing the location of the ridge of the roof in plan. (Fig. 38) Similarly, a 3-dimensional Voronoi can be used to find equidistance surfaces, composed of planar faces. (Fig. 39) Due to its robustness, it can be used in many different ways – most of the time with complex outcomes. Yet, the diagram itself does not produce complexity – with a regular set of input points the result is also regular. Using circle packing to arrive at the optimum average placement of points in a plane, the Voronoi diagram for those points will be a hexagonal grid also known as a honeycomb.

With the rapid developments in the digitalisation of design, fabrication and construction, an unprecedented level of automation allows us to break objects down to a more elemental level, resulting in higher degrees of freedom in their assembly. Generative architecture has been influenced by algorithms simulating natural growth, dynamic self-organising systems, group behaviour. Computational models like the Lindenmeyer systems, cellular automata, cellular division, agent base modelling, and so on, simulate element level interactions to create emergent behaviours. But once mastered, these borrowed algorithms become clichés. Furthermore, the interest in constructability raises the question of material processes, fabrication and assembly. This call has been made before. For instance, in the 2002 edition of AD titled "Versioning", guest edited by SHoP, where they called themselves "a 'second generation' of digital architects [who] placed an emphasis on open models of practice where the application of technology promotes technique rather than image" (SHoP 2002: 132). Other than a reduction in curvilinearity and an increase in buildability, no radical shift is notable from the first generation of digital architects

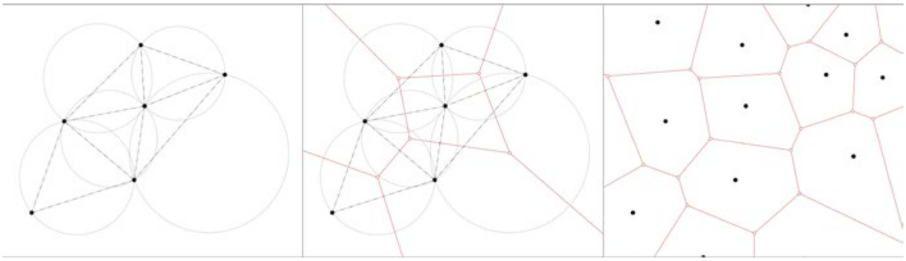


Fig. 37. Delaunay triangulation and Voronoi diagram.

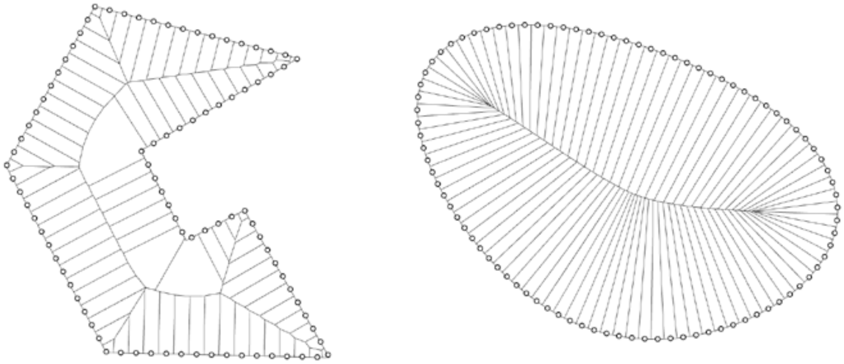


Fig. 38. Approximating the equidistant curve of the boundary – the topological skeleton – using the Voronoi diagram.

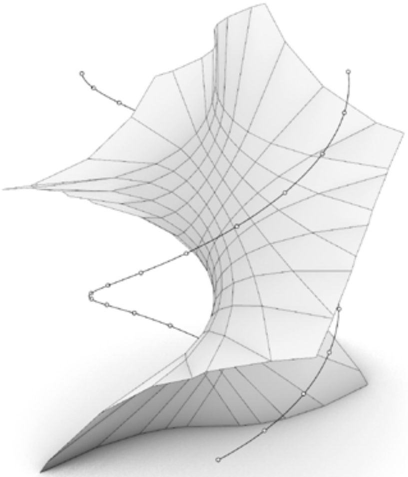


Fig. 39. Approximating the equidistant surface of two helical curves, using the Voronoi diagram, resulting in planar facets.

(Carpo 2013: 131). Looking at the bottlenecks in the physical construction of digital designs, infinitesimal variation has proved to be one of the biggest problems. Architecture needs to move towards a manufacturing logic, where economies of scale do not disappear, even with full automation. Adding to this, the practice of post-rationalisation – where continuous surfaces are broken down into geometric families of parts, and where success is measured by the minimum deviation from the design intent and maximum cut in cost – most often translates into how few unique parts a geometry can be translated into. It has become clear that modularity and repetition, discarded by the early digitals as restrictive, is what needs to be brought back to the table.

Yet standardisation is not the greatest term to use when talking about creativity and autonomy. Standardisation is a term that has a military and royal background. It has the connotation of an overarching top-down rule. As I have stated already, today's digital technology is horizontal; the top-down decisions can instantly be influenced by the feedback from local interactions. Digital computation enables the evaluation of top-down and bottom-up decisions simultaneously by animating and studying their effects on the whole. The grid and the element inform each other. Standards are in constant change, updated with every technological or cultural shift. We cannot look at standards as stable universal guidelines. Modularity and standardisation are therefore not necessarily the same thing. Standardisation is a political process, while modularity is a quality that can emerge from this process. Modularity is not an absolute – we can ask: "How modular?" Modularity is the quality of the whole for its parts to be interchangeable. Standardisation creates guidelines for operation and use. Replacing standardised modularity with a constant negotiation rather than top-down guidelines creates an architecture that is flexible and open, a wholistic system, where neither the grid nor the element is pre-eminent – modulated modularity.

2.2. System building – integrated design

> *Philosophy is written in this grand book, which stands continually open before our eyes (I say the 'Universe'), but cannot be understood without first learning to comprehend the language and know the characters as it is written. It is written in mathematical language, and its characters are triangles, circles and other geometric figures, without which it is impossible to humanly understand a word; without these one is wandering in a dark labyrinth.* (Galileo Galilei)

> *…argued through a "system" approach, organic and non-organic phenomena are considered as "open" systems – with interactions back to and from the environment.* (Imperale 2012: 40)

Calculus is a tool for design and evaluation, not construction – continuity cannot be constructed. The same goes for topology. Euclidian geometry is the geometry of automation as, when defined properly, there is only one solution. We can use continuity, vagueness and emergence in design but in construction, I would not bet on it. The word construction is an important one. The triangle and the circle, or ruler and compass, are the basis for geometric construction. Just like in geometry, there is a minimum number of parameters that define a geometry, structure is evaluated as fixed geometries – lines, arcs and triangles. To construct something precisely, the elements, whatever their shape, need to form these fixed geometries to be stable. Hence the long tradition of using triangles and arcs, to compose buildings – it is based on the logic of strictly defined geometries and their construction. The construction process precedes the geometry. To be able to do this iteratively and repeatably we need a system. Before the calculus-based evaluation of continuity, these systems were based on integers and fractions (Lynn 2004: 11).

At the end of the 19th century, "on the threshold of a world increasingly dominated by scientific and technological rationality," Durand sought to base architecture on utility. He declared the square and the circle the most efficient of forms as they have the smallest perimeter to area ratio and discarded Monge's descriptive geometry, used to construct complex 3-dimensional curves and surfaces in favour of simple elements, grids and axes – a straightforward geometric system. With urbanisation, new typologies, clients and challenges emerged; function and economy and thus engineering and science ruled this new reality. Basing architecture on efficiency and utility, Durand comes up with a new method for the creation of architecture (Picon 2000: 3).

A systemic method is a generative tool. With its rules and regulations new opportunities also emerge. Durand deliberately keeps the system simple "to avoid the trap – into which the revolutionary architects had fallen – of the unbridgeable divide between the simple and the composite, between the elements of architecture and its actual productions" (Picon 2000: 38). Using his system, "analysis is inseparable from synthesis. Durand's method is analytical in its simultaneous manipulation of composition and decomposition" (ibid.: 42). Working on these two levels simultaneously reveals a systemic logic. More so, keeping in mind that this is an educational tool and in this sense anticipates others using this method like a script and evokes the question of authorship similar to today's digital architecture. Durand in that sense is one of the forefathers of integrated design – not only creating an interface between the parts and the whole but also architects and engineers. “Composition, as presented by the professor of architecture at the École Polytechnique, was not only a project method but also the bearer of new forms of negotiation between architectural and structural specialists” (ibid.: 44).

More than a hundred years later, systemic thinking in architecture is in full swing with the prefabricated housing boom of the mid-20th century and its most prominent examples by le Corbusier, Buckminster Fuller, Jean Prouvé, Ray and Charles Eames or Konrad Wachsmann (Bergdoll/Christensen 2008). Corbusier’s Dom-Ino is of course the most famous, with its bare minimum of structure embodying the skeleton for the five points of architecture. In the context of modular building systems, the most universal and therefore of most interest within this context, is Konrad Wachsmann’s Packaged House or General Panel System that he developed with Walter Gropius. “This building system illustrates the unique manner in which systems theory as a concept that linked vastly different fields would be explored in the field of architecture” (Imperale 2012: 39).

> *The only goal of science appeared to be analytical, i.e., the splitting up of reality into ever smaller units and the isolation of individual causal trains. Thus, physical reality was split up into mass points or atoms, the living organism into cells, behavior into reflexes, perception into punctual sensations, etc. Correspondingly, causality was essentially one-way…*
>
> *We may state as characteristic of modern science that this scheme of isolable units acting in one-way causality has proved to be insufficient. Hence the appearance, in all fields of science, of notions like wholeness, holistic, organismic, gestalt, etc., which all signify that, in the last resort, we must think in terms of systems of elements in mutual interaction.* (von Bertalanffy 1968: 45)

As Alicia Imperale argues, in its finite number of defined elements the Packaged House system is a closed system, but due to its open-endedness for design it could be considered an open one. General Panel’s system was advertised through adaptability with examples by various architects like Richard Neutra, for example (Imperale 2012: 42). This universality was achieved with meticulous attention to detail. The system in plan was a thickening of the grid lines. This meant that the panels were perfectly symmetrical, always meeting in a single point, making it possible to design a single master joint. Wachsmann was putting so much emphasis on the design of the joint, revisiting it many times, that it could be considered one of the reasons the system never made it into production. Here we see one of the main problems with the uniquely designed building systems of the industrial age. The processes were too slow and stiff. If there is only one factory that can produce your product, it is going to drive up the price, especially if you want to make last minute changes.

With digital fabrication nowadays this dynamic has completely changed. For our Body Building installation, the sectional dimensions of the timber we ordered were off by a few millimetres. This change was fed into the algorithmic joint model, instantly regenerating the geometry and fabrication files. With the Digital Thicket project, conceptually, we went for a similarly system built structure like Wachsmann's Packaged House – one element does everything. The whole installation consisted of a single solid wood part repeated 700 times. (Fig. 40) The design of the single element allowed for last minute optimisations. After getting the first quote from the manufacturer, we also got guidelines on how to minimise machining time on the joint, making it almost twice as fast to produce. The important factor here is that not only can we make last minute changes, thanks to digital fabrication, we can also almost instantly incorporate manufacturers' input into our algorithmic design models. Furthermore, we are in the end not bound to a single manufacturer, but these elements could be produced at any timber house factory using CNC log milling lines.

Wachsmann's open system of modules defines a similar regular grid as Durand's, with a higher degree of abstraction. A similar rigour towards modularity and universality was put into the space frame structures for which he is most famous, like the USAF Aircraft Hangar of 1951. Mass production together with the developments in structural design like the space frame and Buckminster Fuller's geodesic domes sparked architects imagination for spatial structures beyond the orthogonal. Fuller patented the Octetruss in 1961 based on a tetrahedral grid – the basis for many polyhedral experiments around the 60s and 70s. The truss system discards the idiosyncrasies of architectural elements, creating walls, floor and ceiling of the same elements – a truly digitised building system. (Fig. 41)

One of the most influential characters of that time was Yona Friedman with his spatial city. Writing about him, Theodora Vardouli describes the end of the 50s as a time when architecture turned from object to environment, "a spatial field for the expression of the relations and processes of an increasingly complex world" (Vardouli 2011). Cedric Price's Fun Palace was influenced by him, but Friedman saw his approach different from Price's ideas based on the collective. Friedman saw the inhabitants of his endlessly adapted superstructure as individual agents that do not behave according to abstract top-down communal

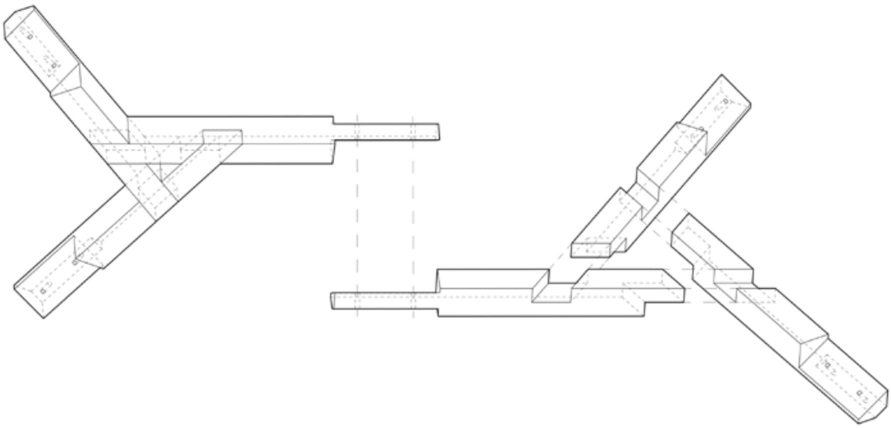
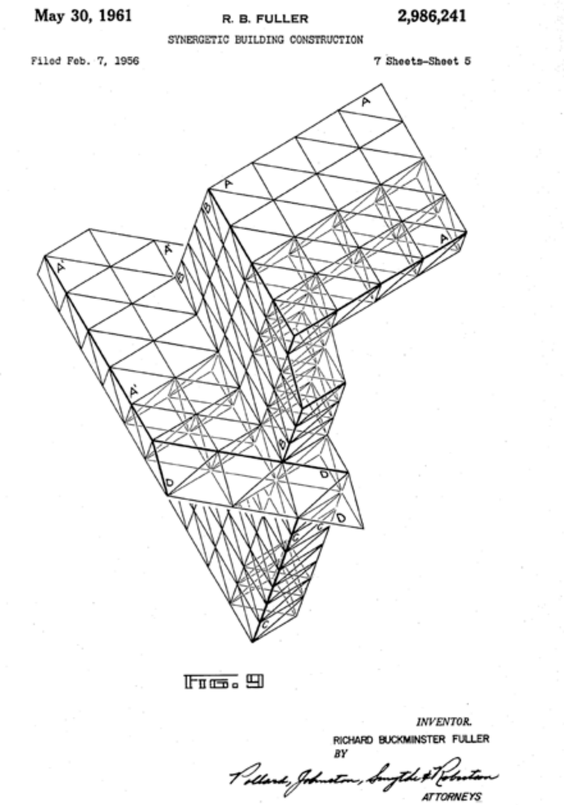


Fig. 40. Digital Thicket 2017. The Y-element consist of three robotically milled timber parts.



May 30, 1961 R. B. FULLER **2,986,241**

SYNERGETIC BUILDING CONSTRUCTION

Filed Feb. 7, 1956 7 Sheets-Sheet 5

INVENTOR.
RICHARD BUCKMINSTER FULLER
BY
Pollard, Johnston, Smythe & Robertson
ATTORNEYS

Fig. 41. The Octetruss. Buckminster Fuller was granted the patent for his synergetic building construction truss system in 1961. United States patent US2986241A.

laws. Here we have the idea of architecture as a self-organising system. Yet a certain framework or infrastructure is seen as essential.

Friedman's contemporary, Eckhard Schulze-Fielitz, had yet another take on this superstructure as an organisational device for the Spatial City:

> *The spatial structure* (Raumstruktur) *is a macro material capable of modulation, in analogy to a hypothetical model in physics, according to which the appearance of the whole can be tracked back to a small number of elementary particles. The physical material is discontinuous, made up of integer components, molecules, atoms, elementary particles. Their combinatory possibilities determine the properties of the material.*
>
> *Not before the modulation of the spatial structure according to type, size, material and position, is it possible to consider it as a wholistic urban organisational device. The Spatial City is a discontinuous continuum, discontinuous in its distinction between part and whole, continuous in its unchangeable possibility for change.*[8] (Schulze-Fielitz 1960: 168, author's translation)

This describes the spatial structure (*Raumstruktur*) as an abstract ordering principle, not infrastructure. It adheres to both industrial mass production and the uncertainty principle. The spatial superstructure is super standardised and in that allows for endless variation, not designed, but coming from within. Not only has automated mass production made possible complex space frame structures and seemingly liberated architecture from gravity, the advancements in technology, science and culture have created a different view on what the fundamental building blocks, the elements, are and how they should be organised.

> *A key attraction of today's parametric design software is its ability to dynamically elastically permute configurations of geometry. Operations and processes are considered as complex componentized machines and the combinatorial ranges of these systems are explored through permutation of*

---

[8] Die Raumstruktur ist eine modulationsfähige Makromaterie, in Analogie zu einem Denkmodell der Physik, wonach die Fülle der Erscheinungen sich auf wenige Elementarteilchen zurückführen läßt. Das physikalische Material ist ein Diskontinuum aus ganzzahligen Einheiten, Molekülen, Atomen, Elementarteilchen. Ihre kombinatorischen Möglichkeiten bestimmen die Eigenschaften des Materials.

Erst die Modulation der Raumstruktur nach Art, Größe, Material und Position erlaubt das Wagnis, sie als umfassendes städtebauliches Ordnungsmittel anzubieten. Die Raumstadt ist ein diskontinuierliches Kontinuum, diskontinuierlich durch die Markierung zwischen Teil und Ganzem, kontinuierlich durch die unveränderlichen Möglichkeiten der Veränderung.

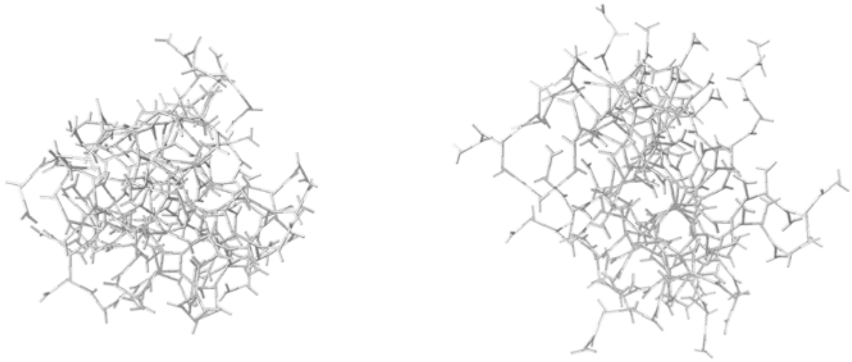
> *their logically atomic components. Through experimentation, designers interrogate a combinatorial range of visual possibilities latent in a system, finding the truth in the system itself.* (Witt 2011: 25)

The cyberneticians of the last mid-century tried to create a model of the world. With the development of computation, science has become as much about creating the world as learning about it (Picon 2008: 75). Rather than a tool that explores reality, it is a tool to simulate it, and as we look beyond mimicry, constructing it.

2.3. Organised chaos – from complicated simplicity to simple complexity

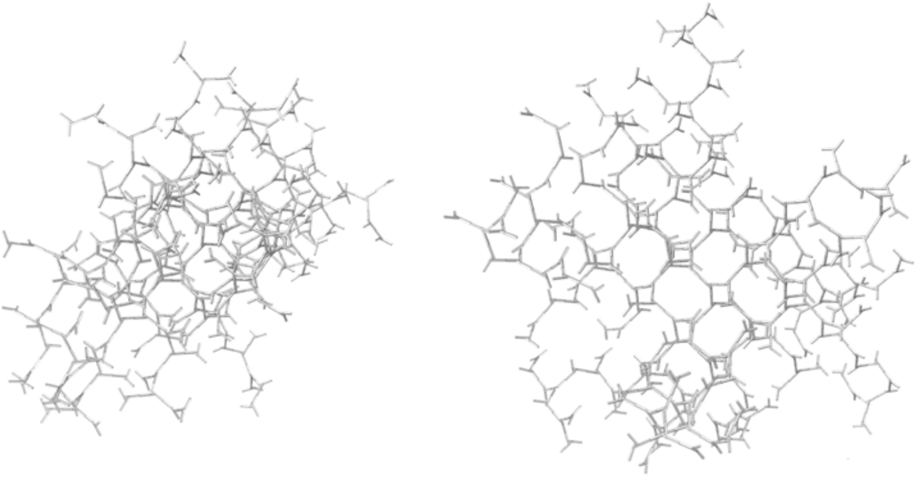
The adaptable superstructure of Friedman was influenced by the uncertainty principle. Cities cannot be planned; they need to accommodate bottom-up change. They need to be open, dynamic systems, described by chaos theory and complexity theory. Chaos theory is often exemplified by the butterfly effect. A small change in the initial conditions can lead to a catastrophic change further down the line. Standards are human constructs and are created in a way as to have predictable influence within a larger framework. When we start questioning some of these underlying principles, catastrophe can be the outcome. Hence the difficulty of making changes in any working system. As these systems are iterative, they need to be simulated and cannot be predicted.

It is easy to see uncertainty and complexity governing the urban scale, but with the simulation of natural complex systems exhibiting emergent behaviour, similar structures start to emerge at different scales. There is a lot of research into growth algorithms, and on how to simulate natural processes. One of those is what is known as the Lindenmayer system, also known as an L-system. The simple rule-based growth and branching system can recursively create complex patterns and is, for example, used to model cellular division and the growth of plants. We used this method to model our first sketches of the Digital Thicket. (Fig. 42) The Digital Thicket geometry is based on Y-shaped elements recursively attaching themselves at open ends. Using a rotation variable for the connection rule, the whole structure can be manipulated to find different configurations, without changing the overall geometry of the elements themselves. Animating this complex structure in this way creates a sort of search engine, where the single angle where the elements aligned and turned from chaotic branching into a space filling lattice structure could be found. Computation allows us to find patterns in chaos, not essentially different, just a special instance of the same.



angle 64°

angle 66°



angle 68°

angle 70°

Fig. 42. Digital Thicket 2017. Aggregation studies at different angles. The model works like a geometric search engine – at the tetrahedral angle of about 70.52° the aggregation turns into a regular cellular structure.

The early modernists went to great lengths to create the appearance of simplicity characterised by literal whitewash. Minimalism needs extreme accuracy and ingenuity in resolving the details. When one looks up the words simplicity and complexity on Google, one sees that the word simplicity became more popular at the beginning of the 20th century and kept rising in popularity until the fifties. Looking at the same usage graph for complexity, it does the reverse, it gains popularity starting from the 50s. What happens during this time is the invention of the modern computer and with it the realisation that complexity arises from very simple interactions. What is different is that we perceive complexity on the object level, while in computation complexity is created from simple statements on the logical level. Michael Hansmeyer and Benjamin Dillenburger's Digital Grotesque Grotto is exuberant as an object, but is based on a simple recursive process – its digital minimalism.

Slavoj Žižek has spoken about the Slovenian band Laibach, that their subversiveness of the system – the prevailing ideology – stems from taking the system more seriously than the system takes itself. "Transgression is always part of the system. To be subversive therefore you have to take the system seriously" (Žižek 1996). For me, this relates to subverting standards by automating them. Through automation and animation new patterns can emerge from the same elements, by changing a single variable for instance.

> *There is really no fundamental difference between a more or less spherical formation and a blob. The sphere and its provisional symmetries are merely the index of a rather low level of interactions, whereas the blob is an index of a high degree of information in the form of differentiation between components in time. In this regard, even what seems to be a sphere is actually a blob without influence: an inexact form that merely masquerades as an exact form because it is isolated from adjacent forces. Yet, blob that it is, the sphere is capable of fluid and continuous differentiation based on interactions with neighboring forces with which it can be either inflected or fused to form higher degrees of singularity and multiplicity simultaneously. Complexity is always present as potential in even the most simple or primitive forms. It is measured, moreover, by the degree of both continuity and difference copresent at any moment. This measure of complexity (the index of which is continuity and differentiation) might best be described as the degree to which a system behaves as a blob.* (Lynn 1996: 60)

The square belongs to the set of quadrilaterals. But in its strict definition it simultaneously belongs to all sets of different types of four sided polygons. So saying that a square is a trapezium is not wrong. In computational geometry it is a closed polyline defined by four points, but could be defined as a Voronoi cell formed by correctly placed five points, it can be defined by edge length, circumcircle or incircle etc. Depending on how a certain geometry is constructed, there are different ways of modifying it. (Fig. 12) Some strategies are more resilient than others. By defining a polygon as a Voronoi cell, in a dynamic system the number of edges might change, but one always gets a closed, non-intersecting polygon. Modulation depends on robustly adaptable precise geometric systems. Order is a special case of chaos. There is a desire for revealing this emergence in computational design, a pattern rising from chaos – the process of formation.

The early iPhone apps imitated real-world materials like wood and fabric. Over time these mimicking strategies have disappeared as people have grown used to interacting with a flat digital slab of glass. Instead of basing the generative algorithm on systems that simulate natural phenomena, we can tweak them, or write new ones, to simulate aggregations of construction codes, elements, spaces, circulation flows etc. Defining the relationships between parts as systemically dynamic and designing parts with more degrees of freedom, creates the potential for overcoming conventions and "otherness" to emerge. Chaos can only be organised based on the real – the conditioning circumstances. Emergence, in this case, is the expression of the real.

2.4. Conditioning circumstances

In the previous subsection, I mentioned the need to transition from computational models that simulate nature towards autonomous algorithms rooted within architecture and construction. Digital architecture needs to face the realities of contemporary construction. There are two important aspects to consider. On the one hand, it is the architectural discourse of the digital that needs to reconsider the history of the pre-90s, pre-digital computational architecture, and on the other hand, update it to meet the conditioning circumstances of the contemporary situation.

Eckhard Schulze-Fielitz (ESF) developed a method for utopian architecture that was based on the realities of the day. With the developments in engineering and automated mass production, architects could imagine new ways of inhabiting space. Together with the social turmoil and considerations about the individual and the collective, these technological means translated into utopian superstructures on the urban scale. ESF developed what he called a macro material capable of modulation –

a geometric structure of space – based on the current capabilities of technology. If we were to construct the macro material of today, we would need to consider a new brief. The need for housing is still there and the preservation of nature and architectural heritage are also still topical. At the same time, we are facing the climate crisis, growing inequality and the risk of global pandemics. With the rise of machine learning and increasing automation, as machines become autonomous, we are also facing the silent but steady loss of our own autonomy, subscribing to more and more platforms of standardised services. With e-governance, the state is becoming one of them. Therefore, utopian open systems are more topical than ever. Yet, with any utopia there needs to be recognisable reality to make it productive. Within this research, the more formative forces of reality are structure, material qualities and means of production – the conditioning circumstances of what can be made define architectural elements and the logic of assembly. Their configuration into structures is limited by structure and open to subjective composition, be it by the designer or user.

The early digitals believed that an ideal version of mass customisation could liberate architecture from modularity and standardisation – giving rise to the idea of non-standard seriality and infinitesimal variation. Today, we see that economies of scale have not disappeared, but have for sure transformed. Instead of mechanical mass production, we have robotic serial production, flexible production or custom mass production. In the construction industry, this change is unfortunately still marginal. Although ideally production in the factory should be more economical, the reality is that building on the construction site, with good old manual techniques, is much cheaper. It is easier to quasi-automate humans than a production line.

On a more positive note, Wachsmann's Packaged House system, would probably have a better chance in today's production chains:

> *One of the lessons that can be learned from the many previous attempts at prefabricated housing production is that uniquely proprietary systems of single-source components are too costly to develop and have almost always ended in economic failure, even when excellent in design, detailing, and production concept*. (Smith 2010: 40)

Using flexible manufacturing and optimising proprietary systems for widespread CNC production creates a situation where many manufacturers can compete for the production of the same unique product driving down price.

The rise in computation power is a more significant change. We can automate composition – the putting together of elements. This brings me back to Durand's innovation:

> *Composition, as presented by the professor of architecture at the École Polytechnique, was not only a project method but also the bearer of new forms of negotiation between architectural and structural specialists*. (Picon 2000: 44)

Not only can we use calculus-based models for organising space, we can simultaneously evaluate this using many objective criteria from material use to structural utilisation to projected energy consumption and production.

> *[I]n [Durand's] eyes, the imperatives of utility, fitness, and economy did not mean that architecture was in any way subordinate to engineering*. (Picon 2000: 52)

Durand here defines the basis for integrated design – a horizontal common platform. Today, the finite element method for structural analysis can be applied to any structure (Ostoja-Starzewski 2002). Taking computational simulation as the basis for digital architecture in the sense described above, it is clear that the realities of fabrication and construction need to be incorporated in the algorithmic design model. Considering what type of material is going to be used will determine what kind of geometries are possible. Using structural plate material, for example, will only enable using planar facets. Considering material efficiency puts further constraints on the type of geometries that can be used. Production line and standard material dimensions add to this equation.

Going modular simplifies this process immensely – from complex simplicity to simple complexity. This happens at all three stages: design, fabrication and assembly. When details are repetitive they can be made more efficient. In production, machine files only need to be made and checked once. Finally, the biggest payoff comes on site, when elements are easily sorted and assembled. A higher degree of standardisation at the part level liberates the whole. Complex formal assemblies are possible with less need for instruction or big machinery. We have tested these ideas in the Digital Thicket series of projects, where large structures were assembled with enormously limited budget, time, and other restrictions (e.g. weight or transportation dimensions).

Automation depends on control loops. There can be either open or closed control loops. The construction of buildings is most often the first – an open loop where we set a machine to produce a part or assemble the parts without the output having any effect on the control action. There is no feedback. This, for instance, is how most 3D printers work and why, quite often when using plastic extrusion, the result can be a fuzzy filament ball instead of your design. Constructing complex structures would be just as hazardous without proper simulation, analysis and optimisation. A closed or feedback loop is much more easily implemented in the digital design phase, where processes can be iterative.

