Architectural Robotics

Bridging the Divide between Academic Research and Industry

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ARCHITECTURAL ROBOTICS: BRIDGING THE DIVIDE BETWEEN ACADEMIC RESEARCH AND INDUSTRY

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SUMMARY

The presented research addresses the question of how to bridge the divide between academic research and industry in the domain of by investigating aspects of computational design , robotic fabrication and their impact on practice via a series of experiments and case studies. Research sub-questions related to the architectural model , geometry and implicit fabrication are investigated in relation to topology optimization, robotic hotwire-cutting , and robotic hot-blade cutting.

The thesis contains both theoretical and experimental contributions that explore the merits of the aforementioned technologies. Initially, an approach to generative design is developed that allies evolutionary computing and daylight simulation, while reflecting on the earlier work of EZCT Architecture & Design Research that explores the generative merits of evolutionary computing for structural design problem.

The altered status of the architectural model is examined providing an epistemic framework for the practical research. Second, the concept of Turing completeness in fabrication is explored on a conceptual level, which is considered an essential property that sets robotic apart from more traditional approaches to CNC (Computer Numeric Control) fabrication, whereas a robot controller can execute logical statements and thus can effectuate design logic at runtime, where a CNC controller merely can execute a toolpath. A shared motif in both articles is the computational perspective, respectively E. Fredkin's concept of a universal computer and Turing completeness. The concept of evolutionary fabrication is explored, effectively consolidating many of the perspectives explored.

A reflection on a volumetric approach to geometry, fueled by the interplay between stereotomy and hotwire cutting is explored. The interest in stereotomy is further advanced by exploring cutting "traites" and "voussoir" elements in natural stone by means of a robotic diamond wire-saw. The topic of stereotomy is further explored by the development of an algorithm that segments free-form surfaces by propagating a front through the levelset method. The approach is explored takes a holistic approach and where geometrical, industrial and economical constraints are addressed in an approach that tries to meet both structural and of aesthetic objectives.

Hotwire cutting was first explored in the mock-up for the Protospace 4 pavilion. The coupled merit of Topology optimization (TO) and hotwire cutting . Whereas TO allows for a considerable reduction of the volume of concrete required to meet structural criteria. However, the intricate geometry of a TO structure is offset economically due to increased cost in formwork, and thus optimal in a narrow sense. Hotwire cutting examined in this context, since it is a cost-effective approach to realising intricate formwork. Finally, *hotblade* cutting is explored; extending the cost-effectiveness to double curved geometry, while hotwire cutting by construction is limited to ruled surfaces. A method to rationalization and segment double curved NURBS surfaces to Euler elastica is developed.

A number of case studies are presented, addressing the question of scaling architectural robotics to projects of industrial application, as demonstrated in the Kirk Kapital project. The potential for scaling an fabrication methodology is gauged via the criteria of performance, transferability, and degrees of freedom. Following the experience of the aforementioned project, the consolidation and normalization of BIM (Building Information Model) is addressed. Generating toolpath data from the consolidated data is explored through an implementation in PythonOCC / IfcOpenShell. Finally, the entrepreneurial outlook of architectural robotics is investigated.

SAMENVATTING

Het gepresenteerde onderzoek behandelt de vraag hoe de kloof tussen academisch onderzoek en de industrie op het gebied van kan worden overbrugd door aspecten van computationeel ontwerp, robotfabricage en de praktische impact te onderzoeken via een reeks experimenten en case studies. Onderzoek deelvragen gerelateerd aan het architectuurmodel, geometrie en impliciete fabricage worden onderzocht in relatie tot topologie-optimalisatie, het maken van bekisting door middel van robotisch gestuurde hete-draad en het robotisch snijden van mallen met een gekromd blad.

Dit proefschrift bevat zowel theoretische als experimentele bijdragen die de voordelen van de eerdergenoemde technologieën onderzoeken. In eerste instantie is een benadering tot generatief ontwerp is ontwikkeld op stoelt van een genetisch algoritme en daglichtsimulatie en reflecteert op eerder werk van EZCT Architecture & Design Research wat het generatief ontwerp potentieel van de toepassing van een genetisch algoritme toegepast op een structureel ontwerp probleem.