Automation of these processes, like finite element analysis, was born out of the need to speed up the evaluation of large civil and aeronautical engineering projects. The result is a fast process for design evaluation, which can be manipulated by any member of the design team, as it comes with built-in specialist expertise. Therefore, it allows architectural design decisions informed by physical constraints from the very beginning, while also bringing computational engineering language (e.g. force flow lines) into architectural design. As most of these automated systems are in part also developed and widely adapted by architects, structural and environmental simulation, analysis and optimisation using genetic algorithms have become the tools of automation for design.

2.5. Growing and pruning the Digital Thicket

Structural concerns are rather simple to incorporate into design models nowadays using finite element analysis through tools like Karamba3D developed by Bollinger+Grohmann. Using the finite element method, structures can be evaluated on the go and optimised using evolutionary algorithms. This approach was used in the design of PART's first competition win: the Bog Fox high voltage power line corner pylon. (Fig. 25) The first model, made using approximate structural loads, gave us an idea of how it would behave even before the engineers set up the correct structural model. Although we used evolutionary optimisation, the proportions were slightly changed to achieve a more appealing form, while the price of the added material was simultaneously displayed, allowing us to evaluate the marginal change in cost compared to the elegance of the form. In setting up these models, the potential for intervention needs to be retained. The critical question is – what is being optimised.

The Digital Thicket series concludes with the Urban Jungle project – an 18-metre-tall vertical garden structure. The introduction of the larger scale and scope of construction – facing realities – created a pivotal moment for this research; that is, concluding the topic of modularity and by reconciling it with variation, developed it into the idea of modulation. The modular Packaged House system could be used for up to two storey buildings – due to physical forces, the modulation of the elements is needed. This is where my approach differs from the macromaterial modulation of Eckhardt Schulze-Fielitz. Modulation in my work becomes a modular algorithm that can incorporate an endless array of computational components or objects. The question then, once more, is – which elements are productive. For me, these are structure and geometry in their relation to materiality and production. But then there is still the most important question of architectural autonomy and expression. Even as we have ditched mimicking nature in favour of generating architectural form based on its own elements, the analogy of growing and pruning is still a productive one. The architect as a gardener, shaping from within, rather than imposing a transcendent order.

The same principle of immanence can be considered within the finite element method. In principle it can be reduced to the atomic lattice models of materials.

> *It is not surprising that spatial trusses and frameworks have been the primary material systems thus modeled. In the case of granular media, the lattice methods are called discrete element models. Spring networks can also be used to model continuum systems by a lattice much coarser than the true atomic one—the idea dates back, at least, to [Alexander] Hrennikoff, if not to [James Clerk] Maxwell in a special setting of optimal trusses. This coarse lattice idea obviates the need to work with the enormously large number of degrees of freedom that would be required in a true lattice model, and allows a very modest number of nodes per single heterogeneity* (*e.g. inclusion in a composite, or grain in a polycrystal*). *As a result, spring networks are a close relative of the much more widespread finite element method.* (Ostoja-Starzewski 2002: 35)

These coarser models are a good enough representation of the actual material structure. So here we arrive at a fundamental element of structure that needs to be designed before we can compute, simulate, analyse and optimise. These models consist of points (nodes or vertices) and lines (springs or beams) and form simple, mostly regular spatial lattice structures. Micro mechanics is taking simple calculation models of statics and applying them iteratively on all the nodes and elements. This means that all the possible scales in between are also computable. Meaning this idea can be applied to ESF's macro material and made productive at any scale from the urban to the micro-material. With computational means we can discover asymmetries and redundancies, incorporate chance, and so on, to evaluate this spatial structure (*Raumstruktur*), and let it evolve not just through social interaction or the will of the inhabitants, as suggested by ESF, but incorporate any number of human and non-human actors to modulate this macro material. This is evidenced in the Digital Thicket series with Digital Thicket 2017 and Here and Elsewhere 2018, where the structures were adjusted on site in the process of assembly, together with construction workers and volunteers. The architects of the 60s were familiar with the idea of topology but had no intuitive way of working with it. In lattice systems, structural topology can result in unanticipated results.

> *When considering a central force (or truss) system, a question of fundamental importance is whether such a structure is a sufficiently constrained system or not. In other words, is it an intrinsically rigid body? This is the subject matter of a field called structural topology.* (Ostoja-Starzewski 2002: 51) (Fig. 43)

Working with this unanticipated otherness again evokes this parallel to gardening. Simulation by definition is imitation. When we are simulating conditioning circumstances that should hold true. The same process can be used to run generative models that are purely explorative. These complex systems exhibit emergent behaviour; there is a certain distancing happening within the design process. We are not imposing our will on matter. In the age of synthetic ecology, it does not really matter if we are up against the laws of nature or the laws of technology, bureaucracy, standardisation – it is all a matter of modulation – a careful measuring of elements – materials, geometries, tools, algorithms, ecologies and economies. There is the designer, the real and the other. The designer (or anyone with the authority to make changes) with their subjective preferences negotiating the customs of the discipline, the conditioning circumstances of the real, meaning what can be made and an automaton, a script, a custom nature – the other.

Durand's method was abandoned soon after its introduction due to the change in scientific methods:

> *Mathematical analysis, as revolutionized by Augustin-Louis Cauchy, had little in common with Condillac's "complete decomposition of an object, and the distribution of its parts into an order in which its generation becomes easy." From physics to engineering, from chemistry to medicine, scientific and technological knowledge was now too complex to be seen in terms of combinations of finite numbers of elements.* (Picon 2000: 53)

It is interesting now to note that in the computational science world of data, the discrete element model is the preferred method for complex problems from structural analysis to thermo dynamics.

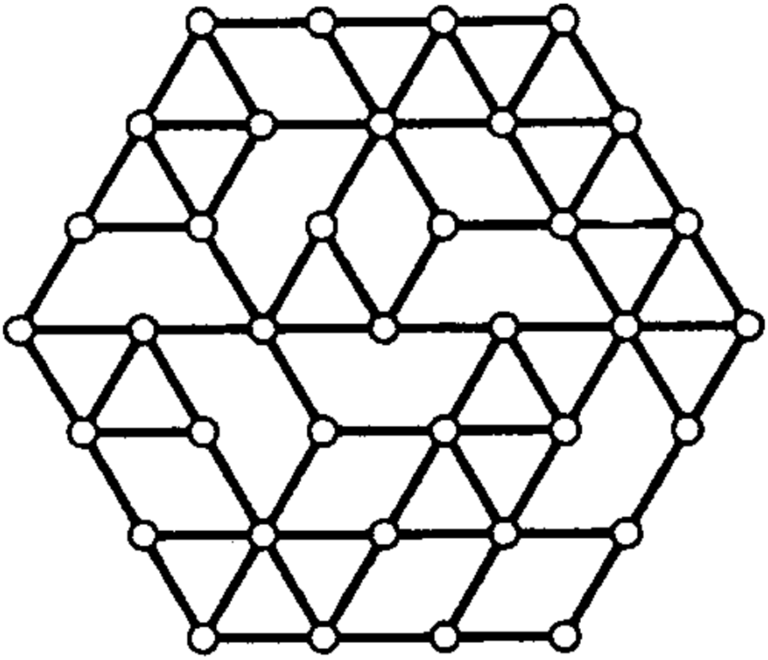
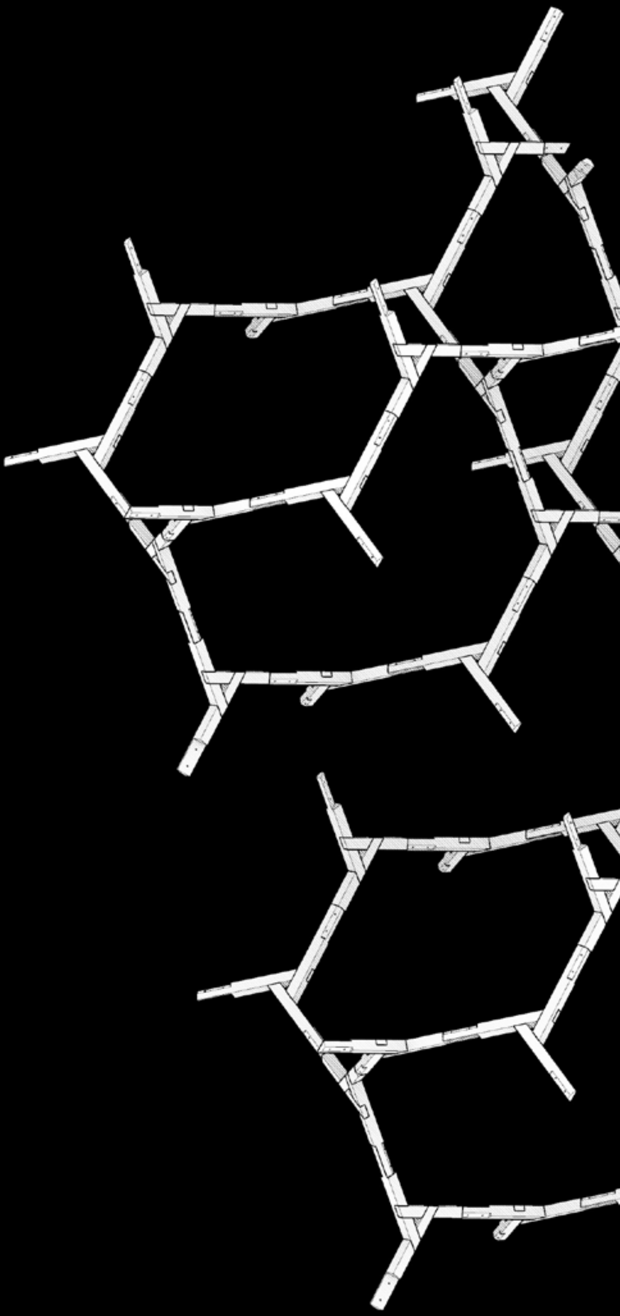
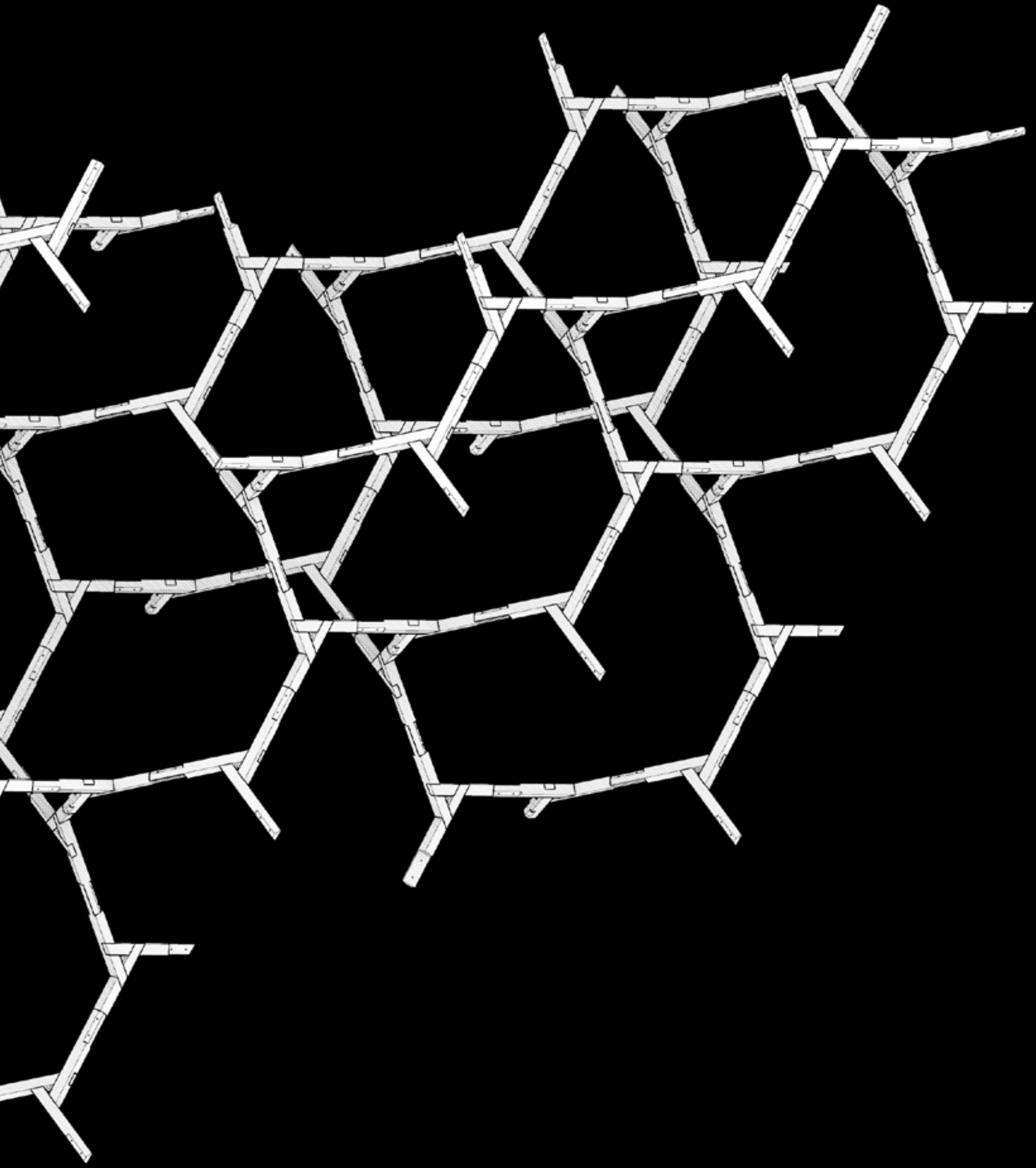


Fig. 43. A triangular lattice with 71 edges and 37 vertices; it is generically rigid. (Ostoja-Starzewski 2002: 52).



2.6.

Milestone project: Digital Thicket series



Digital Thicket

Year:	*2017*
Client:	*Musiccase*
Location:	*Vabaduse square, Tallinn, Estonia*
Scale:	*3000* m^2
Elements:	*700 identical pieces*
Material:	*95x95 mm lumber, 7.0* m^3

With the Body Building installation and other fully variable pieces, the weakest link was assembly. With the Digital Thicket installation for the opening ceremony of Estonian Presidency of the Council of the EU, the scale increased substantially, requiring disproportionate funds from the budget. Therefore, we needed to find a way to automate parts of the assembly process.

We started looking at Lindenmayer systems, particularly at regular Y-shaped modules connected end to end and adding rotation. Setting up a parametric model, we realised, first, that a branching structure would not be structurally viable, and second, that by rotating the elements by about 70.5° or the tetrahedral angle, they interlock and form a modular structure. In further analysis, we found the geometry follows the surface and edges of truncated octahedra, which are space filling polyhedra, (Fig. 44) which can be subdivided into the recurring tetrahedral grid.

The geometric system also follows the logic of the Steiner tree problem; that is, it forms a minimum weight network. This is exactly what we were looking for: a system that uses a minimum amount of material to fill a maximum volume of space. The event happened on one night only, so the structure needed to be easily transported and assembled (as well as disassembled) right before and right after. The Y-module consisting of three identical pieces coming together in a triangle shape with half lap joints formed structurally stable stiff elements. (Fig. 40) The other end was cut at an angle allowing for the 70.5° twist. The Y-modules were connected by two bolts at the centre of geometric axes, where the momentums are the smallest. The geometry of the Digital Thicket is by no means structurally optimal. It is geometrically a spring structure, where forces are directed down through a helical path. However, this is what makes the structure ornamental. Its main aim is not to direct forces to the ground by the shortest route but to create human scale spaces.

The whole structure consists of identical elements of 95x95 mm timber that have a single way of assembly; therefore, eliminating construction mistakes. (Fig. 45) The system does not remove the human from the assembly process, but most tasks, like searching, sorting and fitting, are eliminated, making it a quasi-automated process. (Fig. 46)

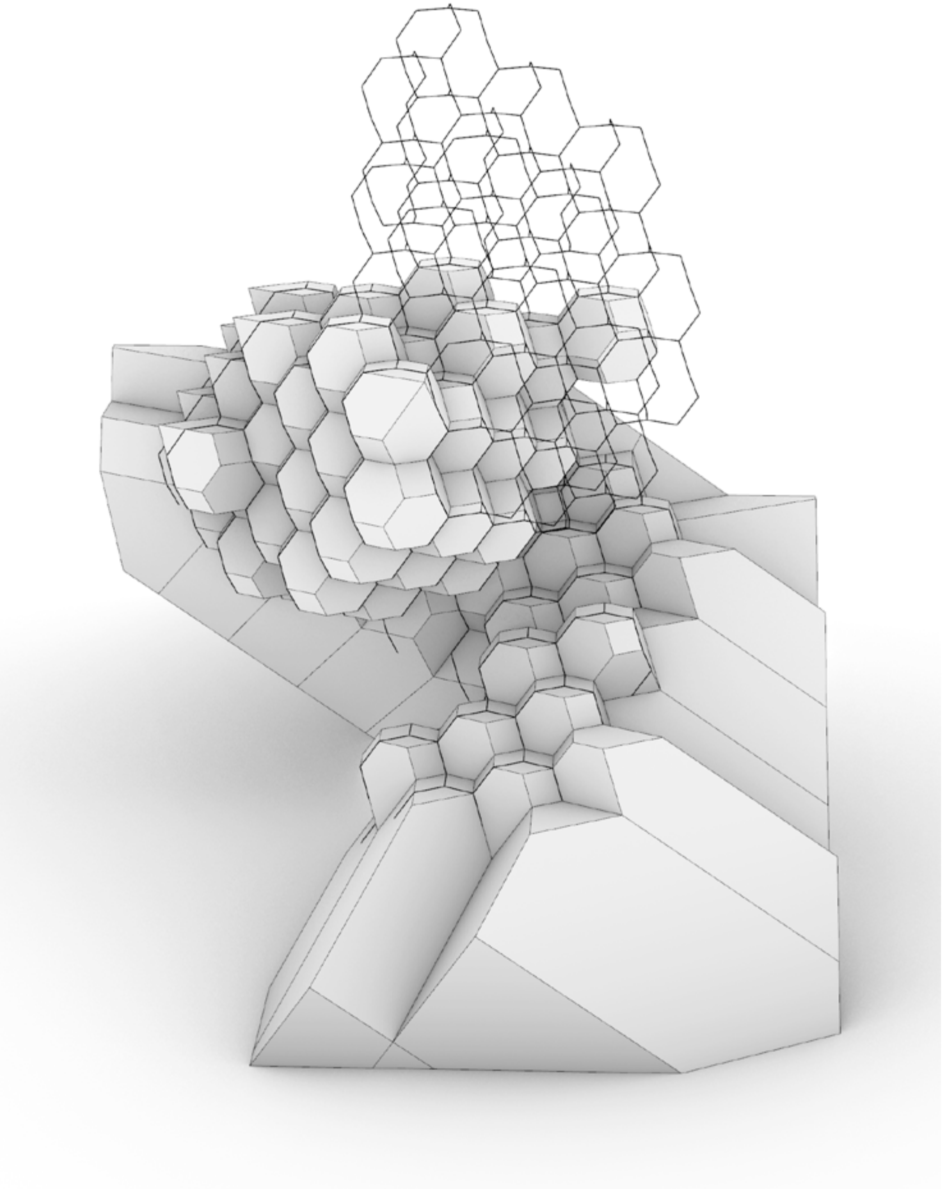


Fig. 44. Digital Thicket series geometric study 2018.

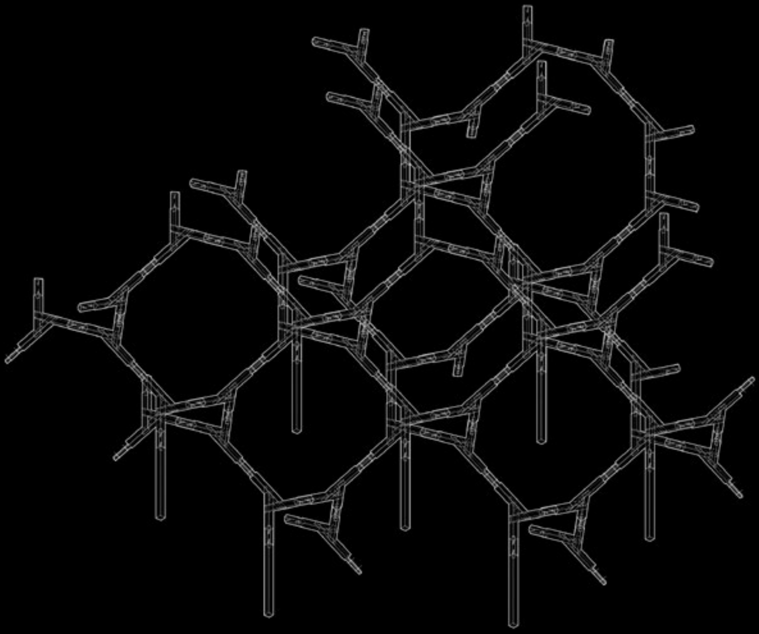


Fig. 45. Digital Thicket 2017, chunk drawing.

Fig. 46. Digital Thicket 2017 by PART Architects.

The whole installation was assembled by non-specialist workers through GoWorkaBit, an Estonian startup for flexible working options. Later the structure has been reassembled in multiple locations around the city, always in a different formation. Similar to the General Panel system, it is in some ways a closed system – there is only a single way of connecting the elements, yet it can also be considered an open system, as it allows endless possibilities for (re-)configuration.

Here and Elsewhere

Year:	*2017*
Client:	*Estonian Centre for Architecture*
Location:	*Design and Architecture Gallery in Tallinn and BOZAR in Brussels*
Scale:	*16 m*^{2}
Elements:	*120 joints in 4 different sizes and 135 round sticks*
Material:	*12 mm plywood, 14.9 m*^{2}*; 35 mm round pine profile, 60 m*

Since the initial project, we have applied this geometric system on various scales from furniture to interiors to urban structures. The Here and Elsewhere project, conceptualised in collaboration with LASSA Architects, looked at the interior scale and created spaces for work, study, leisure and interaction. (Fig. 47) The module was realised on a scale with 40 cm steps to create seating, tables and surfaces to be used while standing. The installation was displayed at the Tallinn Architecture Biennale 2017 (Fig. 48) and at BOZAR in Brussels from November 2017 until January 2018 (Fig. 49). This also implied that multiple assembly and transportation cycles had to be taken into account. The structure filled a space measuring 64 m3 in its assembled state and about half a cubic metre when disassembled for transport. (Fig. 50)

Its roughly 250 joints in 4 different sizes were CNC-milled out of 12 mm plywood. The round pine profiles of 35 mm diameter with notches creating the 70.5° rotation were also 3-axis CNC-milled using jigs. The failure to automate the rotation part of the fabrication process was the biggest weakness of the project. Design-wise the four different sizes of joints allowed various usable surfaces like chairs, tables and information carriers. It also created a variation within the structure, allowing for orientation, and light and shadow effects.

At the furniture scale, the structure exhibits the most feasible possibility for social intervention, as the elements of the structure could be reconfigured without using tools. Within the exhibition this was proposed as an adaptable working space that could change grow or shrink as necessary.

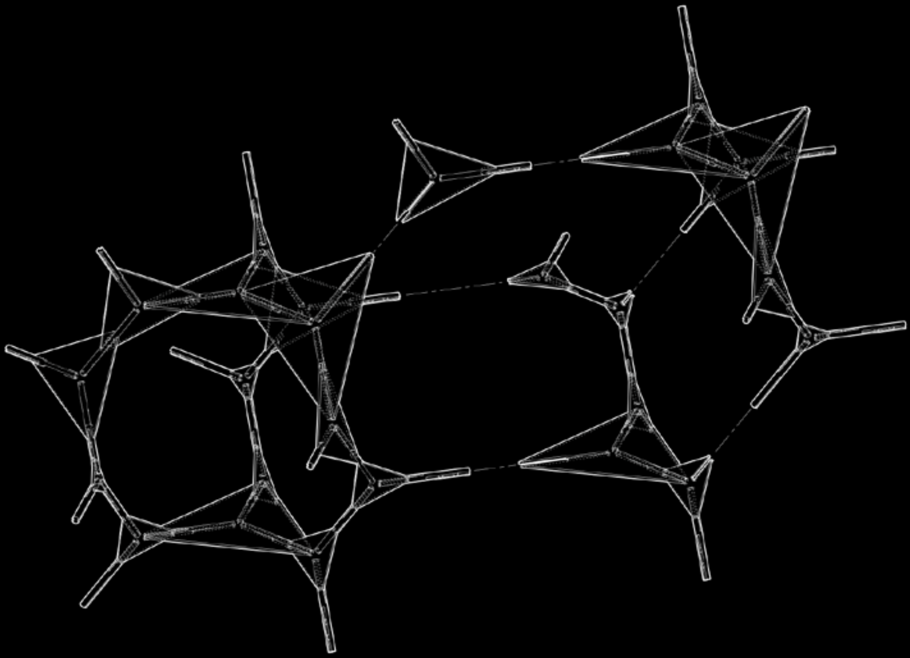


Fig. 47. Here and Elsewhere 2017 by PART Architects and LASSA Architects, assembly drawing.

Fig. 48. Here and Elsewhere 2017 by PART Architects and LASSA Architects at Tallinn Architecture Biennale.

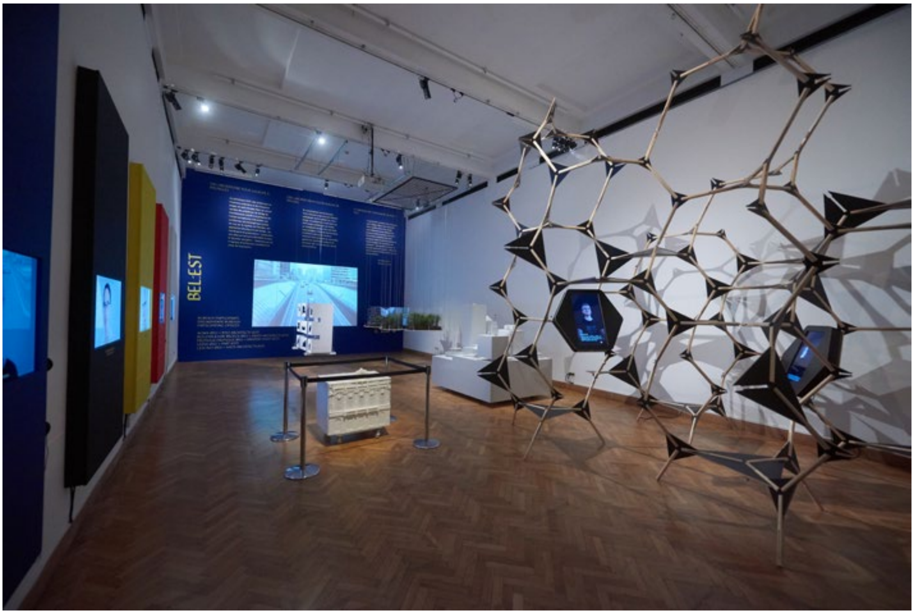


Fig. 49. Here and Elsewhere 2017 by PART Architects and LASSA Architects in Bozar, Brussels at the BEL:EST exhibition.

Fig. 50. Here and Elsewhere 2017 by PART Architects and LASSA Architects, transport drawing.

Fig. 51. PART.icular – Bespoke Timber Architecture. PART's exhibit at Time Space Existence at Palazzo Bembo, part of Venice Architecture Biennale 2018.

Fig. 52. PART.icular 2018, 3D printed details allow for free rotation, yet the structure finds its equilibrium in the Digital Thicket geometry.

PART.icular

Year: *2018*
Client: *GAA Foundation and the European Cultural Centre in Venice*
Location: *Palazzo Bembo, Venice, Italy*
Scale: *10 m*^{2}
Elements: *280 3D printed joints and 385 round sticks*
Material: *PLA plastic, 1.7 kg; 12 mm round pine profile, 60 m*

In the third, the most recent instalment of the Digital Thicket geometric system, we created a shelving system as an exhibition design for PART.icular – Bespoke Timber Architecture as part of Time Space Existence organised by the GAA Foundation and European Cultural Centre at Palazzo Bembo in Venice. (Fig. 51) In this case, the angle was not fixed by using round profiles and joints that allow rotation, meaning the form is self-organising by fixing the wall connections. (Fig. 52)

A further addition was the introduction of a surface. We have been working with nets and stretch fabric to create minimal surfaces filling the cells. In this case, we needed to print on the surfaces, so we decided to go with paper and developable surfaces – triangulation with fillets. The curved folds still give the impression of a doubly curved surface. (Fig. 53) Furthermore, as it is made of paper, it means that while scaling the system up, the same strategy could be used with other bendable sheet materials to fill the cells in a similar manner.

Again the system was installed in different spaces, adapting to the room as needed. The simple kit of parts makes it almost toy-like. (Fig. 54)

Urban Jungle

Year: *2018*
Client: *T1 Mall of Tallinn*
Location: *Peterburi tee 2, Tallinn, Estonia*
Scale: *700 m2, 18 m*
Elements: *522 Y-modules, 268 L-modules, 12 unique welded chunks*
Material: *Steel S355; main structure 90 mm round pipe, varying wall thickness, 11 tonnes*

The last project in this series is the 18-metre-tall vertical indoor garden, designed together with KINO landscape architects. (Fig. 55) On the part of the structure, we arrived at a limit where the elements started to vary in wall thickness due to the structural loads. For me, this project was a huge success in its failures, as it pointed out the conceptual flaws in our modular projects. The elements in the structure are repetitive, the changes in

Fig. 53. PART.icular 2018, printed paper infills.

Fig. 54. PART.icular 2018, kit of parts.

material thickness cannot be perceived. On the one hand, it is concealing the fascinating structural logic of the system, on the other, it meant that for assembly we had to have special weld marks on the elements to know which pipe has which wall thickness. (Fig. 56) Additionally, there was a design flaw in the structure, where one module is just randomly missing. As the structure is calculated without this element, this is no problem. (Fig. 57) Yet this also means that within the structure there are redundancies, meaning we could have eliminated elements by checking their utilisation and made the structure more efficient in one sense, but more importantly adherent to its expression of the computational logic.