De gewijzigde status van het architectuurmodel wordt belicht vanuit een epistemisch kader. Het concept van Turing completeness in fabricage wordt onderzocht op een conceptueel niveau, dat wil zeggen: beschouwd als een essentiële eigenschap die robotica onderscheidt van meer traditionele benaderingen van CNC (Computer Numeric Control) fabricage. Terwijl een robotcontroller logische instructies kan uitvoeren en dus de onderliggende ontwerplogica kan uitvoeren, waar een CNC-controller alleen beperkt is tot het uitvoeren een toolpath. Een gedeeld motief in beide artikelen is het computationele perspectief, respectievelijk E. Fredkin's concept van een universele computer en Turing volledigheid. Het concept van evolutionaire fabricage wordt onderzocht, effectief consolideren van veel van de onderzochte perspectieven

Een reflectie op een volumetrische benadering van geometrie, gevoed door de wisselwerking tussen stereotomie en hotwire snijden is explored. De interesse in stereotomie wordt verder ontwikkeld door het onderzoeken van snij-eigenschappen en voussoir elementen in natuursteen door middel van een robotdiamant wire-saw. Het onderwerp van stereotomie wordt verder onderzocht door de ontwikkeling van een algoritme dat free-form oppervlakken segmenteert op basis van de levelset methodiek. De benadering die wordt onderzocht, is een holistische, waar geometrische, industriële en economische beperkingen worden onderzocht in een benadering die zowel structurele als esthetische doelstellingen tracht te bewerkstelligen.

Hotwire snijden werd voor het eerst onderzocht in de mock-up voor het Protospace 4-paviljoen. De gekoppelde verdienste van topologie-optimalisatie (TO) en hotwire snijden. Terwijl TO een aanzienlijke reductie mogelijk maakt van het volume beton dat nodig is om aan structurele criteria te voldoen. Echter, de complexe geometrie van een TO-structuur wordt economisch gecompenseerd door verhoogde kosten in bekisting, en dus optimaal in enge zin . Hotwire snijden in deze context onderzocht, omdat het een kosteneffectieve benadering is om ingewikkelde bekisting. Ten slotte wordt *hotblade* snijden onderzocht;

zo wordt de kosteneffectiviteit van draadsnijden verbreed om gebogen geometrie te snijden, terwijl draad snijden per constructie is beperkt tot geregelde oppervlakken. Een methode om dubbel gekromde NURBS oppervlakken te rationaliseren en segmenteren tot Euler elastica wordt gepresenteerd.

Een aantal case studies worden gepresenteerd, waarin de kwestie van het schalen van architecturale robotica wordt behandeld om projecten van industriële toepassing, zoals aangetoond in de Kirk Kapital project. Het potentieel voor het opschalen van een fabricage methodiek wordt gemeten via de prestatiecriteria, overdraagbaarheid en vrijheidsgraden. Naar aanleiding van de ervaring van de voorgenoemd project, komt de consolidatie en normalisatie van BIM (Building Informatiemodel) aan de orde. Toolpath data genereren uit de geconsolideerde gegevens worden onderzocht via een implementatie in PythonOCC / IfcOpenShell. Tot slot, de economisch/entrepeneurial visie op architecturale robotica is onderzocht.

CONTENTS

1

INTRODUCTION

The first chapter is focussed on *Computational design* is structured in four sections: the first section explores the shift from a *representational* to an *operative* model 16. The model provides the interface that allows architects and engineers to assess how a building's performance from the model, paving the way for a performance-oriented design. Specifically, the potential of daylight simulation in tandem with an approach to generative design through the use of evolutionary computing is explored 7, as developed by EZCT Architecture & Design Research for the Seroussi Pavilion [57].

The model surpasses the role as *metaphor* for the project to build moving moving beyond representation towards a definition. This transgression of the model from a symbolic description to definition has a dramatic impact on the fabrication, hence practice autonomy and economy of architecture. Though largely, this radical *epistemic* shift has not seen broad deliberation, while the promotion of the architectural model has fueled key developments. Implications of the literal turn of the architectural model are examined in this thesis as follows:

- CNC tool paths are a *derivation* of the project's model, an approximation of the original within a given tolerance, an interface between architectural intention and its manifestation

- By convention simulation is utilized to validate whether a design complies with constraints, industry standards and requirements. *Notes on the potential of simulation for architectural conception* 7 explores simulation is at the heart of architectural conception itself. Introspection (through simulation) of the architectural model drives its continued development, through the mechanism of evolutionary computation

- Topology optimization 85 is a design strategy that explores introspection, and optimizes a design domain in the context of mechanical performance.