Due to its scale, the social aspect and reconfigurability is lost on the overall scale, yet the attachment of surfaces to the structure could be reconfigured easily and the structure made inhabitable.

The Urban Jungle vertical garden structure was the first of the Digital Thicket series to incorporate proper inhabitable surfaces. (Fig. 58) These surfaces were modelled based on the truncated octahedron. As we started designing seating and steps into the landscape, we realised the geometry is too rigid and had to start subdividing. It was not until I saw the finished thing that it dawned on me that these subdivisions are based on the space filling tetrahedral-octahedral honeycomb, the same structural principle Buckminster Fuller patented in his Octetruss system and that has been the basis of many polyhedral experiments by mid-20th century architects, many of which I have discovered in the process of writing up this dissertation, including the macro material of ESF that resonates strongly with my own ideas coming from working with polyhedral geometries and computational analysis.

The project started by defining the spatial structure. As again our aim was to maximise the volume of the installation while being bound by the load restriction on the atrium floor (5kN/m^2). We decided to once again use the Digital Thicket geometry. For structural stability there are no loose ends, meaning the structure consists of cells that can be represented by truncated octahedra. Truncated octahedra can be produced using the Voronoi diagram on the nodes of a cubic honeycomb with centroids also known as the body-centred cubic Bravais lattice (Cubic… 2020). (Fig. 59) The resulting point cloud is identical to the vertices and centroids of the tetrahedral-octahedral honeycomb with centroids. To achieve both maximum structural performance and, subjectively assessed, best compositional possibilities, the grid is oriented on the face of the tetrahedron, which is the same as to say it is balanced on the corner of the cube. (Fig. 60) The truncated octahedra aggregate in a spiral pattern with a step height of a third of the polyhedron height, which corresponds to the height of the tetrahedrons. Therefore, the edge length relates to the step height like the tetrahedron edge relates to its height[9].

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[9] H=sqrt(6)/3*a

Fig. 55. Urban Jungle 2018 by PART Architects in collaboration with KINO Landscape architects at the T1 Mall of Tallinn.

Having defined the spatial structure, an attractor-based force field is used to cull the point cloud. The boundary is represented by a mesh, generated using the marching cubes algorithm in Fig. 61. Populating the point cloud with the cells of the structure, the structure can be evaluated for the spatial qualities it produces, structural behaviour, the amount of material to be used and the number of elements to be fabricated. The initial grid was produced with a 500 mm edge length resulting in a step height of around 400 mm, a good height for seating. We decided to double the edge length to reduce the amount of elements eight-fold – a critical change that created the need to subdivide the truncated octahedra that formed the plywood base. It was this need for subdivision that became the impetus for creating the core algorithm for modulated modularity. Combining the idea behind marching cubes and the experience with space filling polyhedra turned into a tool for modular surface approximation. (Fig. 62) Although we have mainly used the tetrahedral-octahedral honeycomb, any space filling solids would do. (Fig. 63)

Moving towards modularity has definitely allowed PART to jump scales from small-scale installations to apartment buildings. The Urban Jungle project is proof of concept, where the main effort was in working out the repetitive details that were then simple to produce using laser-cutting and welding the elements by hand on a simple jig. (Fig. 64–66) This also means a change in thinking in respect to production. When the digital is mainly connected to mass customisation, our approach has been rather based on custom mass production. This means making full use of contemporary CNC machinery when working out parts and putting more flexibility into a repetitive part that can be mass produced.

The computational model developed for this project can be divided into six computational modules that can be reused and developed independently. (Fig. 67) First there is the spatial structure that divides the space into the basic elements of composition. The second part of the algorithm deals with form generation, influenced by access paths and view corridors. The selection and combinatorics module defines which elements of the generated structure to pick and how to combine them into geometric modules. There are multiple evaluation modules. The most influential one here is the structural analysis component. As the design develops there are multiple detailing modules worked out: structural details, positioning of lights and speakers and so on. Finally there is the data extraction.

Some of these modules are used in multiple projects almost unchanged, only parametrically adapted. Some of them are unique in each project. The way visual programming algorithms are packaged into components that then again can be combined into clusters, makes it fairly easy to reuse and remix parts of these codes.

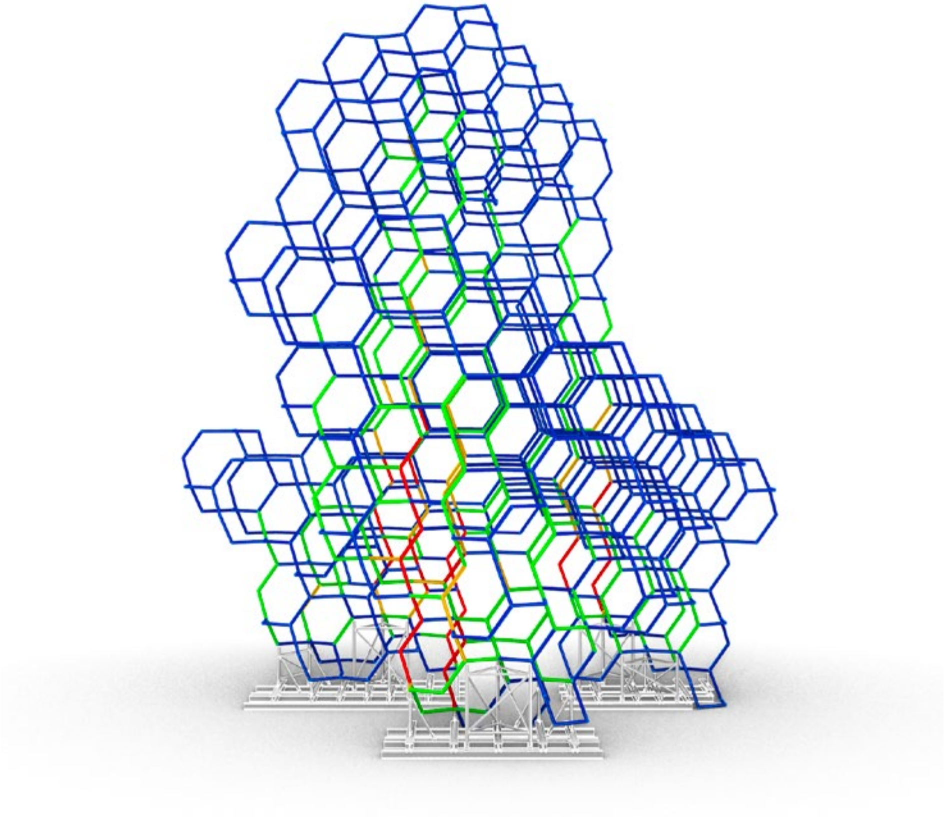


Fig. 56. Urban Jungle 2018, visualisation of varying profile thickness.

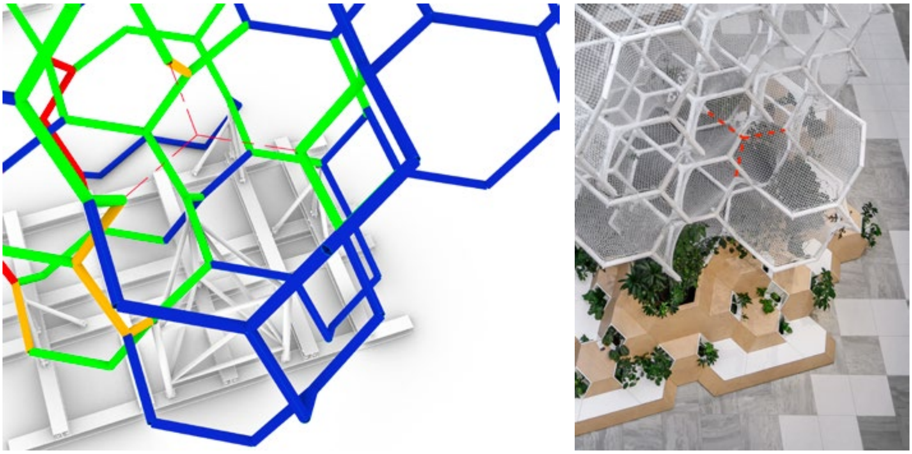


Fig. 57. Urban Jungle 2018, the “missing” element.

Fig. 58. Urban Jungle 2018, plywood landscape, subdivisions of truncated octahedrons.

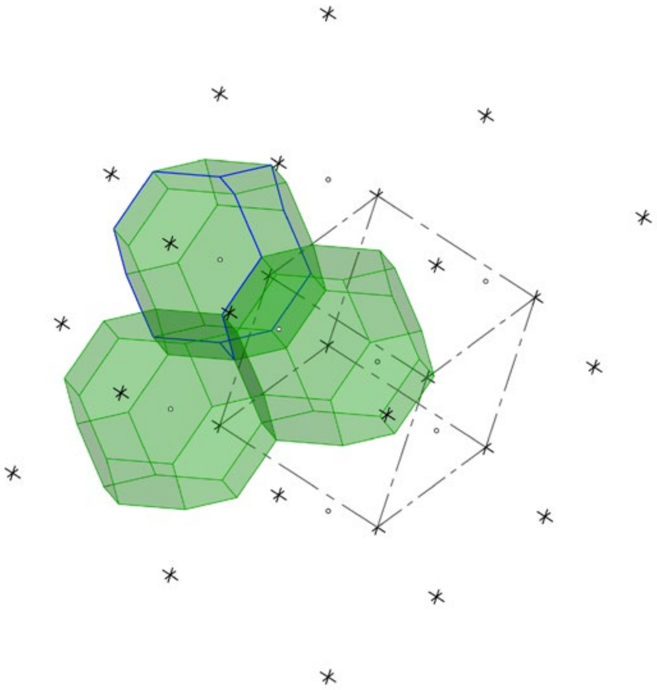


Fig. 59. Truncated octahedra can be produced using the Voronoi diagram on the nodes of both the cubic and the tetrahedral-octahedral honeycomb with centroids also known as the body-centred cubic Bravais lattice.

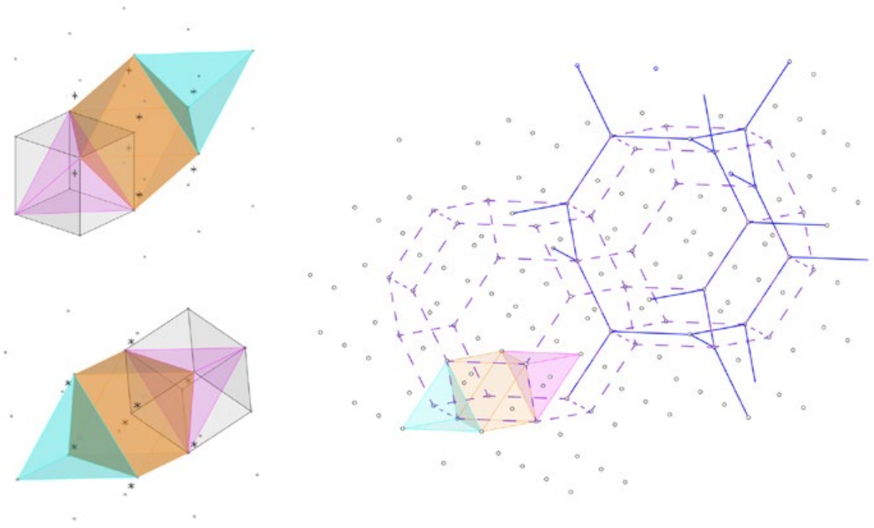


Fig. 60. Urban Jungle 2018, basic geometry. The lattice is oriented on the face of the tetrahedron, resulting in a triangular plan grid and the best structural performance of the Digital Thicket geometry.

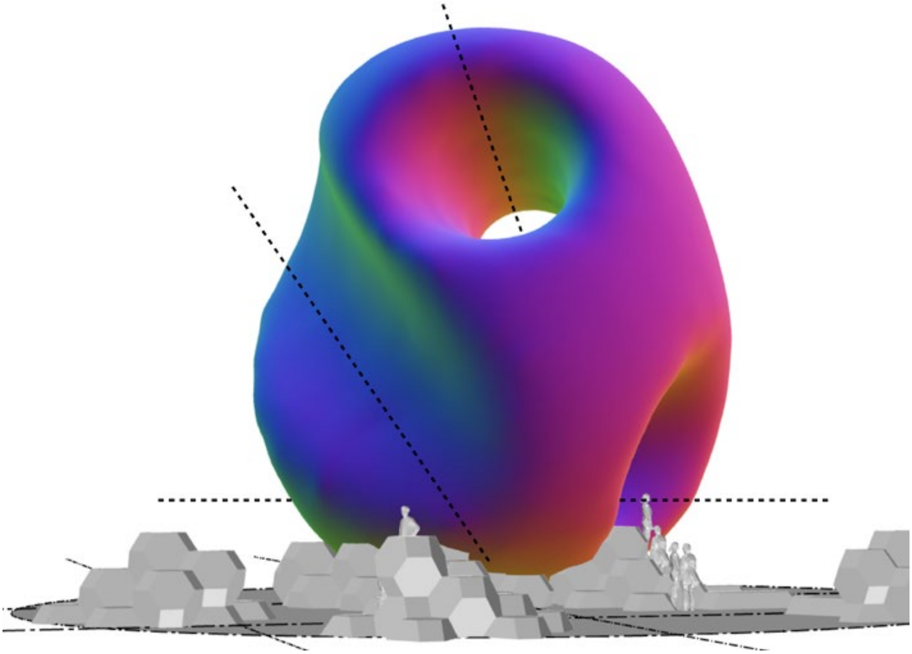


Fig. 61. Urban Jungle 2018, the overall massing is created using force field modelling and an isosurface boundary.

Fig. 62. Urban Jungle 2018, the subdivision geometry on the plinth was an inspiration for the core modulation algorithm used in later projects.

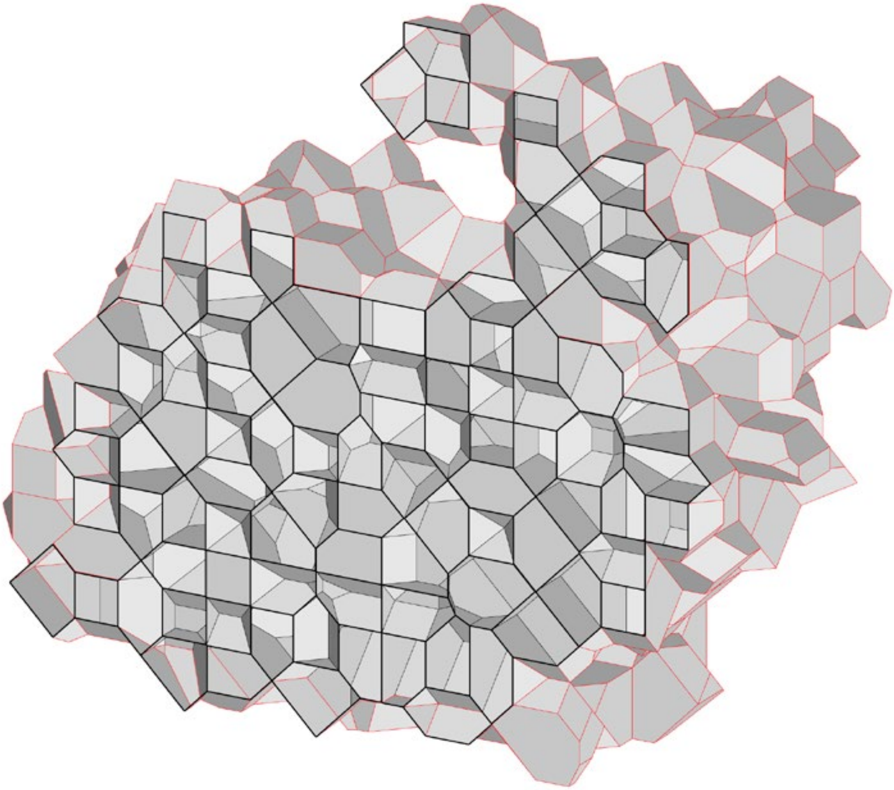


Fig. 63. Modulation of the Stanford bunny. The boundary volume is populated with random points, the coordinates averaged by an integer factor, which results in a random selection of a cubic lattice nodes. This random selection of a regular lattice nodes produces a random aggregation of regular cells.

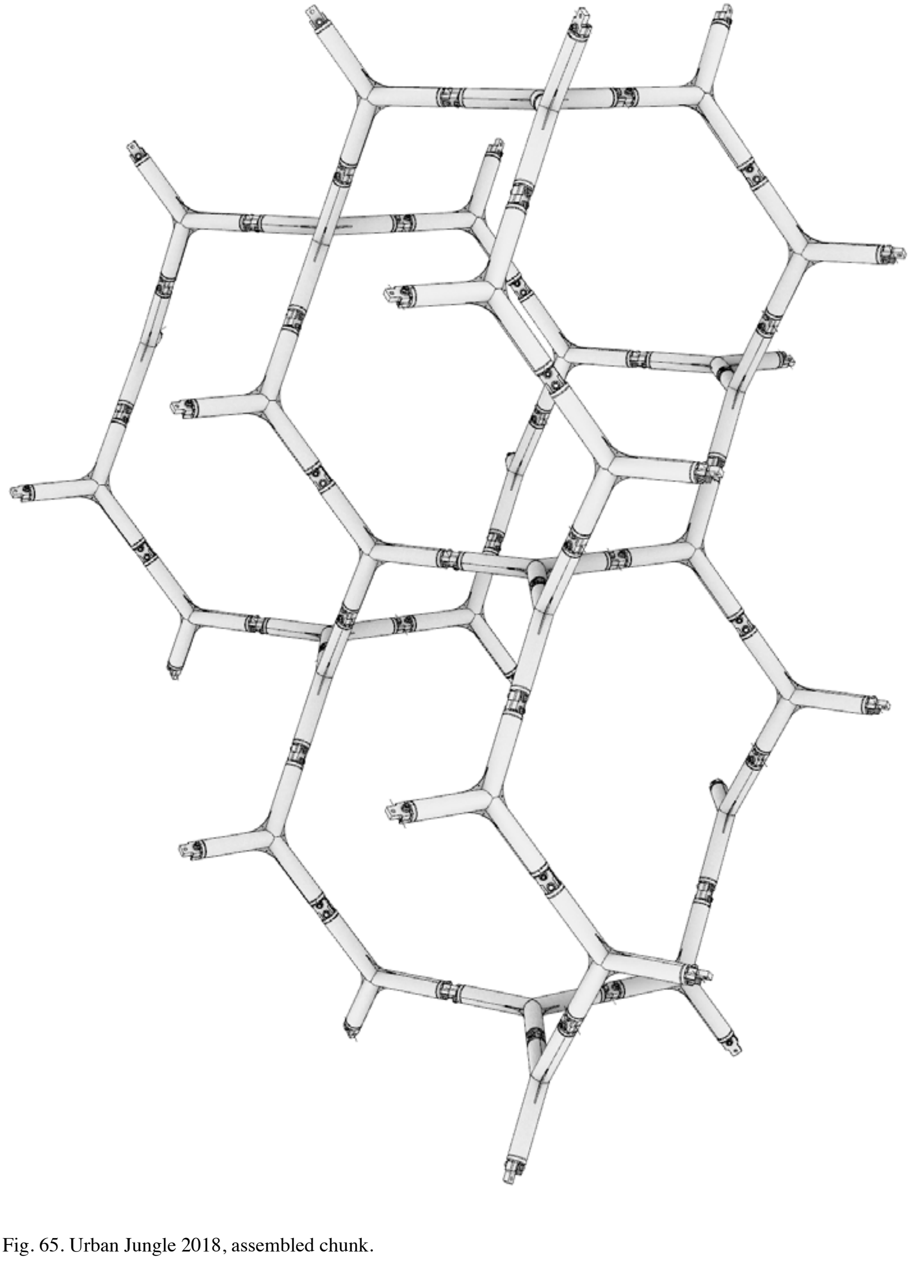


Fig. 65. Urban Jungle 2018, assembled chunk.

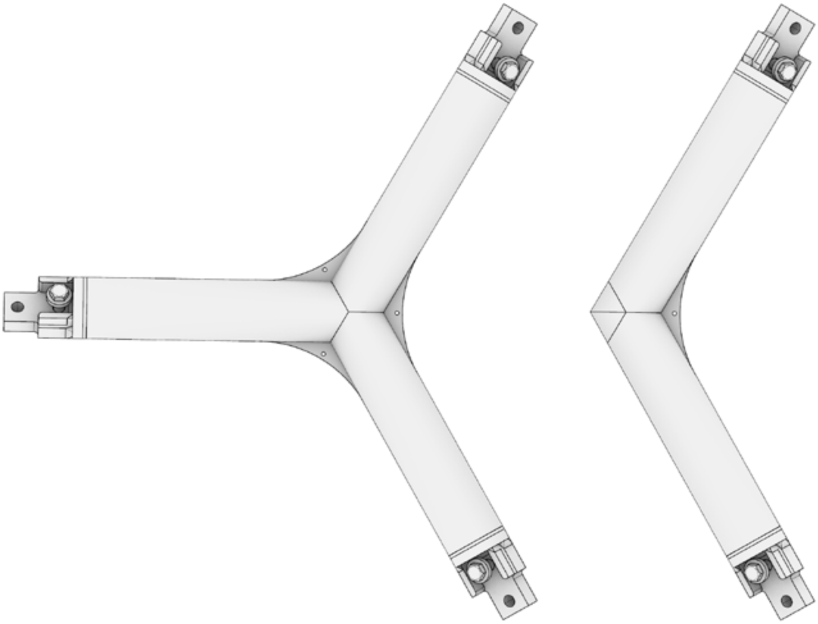


Fig. 64. Urban Jungle 2018, the Y-element and the L-element.

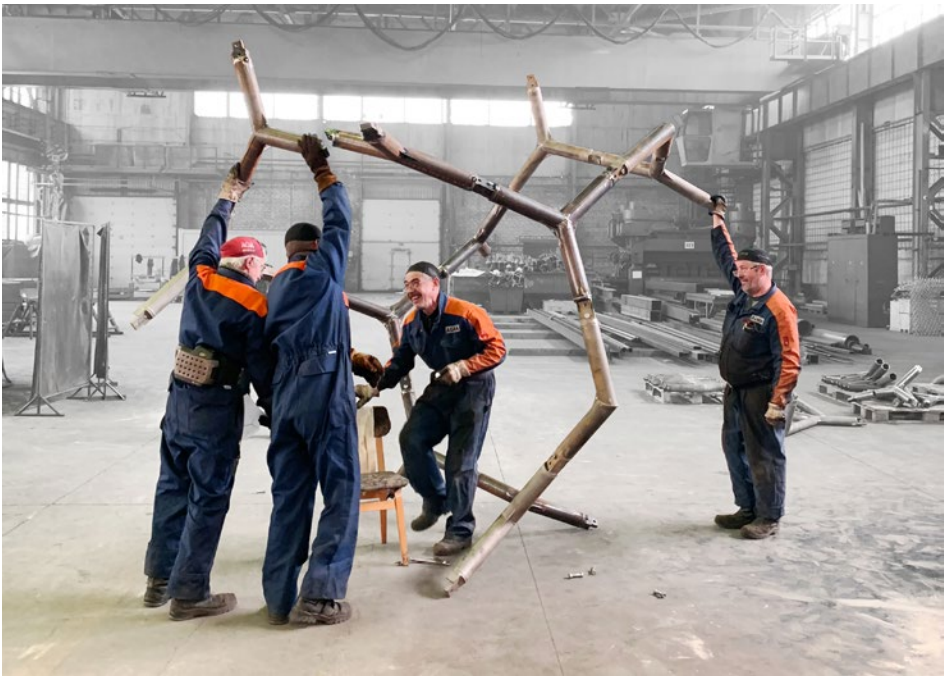
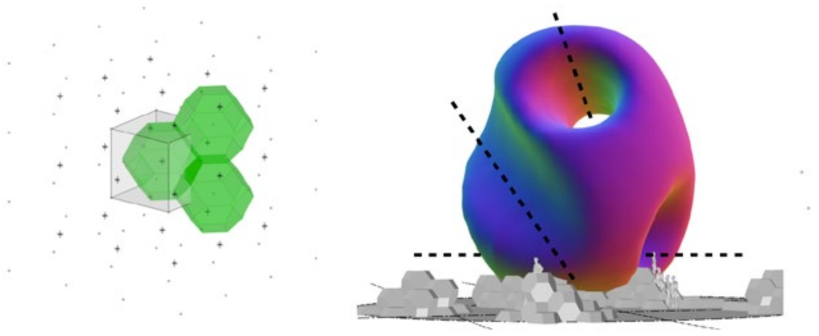
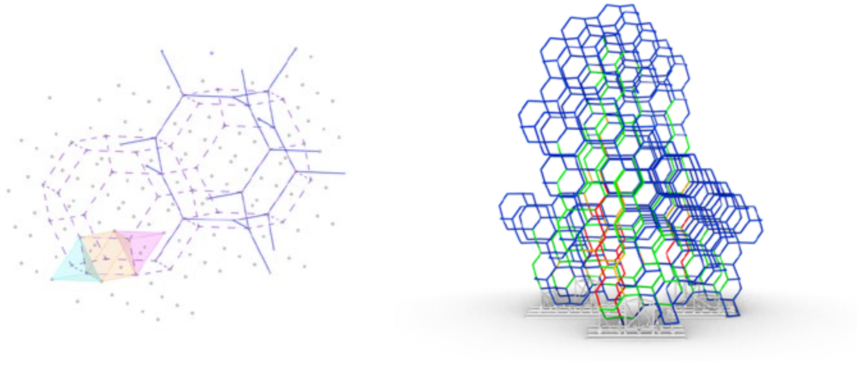


Fig. 66. Urban Jungle 2018, test assembly in the steel factory.



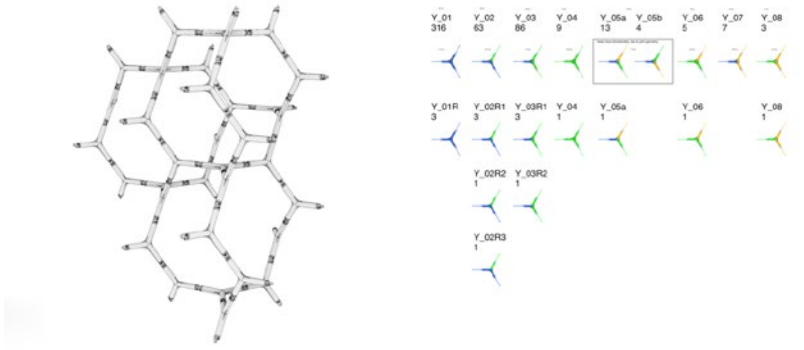
spatial structure

form generation



selection and combinatorics

evaluation



detailing

data extraction

Fig. 67. Urban Jungle 2018, the modules of the design algorithm: spatial structure, with variables for orientation and scale; form generation; selection and combinatorics; evaluation; detailing; and data extraction.

3.

Modulation – from control to negotiation

The digital was originally seen as a means to overcome modularity, standardisation and, ultimately, repetition in architecture. It enabled the non-standard precisely because it can standardise anything – turn it into a reliably computable series of binary code (Shannon 1948). Once you realise this, it is evident that there is a gradient from simplicity to complexity – order to chaos – and the potential to dial back and forth on this scale. Assuming the right setup of the design process, a sphere is a blob or a square is a Voroni cell. (Fig. 12) The modernist standard defines one possibility, in many cases the most efficient at a certain time and place. Once this standard is set, there is no more questioning it. The digital enables a more general, flexible and constantly contestable type of standardisation – modulation. One that, when set up modularly, can be instantly modified when better knowledge emerges and that does not give a best solution but ties the solution to evaluation – meaning, in combining solutions they can be evaluated as a whole and compromises made in different parts of the equation. In energy efficiency, sometimes the combinations are counterintuitive and the most efficient whole might not consist of the most efficient parts. As architects, above all, we have to evaluate the whole on its meaning. I suggest this can be done through the emergent otherness of the *Raumstruktur*.

As most of these automated systems are in part also developed and widely adapted by architects, structural and environmental simulation, analysis and optimisation using, for example, genetic algorithms or the finite element method have become tools for design – automation for design. But as Beaucé and Cache caution us, “in order to efficiently manage [non-standard] data flows and to guarantee full and entire associativeness between conception and fabrication, it is essential above all else to work on the same nucleus, or control program” (Beaucé/Cache 2003: 123). To achieve a proper feedback loop, we need to be working on the same (software) platform that can combine the expertise of different specialists involved in providing input to the algorithmic model. The platform as software is not enough. Design needs to accommodate integration and the possibility to adapt to unforeseen inputs.

The core of this research is not modularity or folding, it is modulation – the algorithmic negotiation between infinitesimal variation in conditioning circumstances and modular repetition in architecture. Traditional mass production is replaced by custom mass production not mass customisation, as the prerequisite for non-standard digital architecture. Based on the idea of custom mass production, by replacing standardised modularity with modulated modularity, top-down standardisation is replaced by computational negotiation. An architecture of modulation expresses this flexible and open attitude towards standardisation – neither the grid nor the element is pre-eminent.

Modulation comes from Old French *modulation* “act of making music” (14c.) and directly from Latin *modulationem* and the Latin *modulari* “regulate, measure off properly, measure rhythmically; play, play upon” which evolves into an “act of regulating according to measure or proportion” (Modulation (n.) 2007). In my use of modulation, it means both the scientific regulation of proper measures for the functioning of a system, as well as the creative act of making music. In fact, for me, they are both part of the same spectrum.

Modulated modularity, like folding, strives for the coherence of the whole, only coherence is more complex than smoothing out the kinks. Complex yet coherent wholes can be achieved from unitised, quasi-digitised, hence computable elements. Modularisation still asks for variation; structural loads create the necessity for the modification of structural members; the environment, topography, various uses create the need for customisation – through modulation the resulting structure expresses its computational logic, yet is open for modifications, for the unforeseen.

Gradually, the idea that architectural design acts in a schizophrenic state, between pragmatic circumstances and desire, has shifted towards seeing more and more connections, and even blurring between the two. Modulated modularity – the emergent aesthetics of animated standards – becomes the characteristic design language in the work of PART. There is a shift from creating form and translating it into physical elements according to structural and fabrication limitations to creating generative algorithms and components that determine the geometric behaviour of the system, the macro material, where form is the result of the modulation of formative forces and architectural elements. Folding removed the contradiction from deconstructivist architecture, pliantly adapting to the forces informing architecture. With modulation, continuity and infinitesimal variation are being removed from the postulates of digital architecture.

3.1. Modulation and control

The macro material being modulated is not far from Gilbert Simondon’s ontology based on modulation, as opposed to the hylomorphism of moulding and the concept of individuation. According to Yuk Hui, in his “Modulation After Control” (Hui 2015), Deleuze was directly influenced by Simondon’s concept of modulation. In Postscript on Control Societies, Deleuze describes a shift from Michel Foucault’s disciplinary society to what he calls a control society. “Deleuze characterises this shift in terms of a shift from ‘moulding’ to ‘modulation’, namely from a form-imposing mode to a self-regulating mode” (Hui 2015: 74). Modulation as described here, is not seen as a Deleuzian mode of control, but rather like Simondon’s individuation, where internal tensions are part of the process of individuation. The critique of modularity, especially one that is based on a global grid, is that it is too rigid. Reading Deleuze's control through modulation, I would argue, not engaging the system of automation from within will lead to his type of modulation where the apparent freedom is misleading, to a loss of autonomy, to the production of more of the same. Modulated modularity proposes a different type of modulation – a resistance from within. So when I say that modulation is similar to optimisation, it is not the oppressive type Antoinette Rouvroy talks about (Rouvroy 2020). Her algorithmic governmentality is "the optimising of the current state of affairs". Whereas I propose a type of optimisation with subjectivity embedded.

> *One of the most important questions will concern the ineptitude of the unions: tied to the whole of their history of struggle against the disciplines or within the spaces of enclosure, will they be able to adapt themselves or will they give way to new forms of resistance against the societies of control?* (Deleuze 1992: 7)

Hui proposes this resistance happens without discarding modulation, with something he calls "'modulation after control', getting beyond the limits of what we might call 'the modulation-control correlation'" (Hui 2016: 87). According to Hui, this can be achieved by modulating relations, by deliberately setting up creative constraints. This can be understood as modifying the algorithmic model (e.g. tweaking parameters, changing programming components) to perform more favourably. Simulation and evaluation create the possibility for trial and error experimentation to explore these creative constraints. Within the scope of this thesis this idea is applied to geometric systems and the results evaluated, apart from quantitative qualities, also subjectively, mainly based on formal and spatial qualities.

Modulation has many political dimensions: the role of the author, the politics of ornament, and the daily politics of digitalisation. As SHoP argued with Versioning, the horizontal integration of the architect being one of the many experts within the process was being replaced by a vertical integration, one where the architect is driving the process (SHoP 2002: 132). With modulation, the role of the author is mixed with the role of the curator. I also propose that modulation creates ornamental expression, and therefore bridges the gap between subjectivity and politics, the individual and the social (Picon 2013: 50). Finally, modulation has to be part of the process of digitalisation, which, not to confuse it with digitisation, is about preparing (social) processes to be augmented by digital technologies of automation.

The moderns have been trying to purify the world of hybrids (Latour 1993) – make it computable and governed by code. Yet rarely can anything be thus. Rather, silently, other forces are at work that we do not acknowledge. The simultaneous purification and translation is seen as the paradox of the moderns – "the more we forbid ourselves to conceive of hybrids, the more possible their interbreeding becomes" (Latour 1993: 12). Automation is becoming a question of design rather than engineering, of creating meaning not just problem solving. After we have realised that we have failed in isolating nature from culture, objective from subjective, and thus never really been modern, everything is a matter of design. "Matters of facts are turned into matters of concern" (Latour 2008). And, while designing these automated systems that condition our lives, we are designing ourselves. It is therefore inevitable that the discussion of digital reality is a political one – it is a question of modulation.

Object-oriented programming is based on treating everything as an object, one that carries data and code – properties and procedures. This type of structure is what puts the I in BIM models. If this is the way we conceive architecture nowadays, then this is what determines the *Raumstruktur* of possible architecture; defining these objects and their degrees of freedom for modulation must be a matter of concern for the discipline of architecture. In Estonia, the standards for the digital delivery of public tenders are being put together at the time of writing this. Soon building permissions will be evaluated by artificial intelligence. This means the structure of the BIM model needs to be standardised (MKM 2020). Very few architects, especially with a thorough understanding of computational architecture, are involved in this process. Luckily, our national digital adviser is an architect and urban planner. Contrary to the promise of AI seamlessly integrating into our world full of noise, we are seeing more and more regulations put in place to make our world machine readable – make it computable.

If everything can be seen as a computational object, then their behaviour is dependent on code. Unlike digital computers we as humans operate through meaning. The difference between humans and machines is that we ask "Why?" or "How come?" and "What for?" Modulation acknowledges these different types of operation: the model and its meaning. However accurate we make our models, however much data we can incorporate into the decision-making, we still need a narrative. That is why Banham includes memorable image into the three characteristics of the honest and logical new brutalism. It not only needs to be brutally honest and logical, it also needs to look like it, in a way that moves us. Modulation is therefore political; it negotiates between the image and the code. Computational modularity on the other hand allows for the code to be constantly updated and modified. Any system that we create needs to have this openness. Not have a 'back door' but be fully transparent.

When Durand created his method of modular composition, he created a scientific method for conceiving utilitarian architecture, efficiently, while at the same time basing the system on his predecessors – combining architectural expression with the pragmatic world of engineering. He not only taught engineers how to create architecture, but he created a link between the two opposing worlds of science and symbolic meaning, negotiating between the two, creating the basis for what we today call integrated design. Here again modulation plays a critical role. It changes the authorial position of the architect from the composer creating notation to be performed as closely as possible, to something more like the curator bringing together a set of objects (people, algorithms, materials, ideas), but not so as to juxtapose them but rather as parts that interact locally and create an emergent whole.

In computational brutalism, the *Raumstruktur* replaces ornament. According to Picon, "in the history of Western ornament, until the end of the 19th century, subjectivity and politics had been connected through a triadic structure: pleasure and beauty, social rank and prestige, communication and knowledge" (Picon 2013: 50). It is easy to imagine pleasure and beauty in computational patterns. Social rank and prestige might be seen as connected to resolution – breaking structures down into smaller parts could be equated to an abundance of ornament. But communication and knowledge, I think, could also be seen as inherent in the same way as through looking at birds we learn about flight, or by looking at termite colonies we learn about natural ventilation. A building that expresses the *Raumstruktur*, similar to data visualisation, says something about the real, the underlying structure of our networked society. Bruno Latour speaks about the unavoidable duality of purification vs hybridisation, translation and mediation. As we try to create clean categories of things we at the same time reveal their relations (Latour 1993). Modulation can do this work of hybridisation, translation and mediation, but on the condition that everything has been turned into an object, an abstract representation with properties and procedures, capable of communication with other objects. Whatever the formal ambitions, by constructing with objects, simultaneously, through the emergence of otherness, they reveal the structure of the *Raumstruktur* – connecting the individual and the social, subjectivity and politics.

3.2. Computational brutalism

With computational probability entering the design field, we can design by saying maybe. Discrete patterns of probability is the language of computation. Instead of the once existing dream of being able to answer any question once one considers all conditioning circumstances, we can now include uncertainty, design by saying maybe. Depending on how much we know, how good our model is, we can evaluate the probability for something to happen. These kinds of non-regular recursive patterns are abundant in computational art, one of the reasons random number generators are so popular in computational design.

This is described by philosopher and cybernetician Max Bense as generative aesthetics.

> *'The aesthetics of production' is concerned with bringing about 'orderly arrangements' which comprise the topological nature of 'form', and the statistical nature of 'distribution' […] In this context 'disorder' is expressed by an even and regular distribution of elements or particles (dots or syllables) in a given space; whereas 'order' means exactly the contrary, i.e. the irregular distribution of elements.* (Bense 1965: 5)

The computational aesthetic depends on information and in a regular distribution there is no information, there is no legible principle of ordering. One of the earliest computational artists, Frieder Nake, studied mathematics and received his PhD in probability theory. His works include a lot of discrete gradients that are using probability as a creative tool. Now that machine learning is a reality, probability is what is guiding decision-making (the person in the picture is 97.8% smiling or the object is 87.2% umbrella), although the aesthetics of machine intelligence and computational automation was invented by these early computational artists.

> *Aesthetic structures contain aesthetic information only in so far as they manifest innovations, or rather innovations of probable reality. The aim of generative aesthetics is the artificial production of probabilities, differing from the norm using theorems and programs.* (Bense 1965: 5)

Innovation, the unexpected, creates aesthetic information as long as it is still comprehensible. Generative aesthetics relies on the emergence of otherness, produced by "a methodical combination of planning and chance" (Bense 1965: 7).

> *Underlying all the technical language of information, complexity, redundancy, and signs was an attempt to salvage meaning in an increasingly dispersed and confused information age, while at the same time expressing an antitotalitarian scepticism about whether such shared meaning was possible or desirable. Bense's generative aesthetics – as well as the experimental practices that it inspired*

> *in [Georg] Nees and other German engineer-artists like Frieder Nake – was a sustained inquiry into the possibilities for a more transparent, participatory process of collective communication.* (Caplan 2020)

This kind of methodological combination of planning and chance, with complex part-to-whole relationships can also be perceived in contemporary digital architecture. There is a rising interest once again in automation, modularity and standardisation. Contemporary computational designers are automating architectural elements from the urban to the micro scale, but all of the work adheres to the generative aesthetics balancing between determinism and chance as a creative domain. They use ruthless computational logic in their compositions and produce open, aformal, endless patchworks of structure, with a coherent characteristic of unfinishedness. Their work is characterised by the "valuation of materials 'as found'": be it timber in all its raw and industrial forms, or more often the Rhino default shader. The expression of this architecture is derived from the "clear exhibition of structure" and of course "structure, in its fullest sense, is the relationship of parts". There is nothing but structure. And of course, as with the Instagram generation, they are most concerned with "memorability as an image". Yes, I am talking about the computational brutalists.[10]

In 1955, Banham defined new brutalism as follows:

> *The definition of a New Brutalist building derived from Hunstanton [ ] must be modified so as to exclude formality as a basic quality if it is to cover future developments and should more properly read: l, Memorability as an Image; 2, Clear exhibition of Structure; and 3, Valuation of Materials 'as found.' Remembering that an Image is what affects the emotions, that structure, in its fullest sense, is the relationship of parts, and that materials 'as found' are raw materials.* (Banham 1955: 361)

Parts today are considered computational building blocks. They define the whole according to local relationships. In our work, parts are the basis for a spatial structure (*Raumstruktur*) that characterises the design space of possibilities for modulation.

> *Banham amplified an echo of Wittkower in his own formulation – both historians stressed the clear presentation of abstract organizational systems and integrated part-to-whole relationships that gave buildings their convincing sense of unity.* (Gannon 2017: 31)

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[10] All the quoted sections are from Banham's "The New Brutalism" (1955).

> *Yet, above and beyond this claim to newness, the primary issue [in Banham's "The New Brutalism"] was to demonstrate that, besides its technical, constructional or functional stipulations, architecture was also the 'image' – or … to quote Wittkower, the 'symbolic expression' – of a society that defined itself in scientific terms*. (Stalder 2008: 275)

Memorability as an image, meaning not only following its brute logic but also expressing it – or to be more honest – at least expressing it. Utopian architecture follows its logic through, even if there are contradictions. Moving from Instagram to construction adjustments have to be made. In design proposals, compromises can be made on behalf of the conditioning circumstances; once they move into planning and construction, the brute logic mostly will start to give. Modulation in that sense is trying to negotiate the best deal. Any discrete logic will at some point run up against variable conditioning circumstances. To avoid losing coherence, the brute logic will have to accommodate the chance of modulation.

The ideas of the computational brutalists of today have strong ties with Banham's *une architecture autre* of the mid-20th century. As was the case with Durand's method in the beginning of the 19th century, the computational spirit of the 1950s and 60s was ahead of its time. Cybernetics, artificial intelligence, virtual reality, robotics – all products of that era, are only now going mainstream.

3.3. Modularity, object orientation and modulation

One of the first architectural competition wins for PART was a pedestrian bridge and tunnel in Tartu, Estonia; the project is called Son of a Shingle (*Sindlinahk*[11]). (Fig. 68) The rigid shingles were designed to follow the surface loosely, with their own logic of connection. While the smooth surface as the base geometry and the negotiated geometry of the shingles appeared to be identical from a distance, a lot of effort was put into defining the relationships between the parts to work out the actual assembly logic. (Fig. 69) I then called it object-based design – taking elements 'as found' and working out a system to produce pattern and form. The project conformed to aspects of Bense's 'orderly arrangements': the topological nature of 'form' and statistical nature of 'distribution'.

In programming, objects and modules are different things. Modularity means that certain parts of the finished code can be used in different programs to serve the same purpose. (Fig. 67) Objects in programming are entities that contain data and code. The data in the object can be modified on the basis of its code and it can communicate with other objects,

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[11] The literal translation would be shingle skin. Currently in construction.

Fig. 68. Son of a Shingle 2017. Rendering of the winning competition entry by PART Architects.

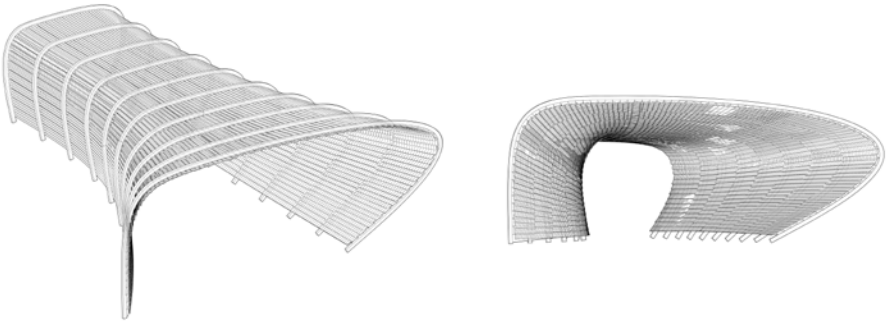


Fig. 69. Son of a Shingle project 2017, drawing of shingles and substructure.

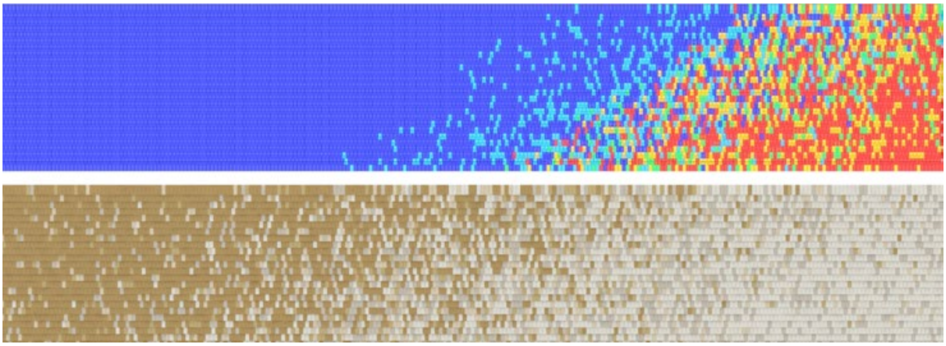


Fig. 70. Discrete gradient for the Son of a Shingle project 2017.

making it responsive (Object... 2020). Modules in architecture, in computational terms, are objects. Modular construction in that sense relates to object-oriented programming. The physical module relates to its parts like the computational line relates to its endpoints. Depending on the definition of the object, they have defined ways of interaction – without two endpoints, there is no line. Defining these interactions in architectural terms is what creates the brute logic of computational brutalism.

Architecture, of course, is never the result of a single linear logic. It is bringing together productive components and the modulation of conflicting criteria. Looking back at Durand's or Wachsmann's methods allows us to re-evaluate them in computational terms. Using the modular and object oriented programming logic, it is easy to see how the grid could be switched out, or morphed. What if Durand's elements of standardised classicism were replaced by an industrial panel system? What if Wachsmann's panels were connected at 60° angles instead of 90°? Or what if they had an 80% chance of connecting at 90° and a 20% chance of connecting at 60°? The basic geometric properties of the module define the possible grid, as in the panel system, while the grid can be a container for any object, as in Durand's model.

The Son of a Shingle project makes use of a computational module that often recurs in our projects. Timber shingles turn grey in UV-light. We wanted the shingles exposed to sun light to be toned grey and the ones in the tunnel to have a warm red hue. Then again, the whole project is about continuity and fluidity. We needed to have a gradient from grey to red, but to keep things simple, this had to be achieved with five tones. So to create the smooth transition we use a probability gradient, each element, based on its location, has a certain probability of being a certain colour. (Fig. 70) This is decided by a random number generator, resulting in a blend of different coloured elements rather than a legible break between one and the other. The same module can be used for any discrete gradient problem. For instance, it was used to create a tiling pattern of two different colours underneath our Urban Jungle installation. (Fig. 55) The algorithm can literally be copy pasted from one script to the other, connected to inputs and the falloff parameters tweaked to arrive at the desired result.

> *Given the visual interfaces of better software today, with the right process mindset, you might not even know you are coding. The trick is to see patterns, and then to find the free play within the structures of them. Surely, this is a form of intelligence.* (McCullough 2006: 187)

The (almost) instant visual feedback is the real game changer. The parametric modulation of code is visualised while you do it. The complicated mathematics of calculating smooth gradient fall offs, like the fuzziness of the photoshop brush, can now be controlled with sliders and graph mappers – allowing the designer to study the behaviour of the algorithm and develop a certain empathy for it.

3.4. Formality – modulation of the *Raumstruktur*

The grid is a device for grasping and translating the infinitesimal variation of the natural world into discrete patterns. Discretisation is the process of removing noise and creating information (Shannon 1948). Like speech being defined by discrete syllables or sounds. "Phonemes accomplish the digitalization of the auditory medium of speech" (Dennett 2017: 199). There are differences in languages in the way sounds are discretised. That is why it is so difficult to even make sense of words in some foreign languages. Not to mention speak them. In different languages there are different ways of discretisation – of defining the basic elements.

"As Turing noted, nothing in nature is truly digital; everywhere there is continuous variation; the great design move is making devices that treat all signals as digital, discarding instead of copying the idiosyncrasies of particular tokens" (Dennett 2017: 200). This means we need to find underlying patterns that remain the same. With visual information this has been proportion. When perceiving a human figure, we realise instinctively whether it has the right proportion. When drawing, this tacit knowledge needs to be made explicit. So we use modular proportioning systems. Anyone who has drawn a figure will know that if you use standard proportions, it will look right. The same method has been generalised in drawing grids since the 15th century. Grids make it possible to keep track of proportion and position. Proportion and rhythm help us make sense of the world around us. Then again, it is the deviation from the norm that gives character. The accent or the tone of voice can give more information, than the phonemes uttered.

The grid was originally used in architecture to create axial organisations in plans and elevations. Durand developed this method into an almost proto-pixelation. This abstract system relied on the architectural elements to be perceived as architecture. With computational geometry, planes, grids and axes have become something completely different. Coordinate systems can be transformed and nested, geometry made conditional. (Fig. 71) Our ways of manipulating the underlying structure have increased immensely. Architecture nowadays is not drawn, it is computed – going from drawing grids to computational spatial structures. The early digitals created undulating surfaces and then panellised and optimised them to create panel families of a limited number of geometrically different members. We can flip this idea and start designing with a limited

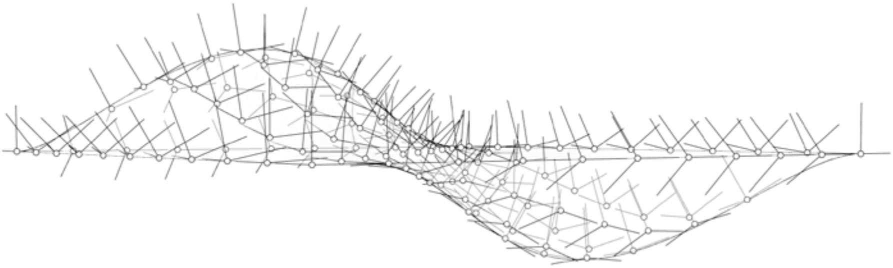


Fig. 71. Nested spaces – the undulating surface warps space, sampled in a 10x10 grid.

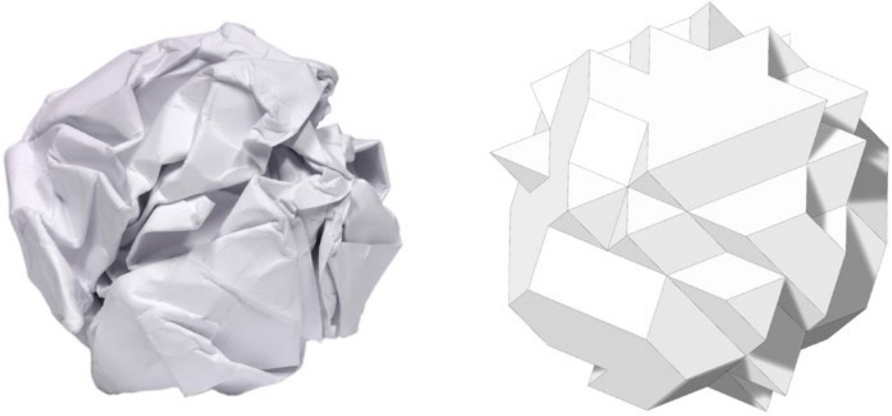


Fig. 72. Moulding vs. modulation – crumpling polygons instead of paper.

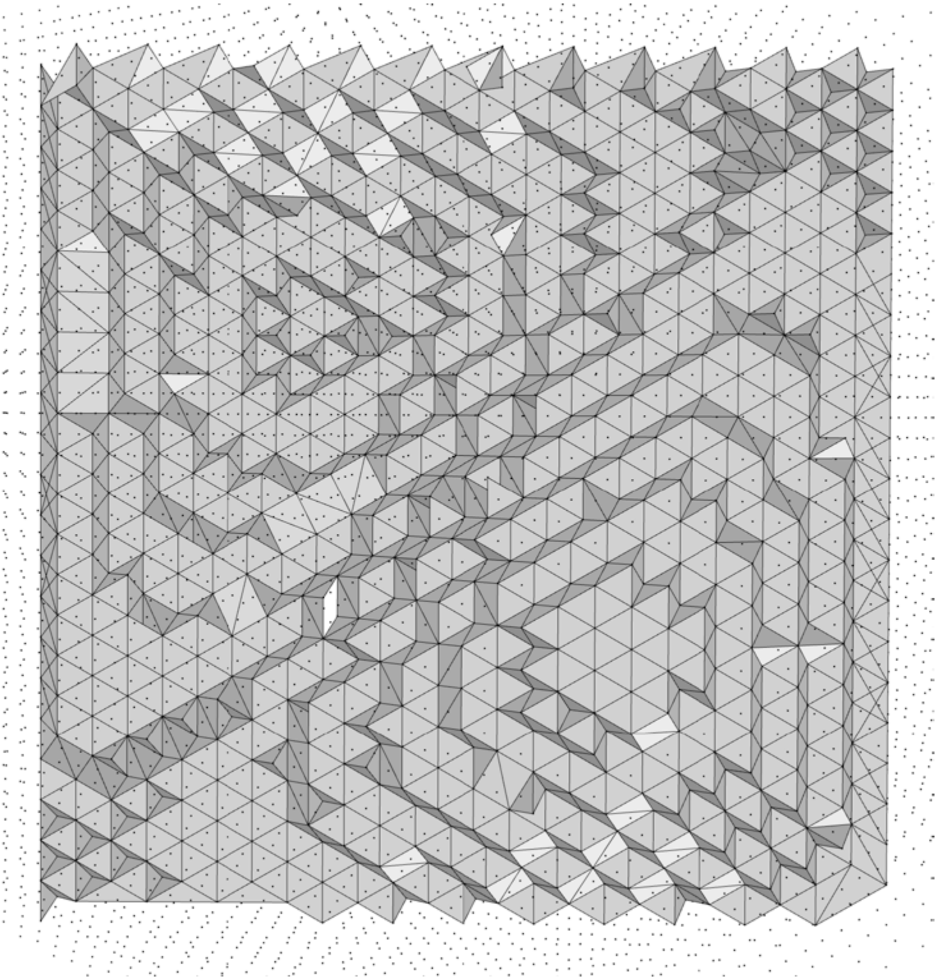


Fig. 73. *Raumstruktur*. The spatial grid limits the surface panelisation to a very limited number of elements.

number of elements – removing the process of translation and the discrepancy between the ideal and the real – designing with objects. By compiling conditioning circumstances, structural and geometric limitations, we can model the structure of what can be made. I believe this is close to what ESF calls *Raumstruktur* and similar to what Picon refers to as the real.

Dynamic geometric models let us play with these realities, changing the parameters in the (computational) objects that the modulated *Raumstruktur* is made up of, and within them, exploring and evaluating possibilities for materialisation. I like to use the analogy of crumpling paper vs. crumpling polygons. (Fig. 72) Frank Gehry uses material techniques to produce form and then painstakingly digitising it to be able to reproduce it at a larger scale. When crumpling polygons within a constrained design space, we get a similar feel for the digital materiality, or rather formality, of the object. If materiality is about the way we perceive materials and have assumptions about their qualities, formality is about how we perceive and understand the capacity for formation. The modulated *Raumstruktur* creates an emergent formality. (Fig. 73)

> *"Otherness", that is the possibility to mobilize processes foreign to the human mind, plays a fundamental role in most algorithmic approaches. […] "Otherness" is rooted in the dynamic property of emergence, [which] is generally defined as the capacity of recognizable order to arise from an initial state of apparent randomness. Emergence seems to be at work everywhere, from nature to computer calculation.* (Picon 2010: 97)

The otherness emerging from both nature and computer calculation is the result of creative friction against reality. One cannot create in a vacuum. Standards, rules and regulations – social conventions – and structural, material and environmental conditions – laws of nature – all feed into this complex system. This relates back to Deleuze's modulation and Simondon's individuation and the creative constraints that modulate relations and speaks for modulation–individuation correlation – not just a frictionless optimisation, but also individuation due to inner tensions.

While this research started with the question of how to reconcile pragmatic realities with design ambition, it has become clear that on the elemental level, standardisation is key to developing robust modular systems that enable, on the one hand, design intent to materialise, and on the other hand, the automation of standards into an algorithmic tool that becomes the carrier of design language and becomes then a part of the design – the creative constraint. Meaning that all the different agents and components really exist in a Deleuzian virtual soup that is instantiated into specific projects – there is no clear boundary anymore, between architecture's autonomy and scientific rationality.

Algorithmic geometry displays behaviours, formality, which means after a while we get an intuitive feel for how digital representations of structures behave once we have simulated them. Manipulating interactive structural models creates a feeling for this behaviour. Animation and simulation have a huge impact on how humans perceive the world. All of a sudden, we can experience vast structures deforming and see how this behaviour changes when the model is altered. A similar sensation encompasses us when we see physics engines simulate different materials. It used to be students in digitally advanced architecture schools simulating fluid flows. Now this fascination has reached Instagram, people are watching simulations of pastes of different viscosity being extruded and cut and are getting "brain orgasm" from manipulating virtual slime on the touchscreens of their smartphones. (Fig. 74) Dynamic geometric systems based on the realities of standard materials and industrial manufacture result in a similarly fascinating formal behaviour.

This experience of formality through the dynamic modulation of geometry has its appeal precisely because of its animation. To express it in static form, the process of formation needs to be legible, meaning the various effects that the system is capable of producing need to be revealed, making a partial misalignment between the massing and the its modulation necessary. For the expression of the spatial structure variation is needed, even though it is based on repetition. It is evident that this is leading towards the concept of rhythm. Modulation in that sense is about creating discrete repetitive rhythms rather than the variable flow of the early digital or agent-based algorithmic systems.

> *Contemporary science and architecture might very well not converge but meet on the common ground of an inquiry regarding the changing nature of the material world that surrounds us, a world totally permeated by calculation and at the same time full of unpredictable events, a world of abstract and complex formula and extremely concrete patterns, textures and sensations*. (Picon 2008: 79)

I am interested in the formal language that relates to formation and emergence. It is the experience of modulated formality that I am trying to achieve in my work. If materiality is our perception of qualities related to matter, formality is our perception of dynamic geometric systems. These two are in a way inseparable as we visually perceive material processes through geometric manifestations – the way something breaks, bends, folds, blends etc. Using algorithms, we can simulate material processes through abstract geometry (e.g. coarse lattice representation in micro mechanics), but can just as well construct virtual materials that behave according to a precisely defined design space.

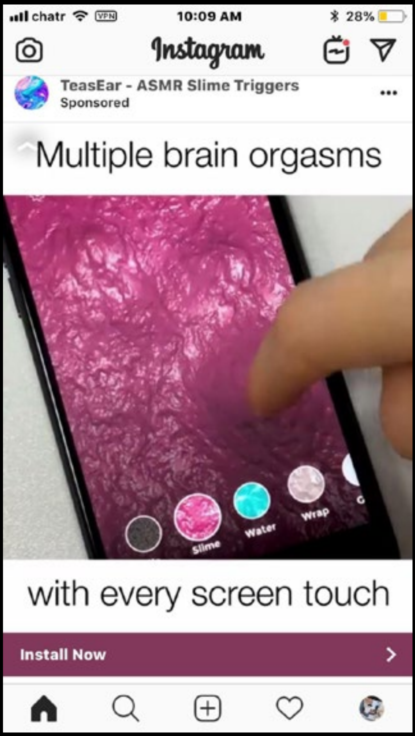


Fig. 74. TeasEar advertisement on Instagram promising “multiple brain orgasms with every screen touch”.

Fig. 75. The Cloud carpark 2019, competition entry, honourable mention, by PART Architects.