The second section on *implicit fabrication* 26 examines the implications of the computational turn of manufacturing. Specifically appraising the merit of *Turing completeness* in fabrication. The execution of NC[1] toolpaths is without any feedback loop, sensing or executing logic while running the toolpath. Technically, online introspection through methods such as SLAM[2]

The role of NC in fabrication is at a pivotal point in architecture; due to its widespread adoption, limitations of the approach have come within view. The limitations and bottlenecks are sought out and identified in order to develop a critical position towards the position and status of NC in manufacturing architecture.

With the mechanization of work the dilemma of production progressively is no longer managing hordes of workers, but recast to become the more abstract and intellectual ability to express construction of an artifact as a set of executable instructions – as code. A decade after architecture's linguistic turn [43, 49], the moment is here to reflect on NC's original intentions [8] and the merits and shortcomings and to look forward and extrapolate what course of action lies ahead of us.

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[1] Computer numeric control

[2] Simultaneous localization and mapping

The third section 37 addresses aspect related *architectural geometry*, which focuses on material processes that support a volumetric instead of sheet-based architecture 37. Such geometry can be cut with a hotwire, which provides a method whose historical precedent can be associated with stereotomy and developable surfaces of traditional stone masonry.

Further developing the topic of stereotomy and funicular vaults, the *RDM vault* presents a collaboration between the author, the Block Research Group and ROK Office (with respectively Matthias Rippmann and Silvan Oesterle contributing). Earlier work such as *Protospace 4* 71 identified the necessity of dealing with structural design aspects as well as fabrication constraints early on in the design phase. RhinoVault developed by Matthias Rippmann, as part of his PhD thesis [125]. RhinoVault provides powerful and intuitive design tools for the design of compression-only structures. The RDM vault in 2012 was the first CNC or robotically fabricated structures to explore this potential at the scale of a 1:1 mock-up.

The fourth section presents *an experimental developable-transform* 48 – the segmentation of a free-form surface to a set of panelizable elements is a quintessential problem of *architectural geometry*. The developable-transform is a manifestly architectural problem since it involves aspects that are geometrical, industrial, economical, structural and of aesthetics. Much of the current work is focused on either of these aspects – however, an ideal approach would synthesize a number of these. Precisely such a multivariate approach is explored in a project for the design of a roof of a factory hall is presented that seeks to integrate both geometrical, industrial and structural aspects. The approach evolves a front propagated by the levelset method [21] over an anisotropic distance field, where the distance is adjusted according to local gaussian curvature [113]. The front originates from local maxima within the distance field, consequentially traces the topological skeleton of the free-form surface.

The second chapter focuses on *Robotic fabrication* 67 and has three sections: the first presents investigations in design and fabrication. Early in the development of the Protospace pavilion it was clear that manufacturing components by CNC milling was prohibitively expensive. CNC milling was found to be suboptimal for the intended design for the following reasons:

- Placing the hexagonal components on the table of a large milling machine would require many transformations to make the object accessible to the milling bit. This re-positioning of the object being milled delimits the effectiveness of the milling process

- Milling EPS[3] foam generates considerable non-recyclable waste, which is costly to dispose of

- Due to the fragility of the material it is necessary to protect the components when transported. Therefore, a partial negative shape of the component has to be milled as well

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[3] expanded polystyrene

Cutting the EPS blocks by heat rather than a milling bit results in a smoother surface and better finish. Hence, shaping the large foam blocks with a CNC hot-wire cutting machine offered an effective and efficient solution.

In continuation of wire cutting experiments, the second sections presents formwork systems for cost-effective realization of topology-optimized concrete structures. The project explores the rationalization of ruled surface and a robotic approach to the wire cutting of 3d formwork systems in EPS. A 21m spatial concrete structure was build demonstrating and validating the approach. The EPS formwork was realized with a containerized robot workcell comprised of an ABB 6700 industrial robot and equipped with an additional rotary axis.

The third section addresses *robotic hot-blade cutting*72 implemented for a project of large scale that implied large local radii (between 1 and 2 m) of the surfaces. In this project the constraint of a geometrical approximation being limited to ruled surfaces is overcome by bending a hot-blade rather than a hotwire. As such the favorable economics of hot-wire cutting are extended beyond the domain of ruled surfaces.