> *It is Utopian to seek to free architecture from technical and economic constraints while simultaneously proclaiming their preeminence. After Durand, many other architects were to succumb to the same temptation, including the principal representatives of the modern movement, from Walter Gropius to Le Corbusier.* (Picon 2000)

I would like to think there is no preeminence. In that sense the quest for autonomy is probably more of a quest for integration. This discussion about blurring this duality, schism even, in architecture is exemplified by the development of architectural ornament, that by definition used to be something that was added to the essential parts of a structure, to turn it into architecture. With the development of modern thought, this addition was deemed unnecessary, unethical even. Nonetheless, it found its way back in, as "to replace ornament and explicit symbolism, Modern architects indulge in distortion and over-articulation. Strident distortion at large scale and 'sensitive' articulation at small scale result in an […] architectural soap opera in which to be progressive is to look outlandish" (Venturi et. al. 1972: 139). One can debate whether it is a soap opera, or the desire to unify beauty with function into functional beauty like Snooks' structural ornament (Snooks 2014: 16). In Lynn's description of intricacy, the expression of functional detail turns from a singular accent to the articulation of the whole (Lynn 2004: 9). The ornamental quality is folded into the materiality – it is integrated.

Classical decorative ornament did not cover the whole building, it was used to accentuate specific parts like structural elements or openings. Computational formality makes architectural form behave in a similar way – any change in the overall geometry, or any other underlying force, is accentuated by the changing relationship between the elements – similar to Gramazio Kohler's undulating bricks turning a tight corner, or in the case of PART's Tartu carpark, this relationship manifests itself on the rounded wall similarly to isometric curves on topographic maps. (Fig. 75)

Computational design is based on mathematical models that represent the real. How accurately, is up to the designer-programmer. Any model is a representation of something – never exact, just good enough for the task at hand. This discrepancy between the model and the real becomes another creative domain. The model is, and should not be the real that it approximates. Like the map and the territory – the model becomes productive exactly because of its difference to the real. In digital design, this discrepancy tends to produce so-called happy accidents. This conflict of expectation and result is where innovation can happen. Writing code is often done through trial and error. These inexact models come alive, become the other. Computers are human constructs. They follow our logic;

they are just more rigorous about it. The errors often reveal the inner logic of the system, helping us to get to know and interact with the emergent otherness.

What is probably the most significant realisation dealing with these dynamic computational systems, is that this highly technical approach at the same time enforces subjective judgement and intuition within the process of design in the age of automation, which by definition is about removing the human from the equation. Designing automated systems to incorporate human intuition creates a machine-human feedback loop, where one is not only making a judgement about the machinic output but rather is also trained to look differently at the world through the constantly evolving perception of materiality and formality. I have pointed out how fabrication and structure start to define a discrete design space by favouring certain geometries. Structure on the other hand starts to give shape to this design space by limiting global decisions. Modulation turns it into a method for design.

3.5. Modulated modularity: a design method

What are the qualities of modulated modularity? Quite often when trying to apply algorithms in actual projects, they tend to be too totalitarian. Digital design tools have a tendency to give the same answer to every problem – to be too homogeneous in their complexity. With modulation, I am trying to find a way to mix the algorithmic other, with the ordinary. This is where dynamic geometric systems come into play. This allows for regular floor plates and stable structural systems to be modulated into a complex algorithmic system. (Fig. 76)

3.5.1. Spatial structure

Within this system whether it is bottom-up vs top-down does not really matter. What matters is the relationships between the parts. For a fool proof aggregation of standard elements, standardised relations are essential. A grid is needed. The non-modular projects were based on non-standard organised point grids. They were generated either by evaluating fields or surfaces. In both cases the spaces were curved, meaning in the third dimension they sooner or later produce intersections. (Fig. 71)
As we learned from the Digital Thicket project, changing the relations between elements can be used to find repetitive structures in seemingly chaotic branching systems. The study of this geometry led me to study space filling polyhedra and look for precedents. Reading Schulze-Fielitz or the more recent work by Poltak Pandjaitan (Pandjaitan 2018), there is sufficient research into crystallography for the purposes of this

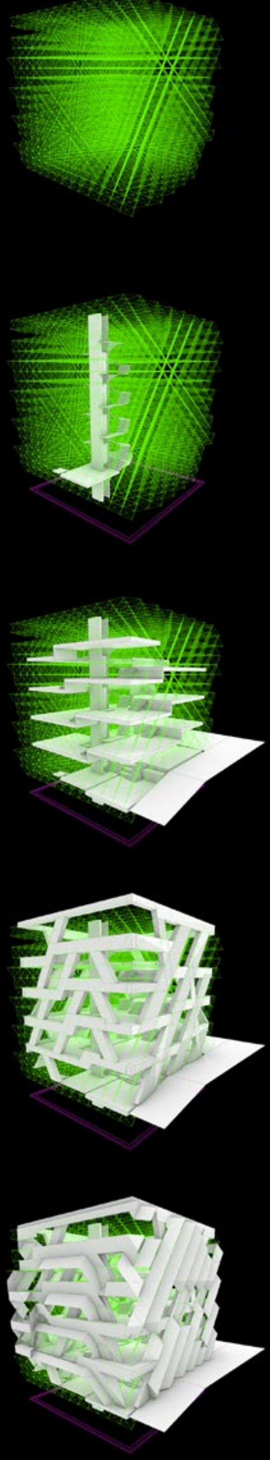


Fig. 76. Shift Lofts 2019 by PART Architects. The building is organised in a tetrahedral grid, starting from the spiral stair and helical floor plates, resulting in the modulation of the load-bearing facade.

investigation. Some of the more important aspects to note here is that the spatial structure is foremost defined by nodes – the lattice. The tetrahedral-octahedral and cubic honeycombs with cell centres produce the same lattice. (Fig. 60) This is the lattice used in PART projects. How the nodes are connected is then a matter of defining connections between the nodes – the topology of the network.

3.5.2. Massing and formation

The whole can be formed either by growth or a global geometry or a field. Most of our projects use an underlying global geometry. The Digital Thicket project grew out of an L-system, many are defined by volumetric iso-surfaces (a surface derived from the evaluation of a field). In the case of actual projects for houses, the massing, the overall form, is most often really defined by the detailed plan or local regulations. The initial evaluation of the relation of the massing and the spatial structure can be achieved by creating a boundary isosurface, similar to marching cubes, but following the topological network. This is done by filling the massing with the cells of the spatial structure. Both massing and the spatial structure can be modified to achieve the desired results.

3.5.3. Selection and combinatorics

The chunk of cells defined by the spatial structure and the boundary is then sorted into building elements. Cells can be combined into blocks, linear profiles, plate elements or combined into more complex modules. (Fig. 77) One way to automate this process is to sort the cells by the longest axes formed, to minimise part count. (Fig. 5) Another way could be to use structural analysis to determine more critical connections.

3.5.4. Evaluation

Structural analysis is instrumental in the design process in many ways. In the Digital Thicket project we evaluated the structural capacity and defined the maximum height and cantilever length, otherwise no limits were set to the aggregation. At other times such a strict limit is not possible. To optimise structural performance there are multiple methods. In the Urban Jungle project, we modified the overall form but also had to use varying profile thicknesses. Uniform lattice networks often have redundancy, so also culling elements is possible to achieve heterogeneity and structural efficiency. The numeric feedback also enables subjective design intervention. The final form for the Bog Fox was slightly suboptimal

Fig. 77. Prototypes from EKA third year architecture studio ELEMENTerial, 2020. Tutors: Sille Pihlak and Siim Tuksam. Students: (from left to right) Uku Tarvas, example by Siim Tuksam, Miko Vahane, Olga Krasnova.

to achieve a less symmetric composition, yet the difference in material amount added was below 2%.

3.5.5. Detailing

Structure, cost and fabrication limits need to be taken into account. In the Body Building installations, the overall geometry was optimised to maximise the lap joint surface area. With modular structures, this type of optimisation is not possible. On the other hand the limited joint geometry allows for the joint to be optimised for this specific geometry, not to mention the advantages in mass production and ease of assembly. For Urban Jungle, a single symmetrical connection detail was developed for all the modules. (Fig. 64)

3.5.6. Data extraction

In modulated modular construction, the number of unique elements is considerably smaller than the project utilising infinitesimal variation. Yet with the growing scale and complexity of projects the number of types of elements increases. Similarly, the construction process needs to be planned out, elements grouped and categorised. Doing this as part of the design model is preferable towards standard factory software solutions. With the structured model, it is easy to logically sort elements. With Body Building, the machine files were generated directly from the 3D model and numbered according to the hsb-cad numbering logic. This complicated the assembly process and the non-intuitive sorting process was only possible by painstakingly looking for them in the model. In the Urban Jungle, we ended up with 37 unique types for the 802 elements of the main structure. Due to the structural logic, it was possible to build up starting with the strongest profiles. Two-thirds of the structure were identical elements of the thinnest profile, that could be assembled around the stronger elements. Again the 3D model was still needed for correct assembly. Exploring augmenter reality aided assembly should definitely be explored further.

The ultimate quest in this research has been looking for the new normal – is there a way of constructing digital architecture that is efficient. Initially, it was about realising something in the formal repertoire of calculus-based folding – curvilinear voluptuous form, stochastic emergence and intricate assembly. Gradually, some of the postulates of digital architecture have been rethought, removed and others added. (Fig. 78)

The idea, that the sphere is a blob with a lower level of interactions, creates a gradient, that can be applied just as much to folding as to modernist minimalism, with different levels of interaction and degrees of

Fig. 78. Evolution from variation to repetition to modulation: Body Building installation, Urban Jungle vertical garden and Shift Lofts apartment building by PART Architects.

freedom (DoF). In many scientific fields, DoF is the number of parameters in a system that can vary independently. In digital fabrication, DoF defines the number of linear or rotational axes, a drill has a DoF of one, a CNC milling machine usually three, whereas industrial robot-arms commonly have six degrees of freedom, meaning they can be positioned and oriented in three dimensions. This realisation is at the core of modulation – a gradient of topological and tectonic resolution – degrees of freedom can be reduced or added and limited in range. The blob can be informed by modules.

The main conceptual issue that brings modulation into opposition with folding is the idea that in folding an ideal curvilinearity is translated into the real with a certain loss. There is always a level of resolution that by definition is not the same as what it represents – smooth calculus-based elements are translated into discrete elements with infinitesimal variation. These discrete elements most often are further optimised for production. Creating another level of discrepancy between the design and the product. Yuk Hui points out that Deleuze's "project in regard to Leibniz is, in hindsight, to understand folding as a form of modulation that distances itself clearly from classical hylomorphism" (Hui 2016: 77).

> *The new status of the object no longer refers its condition to a spatial mold – in other words, to a relation of form-matter – but to a temporal modulation that implies as much the beginnings of a continuous variation of matter as a continuous development of form.* (Deleuze 1993: 19)

A continuous variation of matter does not necessitate continuous matter. Solid matter most often is not continuous. The digital is a technology of folding, but as soon as we encounter matter, formation becomes a matter of modulation. Materiality in its physicality, but just as much, in the sense of how we perceive it, becomes of essence. One way to overcome this conceptual discrepancy of translation from the computational to the material, is to rely on material processes like active bending, stretching, inflating, and so on, and through meticulous simulation, try to anticipate the real-world behaviour of material systems. The other way is to introduce standardisation and modularity at the element level as the basis of formation – as the matter itself. Considering industrial production as material processes, modulated modularity takes the latter idea as its basis. We first define what is possible to design within a certain workflow and technological context and automate the processes as geometric constraints that define the design space of what is possible to be made – the spatial structure. Then we use this underlying structure to design the ideal as actual, moving from post-rationalisation to pre-rationalisation.

Although computational architecture as a more general term precedes the digital discourse, it cannot be neglected that the triumph of digital technologies, and the accompanying theories, is set in the 90s. In light of earlier 20th century developments, it is not so surprising that the digital actually appeared almost fully formed, at the right time in history, due to the advancements in technology. Neither that in its 30 years of development, conceptually not much has been added, but reconfigured and realised. It has also become evident that the speculative and the real have diverged too far and a middle ground needs to be explored. Within my thesis, it is the introduction of modularity into folding through modulation that tries to reconcile the speculative utopia with the *Raumstruktur*.

When Nikolai Ivanovich Lobachevsky replaced the parallel postulate of Euclidean geometry, he was compared to Copernicus (Bell 1986: 336). It doesn't take much to change a system radically. Sometimes an added postulate or simplification can be just as fruitful as removing limitations. The question is which ones to remove, and which ones to add. When Durand came up with basing architectural design on the Euclidean grid, he invented a productive simplification. A grid cell is a container, an abstraction that can be used to perform complex calculations, while in the end it is just that, a placeholder something to be filled in, a drawing grid to allow for endless complexity – just like the pixels on a digital screen.

If we take Durand's method and put it into the modern day context, replacing the elements or parts, with today's best practice options and with the augmentation of digital computing, we are able to replace the Euclidean grid with any computational model of space – we have what is at the core of modulated modularity. The rest is conditioning circumstances and subjective decision. Hopefully, well informed subjective decision, but who knows, in the age of fake news.

Throughout this research I have been developing a method for designing that would combine all these ideas into an algorithmic model for design, that is based on current algorithmic best practices in design, fabrication and construction. (Fig. 79) The key in standardisation is finding the balance between heterogeneity and repetition. Durand's grid and its elements are probably too stiff. Dillenburger and Hansmeyer's sand grain (Dillenburger/Hansmeyer 2014) doesn't really inform architecture enough to be the basis for a spatial structure. That is why I propose not a solution to the question, but rather a method that is abstract and scaleless – the method of modulated modularity. It is a simulation of simulations – meta materiality of space. Combining all the previously mentioned parts – the subjective, the real and the other – we arrive at a tool that is itself modular and ever changing, always a beta version. The modules are structuring, formation and combination (organisation), evaluation and optimisation (environment), detailing and data extraction

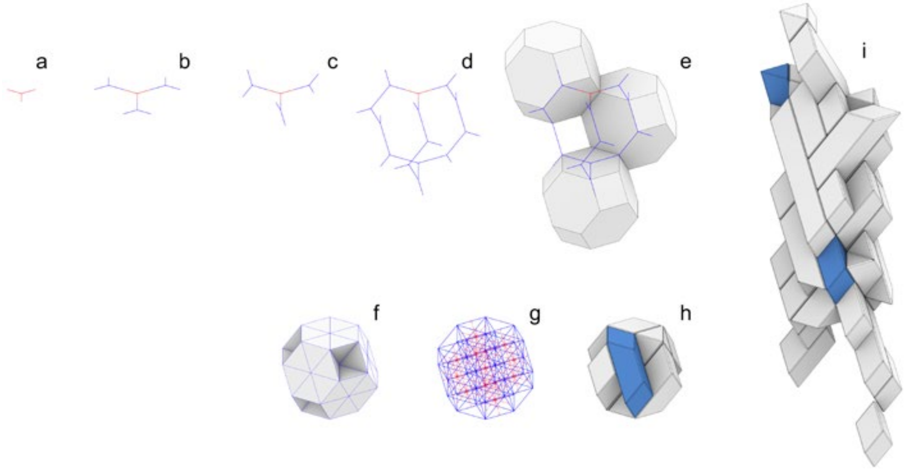


Fig. 79. Transition from Digital Thicket to the Modulated Man – a: element; b: assembly; c: transformation; d: the chunk, defining a grid cell; e: relation to space filling truncated octahedrons; f: subdivision of a truncated octahedron; g: the resulting grid and the cell axes; h: cells combined based on resulting part length; i: the Modulated Man.

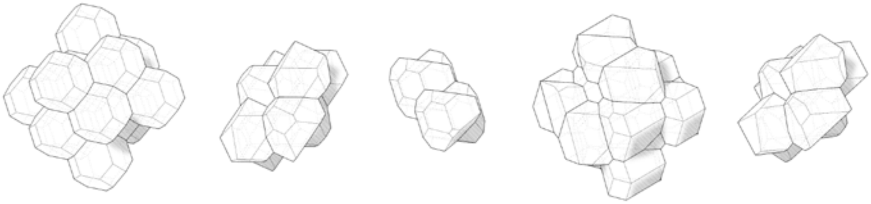


Fig. 80. Repetitive non-regular space filling polyhedra, using the 3D Voronoi diagram and custom periodic point grids.

(construction) – not in this order but rather as a parallel process, where any part can be modified, replaced, removed etc. This of course is nothing new. How the specific parts are combined and where shortcuts and exceptions are inserted is what makes this method specific. What the early digitals missed with the non-standard is that variation in the digital is the result of extreme standardisation – pixelation.

What I am proposing is to look at the genesis of a project in a similar way as Durand – define axes of circulation within the grid and fill them with elements to create different types of enclosures. Only the axes do not need to be straight, nor in plane, parallel or orthogonal in any way, the elements are computational objects and there are no predefined types of spaces. Instead I am proposing to use adaptive point clouds, where point to point positions are repetitive to a degree that satisfies the design brief and intent. (Fig. 80) In mesh geometry, there is a well-known re-meshing algorithm called the marching cubes. I have developed this idea by replacing cubes with any space filling cell and next to surfaces included volumes by algorithmically joining these cells. The surfaces, volumes and elements can be defined by combining or subdividing the cells to the desired resolution.

The process of design in our case starts with defining the grid cell, based on the basic geometric principle of production. As we are dealing mostly with plate materials, we have tried to find ways of constructing our geometries based on equilateral triangles and squares to avoid waste material, as these are the only shapes to form regular tessellation. (Fig. 81) The grid cell could just as well be any shape. One of the ideas behind modulation is that modular arrangements can be subdivided or combined to change resolution and transform from one arrangement to another, including irregular cells if needed. (Fig. 82) These cells, whether arrayed or generated by using generative algorithms, form the spatial structure. This grid at the same time is evaluated on the basis of the types of elements it produces and can be further modified if needed. A change in the basic geometry of the element will affect the grid – the element is not separate from the grid, there is no hierarchy.

That being said, variation is not a rule, but the exception. None of our office projects have used transformations, only subdivision – increasing resolution. The modularity of the system can be modulated, tuned, by manipulating the point grid. When this modification is global, the number of unique elements does not change. Creating local differences in the grid adds types of modules. This defines a three dimensional grid – materiality, organisation and access have to then operate within it. In our projects, the architectural expression relies on the definition of this spatial structure and the corresponding spatial cell or element, within which patterns of circulation and habitation create enclosure.

Fig. 81. Modulated modularity projects: Käsmu bus stop, Shift Lofts, the Cloud carpark and Pärnu Art Hall. All projects by PART Architects.

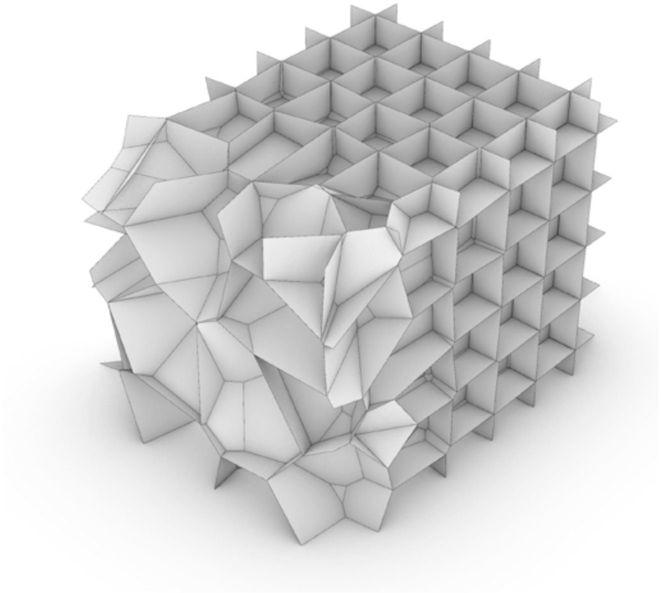
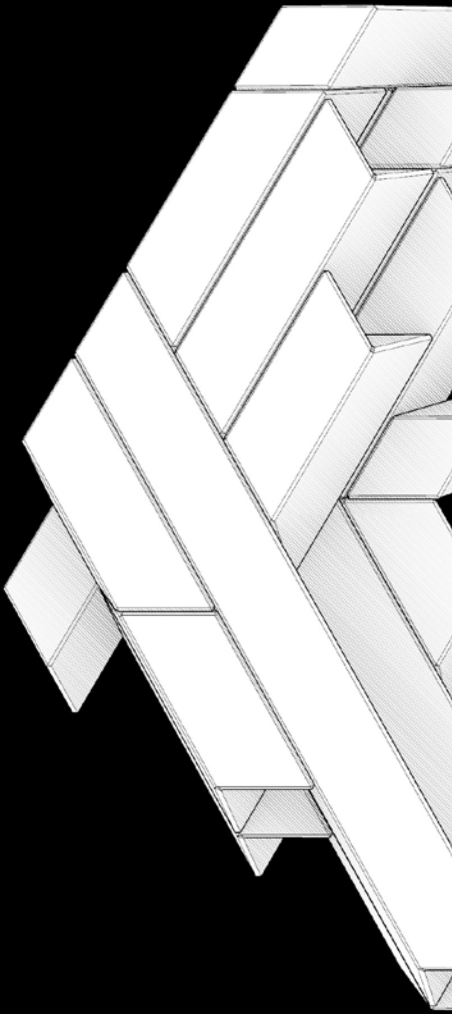


Fig. 82. Transformation of a spatial grid from modular to bespoke.

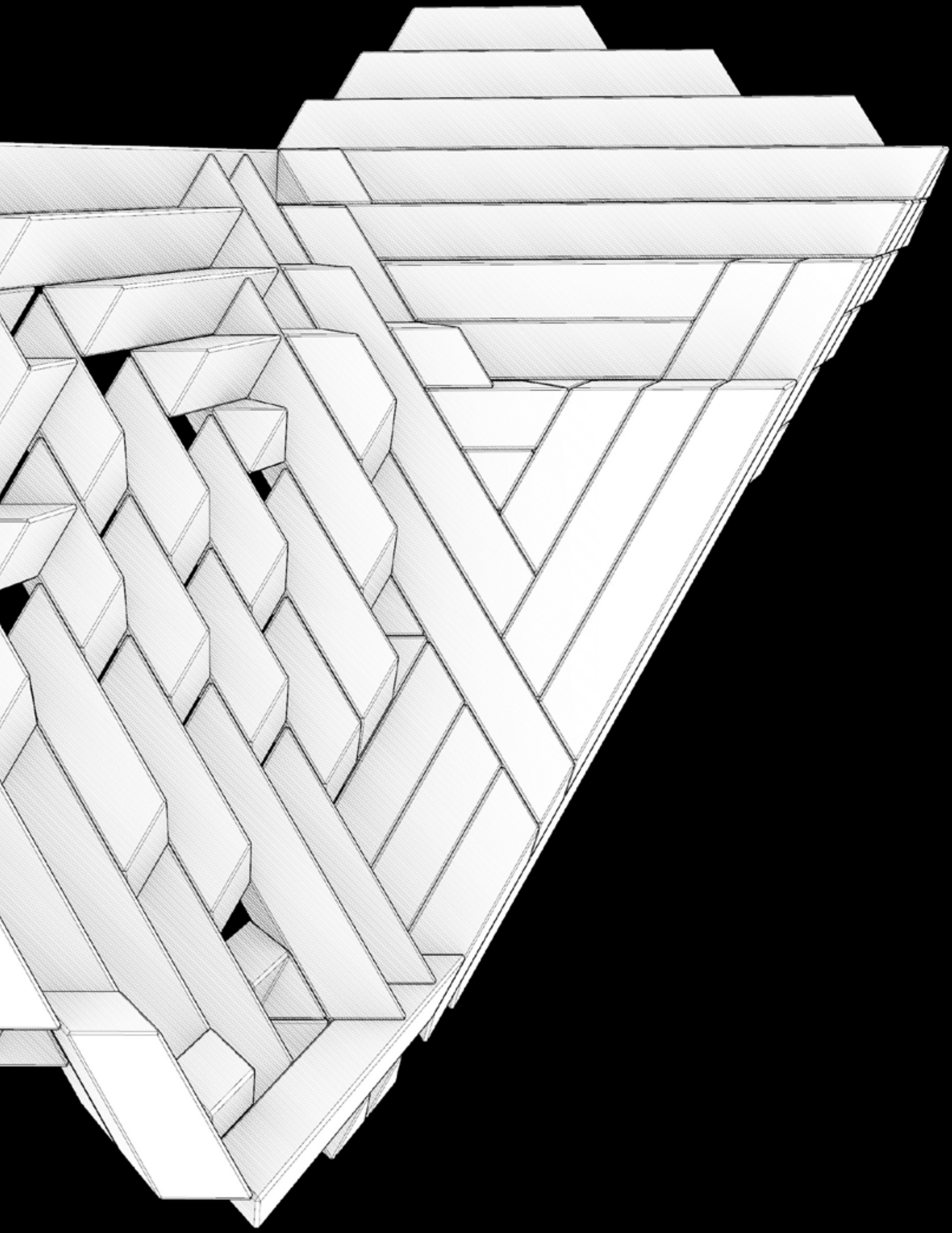
The cells of the spatial structure are not the elements, the actual elements, just like when using a regular grid, are defined through their relationship to the cell. The geometry, apart from the connection to its neighbour, and the materiality of the element are not defined by the spatial structure.

The described approach allows for modularity that is in line with contemporary means of design, fabrication and construction – a flexible system for bespoke designs that consists of repetitive components. Modulation, as used within this research, allows for subjective expression with geometric modularity that is based on pragmatic considerations. It defines a design space that already satisfies most of the requirements, leaving architectural expression and subjectivity part of the game. The result is evaluated as architectural design by maximising the legibility of the underlying computational logic, while minimising the use of resources; a good balance between simple and complex – flat and articulated. This produces the ornamental quality of the work. Although conceptually, similar to intricacy, the volume consists of just details (cells and elements), these details are only expressed in specific parts, articulating borders and changes in direction. In other parts, the elements can be fused into larger parts like beams, columns, floor slabs and walls with dimensions based on logistics and structure. The same logic as with ornamentation – only there is no ornament just the modulation of the *Raumstruktur*. What I am trying to suggest with modulation is that by combining computational and parametric approaches – it allows for real-time subjective manipulation of spatial structures, where the emergence of beauty is the result of manipulating the model. We have at our disposal a rich variety of computational objects; the first step is to set up a syntax and then to write the poetry.



3.6.

Milestone project: Shift Lofts apartment building



Year:	*ongoing since 2019*
Client:	*private*
Location:	*Võistluse 7, Tallinn*
Scale:	*800 m2*
Material:	*cross laminated timber*

A loft apartment refers to an adaptable large open space or it could be understood as the last storey. In the Shift Loft apartment building, designed by PART in 2019, it could be understood as both. The building is based on a spiralling array of floor slabs, (Fig. 83) creating the possibility of considering it a single storey building and making it possible to subdivide the space into as many units as needed. This spiralling is achieved through a plastic shift in the floor slabs. This also creates the possibility for the carpark entrance to slip under the building, instead of cutting away part of the ground floor.

The design has its origin in the plywood seating landscape of the Urban Jungle project described at the end of the previous chapter. The structure was composed of truncated octahedrons, at two different scales. Looking back at the design, with the adjustments made by subdivision in order to incorporate inhabitable surfaces, I realised that on an elemental level the geometry was rather based on tetrahedrons and octahedrons. This realisation made me develop an algorithm that could be used to transform any geometry into these elements. What started as a surface discretisation algorithm, inspired by marching cubes, turned into a volumetric approach. The cells of the grid are generated and culled to form enclosure and further subdivided or joined to form architectural parts, like stairs, columns, slabs. This project is still in conceptual phase and its development will be the next step after this thesis is concluded. For now the spatial structure is used to organise the spiralling floor plates, the main load-bearing structure and the facade.

This approach was first used to re-design a bus stop in a historic captains village in Estonia. (Fig. 84) The design was initially inspired by the huge rocks populating the local shores. Models of these rocks were used to conceptually carve spaces into a primitive solid, by geometric subtraction, to form interior spaces. In the following design iterations these shapes evolved from textured blobs into faceted simplifications, ultimately to the modulated mass of the structure itself. (Fig. 85) In this basic version of the algorithm, the primitive is filled with elements of the spatial structure and to create enclosure and inhabitable volumes, cells are then culled, leaving us with a structure consisting, in this case, of tetrahedrons and octahedrons. Finally, based on structure and material efficiency, these elements are joined to form linear and 2-dimensional elements (Fig. 86), to be cut out of cross-laminated timber leftovers from timber house manufacturing.

The same approach is used in the Shift Lofts, where the maximum buildable volume is filled with our spatial structure. (Fig. 87) Within this structure, where every square metre is counted, the *Raumstruktur* is used to organise the most basic components of timber construction in the interior spaces and is only legible within the vertical circulation core and the

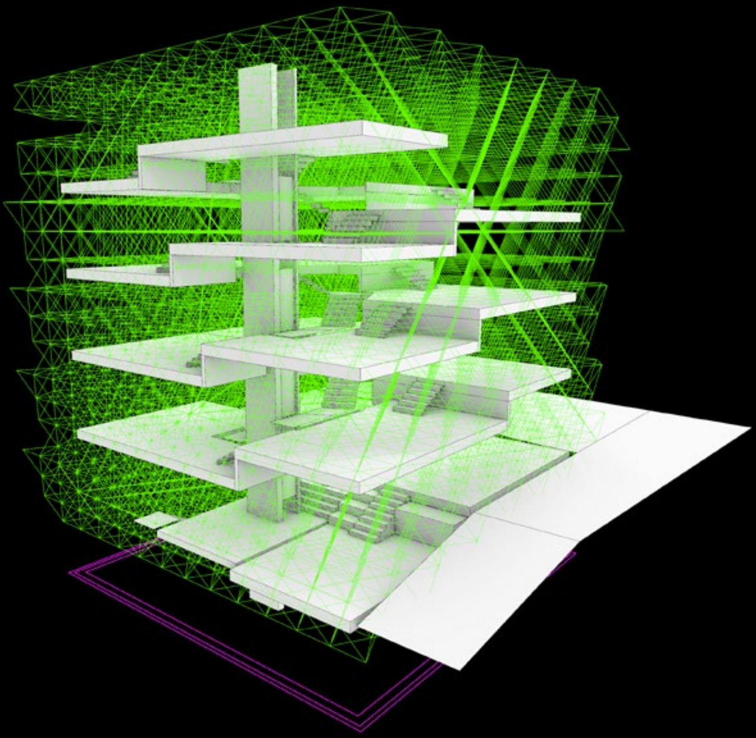


Fig. 83. Shift Lofts 2019 by PART Architects. The spiralling floor slabs are derived from the spatial structure.