The third chapter addresses *impact* explores how the shared technological platform of robotics with industry encourages the transfer of knowledge from academia to industry 107. Researchers share the parlance of industry —code interpreted by the robot controller— with dialects differing from ABB's *RAPID*, Kuka's *KRL* or Staübli's *VAL3* robot language. Operating on a similar platform blurs where technological innovation stops and industrial adoption starts. Through the shared platform of industrial robotics new manufacturing technologies are allowed to gradually evolve from initial experiments to industrial processes. The chapter presents *case studies* such as the *construction of the Kirk Kapital headquarters*. This case study 113 is discussed from the point of view of the construction industry assessing the potentials of industrial robotics can provide. Architectural robotics has been enthusiastically embraced by the design-led academic research community. With considerable enthusiasm, the specific characteristics of these novel fabrication processes have been gauged for their tectonic potential. The new freedoms, control and cultivation of new material avenues that are provided by digital fabrication has been a key driver for the past decade. Motivated by this quest for novelty, and the lack of large-scale industrial uptake, quantitative performance on an industrial level is rarely discussed.

So far, the literature lacks an accepted methodology and criteria to assess and contrast the relative merits of various existing technologies. As such, there is no accepted process of benchmark and contrasting the heterogeneous fabrication methodologies, and no approach to calibrate the virtues of the distinct approaches. To further contrast, weigh and define the merits of the various approaches and technologies that have been presented were assessed via the following criteria

- Transferability – how relevant is an fabrication method across application domains?
- Performance – what does a fabrication method offer from a quantitative perspective in contrast to existing approaches?

- Degrees of freedom – does the fabrication method open up uncharted approaches to production? Are existing constraints relaxed, are new previously unexplored approached coming into view?

With these criteria as guidelines to establish the quantitative and qualitative merits are gauged in tandem and assessed with their respective potential for impact in the building industry. The chapter concludes with a discussion on current developments *towards a seamless integration of modeling and manufacturing* 124.

Odico produced the complex formwork by robotic means for an architectural project built in Vejle, the Kirk Kapital HQ 115 by the Danish artist Olafur Eliasson. The CAD models stem from various actors (designers, architects, engineers, municipalities) in this project that reflect the numerous competences that a complex project require. As such the geometric definitions flow from various project participants, and reflect at heterogeneity of software tools utilized, including surface modelling software Rhino (McNeel), mechanical engineering software such as Inventor (Autodesk) and Tekla (Trimble). Consolidations of variegated origins and design intentions reflected in this mix of models proved to be demanding. While IFC[4] was considered, an omission of the *IFC 2x3* standard is no support for bézier splines and NURBS[5] surfaces, as necessitated by the project's broad use of curved geometry.

For future projects, interoperability is expected to improve with the *IFC 4* standard supporting NURBS. Conjectured is that the IFC/BIM[6] model increasingly will overtake the legal status of the drawing set. While the aforementioned software packages don't (yet) support this (version) of the IFC standard natively, the status of IFC as a medium of interchange is undisputed. As such it is considered a key data format for robotic manufacturing in the construction industry and its industry wide adoption is rapidly evolving. The lack of IFC support for higher order geometry has stalled adoption of the standard in terms of robotic manufacturing. With the advent of *IFC 4* supporting NURBS, the avenue of manufacturing from IFC data comes into view and seems a reasonable extrapolation. A practical implementation of robotic manufacturing on the basis of *IFC 4* was explored 124.

Methodology In terms of overall approach, this thesis is a published papers-based dissertation and presented work is the result of collaborations between academic and industry partners. The overall aim is to challenge current practices that are lagging behind in adopting computational design and robotic production technologies.

In terms of methodology, the dissertation relies on a research-by-design approach, which involves academic investigation wherein design is employed as a method of inquiry [82]. Numerical simulation and lab experimentation were used as main means to test ideas.

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[4] Industry Foundation Classes

[5] Non-uniformal rational b-splines

[6] Building information model

2

COMPUTATIONAL DESIGN

2.1. ARCHITECTURAL MODEL

2.1.1. NOTES ON THE POTENTIAL OF SIMULATION FOR ARCHITECTURAL CONCEPTION

With the projects described in this paper, EZCT Architecture & Design Research has demonstrated a reversal of the traditional role of simulation in architectural conception. Traditionally the role of simulation has been to see whether a design complies to its aims. In the projects described in this paper simulation is at the heart of architectural conception itself. optimization facilitates the role of simulation as a tool that can be applied towards design.

This section is based on *J. Feringa. Notes on the potential of simulation for architectural conception, ACADIA 2008, Silicon + Skin: Biological Processes and Computation* [60]

> *If mechanical forces can be distinguished*
> *it is not because*
> *living matter exceeds mechanical processes*
> *but mechanisms are not sufficient to be machines*
> *A mechanism if faulty not for being*
> *too artificial to account for living matter*
> *but for not being mechanical enough*
> *for not being adequately machined*
>
> G. Deleuze
> The Fold: Leibniz and The Baroque

> *Evolutionary computing is the mechanization of the scientific method*
>
> John Holland

Computational Chair design project In recent projects EZCT Architecture & Design Research (hereafter EZCT) investigated the potential of simulation applied towards architectural conception. What does it imply to know the structural, thermodynamic capacity as well as the daylight penetration of a building a priori for architectural conception? EZCT initiated the Computational Chair Project(hereafter CCD) project in order to understand this epistemological shift. The CCD project started the collaboration with Marc Schoenauer, who is a leading researcher in the domain of evolutionary computing and machine learning. For the CCD project[1] a genetic algorithm was develop that evolves a volume such that the forces inflicted upon it are dissolved as efficient as possible, while reducing the volume. One of the aims of the project is to arrive at a mechanization of the design process, such that instances of the concept can be produced fully automated. This is indispensable to fully develop the potential of non-serial fabrication of objects. In his article *Towards a Fully Associative Architecture*[37] B.Cache confirms this: “the design process itself would need to be automatized and we cannot have a piece of software written for each type of design problem”. Instances of an idea; J.Holland too defines evolutionary computing as the mechanization of the scientific method, appropriated to architecture the mechanization of the conceptual method.

Following Cache’s architectural and Holland’s computational theory the automation of design is precisely what the CCD project focuses on. Such an approach differs radically with that of Mass Customization, where commonly a parametrized design is adapted as such is the case in the *Variomatic*[33] project of K.Oosterhuis. The project intended

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[1] EZCT Architecture & Design Research (Philippe Morel, Felix Agid, Jelle Feringa) Studies on Optimization: computational chair design using genetic algorithms 2004-2006. Concept: EZCT Architecture & Design Research. Genetic algorithms and structural calculation: Hatem Hamda, Marc Schoenauer

the idea of designing by means of simulation. The fitness function of the genetic algorithm developed for the CCD project consists of a structural evaluation analysing how forces inflicted upon the chair are dissolved throughout the volume. Assumptions and abstractions that are common in engineering have been left out. Evolutionary computing is applied to control the full extent of the complexity of the problem presented. The outcome of such a process therefore often is hard to interpret. Its undemanding to observe that the a pre-defined condition has been met, but its an entirely different issue to fathom why such is the case. Darwinistic evolution is capable of producing results that are so rational that it can be hard to interpret these as such! Hence it seems that evolutionary computing coupled with a fitness function based on simulation is capable of generating hyperrational designs.

By controlling the complexity of the optimization process rather than reducing it, an object surfaces that is on the threshold of a mechanical form becoming organic. To converge a design, it is preceded by an vast series of possible designs. The model "Test1-860" shown below is 860 generations old. A generation is comprised of a hundred individuals, so that 86.000 potential designs have been generated before the design was converged. The vast number of potential designs that have been evaluated explain the dimension of the voxels which the chairs is built from. If a structural evaluation took 10 seconds then the evolutionary development takes up 9,95 days for the design of a single chair to complete. Fortunately the process can be easily distributed over a large number of computers. The grid computing facilities of the INRIA[2] have been applied for the design of the 25 chairs of which the CCD projects consists of. Since the application of a genetic algorithm leads not to a single solution but rather a family of solutions, it is only natural that the project has resulted in a series of chairs.

Figure 2.1: different stages of evolution of the test-9 chair

Figure 2.2: matrix of all chairs that make up the ccd project; as installed at the permanent collection of the centre pompidou, paris, france

Seroussi pavilion Recently EZCT participated in an architecture competition appointed by miss Seroussi, art dealer living in the former estate of André Bloc[3]. For the competition several agencies working in the domain of computational architecture were invited: DORA, EZCT, Gramazio & Kohler, IJP and Xefirotarch[4]. EZCT won the competition in execo with DORA.