Fig. 84. Käsmu bus stop, revised 2019, by PART Architects, waiting area and stair.

spiralling formation of the floor slabs. The structural exoskeleton (Fig.88) and the facade express the modulation of the *Raumstruktur*, in the geometry of openings, balconies and the shading system (Fig. 89).

While creating a new approach to the spatial typology of apartment buildings, this project also expresses its materiality. (Fig. 90–92) CLT is widely used, yet considering its ease of manufacture and cost the repertoire of its formal possibilities have not been widely explored. We think, in order to introduce new materials and processes into construction, the resulting architecture cannot remain unaffected. The possibilities of the material and its ease of use must be expressed, as with the introduction of new technologies, the underlying conditioning circumstances, the real, the *Raumstruktur*, has changed.

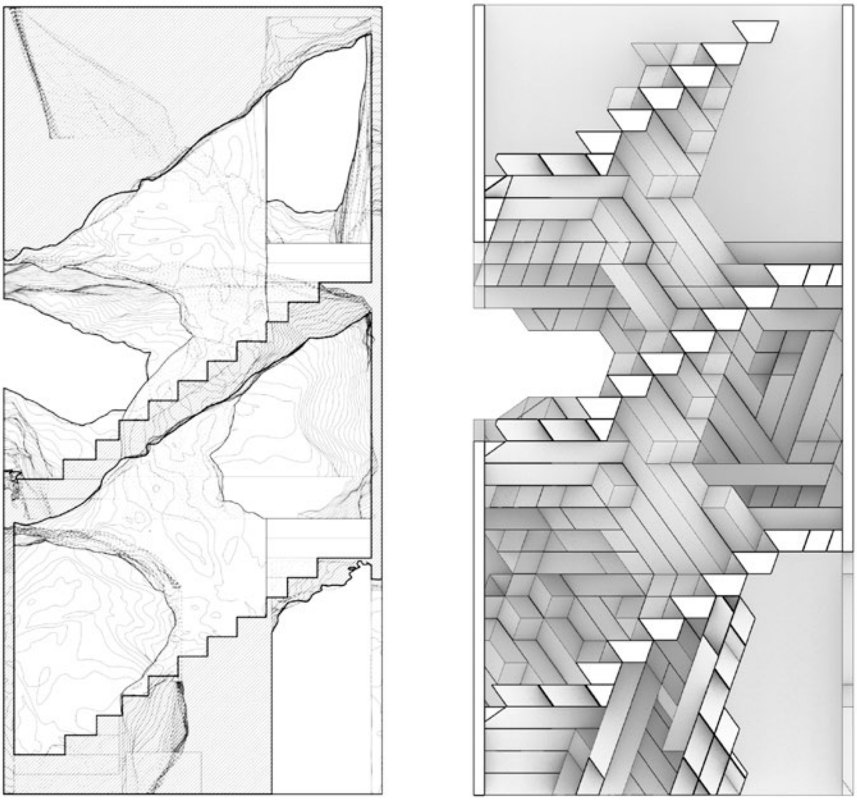


Fig. 85. Käsmu bus stop section drawing 2018 and the revised version 2019.

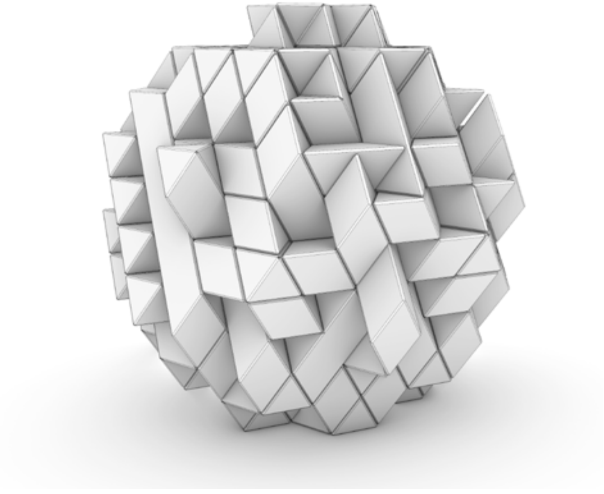


Fig. 86. Modulated sphere 2020.

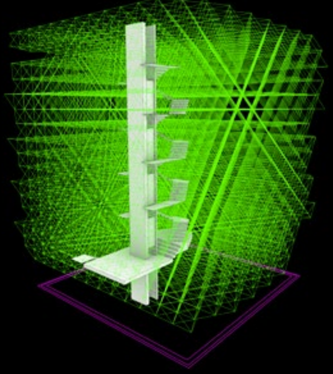


Fig. 87. Shift Lofts 2019 by PART Architects. The spiralling stair core and the spatial structure.

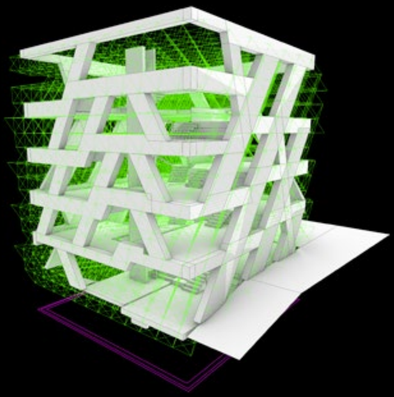


Fig. 88. Shift Lofts 2019 by PART Architects. The load-bearing CLT facade and the spatial structure.

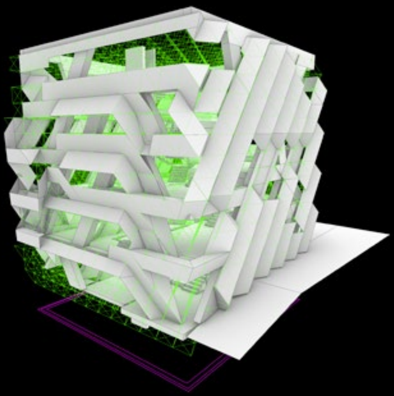


Fig. 89. Shift Lofts 2019 by PART Architects. The volumetric facade with balconies and shading with the spatial structure.

Fig. 90. Shift Lofts 2019 by PART Architects. Western elevation rendering.

Fig. 91. Shift Lofts 2019 by PART Architects. Southern front elevation rendering.

Fig. 92. Shift Lofts 2019 by PART Architects. View from south-east.

Summary

With the rise of digital technology over the last 30 years and its promise of individual liberation, it seemed a fully democratic completely individualised society is about to emerge. A few decades later, we are seeing how big data actually makes us predictable and manipulatable and has created stronger hierarchies in power. As most prominently evidenced by the Cambridge Analytica scandal. Yes, we are more individualistic than ever, but we are also more connected than ever, meaning statistically we are all classifiable datasets for machine learning algorithms. Considering this, is the digital really an enabler of endless variation, as proposed by the first generation of digital architects, or rather a contingent system of standardisation? In this thesis I am proposing modulation as an act of subversion through creative constraints similar to what is proposed by Hui with modulation after control rather than Rouvroy's optimisation through algorithmic governmentality.

How is variation created in the manufacture of digital designs? The digital colour printer does produce endless variety, but on the basis of strict standardisation – it is placing dots of three specific colours onto paper. The same with the screen – it is an array of three coloured pixels that light up in different intensities. The same technology has been applied to building facades in lower resolutions. Where in some of the more successful designs, the pixel itself has become an architectural detail. Pixelation, or rather voxelation can be used to create a similar level of automated modularisation of form. So that leaves us with the question, what is a good 3-dimensional pixel – a module – in construction? I would argue there are two main somewhat contradictory parameters at play here – efficiency vs flexibility or rather resolution in this context. A lower resolution results in fewer elements but also fewer possibilities for spatial articulation.

If we look at the way construction elements and modules are designed, they are mainly optimised for the logistics of mechanical fabrication, transport and manual construction, not necessarily architectural flexibility. Custom or rather computer aided mass production allows us to rethink some of these parameters in favour of higher degrees of freedom. Still, automated fabrication today is more reliable in repetition. It is easy to automate the production of almost any detail to be produced in bulk. Producing a unique part every time remains inefficient and carries a high margin of error. Not to mention the only zero-waste approach to creating non-standard elements is additive manufacturing, where the margin of error is also the highest. So still, through the projects that we have done with PART and our experience talking to engineers in the industry and working on large-scale non-standard projects, the most viable way of producing elements is machining standard stock materials, mostly cutting and milling. This means stock waste is also an issue.

These practical constraints can be seen as the conditioning circumstances of the modulated modularity method. It is based on a repetitive algorithmic subdivision, where the resulting elements can be evaluated for material efficiency. Due to this fact we have been using the body-centred cubic lattice as a structuring system to achieve rectangle and equilateral triangle based elements. This geometry was first used in the plywood base of the Urban Jungle vertical park as an inhabitable landscape. (Fig. 62) Through further studies block, linear profile, plate and complex module aggregations have been tested. (Fig. 77) Still in development is the system utilised in the Shift Lofts apartment building. (Fig. 92) Apart from fabrication limits, structural analysis and optimisation can be used to determine the materiality and placement of these elements. (Fig. 56) All of these practicalities form 'the reality' that becomes a virtual model that defines the modulation of form.

The term modulated modularity suggests an algorithmic play on, or rigorous modification of modularity. The classical tool of modularisation has been the grid. Due to mechanical production and the way of conceiving architecture in two-dimensional drawings, the grid has classically been a projection of parallel axes. The algorithmic means of design allows us to look at the grid not just as a less constrained periodic subdivision of space but as a design tool that is adaptable, based on the real and allowing for both evolutionary optimisation and subjective intervention. The German term *Raumstruktur* carries this very meaning and has been used as the basis for the Spatial City project by Eckhardt Schulze-Fielitz. He referred to the spatial structure as a macro material, capable of modulation (*Modulationsfähige Makromaterie)* (Schulze-Fielitz 1960: 168). The *Raumstruktur* as an abstract idea is too complex to be the basis for any actual spatial structure. Modulation therefore helps us decide which aspects of the real are essential and which not – which of them to include in the computational model of the *Raumstruktur* and their proper measure.

Bringing this kind of modulation to algorithmic architectural design creates another layer in this process. Not only is form modulated by the actual forces and their materiality, but also by the designed algorithmic model that governs these relationships, where the objective and subjective aspects become, well, modulated. Modulation, in this context, is therefore not a strictly self-organising system but a designed system with partially self-organising characteristics.

This dynamic play with geometry also has a relation to simulation. When we simulate physical forces on the screen, we get a certain idea of how a structure might behave. Something similar happens with dynamic geometric systems – we get a feeling for the geometry almost like a new materiality – or rather formality. The fascination with the developed method of modulation does not really lie in the efficiency of combining constraints of fabrication and construction but rather developing a behavioural system which reveals a certain emergent formality. For this formality to emerge, differentiation is needed. In the Shift Loft project, this differentiation is achieved by orienting the body-centred cubic grid on the corner of the cube, resulting in a triangular grid floor plan juxtaposed on a rectangular footprint. Further subdivision of the facade is due to the spiralling floor plate. (Fig. 91)

Negotiating contradictory goals is where algorithmic design creates the most interesting results – the other, the strange, the unexpected. To borrow words from Manuel Delanda, "the virtual is manifested in those situations where intensive differences are not cancelled out" (DeLanda 2002, 64). In Deleuzian terms, it is the actualisation of the virtual that creates the fascination in algorithmic design. In PART's designs, we use this method of modulation so as to reveal the designed virtual model through the process – exploring the emergent qualities of the negotiation between the forces of formation and the conditioning circumstances of the spatial structure.

Modulation is most often connected to music and also raises questions of rhythm, proportion, and the relation to the human body in architecture. This in turn could be considered another reasoning for digital architecture to turn from the continuity of calculus to the granularity of data. Modern architecture has often been criticised for the lack of the human scale. The new rise in discrete tectonics, arguably connected to the automation of assembly (Picon 2010, 166), could also be considered a return of the human scale. The changing perception of the body, and therefore any corpus – natural, textual, artefactual, social etc. – has changed from a Vitruvian centralised hierarchical organism (McEwen 2002) to an open complex system composed of a multitude of agents and understood through computational models (Monteiro 2011). The scale explored within this thesis ranges from furniture to floor height. (Fig. 81) For the projects dealing with solid modules, like the Käsmu bus stop, the module is defined by material thickness, in that case 200 mm CLT leftovers. The structural facade panels of Shift Lofts have been considered as single pieces 18 by 1.8 metres. Most probably they will be subdivided to fit the local factory's maximum measurements for CLT plates, which is about 3.5 by 12 metres.

Rhythm is the discretisation of our environment in space and time. Just as we discretise sounds that we make into syllables to manage the noise of the signal, we are dividing our environment into comparable parts to understand and communicate it (Dennett 2017: 199). Proportion and rhythm therefore are tools for making our environment relatable. Not forgetting that edge detection is essential for machine vision – differentiation is needed. Rhythm, the repetition of discrete elements in space or time, is the basis also of Max Bense's generative aesthetics, which is concerned with “bringing about ‘orderly arrangements’ which comprise the topological nature of ‘form’, and the statistical nature of ‘distribution’” (Bense 1965).

Algorithmic regulating lines operate in a different way than those drawn on classical or modernist elevations. Periodic spatial subdivisions reveal how the design volume (e.g. the massing) relates to it. Like isometric lines on topographical maps reveal the undulations of the landscape, modulation emphasises the geometry of the form, driver geometry, or the virtual field of intensities that it emerges from. The modulated articulations reveal the underlying ‘forces’ at play in their conception – creating patterns that can be interpreted as the expression of the modulation of the *Raumstruktur*.

Using algorithmic tools, we are bound to be a lot more precise about following the regulating lines of our automated designs. We are able to set up simple algorithms – rulesets that define relationships within our designs – that then start to govern the spatial structure. Not only that, we can also set parameters inside those governing algorithms that can be changed on the go, based on qualitative or quantitative feedback, creating an opportunity for the subjective manipulation of these automated processes. This creates a duality of human-nonhuman interaction – the subject and the other. The insertion of subjective judgement into the algorithmic model creates greater control of the modulated outcome and its expression. The scale of elements or resolution of the form can be manipulated on the go, creating varying intensities of modulation in relation to the human body and the experience of the space. (Fig. 93)

Modulation suggests the possibility of maintaining the autonomy of the discipline of architecture by developing design methods in line with contemporary scientific and technological rationality, subverting its power the same way Laibach did with the communist regime – by taking the prevailing ideology more seriously than the system takes it self, as “transgression is always part of the system” (Žižek 1996). For me, this relates to subverting prevailing conventions and standards by automating them. By automation and animation, new patterns can emerge from the same elements, as we know from the chaos theory, by changing a single variable the whole pattern can change. This means, we don’t need to impose our will top-down, architecture can be coded in. Even within an overall grid, combinations of elements in various orientations can produce unexpected outcomes. (Fig. 77)

Looking back at the discourse of digital architecture, especially Folding, most of it is still applicable. Calculus-based geometry is a great tool for manipulating complex sets of data and objects. Less so, when it comes to the infinitesimal variation of construction geometry. Talking about information “[Alan] Turing noted, nothing in nature is truly digital;

Fig. 93. Urban Jungle 2018, plywood landscape, subdivisions of truncated octahedrons.

everywhere there is continuous variation; the great design move is making devices that treat all signals as digital, discarding instead of copying the idiosyncrasies of particular tokens" (Dennett 2017: 200). One of the main findings of this research is that the same goes for building information.

Digital in its original sense is the opposite of the continuity of calculus; that is, the basis for folding in digital architecture. Digitising architecture would mean defining the basic computable objects – the fundamental elements of architecture. Durand at the end of the 18th century creates a method for creating architecture, in the spirit of the time, inspired by the analytical method (Picon 2000: 21). Using the Euclidean grid as the basic spatial structure and standardised architectural elements, he creates a discrete method for composition. More than a century later, architects were developing their own standardised elements as mass produced parts for an open system of construction. The General Panel System developed by Konrad Wachsmann with Walter Gropius was one of the closest to a digitalisation of architectural elements. The specially developed connection detail allowed for a perfectly symmetric, universal system.

The space frame liberated those experiments from both orthogonal geometry and seemingly from gravity. Utopian architects of the mid-20th century were developing evolutionary spatial cities – self-organising spatial structures. For Eckhardt Schulze-Fielitz, those were based on the spatial structure (*Raumstruktur*) – a macro material capable of modulation. The German term *Raumstruktur* stands for the organisational structure of space influenced by natural and social processes, the underlying structure that enables reality to unfold. Through modulation, this spatial structure can be considered as a wholistic organisational device of architecture from the urban to the micro scale. The spatial structure is defined by elements, which in our case are produced from standard stock materials. The minimum size is therefore defined by material thickness. For example the Käsmu bus stop is constructed out of 200 mm CLT leftovers. This is used to form stairs with a 200 mm step height and seating of 400 mm height. There are standard dimensions for materials, which is another dimension to consider when defining the base module. Often 150 mm is a good module to define step heights, seating, tables, working surfaces and so on. Modules of 600 mm are often found in appliances and construction materials.

The expression of this organisational device, the spatial structure is what creates the ornamental quality of modulated modularity, and therefore contributes to the creation of meaning in architecture. It is the result of the modulation of the hybrid agency between the subjective, the real and the other. Otherness emerges through the subjective modulation of the *Raumstruktur*. This subversion from within is what I see as the possibility to maintain the autonomy of the discipline of architecture facing the realities of extensive standardisation, automation and artificial intelligence.

The rich legacy of the digital discourse in architecture has provided us with all the tools necessary for this proposed subversion. Lynn's folding, Beaucé and Cache's associative design, Delanda's flat ontology – they all speak of complex systems of parts in mutual interaction, producing emergent wholes. What has been left behind in the discourse of the digital are the ideas of the early computational artists and architects, whose thinking was more in line with industrial production and modularity. The advanced computing power and ease of use of today's visual programming software, makes it possible to explore the full potential of combining these two worlds.

In the emergent whole, the expression of the underlying organisation of reality through subjective modulation connects subjectivity and politics and makes it part of cultural production. This systemic consistency of expression, I would argue is what creates the Banhamian memorable image. Adding to this, the honesty of the materials and the clear exhibition of the structure, as the relationship of parts gives ample reason to call it computational brutalism.

Modulated modularity is a design method based on the idea of modulation, the definition of which, as an underlying concept of digital architecture in the age of automation and machine learning, is what I would argue is one of the key findings of this thesis. The ideas presented in this thesis have been developed mainly through experimental installations and prototypes. The permanent structures finished at this point are a high voltage power line corner pylon we call the Bog Fox, which tests the idea of formation from creative constraints and algorithmic structural optimisation, and the Urban Jungle vertical garden, which serves as proof of concept for this thesis. Testing these ideas in building scale, through projects already in progress, will be the next step for this research.

Moduleeritud modulaarsus – masskohandamisest kohandatud masstootmiseni

Ehitussektoril seisavad ees tohutud katsumused – kliimamuutused ja nendest tulenevad ehituseeskirjad (European Parliament 2010) loovad enneolematu vajaduse tõhustamiseks, standardiseerimiseks ja automatiseerimiseks (McKinsey 2017). Kuigi tehnoloogilised edusammud suurendavad üldist jõukust, kasvab samal ajal ka riikide ebavõrdsus (UNDESA 2020). Konservatismi esiletõus on sellises olukorras mõistetav, kuid ei aita lahendada probleemi. Automatiseerimine on liiga tõhus, et seda peatada. Ehitussektor liigub täieliku digitaliseerimise suunas. Ainus võimalus arhitektidel seda protsessi mõjutada on olla osa sellest.

Arvutuslik mõtlemine omab meie eludele järjest suuremat mõju. Tekib küsimus, kuidas inimesed saaksid jääda inimlikuks sellisel automatiseeritud pimedal ajastul (Bridle 2018). Kas arhitektuurile jääb üldse ruumi selles ülireguleeritud ja -piiratud valdkonnas? Kuidas mõista autonoomiat hüpervõrgustunud maailmas? Muidugi ei ole need küsimused uued. Antoine Picon kirjutab Jean-Nicolas-Louis Durandi „Précis of the Lectures on Architecture“ sissejuhatuses:

> *Mis pole muutunud … on selle katsumuse olemus, mille ees Durand seisis: võimalus säilitada arhitektuur autonoomse distsipliinina maailma lävel, kus domineerib teaduslik ja tehnoloogiline ratsionaalsus.* (Picon 2000: 3, autori tõlge)

Arvutuslikkus on mõjutanud arhitektuuri arvutusliku mõttelaadi tekkest saati (Caetano 2020), kuid terminina on arvutuslik arhitektuur (*computational architecture*) liiga lai, et seletada selle väitekirja fookust. Tegu on originaalse uurimusega sellest, kuidas disainist mõtlemine on arenenud, lähtudes kriitilisest diskursusest nimega digitaalne arhitektuur. Omadus „digitaalne“ ei tähenda siin seda, et arhitektuuri olemus või tulemus oleks digitaalne, vaid et see on arhitektuuri mõttevool, mis on kantud digitaalsest kultuurist ja tehnoloogiast (Picon 2010).

Digitaalset arhitektuuri iseloomustab komplekssuse ja vasturääkivuse (Venturi 1977) ületamine, ühendades sujuva topoloogia muutliku tektoonikaga (Lynn 1996); üha komplekssemad algoritmid, mis suudavad toime tulla komplekssüsteemidega (Sakamoto 2008, Schumacher 2012), samal ajal kui teised algoritmid võimaldavad komplekssust ja esilekerkivust (*emergence*) esile kutsuda (Aranda/Lasch 2006, Terzidis 2006, Snooks 2017, Andrasek 2018); üha keerukamate digitaalsete tootmismeetodite arendamine, mille abil materiaalseid protsesse üleküllusliku vormi ja materiaalsuse loomiseks rakendada (Gramazio/Koehler 2010, Menges 2012), ning viimaks püüd lepitada seda valdkonda digitaalsete tehnoloogiatega võimestatud ehitustööstusega – väljuda uurimislaborist.

Siin pöördub mu uurimus eksperimentaalseks. Eesti puitmajatööstuses digitaalse disaini võtteid testides olen üritanud jõuda üldisema arusaamani nüüdisaegsetest tööstusliku tootmise ja ehitamise praktikatest.

Ajendatuna kasvavast soovist ehitada tavalisi hooneid, mitte ainult uurimispaviljone või ekstravagantseid muuseume, on viimasel ajal toimunud üks märkimisväärsemaid muutusi digitaalse arhitektuuri mõtlemises. Algoritmiliste disainivõtete abil on sotsiaalsete, majanduslike ja keskkondlike reaalsustega arvestamine võimalik, lähtudes olemasolevatest industriaalse tootmise viisidest, ent jäädes digitaalse arhitektuuri piiridesse. Teatav pragmatism on selles valdkonnas käinud lainetena. Ennekõike on digitaalsed töövahendid tõhustanud olemasolevaid töömeetodeid. Joonestusprogramm AutoCAD avaldati 1982. aastal (Caetano 2020: 168). Vahepeal on digitaalne tehnoloogia ja kultuur arenenud ning muundunud – võime näha võimalusi pragmaatiliselt arvutusliku ja kriitiliselt digitaalse lepitamiseks. Usun, et digitaalse arhitektuuri diskursus on olnud tõrges teaduslikult ja tehnoloogiliselt arvutusliku suhtes, justnimelt kartuses kaotada oma autonoomia.

Uurimuse eksperimentaalne ehk praktiline osa on läbi viidud peamiselt minu bürroos PART Arhitektid, mille asutasime koos partner Sille Pihlakuga 2015. aastal, vahetult enne doktoriõpingute alustamist. Seega on meie büroo kõik projektid seotud meie mõlema doktoritöödega ja mõistagi on projektidel jagatud autorlus. Doktoritöö tekstiline osa ning siin väljendatavad ideed ja algoritmilised meetodid on siiski minu isiklik panus. Edaspidi, kui kasutan meie-vormi, mõtlen ma PART Arhitekte.

Selle uurimuse käigus kohaliku tööstusega koostöös tehtud eksperimentidest selgub, et mõned digitaalse arhitektuuri postulaadid tuleb üle vaadata – infinitesimaalsest variatsioonist tuleb ilmselt loobuda ja modulaarsust uuesti kaaluda. Sarnaselt viimasel ajal taas tekkinud huvi ja murdelise arenguga vahepeal unustusse vajunud tehisintellektis ja virtuaalreaalsuses tuleks üle vaadata ka teise maailmasõja järgse küberneetika kuldajastu arvutusliku kunsti generatiivne esteetika (Bense 1965), mis masinõppimise ja automatiseerimise vaimus on hakanud arhitektuuri tagasi imbuma. Sellest taastulemisest ja Reyner Banhami teose „The New Brutalism" (Banham 1955) lugemisest esilekerkivad tugevad sarnasused uue brutalismi ja eelmainitud digitaalse arhitektuuri trendide vahel on minu arvates piisav põhjus, et seda liikumist arvutuslikuks brutalismiks (*computational brutalism*) nimetada.

Selle uurimuse eesmärk oli välja töötada praeguses kontekstis ja hetkes toimiv originaalne disainimeetod, mis funktsioneerib digitaalse arhitektuuri valdkonnas, ning, harutades lahti meetodi loomisel aluseks olnud ideed, kaalutlused ja mõjutused, anda oma panus sellesse diskursusesse. Digitaalse arhitektuuri defineerimine on esimese peatüki teema. Väljatöötatud meetod põhineb mittespekulatiivsetel ehitusviisidel: mitte millelgi, mis hakkab olema võimalik tulevikus, vaid millelgi, mida saab rakenda siin ja praegu. Oleme oma eksperimentide kaudu seda lähenemist testinud ja arendanud ning väljatöötatav meetod on jõudnud teatava küpsuseni, mida oleme demonstreerinud erinevate ehitatud installatsioonide ja rajatistega. Tagasi vaadates on selge, et mõned selle protsessi käigus tehtud avastused on laiendatavad väljapoole digitaalse arhitektuuri diskursust ning rakendatavad tööstuslikult toodetud hoonete projekteerimisel laiemalt.

Uurides modulaarsust digitaalses arhitektuuris, olen jõudnud mõisteni modulatsioon, mis siin tähendab kaalutlemist (*negotiation*) tingivatest asjaoludest (asjaolud, mis ka midagi tingivad) tulenevatel dünaamilistel geomeetrilistel süsteemidel põhineva utilitaarse meetodi ja läbi nendesamade dünaamiliste geomeetriliste süsteemide esile kerkiva ruumistruktuuri (*Raumstruktur, the real*) teisesuse (*otherness*) arhitektuurse väljenduse vahel. Ehk lihtsamalt: modulatsioon on kaalutlemine seaduste (loodus ja ühiskond) ning väljenduse (autor ja valdkond) ehk üldise ja spetsiifilise vahel. Või kui tuua paralleel ühe kulunud ütlusega arhitektuuri kohta, siis vanas prantsuse keeles tähendas *modulation* muusika loomist.

Dünaamilised geomeetrilised süsteemid on arvutuslikult konstrueeritud, täpselt defineeritud suhetega, adaptiivsed ja manipuleeritavad geomeetriad (Aranda/Lasch 2006: 9). Tingivad asjaolud on kõik normid, eeskirjad ja seadused, nii looduslikud kui ka ühiskondlikud, nagu tuulekoormus, ehitusalune pind või prussi standardmõõdud, mis on ruumistruktuuri mudelisse kaasatud. Esilekerkivus ehk emergentsus (Holland 2000) on nii sotsiaalsete kui ka looduslike komplekssüsteemide omadus tekitada korrapäraseid mustreid, mida iseloomustab teisesus – iseorganiseeruvate süsteemide mitteinimlikkus. Ruumistruktuur on viis, kuidas ruum on sotsiaalsete ja/või looduslike protsesside poolt organiseeritud (Gabler Wirtschaftslexikon: Raumstruktur). Saksa arhitekt Eckhardt Schulze-Fielitz mõtles selle all moduleerimisvõimelist makromaterjali (Schulze-Fielitz 1960: 168). Antoine Picon kasutab sama idee kirjeldamiseks ingliskeelset sõna *real* ehk reaalne, mis on alusstruktuur, mis võimaldab reaalsusel lahti rulluda, või virtuaalsus, mis vallandab reaalsuse lahtirullumise (Picon 2010: 212).

Mõiste modulatsioon (ld *modus* – mõõt, viis) siin kontekstis viitab hoolikalt mõõdetud dünaamilisele muutusele, variatsioonile või mängule modulaarsusega. Ruumistruktuur abstraktse ideena on liiga hajus, et olla aluseks reaalsele konstruktsioonile. Modulatsioon on meetod, mille abil otsustada, millised asjaolud kaasata arvutuslikku mudelisse ja milline on nende paras mõõt. Ehk otsustada reaalsuse paras mõõt ja viis mudelis. Minu eesmärk moduleeritud modulaarsusega on luua algoritmiline lähenemine modulaarsusele arhitektuuris, mis ühendaks reeglipärase esilekerkivuse subjektiivse manipulatsiooniga. Seejuures on aluseks võetud nüüdisaegsed tööstuslikud tootmismeetodid. Peamiselt oleme lähtunud puidutööstusest ja materjalidest nagu ristkiht-liimpuitplaat (CLT) või liimpuit.

Ma olen huvitatud nüüdisaegsete (mittespekulatiivsete) ehitusmeetodite ja digitaalse arhitektuuri kohtumiskohast. Kas digitaalse arhitektuuri algoritmiline ettemääramatus on rakendatav ehituseks disainimisel praeguses kontekstis, silmas pidades ka hinda ja säästlikkust? Milliste strateegiate abil on majanduslike ja ehituslike reaalsuste jaoks optimeerides võimalik säilitada generatiivset tunnetust? Selleks et nendele küsimustele vastata, pakun moduleeritud modulaarsusega välja, et tuleks üle vaadata üks modernse arhitektuuri alustalasid – teljestik ehk raster (*grid*). Moduleeritud ruumistruktuur loob mittestandardset ruumirastrit ja mittestandardset moodulaarsust, mis on omavahel vastastikseoses, ilma hierarhiata. Infinitesimaalse variatsiooni asemel on eelistatud kohandatud elementide kordus – masskohandamise asemel kohandatud masstootmine.