One of the concepts EZCT developed for the project is the idea to design a pavilion that will be illuminated by approximately 200 Lux daylight, as homogenous as possible throughout the whole year. The aim of this design was that the exhibited works are best presented and protected of overexposure of UV light. To develop such a condition on say the 21st of June at noon is not a mundane task , but certainly assumptions can easily be made regarding atmospheric conditions. To deliver a homogenous distribution of 200 Lux annually therefore requires a very precise model of atmospheric and solar conditions. A standard CIE sky model, an aging standard from 1906, certainly will not meet this needs, since a uniform hemispheric distribution of 200 Lux anywhere on the planet is assumed. Hence the application of climate based modeling becomes a necessity. Rather than representing the the solar and atmospheric conditions on a moment in time, where either a clear or overcast sky is assumed, the model that J.Mardaljevic developed, is based on satellite climate data [31, 41]. The Radiance atmospheric and solar model is based on the irradiation data of all annual 4380 sun hours. This way a highly accurate model was obtained that is a precise representation of the local climate.

By doing away with irrelevant, sometimes even corrupting assumptions, abstractions and simplifications, it becomes possible to start solving the problem at hand at its full complexity. Evolutionary computing is capable of controlling such dazzling complexity. By increasing the resolution of the problem dramatically, new solutions come to daylight

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[2] The French National Institute for Research in Computer Science and Control

[3] Founder of L'Architecture d'Aujourd'Hui, a major French architecture review. Worked from 1962 until 1964 on the Sculptures-Habitacles, constructed on his former estate in Meudon.

[4] A catalogue has been published:[57]

Figure 2.3: chair model t1-m, after 860 generations

Technical description of the Radiance GA To develop the concept for the Seroussi Pavilion rigorously EZCT implemented a program that evolves an architectural envelope approximating the ideal condition that of the homogenous distribution of ~200 Lux daylight, as close as possible. Since no analytic formulation exists or could be developed for the problem an exploratory optimization technique was applied such that the design would converge to its logical consequence. The architectural program, described in square meters first was interpreted to volumes, such to obtain a precise idea about the volumetric requirements to meet the architectural program. Next a domain was defined encompassing the complete architectural program. In the domain each architectural program is represented as a point. In the first generation of the evolutionary process, the domain will be populated by a set of random points. From this set, the Voronoi diagram is computed. Each cell within the Voronoi diagram is labeled a void or solid. Cells labeled as solids are assigned to Voronoi sites representing the architectural program, until the predefined volume representing the program has been met. Consequently, this set of points fulfills an embryogenic role in the evolutionary process. Since the architectural program is well defined, there is no interest in evolving it.

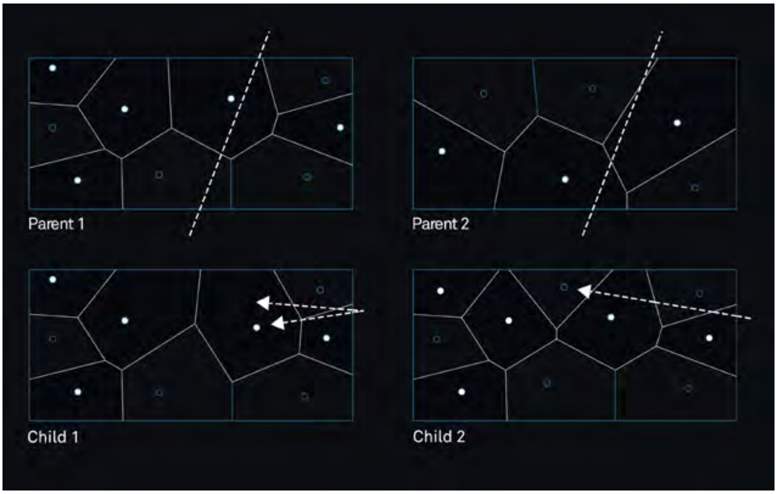

Figure 2.4: diagram of voronoi sites being crossed over (diagram by Philippe Morel. Figure adapted from [30]

Rather it is used as a seed from which the evolutionary process departs from. The barycenter of each cell labeled as void will be sampled in the Radiance simulation, such that the day-lighting performance is evaluated. The sum of the difference of the measured values to that of the target value of all cells labeled void is the fitness criteria of the Radiance GA. After several hundred generations a generation of solid candidates develop that will be further advanced in the continuation of the design process.