Uurimisküsimused

See uurimus sai alguse 2016. aastal, vahetult pärast 2015. aasta Tallinna arhitektuuribiennaali, kus me kureerisime peanäituse „Keha ehitus“ ja ehitasime näituse pikendusena Eesti Arhitektuurimuuseumi ette samanimelise installatsiooni. Näituse ja installatsiooni eesmärk oli kaardistada digitaalse arhitektuuri hetkeolukord.

> *Keha Ehitus, 2015. aasta Tallinna arhitektuuribiennaali kuraatorinäitus, uurib ehitamise hübriidvorme, kus tipptasemel tehnika ja teadus kohtuvad isekasvavate süsteemide mitmekesisusega ja kus vabaduse ja piirangute eri tasemed loovad arvutult uusi väljundeid, püüdes leida tasakaalu kontrollimatu ja etteaimatava – keha ja ehitise – vahel.* (Pihlak/Tuksam 2015: 2)

Näitus oli organiseeritud kahemõõtmelisel väljal: digitaalne-füüsiline telg ja kontroll-autonoomia telg. Välja neli nurka väljendasid tekkepõhimõtte äärmusi: digitaalne kontroll (abstraktne), füüsiline kontroll (materjaliga arvestav), füüsiline autonoomia (materjalist tulenev), digitaalne autonoomia (generatiivsetel algoritmidel põhinev). Meie installatsiooni eesmärk oli tuua need neli äärmust kokku ühtsesse keha ehitusse. Üritades tuua digitaalse arhitektuuri ideid nüüdisaegsesse ehitusse, ilmnesid mitmed puudujäägid meie mõtlemises ja disainist ehitusse liikumise protsessides.

Alates 2010. aastal ettevõttes Gehry Technologies saadud praktikakogemusest on mulle huvi pakkunud arhitektuuri tehniline ja kunstiline duaalsus. Gehry Tech tegeles n-ö järelratsionaliseerimisega: disainpindade arhitektuurseteks elementideks tükeldamise ja sõlmede lahendamisega. Seal töötasid peamiselt arhitektid. On selge, et spetsialiseerumine on vajalik ja erinevate oskustega arhitektid töötavad projekti eristaadiumitega. Samal ajal võimaldab digitaalsus luua kollektiivset intelligentsust (Hight/Perry 2006), millest tulenevalt saaks erinevaid teadmisi rakendada samaaegselt ja horisontaalselt või vähemalt tagasisideringis. Algne küsimus oli minu jaoks seega, kuidas tuua kokku pragmaatilised asjaolud ja arhitektuurne väljendus, üht teisele ohverdamata. „Keha ehituse“ installatsioonist saadud kogemuse põhjal soovisin ma mõista, kuidas oleks võimalik mõjutada seda, kuidas asju ehitatakse, alates integreeritud disainist (nt konstruktsiooni ja energiatõhususe analüüsi kaasamine) kuni sujuva failist-tehasesse protsessi ja eksimust välistava ehituseni. Millest omakorda kerkib küsimus, miks seda üldse teha, kui sellele nii palju vastupanu leidub? Mis on nende asjade kultuuriline väärtus, mida me teeme? Ja mis on üldse arhitekti roll andmepõhises algoritmilises arhitektuuriloomise protsessis? Siinkohal sõnastaksin ma need küsimused nii:

1. Kuidas säilitada distsipliini autonoomiat ja autoriteeti, seistes silmitsi ulatusliku standardiseerimise, automatiseerimise ja tehisintellektiga?

2. Mida saaksime õppida arvutusliku disaini põhimõtetest, mis aitaks meil välja töötada meetodeid, mis oleks kooskõlas nii nüüdisaegse ehitustööstuse reaalsustega kui ka digitaalsuse kriitilise diskursusega?

3. Mis on nende disainimeetodite esteetiline, poliitiline ja kultuuriline olulisus?

Vajadus säilitada autonoomia tähendab säilitada väljendusvabadus, mis teeb arhitektuurist kultuuriloome osa. Keskkonna probleeme ja pidevalt kasvavat populatsiooni arvesse võttes tuleb seda teha säästlikul ja efektiivsel viisil. Automatiseerimine ja standardiseerimine arhitektuuri-, inseneeria- ja ehitustööstuses on seejuures möödapääsmatu. Algoritmiline disain ja raaljuhitud tootmine (CAM – *computer aided manufacturing*) on alarakendatud (McKinsey 2017). PARTi juhtumiuuringutes oleme märganud, et arvjuhitud (CNC – *computer numerical control*) tootmisliinid on tööstuses olemas, kuid professionaalses keskkonnas kasutatakse neid seeriatootmiseks, mitte nii nagu akadeemilises keskkonnas, universaalse tööriistana masskohandamise saavutamiseks. Kui kord on masinad programmeeritud ja tööfailid kontrollitud, on vaja teatud aja lasta masinatel katkestusteta töötada, et saavutada kuluefektiivsus. Kohandatud toote lisandväärtus peab kaaluma üles tootmisliini seadistamisest tuleneva lisakulu (Piller 2004). Rääkimata sellest, et tootmine on ehituses vaid esimene samm. Arvesse tuleb võtta nii detailide monteerimine, parandamine kui ka asendamine ja lõpuks demonteerimine – kogu elukaar. Kuidas võiks see mõjutada ruumistruktuuri moduleerimist ja seeläbi arhitektuurset väljendust?

Eeldus, et tulevikus asendab masskohandatu masstootmise ning sellest tulenevalt loobutakse modulaarsusest ja kordusest, oli ilmselt üks 1990. aastate eesrindlike arhitektide suuremaid eksiarvamusi. Automatiseerimine eeldab standardiseeritust. Universaalne standardiseerimine on digitaalse variatsiooni alus – seetõttu eksisteerib näiteks infoühik bitt, pildielement piksel, ruumielement voksel ja resolutsioon ehk elementide tihedus. Nüüd kui oleme jõudnud retinaresolutsioonini (kõrgem tihedus kui inimsilm eristada suudab), võib resolutsiooni uurida esteetilise domeenina, kus granulaarsus, mittepidevus ja matemaatiline diskreetsus on kvaliteedid, mitte puudujääk. Sellisest vaatenurgast näeme, et standardiseerimine on variatsiooni aluseks – avatud tööriist, mitte piirav reeglistik. Arhitektuuri elemendid tuleb sellest lähtuvalt üle vaadata. Kui hakata uurima standardiseerimist ja modulariseerimist, võib öelda, et arhitektuuri pikseleerimine ehk rasterdamine arhitektuuri loomise meetodina on palju vanem kui digitaalsed tehnoloogiad.

Olles võimaldanud variatsiooni, tekkib omakorda küsimus poliitikast ja esteetikast, mis Jacques Rancière'i järgi on omavahelises seoses. „Millist poliitikat tehnoloogilised paradigmad võimaldavad?" küsis Roemer van Toorn 2019. aasta EKA teaduskonverentsil „Ruum ja digireaalsus" (Tuksam 2020: 105). Tehnoloogial on ruumilisele organisatsioonile suur mõju. Antud juhul on uurimise all tektoonika ja vormiartikulatsiooni muutuv kvaliteet ehk kuidas mateeria on ruumi ja kogemuse loomiseks organiseeritud. Arhitektuuriajaloos on läbi aegade ruumilise organisatsiooni ja selle tunnetuse uurimise aluseks olnud proportsioon ja rütm – inimese suhe tehislikesse ja looduslikesse objektidesse. Keha ja seeläbi igasuguse korpuse (looduslik, tekstiline, tehislik, sotsiaalne jms) mõistmine on muutunud vitruviuslikust tsentraliseeritud hierarhilisest organismist (McEwen 2002) avatud komplekssüsteemiks, mis koosneb hulgalistest agentidest ja mida mõistetakse läbi arvutuslike mudelite (Monteiro 2011).

Tehnoloogia muudab seda, kuidas me maailma tunnetame, loome ja selles elada tahame. Selles mõttes on vorm ja tektoonika samuti ligipääsu loovad, väljendades vormi andvaid jõude ehk ruumistruktuuri, ja on seega sotsiaalse mõõtmega. Sellise kommunikatiivse tahu esilekerkimine on üks aspekte, mis paneb Antoine Piconi rääkima ornamendi tagasitulekust (Picon 2013) ja mis, ma eeldan, on see, millele viitab Reyner Banham, kui ta räägib meeldejäävast pildist (*memorable image*) (Banham 1955, Gannon 2017). Autonoomia tähendab, et arhitektuur areneb iseseisvana ehitusest. Rancière ütleb: „Nii nagu ei ole alati kunsti (kuigi on alati muusika, skulptuur, tants ja nii edasi), ei ole alati poliitikat (kuigi on alati võimu vormid ja nõustumine)" (Rancière 2009, autori tõlge). Alati ei ole ka arhitektuuri, kuigi on alati ehitus, linnad, majad ja nii edasi. Arhitektuur peab erinema ehitusest. Arhitektuuris peab olema ornamentne kvaliteet, mis seob kokku esteetika ja poliitika, subjektiivse ja kollektiivse.

Proportsiooni uurimisest ja loomisest rääkides ei saa mööda vaadata teljestikest ehk rastritest. Rastreid ja reguleerivad jooni on klassikaliselt kasutatud kahemõõtmeliste pinna organiseerimise vahenditena, mille kasutuselevõtt arhitektuuris suures pildis korreleerub projektiivse geomeetria leiutamisega 15. sajandil (Carpo 2011: 58). Tuues selle idee 21. sajandisse ning arvutusliku geomeetria ja piirangmodelleerimise (*constraint modelling*) (Clayton 2014: 30) pärusmaale, saavad rastritest ja reguleerivatest joontest mitteeukleidilised ruumid, mis lubavad jätkuvat topoloogilist transformatsiooni ja ruumide rekursiivsust – ruumi ruumis. Selliseid ruume olen uurinud eesmärgiga luua ruumilisi sõrestikke ja mahulisi alajaotusi.

Ruumistruktuuri modulatsioon ruumilisteks rastriteks (telgede asemel on ruum jaotatud rakkudeks) on muuhulgas poliitiline ja esteetiline operatsioon – kommunikatsiooniviis omaenda süntaksiga. Kas sellest lähtuvalt võib öelda, et on olemas digitaalse arhitektuuri keel? Minu arvates on ehitamisest huvituvas digitaalses arhitektuuris praegu moodustunud kaks selget haru: praktiseerijad ja uurijad. Praktiseerijad, keda toetavad suurettevõtted ja kiirelt arenevate regioonide valitsused, väljendavad infinitesimaalarvutusel põhinevat varase arhitektuuri tunnetust. Nendest kõige prominentsem, lihtsalt ühe näitena, on ilmselt Zaha Hadid Architects eesotsas Patrick Schumacheriga, kes on pea totalitaarse koherentsuse ja jätkuvuse eestkostja omaenese kirjeldatud parametritsismiga (Schumacher 2012).

Uurijad tegelevad digitaalse simulatsiooni ja tootmistehnika arendamisega, toetudes avaliku ja erasektori teadusrahastusele. Prominentseimad neist on ilmselt ETH Gramazio Kohler Research, mida juhivad Fabio Gramazio ja Matthias Köhler, ning Stuttgarti ülikooli arvutusliku disaini ja ehituse instituut (ICD), mida juhib Achim Menges. See ei tähenda, et uurimus ja praktika oleksid täielikult eraldunud, kuid on eristatav selge fookus ühele või teisele, mis väljendub ka tulemuses. Kuid on ka kolmas haru, mille fookuses on digitaalse arhitektuuri väljatoomine laborist ja allatoomine staararhitektuuri elevandiluutornist, jäädes kriitiliseks *status quo* suhtes ning edendades autonoomset arhitektuuri diskursust, ühendades praktika ja uurimuse. Kõigil neil harudel on oma keel ja poliitika, kusjuures viimane ei ole ilmtingimata segu kahest esimesest. Samas on neil sarnane arvutuslik alusloogika, mis võimaldab moduleeritud hübriide.

Modulatsioon on optimeerimisvahend. Kuid nagu alati optimeerides on vaja teada täpseid parameetreid, mida optimeerida. Sisuliselt on eesmärk leida tasakaal selle vahel, mida saab teha ja mida soovitakse teha. Paradoks seisneb selles, et piirangud on tihtipeale loovamad kui vabadused. Uued kvaliteedid ja ootamatused kerkivad enamasti esile, optimeerides vastandlikke eesmärke ja piiranguid. Modulatsioon selles mõttes ei ole kompromissi otsimine, vaid õigete komponentide ideaalse kombinatsiooni otsimine. Eduka modulatsiooni korral peaksid kaasatud osised jääma loetavateks osadeks tervikust, mitte sulanduma seguks. Modulatsioon ei ole seega ideaalse ja reaalse vastandamine, vaid komplekssüsteem tingivatest asjaoludest, olgu need konstruktiivsed, materiaalsed, sotsiaalsed või puhtalt arhitektuursed, esteetilised või subjektiivsed. Selle protsessi tulemust saab hinnata, kaaludes kvalitatiivseid omadusi kvantitatiivsete vastu. Moduleeritud ruumistruktuuri väljendamiseks on vaja teatavat komplekssust, võimaldamaks arvutuslikku esilekerkivust.

Arhitektuur on alati olnud kombinatsioon inimlikest ja mitteinimlikest mõjutajatest – looduse ja kultuuri vastandus või koosmõju. Viimasel ajal on sellest saanud tehnoloogia ja kultuuri duaalsus – arvutuslik (ja bürokraatlik) esilekerkivus on saanud loodusest mõjusamaks mitteinimlikuks komponendiks meie keskkonnas. See mitteinimlik teisesus on loova vastupanu allikaks. Arvutuslikus disainis kerkib teisesus esile digitaalse automatiseerimise kaudu. See loob uue duaalsuse loodud korra ja iseorganiseeruva, keeruka lihtsuse ja lihtsa komplekssuse vahel. Oma töös üritan ma seda duaalsust moduleerida.

Metodoloogia

See töö on oma alguse saanud avatud lõpuga disainiuurimusest, kus loominguliseks kütuseks on masskohandamisel põhineva digitaalse arhitektuuri pärandi ja nüüdisaegse tööstusliku tootmise ebakõla – tööstuspartnerite, standardsete materjalide, ehitustööliste, konstruktiivsete piirangute, säästlikkuse ja eelarve küsimuste komplekssuse ja vasturääkivuse disainiks voltimine infinitesimaalse variatsiooni abil. Eksperimentide seeriast õpitu on seda uurimust suunanud loodust jäljendavatelt algoritmidelt ja muutlikult tektoonikalt niinimetatud eelratsionaliseeritud lähenemisviisile, kus simulatsiooni, analüüsi ja optimeerimise algoritmilised tööriistad on loodud, kombineeritud ja kaasatud disainimudelisse algusest peale. See on samaaegselt projitseeriv ja reflekteeriv disainiuurimus, mis põhineb eksperimentidel ning mis seejärel pöördub praktikapõhiseks ja teoreetiliseks uurimuseks. See on PART Arhitektide lõpetatud ja lõpetamata projektide kriitiline analüüs ja pidev taasseadistamine.

Uurimuse praktiline pool koosneb nelja aasta jooksul tehtud projektidest, mis tegelevad algoritmilise disaini ja digitaalse tootmisega Eestis, kus meie teadus- ja arendustegevus ei toimu mitte ülikooli tootmislabori turvalises mullis, vaid on algusest peale põhinenud koostööl tööstuspartneritega. Ühest küljest on see empiiriline eksperimentaalne uurimus ja teisalt ka töö seotud areneva digitaalse arhitektuuri diskursusega, millesse loodan panustada. Meie projektid kajastavad ideede evolutsiooni sellest, mis suunas digitaalne arhitektuur võiks areneda. Hüpoteesid on pidevas ümbersõnastamises, lähtudes viimastest eksperimentidest. See väitekiri on seega meie praksise ideede ja teemade hetkeseisu dokumentatsioon, paigutatuna praegusele arhitektuuriväljale, defineerides meie positsiooni ja unikaalset panust selles.

PART Arhitektide mõlemad partnerid kirjutavad väitekirju samaaegselt, vaadeldes samu projekte erineva pilguga. Minu fookuses on tehnoloogia ja disaini suhe. Otsin viise, kuidas moduleerida esilekerkivust ja subjektiivsust, et tasandada olemasolevad hierarhiad võimaluste väljaks, kus saab toimuda nii kvantitatiivne kui ka kvalitatiivne optimeerimine. AEC tööstus seisab ulatusliku algoritmilise automatiseerimise ja tehisintellekti kaasamise lävel. Sellesse protsessi sekkumine on muutunud arhitektuurse disaini osaks – arvutuslikud tehnoloogiad on hägustanud piiri immanentse ja transtsendentse vahel, osa ja tervik on horisontaalses vastastiksuhtes. Manuel DeLanda kirjeldab lamedat ontoloogiat järgmiselt:

> *… kui üldiste tüüpide ja üksikjuhtumite suhtel põhinev ontoloogia on hierarhiline, nii et iga tasand esindab erinevat ontoloogilist kategooriat (organism, liik, perekond), siis käsitlus, mis võtab aluseks vastastikmõjus osad ja emergentsed tervikud, viib lameda ontoloogiani, mis koosneb üksnes unikaalsetest, singulaarsetest indiviididest, mis erinevad aegruumilise suurusjärgu, aga mitte ontoloogilise staatuse poolest*. (DeLanda 2019: 79)

Moduleeritud modulaarsus on meetod, kus hierarhiate kokkukukkumist kasutatakse ära arhitektuurse kompositsiooni loomisel ning kus osa ja tervik eksisteerivad vastastikmõjus. Emergentsus muutub selles meetodis justkui otsingumootoriks. Emergentsed kvaliteedid tekivad topoloogia ja tektoonika ühendamisest. Greg Lynn, üks esimesi digitaalse arhitektuuri defineerijaid andis 1993. aastal välja AD erinumbri „Folding in Architecture“ (Lynn 2004), viidates Gilles Deleuze'i *le pli*-le (Deleuze 1993), mille õige tõlge oleks, lähtudes Deleuze'i varasematest tõlgetest, „kurdumine“ või „kurrutamine“ arhitektuuris, kuigi tegusõnana on „voltimine“ lihtsamini kasutatav. Kurdumises räägib Lynn peenekoelisusest (*intricacy*), kus kõverad pinnad külvatakse üle (*populate*) adaptiivsete komponentidega, luues infinitesimaalset variatsiooni. Moduleerimisel on see adaptsioon rangelt reguleeritud, mis loob elementide ja vormi vahel vastastikmõju, kus variatsioon muutub muutujaks. Usun, et kurdumise lepitamine modulaarsusega moduleerimise kaudu on viis, kuidas säilitada arhitektuuri autonoomia maailma lävel, kus domineerib automatiseerimine ja masinad on õppimisvõimelised. Selleks välja töötatud meetod on moduleeritud modulaarsus.

Struktuur

Selles uurimuses on selgelt eristatavad kolm staadiumi, mis katsetavad selgelt eristatavaid teoreetilisi lähenemisi ja mis väljenduvad selgelt eristatavas arhitektuurikeeles. Väitekiri on struktureeritud nende kolme teema ümber:

1. Variatsioon – varajane digitaalne arhitektuur, mida iseloomustab kurvilisus, variatsioon ja masskohandamine. Arvuti võimaldab enneolematut kontrolli autori loomingus – infinitesimaalarvutusel põhinev terviku elegantne manipuleerimine võimaldab luua komplekssust ja lõputul hulgal erikujulisi detaile. Neid ideid on testitud meie esimestes projektides: installatsioonid „Keha ehitus", „HeliLained" ja „Rheoloogiline formatsioon".

2. Korduvus – süsteemi ehitus, modulaarsete süsteemide generatiivsed meetodid, mida iseloomustavad emergentsus, komplekssus ja iseorganiseerumine. Loomeprotsess muutub kureerimiseks ja otsimiseks – osade geomeetrilised ja käitumuslikud reeglid genereerivad kompleksse terviku. Neid ideid on testitud modulaarsetes installatsioonides ja rajatistes, mida ma nimetan „Digitihniku" seeriaks: „Digitihnik", „Siin ja mujal", „Linnadžungel".

3. Modulatsioon – arvutuslik brutalism, püüe lepitada kurdumist ja modulaarsust ning mõtestada ümber digitaalne arhitektuur, lähtudes ruumistruktuuri moduleerimisest. Moduleerimine kaotab hierarhia osa ja terviku vahel ning muudab selle horisontaalseks protsessiks, kus lokaalne ja globaalne on samaaegselt loodud ja analüüsitud, võimaldamaks paralleelset kvantitatiivset ja kvalitatiivset optimeerimist.

Neid kolme etappi markeerivad kolm pöördelise tähtsusega projekti. Neist esimene, „Keha ehitus", oli meie esimene puitinstallatsioon PARTina. See rajatis sai toodetud puitmajatehases, ilma igasuguse eelneva kogemuseta selles kontekstis. Kuigi vormikeelelt on see lähenemine kõrvale jäetud, on selles projektis palju osiseid, mis on teistesse projektidesse edasi kandunud, nagu adaptiivsed sõlmed, arvestamine tolerantsidega, disainimine objektidega ja nii edasi. 1990. aastate visioon masskohandamisest tööstuses ei ole ennast tõestanud, kuid algoritmilised printsiibid ja topoloogiline mõtlemine on endiselt ülimalt relevantsed. Mitmuslisuse idee on üks modulatsiooni keskseid printsiipe: arvutuslik geomeetria ei ole staatiline ega fikseeritud, vaid sama loogika, mis ühes olukorras võib luua kera või kuubi, võib teistel tingimustel tekitada amorfse *blob*-i.

Eesmärgiks on neid suhteid moduleerides saavutada toimivaid lahendusi. Digitihnik sai sellisel printsiibil loodud. Ühendades generatiivsed algoritmid juhitavate muutujatega, on võimalik süsteemi tundma õppida ja leida selles korrapära. Lähtudes ideest, et võimaluste väljadel on tihti mitu optimumi ja et ei eksisteeri ainult üks parim lahendus, viis moduleeritud modulaarsuseni. Variatsiooni ja korduvuse ühendamine ühtseks dünaamiliseks geomeetriliseks süsteemiks võimaldab luua loogilisi üleminekuid erinevate modulaarsete süsteemide ja erikujuliste osade vahel. See idee sai esmakordselt testitud kortermaja projektis „Shift lofts".

Selle uurimuse fookuses on ruumistruktuuri tingivate asjaolude automatiseerimine disainitööriistaks. Järelratsionaliseerimine on alati tegeliku kavandi ligikaudne realiseerimine. Moduleeritud modulaarsus estetiseerib seda lahknevust ideaalse ja tegeliku või idee ja mudeli vahel. Üritades lepitada heterogeensust ja standardiseeritust, peame määrama skaala, kus need kohtuvad. Algoritmilise konstruktsiooni arvutuse ja evolutsioonilise optimeerimise lisamine loob võimalike arhitektuuride välja, mille määratleb nüüdisaegse ehituse reaalsuste mudel. Minu jaoks on digitaalsuse võimsaimad tööriistad algoritmiline simulatsioon (generatiivsete algoritmide kasutamine selleks, et genereerida komplekssüsteemide võimalikke tulemusi), analüüs (tulemuste hindamine lähtuvalt sisenditest ja väljunditest) ning optimeerimine (võimaluste välja kaardistamine, et leida sobivaid lahendusi). Modulatsioon mitte ainult ei lepita variatsiooni ja korduvust (kurdumist ja modulaarsust), vaid ka emergentsust ja ekspressiivsust, kirjutades arhitektuuri kui kultuuripraktika sellise tehnilise valdkonna nagu ehituse aluskoodi.

Kokkuvõte

Digitaalse tehnoloogia võidukäiguga 30 aastat tagasi ja seeläbi individuaalse vabanemise lubadusega näis, et täielikult demokraatlik individualiseeritud ühiskond on iga hetk tärkamas. Mõned kümnendid hiljem näeme, kuidas suurandmed muudavad meid etteaimatavaks ja manipuleeritavaks ning loovad veel suuremaid võimuhierarhiaid. Eriti tugevalt tõi selle välja Cambridge Analytica skandaal. Jah, me oleme individualistlikumad kui eales varem, kuid me oleme ka võrgustunumad kui eales varem ehk statistiliselt oleme klassifitseeritavad andmekogud masinõppealgoritmidele. Kas seda arvesse võttes on digitaalsus tõesti lõputu variatsiooni võimaldaja, nagu digitaalsete arhitektide esimene generatsioon välja pakkus, või on pigem tegu vastastikmõjulise standardiseerimise süsteemiga?

Kuidas digitaalsuses variatsiooni luuakse? Digitaalne värviprinter suudab tõesti toota lõputut variatsiooni, aga teeb seda range standardiseerimise kaudu, asetades kolme standardiseeritud tooni punkte õigetes kohtades õiges koguses paberile, moduleerides nende vahekorda. Sama on digitaalse ekraaniga: kolme värvi pikslid süttivad õigete intensiivsustega. Seda ideed on kasutatud ka fassaadide disainimisel, kusjuures edukamates versioonides on piksel ise arhitektuurse disaini osa.

Pikseliseerimine või pigem vokseliseerimine võimaldab vormi automaatset modulariseerimist.

Tekib küsimus, mis oleks hea voksel arhitektuuris, arhitektuuri baaselement? Siin tulevad mängu vastandlikud eesmärgid: efektiivsus ja paindlikkus. Antud olukorras oleks täpsem öelda resolutsioon. Madalam resolutsioon tähendab vähem elemente, aga ka vähem võimalusi ruumiliseks artikulatsiooniks. Kui vaadata, kuidas ehituselemente ja -mooduleid enamasti kavandatakse, on ilmne, et neid optimeeritakse logistikast lähtuvalt. Siin on parameetriteks tootmisliini võimekus, transport ja kandevõime, mitte arhitektuurne väljendus. Kohandatud masstootmine võimaldab mõningaid nendest parameetritest küsimärgi alla seada ja nii saavutada suurem vabadus artikulatsioonis. „[Alan] Turing täheldas, et looduses pole miski tõeliselt digitaalne; kõikjal on pidev variatsioon; disaini suursaavutus on luua selliseid seadmeid, mis käsitlevad kõiki signaale digitaalsetena, konkreetsete instantside iseärasuste kopeerimise asemel loobuvad neist“ (Dennett 2017: 200). Üks selle uurimuse leide on, et ehitusinformatsioonis kehtib sama printsiip: ehituselementide digitaliseerimine võimaldab projekti realiseerimisel vältida tõlkevigu.

Digitaalsus oma algses tähenduses on jätkuvuse vastand. Arhitektuuri digiteerimine tähendaks selle elementaarosakeste defineerimist ja arvutuslikeks objektideks jaotamist. 18. sajandil Durand just seda teebki, ajavaimus. Lähtudes analüütilisest meetodist, jaotab ta arhitektuuri elementideks nende teaduslikus tähenduses – produktiivsed algosakesed (Picon 2000: 21). Ta loob diskreetse kompositsiooni meetodi, kasutades selleks korrapärast teljestikku ehk rastrit ja standardiseeritud arhitektuurseid elemente. Rohkem kui sajand hiljem loovad arhitektid standardiseeritud masstoodetavaid elemente ja nendest koosnevaid ehitussüsteeme. General Panel System, mille töötas välja Konrad Wachsmann koos Walter Gropiusega 1940. aastatel, oli üks lähedasemaid süsteeme arhitektuuri digiteerimisele. Wachsmann pööras nimelt suurt tähelepanu ühendussõlmele, mis võimaldaks luua perfektselt sümmeetrilist ja universaalset süsteemi.

Samal ajal vabastas ruumsõrestik arhitektuursed eksperimendid ortogonaalsest geomeetriast ja näiliselt ka gravitatsioonist. 20. sajandi keskpaiga utopistlikud arhitektid arendasid evolutsioonilisi ruumilisi linnu – iseorganiseeruvaid ruumilisi konstruktsioone. Schulze-Fielitzi jaoks põhinesid need ruumistruktuuril, mis on moduleerimisvõimeline makromaterjal. Ruumistruktuur, või ka reaalne, mida kasutab Picon, võimaldab moduleerimise kaudu organiseerida arhitektuurset ruumi linnast mikroskaalani. Ruumistruktuuri väljendus annab moduleeritud modulaarsusele ornamentse mõõtme ja on seeläbi seotud tähenduse loomisega arhitektuuris. Tähendus on subjektiivse, reaalse ja neist esilekerkiva teisesuse hübriidagentsuse moduleerimise tulemus. Reaalsuse alusstruktuuri väljendus, mis subjektiivse modulatsiooni kaudu kerkib tervikus esile, ühendab subjektiivse ja poliitilise ning teeb sellest osa kultuuriloomest. Ma usun, et see süstemaatiline väljenduse järjepidevus loob banhamliku meeldejääva pildi. Lisades siia materjalitruuduse ja struktuuri kui osade suhete selge väljenduse, annab piisava põhjenduse, et nimetada seda arvutuslikuks brutalismiks.

Automatiseeritud tootmine on täna sõltuv korduvusest. Lihtne on pea ükskõik kui keerulist elementi toota hulgi. Unikaalsete elementide tootmine on endiselt ebaefektiivne ja seotud kõrge ebaõnnestumisriskiga. Rääkimata sellest, et jäägivabaks tootmiseks on keerukate unikaalsete detailide puhul ainus võimalus 3D-printimine, kus õnnestumisprotsent on kõige madalam. PARTiga loodud projektide käigus õpitust ja tööstuses töötavate inseneridega suhtlemisest on selgunud, et suurte ebastandardsete projektide korral on endiselt kõige õigem lahendus lähtuda standardmaterjalidest ja eemaldavatest tootmisviisidest ehk lõikamisest ja freesimisest, mis ühtlasi tähendab, et materjalijääkidega tuleb arvestada ja neid minimeerida.

Neid praktilisi piiranguid võib näha kui moduleeritud modulaarsuse tingivaid asjaolusid. Neist lähtudes olen loonud kordusel põhineva ruumistruktuuri moduleerimise ehk ruumilise organiseerimise ja alajaotamise algoritmi, millest tekkivaid elemente saab matejalikasutuse põhjal hinnata. Lisades sellele konstruktsiooni analüüsi ja optimeerimise, saab hinnata ja otsustada elementide materiaalsust ja paiknemist selles ruumirastris. Kõik need osised loovad mudeli ruumistruktuurist, milles vormi on võimalik moduleerida. Schulzefielitzliku modulatsiooni mõiste toomine algoritmilisse arhitektuursesse kavandamisse tekitab uue kihistuse selles protsessis. Ruumistruktuuri ei moduleeri mitte ainult reaalsed vormivad jõud ja materiaalsus, vaid ka loodud algoritmiline mudel, mis nende suhteid korraldab ja kus objektiivne ja subjektiivne saavad moduleeritud. Modulatsioon ei ole seega iseorganiseeruv süsteem, vaid loodud kord, milles esineb iseorganiseerivust.

Dünaamiliste geomeetriliste süsteemide manipuleerimine on sarnane simulatsiooniga. Simulatsiooni kaudu saame tunnetuse simuleeritavast. Koormates virtuaalset konstruktsioonimudelit jõuvektoritega, näeme, kuidas see deformeerub ja tekib tunnetus sellest, kuidas konstruktsioon käitub. See võib olla põhjus, miks inimesed vaatavad Instagramis seebilõikamise videoid või kasutavad rakendusi, mis võimaldavad ekraanil manipuleerida digitaalset lima. Midagi sarnast juhtub dünaamilise geomeetriaga, kus tekib geomeetria käitumise tunnetus, olgugi et materiaalsusega pole seal mingit pistmist – tegu on formaalsusega. Loodud meetodi arhitektuurne kvaliteet ei seisne mitte selle tootmisest ja ehitusest tulenevate piirangute integreerimisest johtuvas efektiivsuses, vaid just selles käitumuslikus süsteemis, millel on teatav emergentne formaalsus.

Vastandlike eesmärkide lepitamisel tekivad algoritmilistes protsessides kõige huvitavamad tulemused – teisesuse esilekerkimine. DeLanda järgi „saab virtuaalne olemasolu ilmsiks olukordades, kus intensiivsed erinevused ei kustu“ (DeLanda 2019, 105). Virtuaalse olemasolu ilmsikstoomine on algoritmilise disaini peamisi võlusid. Oma projektides kasutame modulatsiooni meetodit selleks, et tuua esile loodud virtuaalse mudeli omadusi – avastame ruumistruktuuri ja formatiivsete jõudude vastastikmõjus esile kerkivaid kvaliteete.

Modulatsioon on algselt seotud muusikaga ja nii tõstatub ka siin rütmi ja proportsiooni temaatika ehk inimkeha suhe arhitektuuri. See on omakorda üks põhjendusi digitaalse arhitektuuri pöördumiseks infinitesimaalarvutusepõhisest jätkuvusest andmepõhise granulaarsuse suunas. Modernset arhitektuuri on tihti inimmõõtme puudumise pärast kritiseeritud. Diskreetse tektoonika uut tulemist, mis võib olla seotud ehituse automatiseerimisega (Picon 2010: 166), võib pidada ka inimskaala naasmiseks. Nagu eespool mainitud, on arusaam kehast digitehnoloogia arenguga muutunud: täiuslikust autonoomsest organismist on saanud avatud süsteem, mille toimimist mõistame usutavalt vaid läbi arvutuslike mudelite (McEwen 2002, Monteiro 2011).

Rütm on meid ümbritseva diskretiseerimine ajas ja ruumis. Samuti nagu diskretiseerime helisid, mille jaotame foneemideks, et eraldada mürast signaal (Dennett 2017: 199), jagame end ümbritsevat võrreldavateks osadeks, et seda mõista ja seda edasi anda. Proportsioon ja rütm on seega vahendid, mille kaudu suhestuda keskkonnaga. Rääkimata sellest, et ääretuvastus (*edge detection*) on masinnägemise alus. Eristus on vajalik! Rütm, diskreetsete elementide kordus ruumis ja ajas, on ka Max Bense generatiivse esteetika alus. Generatiivne esteetika on seotud „‘korrapäraste seadete’ tekkimisega, mis koosnevad topoloogilisest ‘vormist’ ja statistilisest ‘jaotusest’“ (Bense 1965: 5, autori tõlge). Nüüd kui masinõppimine on reaalsus, on statistika roll otsuste tegemisel tohutult kasvanud (inimene pildil 97,8% tõenäosusega naeratab või objekt on 87,2% vihmavari), kuid masinintellekti ja arvutusliku automatiseerimise esteetika leiutasid varajased arvutusliku kunsti viljelejad.

> *Kuna esteetilised struktuurid sisaldavad ‘esteetilist informatsiooni’ vaid siis, kui neis ilmneb uuendusi ja need muidugi kujutavad kõigest tõenäolist, mitte kindlat reaalsust, siis võib öelda, et normist erinevate tõenäosuste kunstlik produktsioon teoreemide ja programmide abil on generatiivse esteetika ja selle projektide keskne eesmärk.*[12] (Bense 1965: 2, autori tõlge)

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[12] *Da nun ästhetische Strukturen nur insofern “ästhetische Information” enthalten, als sie Innovationen aufweisen und diese natürlich stets nur eine wahrscheinliche, keine definitive Wirklichkeit darstellen, kann man sagen, dass die künstliche Erzeugung von einer Norm abweichender Wahrscheinlichkeiten durch Theoreme und Programme das zentrale Motiv der generativen Ästhetik und ihrer Projekte ist.*

Innovatsioon, ootamatu uuendus, loob esteetilist informatsiooni vaid siis, kui see on endiselt tõenäoline ehk mõistetav. Generatiivne esteetika põhineb teisesuse esilekerkimisel, mida loob „planeerimise ja juhuse metoodiline kombinatsioon“ (Bense 1965: 7).

Algoritmilised reguleerivad jooned toimivad teisiti kui need, mida on kasutatud klassikaliste ja modernistlike fassaadide konstrueerimiseks. Perioodilised ruumijaotused (ruumiraster) väljendavad seda, kuidas n-ö disainimaht (näiteks planeeringust tulenev mahuline piir) sellega suhestub. Nii nagu samakõrgusjooned topograafilistel kaartidel väljendavad muutusi reljeefis, rõhutab ruumistruktuurist tulenev modulatsioon vormi alusgeomeetriat või virtuaalset välja läbi nihke – lamedal pinnal pole samakõrgusjooni. Modulatsioon artikuleerib selle aluseks olnud tingivaid asjaolusid ja jõudusid – mustreid, mida on võimalik lugeda kui tõenäolise reaalsuse moduleeritud väljendust.

Kasutades algoritmilisi tööriistu, oleme sunnitud olema palju täpsemad paika seatud reguleerivate joonte järgimisel. Saame paika seada lihtsad algoritmid ehk reeglikogumid, mis omakorda panevad paika suhted erinevate osade vahel ja seeläbi valitsevad ruumistruktuuri. Kuid me saame nendesse reeglikogumitesse sisestada ka muutujaid, parameetreid, mida on võimalik vajadusel kohandada, hinnates süsteemi kvantitatiivseid ja kvalitatiivseid omadusi. Tekib võimalus sellesse automatiseeritud protsessi subjektiivselt sekkuda – tekib dialoog subjekti ja emergentse teise vahel. Nii on võimalik modulatsiooni tulemust, selle väljendust kontrollile allutada. Näiteks on võimalik muuta elementide resolutsiooni, suunda, nende eksisteerimise tõenäosust – luua modulatsioonis erinevaid intensiivsusi ning kureerida ruumikogemust ja inimkeha suhet objekti skaala, proportsiooni, rütmi, formaalsuse ja materiaalsuse kaudu.

Modulatsioon võimaldab säilitada arhitektuuridistsipliini autonoomia, luues meetodi, mis on kooskõlas nüüdisaegse teadusliku ja tehnoloogilise ratsionaalsusega, õõnestades selle ülemvõimu, nii nagu Laibach tegi seda kommunistliku režiimiga, võttes valitsevat ideoloogiat tõsisemalt, kui see võtab iseend, kuna „üleastumine on alati süsteemi osa“ (Žižek 1996). Jutt on siin sotsiaalsetest süsteemidest. Algoritmilised süsteemid transgressiooni ei luba, kui see ei ole just eksplitsiitselt sisse kirjutatud, nullides mässulise akti. Minu jaoks lähtub siit võimalus vabamänguks süsteemisiseselt, seades küsimärgi alla kehtivad tavad neid automatiseerides. Automatiseerimisest ja animeerimisest kerkivad esile uued mustrid ja tunnetus. Nagu teame kaoseteooriast, võib väikestel, näiliselt ebaolulistel muutustel olla tohutu mõju tulemuse kujunemisele. See aga tähendab, et arhitektuuri pole vaja peale suruda, selle saab sisse kodeerida.

Moduleeritud modulaarsus on disainimeetod, mis põhineb modulatsioonil. Modulatsiooni tuvastamine ja defineerimine digitaalse arhitektuuri alusprintsiibina automatiseerimise ja masinõppimise ajastul on minu arvates selles väitekirjas üks peamisi leide ja panuseid teadmisse.

Glossary of terms

algorithmic – using a computational procedure, based on a series of instructions.

automation – the removal of human action from a process. Quasi-automation is understood as a process, mainly in assembly, where a fool-proof logic removes the possibility of human error.

blob – an indeterminate roundish mass or shape. Blobs are described by Greg Lynn: blobs possess the ability to move through space as if space were aqueous; blobs can absorb objects as if they were liquified: the term blob connotes a thing which is neither singular nor multiple but an intelligence that behaves as if it were singular and networked but in its form can become virtually infinitely multiplied and distributed (Lynn 1996: 59).

complexity – the state or quality of being intricate or complicated. Complexity characterises the behaviour of a system or model whose components interact in multiple ways and follow local rules, meaning there is no reasonable higher instruction to define the various possible interactions (Wikipedia. https://en.wikipedia.org/wiki/Complexity accessed 4 June 2020).

computational brutalism – architectural movement. Derived from Reyner Banham's new brutalism, computational brutalism is characterised by a ruthless computational logic in composition, aformality, endless patchworks of structure, a coherent characteristic of unfinishedness, "valuation of materials 'as found'": be it timber in all its raw and industrial forms, or more often the Rhino default shader. The expression of this architecture is derived from the "clear exhibition of structure" where "structure, in its fullest sense, is the relationship of parts" . There is nothing but structure. And of course, as with the Instagram generation, they are most concerned with "memorability as an image" (Banham 1955: 361).

conditioning circumstances – the forces shaping the spatial structure or the *Raumstruktur*.

custom mass production – a means of production, where CNC technology is used to serially produce customised products in large quantities, similar to producing custom product packaging.

design space – the space of possible designs, characterised by the modulated spatial structure, meaning the space where the modulated conditioning circumstances govern what can be designed.

digital architecture – the architecture part of the critical discourse on the digital in architecture that emerged with the wider spread of personal computers and digital culture at the beginning of the 1990s.

element – the lowest level productive part. In modulation, it is the elementary particle of the modulated spatial structure. These elements are abstract particles that can be joined into larger parts.

emergence – emergence occurs when an entity is observed to have properties its parts do not have on their own (Wikipedia. https://en.wikipedia.org/wiki/Emergence accessed 4 June 2020). Emergence can occur in both natural and social processes. Emergence of unpredictable patterns from complex systems is connected to the notion of otherness or the other.

folding – "For me, it is calculus that was the subject of Folding in Architecture and it is the discovery and implementation of calculus by architects that continues to drive the field in terms of formal and constructed complexity. The loss of the module in favour of the infinitesimal component and the displacement of the fragmentary collage by the intensive whole are the legacy of the introduction of calculus" (Lynn 2004: 11).

formality – manipulating dynamic geometric systems, we get a feel for the digital materiality, or rather formality, of the system. Using a constrained design space or *Raumstruktur* formality is what describes this space. If materiality is about the way we perceive materials and have assumptions about their qualities, formality is about how we perceive and understand form. There is an emergent formality in designing within the constrained *Raumstruktur*.

mass customisation – in architecture, refers to the idea that in digital fabrication every part can be unique, at no extra cost. This does not take into account industrial digital fabrication, where economies of scale still apply.

modularity – the quality of having replaceable elements. In computation, modular programming refers to pieces of code being modular – blocks of code that fulfil a specific task and can be reused. Physical modularity refers to the use of repetitive parts, with standardised interfaces.

modulation (n.) – late 14c., *modulacioun*, "act of singing or making music, harmony," from Old French *modulation* "act of making music" (14c.) and directly from the Latin *modulationem* (nominative *modulatio*) "rhythmical measure, singing and playing, melody," noun of action from past-participle stem of *modulari* "regulate, measure off properly, measure rhythmically; play, play upon," from *modulus* "small measure," diminutive of *modus* "measure, manner" (from PIE root *med- "take appropriate measures"). Meaning from the 1530s "act of regulating according to measure or proportion"; by the 1690s becomes the musical sense of "action or process of changing from one key to another". (Online Etymology Dictionary. – modulation (n.))

other – or the notion of otherness is evoked through the emergent patterns of complex natural and non-natural systems.

real – the underlying structure "that enables reality to unfold, or as a virtuality that triggers the unfolding of reality" (Picon 2010: 212). See *Raumstruktur*.

Raumstruktur – the way in which space is organised through natural and/or social processes. As the material substrate of these processes, the spatial structure provides information about past and present natural laws and/or economic, social and political patterns of action. It also represents one of the conditions under which economic and social action takes place. (Gabler Wirtschaftslexikon: *Raumstruktur*)

resolution – element density. See *element*.

spatial structure – see *Raumstruktur.*

Figures

Fig. 1. Body Building exhibition, Tallinn Architecture Biennale 2015, PART Architects. Photo by Tõnu Tunnel.

Fig. 2. Body Building installation, Tallinn Architecture Biennale 2015, PART Architects. Photo by Tõnu Tunnel.

Fig. 3. Surface panelisation, example by the author.

Fig. 4. Resolution in PART projects ranging from step to floor height.

Fig. 5. The Modulated Man by the author.

Fig. 6. Geometry samples from the Body Building installation and the Digital Thicket structure by PART Architects and the modulated modularity algorithm for generating linear elements following a base geometry by the author.

Fig. 7. Beijing Daxing International Airport 2019, Zaha Hadid Architects. Photo/Map: Arne Müseler / arne-mueseler.com / CC-BY-SA-3.0 / https://creativecommons.org/licenses/by-sa/3.0/de/deed.de, https://commons.wikimedia.org/wiki/File:Beijing_Daxing_International_Airport_12.jpg (accessed 11 June 2020).

Fig. 8. Complex Timber Structures 2013, Gramazio Kohler Research, ETH Zurich. Photo: Gramazio Kohler Research, ETH Zurich. https://commons.wikimedia.org/wiki/File:Complex_Timber_Structures_(Gramazio_Kohler_Research,_ETH_Zurich).jpg (accessed 11 June 2020).

Fig. 9. ICD/ITKE Research Pavilion 2011, University of Stuttgart. © MSeses / Wikimedia Commons / CC BY-SA 4.0. https://commons.wikimedia.org/wiki/File:ICD_Research_Pavilion_2011_Stuttgart_01.jpg (accessed 11 June 2020).

Fig. 10. Modulation of an undulating surface in two different resolutions, diagram by the author.

Fig. 11. The milestone projects, from left to right: the Body Building installation, Urban Jungle vertical garden and Shift Lofts timber apartment building. © PART.

Fig. 12. Transformations in computational geometry. A sphere is a blob, a square and a hexagon are both Voronoi cells. Diagram by the author.

Fig. 13. Digital Thicket, early sketch. The parametric model was used as a search engine to find the final cellular lattice structure geometry. © PART.

Fig. 14. Rheological Formation 2017. The smooth surface is populated with adaptive timber frames using a simple technique called contouring. Each contour is then the base for the timber frame to adapt to. © PART.

Fig. 15. The San Carlo alle Quattro Fontane church by Francesco Borromini is known for its rigorous geometric construction. Photo and drawing by the author.

Fig. 16. SwarmRelief prototype by Roland Snooks at the TAB 2015 Body Building exhibition. Photo by Tõnu Tunnel (edited).

Fig. 17. Body Building installation 2015. All the pieces are unique, robotically machined with three types of algorithmically generated half lap joints. Photo by Tõnu Tunnel.

Fig. 18. Aluminium facade panelisation of the Galaxy Soho (completed 2012) by Zaha Hadid Architects. Photo by Forgemind ArchiMedia. https://www.flickr.com/photos/eager/10788941144/in/photostream/ (accessed 14 June 2020).

Fig. 19. FrAgile 2: Porous Cast at the Body Building exhibition 2015 by REX|Lab, Marjan Colletti and Kadri Tamre. Photo by Tõnu Tunnel (edited).

Fig. 20. The Body Building installation, while exhibiting the expressive range of contemporary timber structures, becomes an urban ornament – being simultaneously a way-finding device, pointing at the three main venues of TAB 2015 and a pergola. Photo by Tõnu Tunnel.

Fig. 21. A regular heat gun used as an end of arm tool for the sPhysical project. Team: Erin Besler, Eugen Kosgoron, Siim Tuksam and Peter Vikar. 2011 winter term in Studio Testa, Sci-Arc, Los Angeles.

Fig. 22. sPhysical 2011. The project subsists on the translational discrepancies that arise during the interplay between an excessively controlled but exceedingly irresolute digital environment and its materialisation into the reality of physical space. sPhysical seeks the epitome of synthesising digital tools with physical expression by re-conceptualising material design processes and applications in the field of architecture. The problem of materialisation exists as the limitation of digital control and resolution. Matter and form are subjugated through a logic of rigging, a concept derived from and informed by robotic motion-control, and embedded with a certain propensity and agency. A design methodology, one that realises the potential of designed properties, will be achieved through the conceptualisation of rigging matter and form. Team: Erin Besler, Eugen Kosgoron, Siim Tuksam and Peter Vikar. 2011 winter term in Studio Testa, Sci-Arc, Los Angeles.

Fig. 23. Structural Oscillations 2008 by Gramazio Kohler Research, ETH Zurich. https://commons.wikimedia.org/wiki/File:Structural_Oscillations_(Gramazio_Kohler_Research,_ETH_ Zurich).jpg (accessed 14 June 2020).

Fig. 24. Digital Thicket 2017, assembled by volunteers. Photo by Tõnu Tunnel.

Fig. 25. Bog Fox 2016–2020, high voltage power line design pylon. Using Karamba3D, in collaboration with Bollinger+Grohmann, we set up structural and geometric checks to be able to run a genetic algorithm for material weight minimisation. Manual adjustments were made afterwards to balance additional weight versus aesthetic preferences. © PART, photo by Tõnu Tunnel.

Fig. 26. Body Building installation, Tallinn Architecture Biennale 2015. Photo by Tõnu Tunnel.

Fig. 27. Body Building installation 2015: a – magnetic field simulation for formal control, b – linear segmentation of the main axes, c – initial Karamba3D analysis, d – geometrically and structurally optimised main axes, e – added cross bracing, secondary axes, f – Karamba3D analysis after optimisation, g – element orientation optimisation for equal transition angles along main axes, h and i – as internal corners were not possible to be milled, cuts had to go through, creating the need to choose which direction to cut away to minimise cut-away material based on the angle between the axes of two consecutive elements along the main axes, j – main axes elements, k – added horizontal 'belt', l – added secondary elements. © PART.

Fig. 28. Body Building installation 2015 construction process. Photo by Tõnu Tunnel.

Fig. 29. Body Building installation 2015 close up – "homogeneity at a distance and near formal incoherence in detail" (Lynn 2004: 11) – the machined elements fit perfectly at seemingly random angles. Photo by Tõnu Tunnel.

Fig. 30. The drawings of the Body Building installation 2015 were generated for purely documentation purposes. Fabrication files were generated directly from the 3D model, which was also used as a guide for assembly. © PART.

Fig. 31. SoundWave I. 2016 Tallinn Music Week City Stage at Musumägi, in collaboration with 2nd year students from the Interior Architecture department at the Estonian Academy of Arts. Team: Mariann Drell, Ardo Hiiuväin, Lennart Lind, Henri Kaarel Luht, Andrea Miku, Mariette Nõmm, Johanna Sepp, Kertti Soots, Sabine Suuster, Teele Tomson, Birgit Õigus. Photo by Tõnu Tunnel.

Fig. 32. SoundWave II. 2016 Tallinn Music Week City Stage at Musumägi, in collaboration with 2nd year students from the Interior Architecture department at the Estonian Academy of Arts. Team: Mariann Drell, Ardo Hiiuväin, Lennart Lind, Henri Kaarel Luht, Andrea Miku, Mariette Nõmm, Johanna Sepp, Kertti Soots, Sabine Suuster, Teele Tomson, Birgit Õigus. Photo by Tõnu Tunnel.

Fig. 33. SoundWave III. 2016 Tallinn Music Week City Stage at Musumägi, in collaboration with 2nd year students from the Interior Architecture department at the Estonian Academy of Arts. Team: Mariann Drell, Ardo Hiiuväin, Lennart Lind, Henri Kaarel Luht, Andrea Miku, Mariette Nõmm, Johanna Sepp, Kertti Soots, Sabine Suuster, Teele Tomson, Birgit Õigus. Photo by Tõnu Tunnel.

Fig. 34. Rheological Formation 2017. Installation by PART Architects for the Into the Valley music festival. Photo by Tõnu Tunnel.

Fig. 35. Body Building installation 2015. The magnetic field lines are evaluated at 19 points and divided into 6 segments. Diagram by the author.

Fig. 36. Digital Thicket 2017 by PART Architects. Photo by Tõnu Tunnel.

Fig. 37. Delaunay triangulation and Voronoi diagram. Example by the author.

Fig. 38. Approximating the equidistant curve of the boundary – the topological skeleton – using the Voronoi diagram, example by the author.

Fig. 39. Approximating the equidistant surface of two helical curves, using the Voronoi diagram, resulting in planar facets, example by the author.

Fig. 40. Digital Thicket 2017. The Y-element consist of three robotically milled timber parts. © PART.

Fig. 41. The Octetruss. Buckminster Fuller was granted the patent for his synergetic building construction truss system in 1961. United States patent US2986241A. https://patents.google.com/patent/US2986241?oq=octet+truss (accessed 16 June 2020).

Fig. 42. Digital Thicket 2017. Aggregation studies at different angles. The model works like a geometric search engine – at the tetrahedral angle of about 70.52° the aggregation turns into a regular cellular structure. © PART.

Fig. 43. A triangular lattice with 71 edges and 37 vertices; it is generically rigid. (Ostoja-Starzewski 2002: 52).

Fig. 44. Digital Thicket series geometric study 2018. © PART.

Fig. 45. Digital Thicket 2017, chunk drawing. © PART.

Fig. 46. Digital Thicket 2017 by PART Architects. Photo by Tõnu Tunnel.

Fig. 47. Here and Elsewhere 2017 by PART Architects and LASSA Architects, assembly drawing. © PART.

Fig. 48. Here and Elsewhere 2017 by PART Architects and LASSA Architects at Tallinn Architecture Biennale. Photo by Henri-Kristian Kirsip.

Fig. 49. Here and Elsewhere 2017 by PART Architects and LASSA Architects in Bozar, Brussels at the BEL:EST exhibition. Photo by Yannick Sas.

Fig. 50. Here and Elsewhere 2017 by PART Architects and LASSA Architects, transport drawing. © PART.

Fig. 51. PART.icular – Bespoke Timber Architecture. PART's exhibit at Time Space Existence at Palazzo Bembo, part of Venice Architecture Biennale 2018. Photo by Tõnu Tunnel.

Fig. 52. PART.icular 2018, 3D printed details allow for free rotation, yet the structure finds its equilibrium in the Digital Thicket geometry. Photo by Tõnu Tunnel.

Fig. 53. PART.icular 2018, printed paper infills. Photo by Tõnu Tunnel.

Fig. 54. PART.icular 2018, kit of parts. Photo by author.

Fig. 55. Urban Jungle 2018 by PART Architects in collaboration with KINO Landscape architects at the T1 Mall of Tallinn. Photo by Tõnu Tunnel (edited).

Fig. 56. Urban Jungle 2018, visualisation of varying profile thickness. © PART.

Fig. 57. Urban Jungle 2018, the "missing" element. © PART, photo by Tõnu Tunnel.

Fig. 58. Urban Jungle 2018, plywood landscape, subdivisions of truncated octahedrons. Photo by Tõnu Tunnel (edited).

Fig. 59. Truncated octahedra can be produced using the Voronoi diagram on the nodes of both the cubic and the tetrahedral-octahedral honeycomb with centroids also known as the body-centred cubic Bravais lattice. Diagram by the author.

Fig. 60. Urban Jungle 2018, basic geometry. The lattice is oriented on the face of the tetrahedron, resulting in a triangular plan grid and the best structural performance of the Digital Thicket geometry. Diagram by the author.

Fig. 61. Urban Jungle 2018, the overall massing is created using force field modelling and an isosurface boundary. Diagram by the author.

Fig. 62. Urban Jungle 2018, the subdivision geometry on the plinth was an inspiration for the core modulation algorithm used in later projects.

Fig. 63. Modulation of the Stanford bunny. The boundary volume is populated with random points, the coordinates averaged by an integer factor, which results in a random selection of a cubic lattice nodes. This random selection of a regular lattice nodes produces a random aggregation of regular cells.

Fig. 64. Urban Jungle 2018, the Y-element and the L-element. © PART.

Fig. 65. Urban Jungle 2018, assembled chunk. © PART.

Fig. 66. Urban Jungle 2018, test assembly in the steel factory. Photo by the author.

Fig. 67. Urban Jungle 2018, the modules of the design algorithm: spatial structure, with variables for orientation and scale; form generation; selection and combinatorics; evaluation; detailing; and data extraction. Diagram by the author.

Fig. 68. Son of a Shingle 2017. Rendering of the winning competition entry by PART Architects. © PART.

Fig. 69. Son of a Shingle project 2017, drawing of shingles and substructure. © PART.

Fig. 70. Discrete gradient for the Son of a Shingle project 2017. © PART.

Fig. 71. Nested spaces – the undulating surface warps space, sampled in a 10x10 grid. Diagram by the author.

Fig. 72. Moulding vs. modulation – crumpling polygons instead of paper. Diagram by the author.

Fig. 73. Raumstruktur. The spatial grid limits the surface panelisation to a very limited number of elements. Diagram by the author.

Fig. 74. TeasEar advertisement on Instagram promising "multiple brain orgasms with every screen touch". https://i.redd.it/b21tzk0obm141.jpg (accessed 17 June 2020).

Fig. 75. The Cloud carpark 2019, competition entry, honourable mention, by PART Architects. © PART.

Fig. 76. Shift Lofts 2019 by PART Architects. The building is organised in a tetrahedral grid, starting from the spiral stair and helical floor plates, resulting in the modulation of the load-bearing facade. © PART.

Fig. 77. Prototypes from EKA 3rd year architecture studio ELEMENTerial, 2020. Tutors: Sille Pihlak and Siim Tuksam. Students: (from left to right) Uku Tarvas, example by Siim Tuksam, Miko Vahane, Olga Krasnova.

Fig. 78. Evolution from variation to repetition to modulation: Body Building installation, Urban Jungle vertical garden and Shift Lofts apartment building by PART Architects. Photos by Tõnu Tunnel, rendering © PART.

Fig. 79. Transition from Digital Thicket to the Modulated Man – a: element; b: assembly; c: transformation; d: the chunk, defining a grid cell; e: relation to space filling truncated octahedrons; f: subdivision of a truncated octahedron; g: the resulting grid and the cell axes; h: cells combined based on resulting part length; i: the Modulated Man. Diagram of the thought process by the author.

Fig. 80. Repetitive non-regular space filling polyhedra, using the 3D Voronoi diagram and custom periodic point grids. Diagram by the author.

Fig. 81. Modulated modularity projects: Käsmu bus stop, Shift Lofts, the Cloud carpark and Pärnu Art Hall. All projects by PART Architects. © PART.

Fig. 82. Transformation of a spatial grid from modular to bespoke. Diagram by the author.

Fig. 83. Shift Lofts 2019 by PART Architects. The spiralling floor slabs are derived from the spatial structure. © PART.

Fig. 84. Käsmu bus stop, revised 2019, by PART Architects, waiting area and stair. © PART.

Fig. 85. Käsmu bus stop section drawing 2018 and the revised version 2019, by PART Architects. © PART.

Fig. 86. Modulated sphere 2020, drawing by the author.

Fig. 87. Shift Lofts 2019 by PART Architects. The spiralling stair core and the spatial structure. © PART.

Fig. 88. Shift Lofts 2019 by PART Architects. The load-bearing CLT facade and the spatial structure. © PART.

Fig. 89. Shift Lofts 2019 by PART Architects. The volumetric facade with balconies and shading with the spatial structure. © PART.

Fig. 90. Shift Lofts 2019 by PART Architects. Western elevation rendering. © PART.

Fig. 91. Shift Lofts 2019 by PART Architects. Southern front elevation rendering. © PART.

Fig. 92. Shift Lofts 2019 by PART Architects. View from south-east. © PART.

Fig. 93. Urban Jungle 2018, plywood landscape, subdivisions of truncated octahedrons. Photo by Tõnu Tunnel (edited).

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The digitalisation of the construction industry is in full swing. The infrastructure for the computer-aided fabrication of buildings is here, yet mass customisation by robotically manufactured infinitesimally variable components, as suggested by the early digital architects of the 1990s, is still not viable on an industrial scale. Architecture is seemingly forced to adapt to the industry rather than the other way round. How is it possible, within this context, to maintain the autonomy of the architectural discipline, facing the realities of extensive standardisation, automation, and artificial intelligence?

Digital architecture as a critical discourse was largely built upon Gilles Deleuze's idea of folding, proposing a continuous formation of matter based on intensities. Folding in architecture resulted in an almost frictionless combination of topology and tectonics, where the whole consists of continuously variegated adaptive details. It is this continuous adaptation that is contested within the thesis in which modulation is proposed as an active intervention rather than frictionless optimisation – subverting the prevailing ideology from within by taking the system more seriously than the system takes itself, to paraphrase Slavoj Žižek.

The study is projective and reflective at the same time – experimental research by design that turns into both practice research and theoretical research. Through a series of projects in collaboration with the Estonian wooden house manufacturing industry, this exploration has evolved from looking at mimetic algorithms and variable tectonics towards a pre-rationalised design approach – modulated modularity.

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