The Voronoi diagram is an excellent genotype for spatial applications. The power of evolutionary computing lies in the fact that the design is abstracted and encoded. The performance of the evolutionary processes therefore is directly related to the effectiveness of the genotypical encoding. The more powerful the abstraction represented by the encoding, the more likely that the evolution will be effective. The brain for instance consists of about a hundred billion connections, though only thirty thousands active genes describe the brain. Such a ratio is unprecedented in evolutionary computing, though the Voronoi diagram develop by M.Schoenauer is an important contribution to the development of an efficient genotype for spatial applications. A common representation in evolutionary computing is a binary matrix. The domain bounding the design space is discretized in a grid of cells. The evolutionary development hence is basically reduced to flipping the switch whether cells are represented as mass or void. Other than the binary

Figure 2.5: evolutionary convergence of the radiance ga

matrix the Voronoi diagram is adaptive. The binary matrix, necessary to encode a volume increases in a cubic fashion, where in the case of a Voronoi diagram, a large or small volume can be encoded with a few points[30].

Although the projects differ radically its been possible to apply the genotype based on the Voronoi diagram in both the CCD project as well as the Seroussi Pavilion project. Therefore can be speculated that its worthwhile to invest an effort in the development of software components. Architectural production deals with a severe degree of entropy since a relatively small subset of projects conceived (a 1:10 ratio is not uncommon) actually is realized. Hence the development of sufficiently abstract software components seems a viable method of capturing the knowledge materialized during the project.

Software development Other than for the CCD project which was implemented by H.Hamda, the software for the Seroussi Pavilion was written by M.Schoenauer and J.Feringa. M.Schoenauer implemented the genetic algorithm where J.Feringa implemented the fitness function. The program has been developed on top of a number of open-source libraries and software. The genetic algorithm is implemented in C++ on top of the Evolving Objects , a highly modular frame- work paradigm-free[5] for evolutionary computing. The fitness function was implemented in Python, using the CGAL[6] module to compute the Voronoi tesselation. Python generates the data that is the input for Radiance, a toolset for photometrically validated light simulation which is the defacto standard for (day)light simulation[23].

Motivation for evolutionary computing In his essay 'Next Babylon, Soft Babylon'[24], M.Novak writes "Elegance is the achievement of maximal effect with minimal effort". This statement can be interpreted as an aesthetic motivation to apply optimization processes to architectural conception. Elegance seems to be a property is that can be defined in terms of information theory; the more informed matter is, the more meaningful it is hence the more elegant it becomes. The approach described in this paper is more related to minimalism, rather than a baroque bio-mimetic approach. Principles from biology have been applied in the projects, rather than there was a formal grammar that suggested a bio-mimetic aesthetics. When one thinks of the scientific achievements and the fundamental understanding of the principles of nature, it seems almost perverse to simply mime its results rather than applying its underlying principles. An example is the widespread adaption of Voronoi diagram. Where computational geometry exploits the fundamental properties of the algorithm, in architecture its seems to have been adapted for its capacity to mime patterns occurring in nature.

Conclusion With the projects described in this paper, EZCT has demonstrated a reversal of the tradtional role of simulation in architectural conception. Traditionally the role of simulation has been to see whether a design complies to its aims. In the projects described in this paper simulation is at the heart of architectural conception itself. Optimization facilitates the role of simulation as a tool that can be applied towards design.

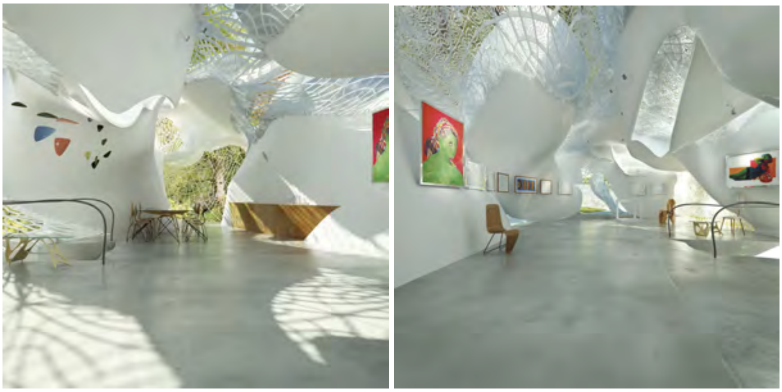

Figure 2.6: diagram of workflow between people and software utilised on the Seroussi pavilion project

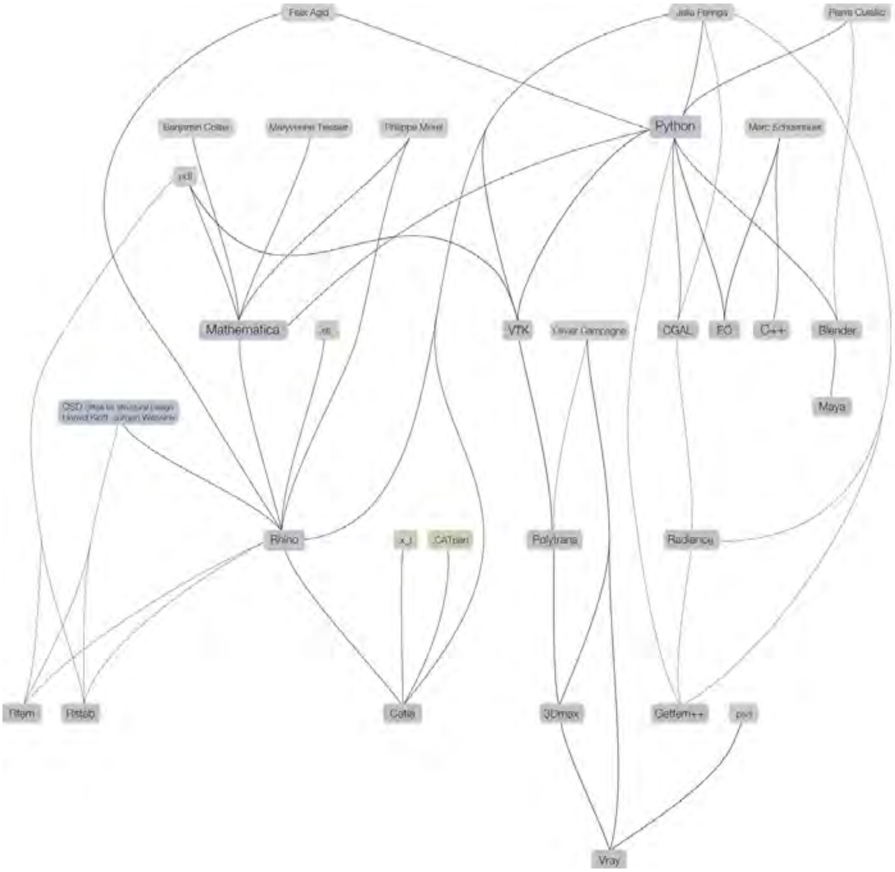

Figure 2.7: diagram of workflow between people and software utilised on the Seroussi pavilion project

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[5] EO allows one to easily mix paradigms coming from Genetic Algorithms, Genetic Programming, Evolutionary Strategies, Evolutionary Programming

[6] Computational Geometry Algorithms Library

2.1.2. THE PROMOTION OF THE ARCHITECTURAL MODEL

'I understand nothing,' Ivan went on, as though in a delirium. 'I don't want to understand anything now. I want to stick to the facts. I made up my mind long ago not to understand. If I try to understand anything, I shall be false to the facts, and I have determined to stick to the facts.'

Dostojevsky
The brothers Karamazov

Introduction In his article "Finite Nature" [12] physicist E. Fredkin states a radical, provoking idea: "What cannot be programmed cannot be physics. If a process cannot be programmed on a particular universal computer, despite having enough memory and time, then it cannot be programmed on any computer. If we can't program it on an ordinary computer, finite nature implies it can't be a part of physics because physics runs on a kind of computer." Is there an architectural analogy to this statement? However literal the interpretation "what cannot be computed cannot be built" might be, that statement is increasingly gaining in relevance, given that both the conception and manufacturing of architecture increasingly "runs on a kind of computer." The forefront of architecture has become a computational universe.

Therefore it's worthwhile to examine whether Fredkin's theory of computing and physics can be interpreted in an architecturally meaningful manner. However true even this over simplistic appropriation of Fredkin's theory might be, it doesn't do justice to its depth. The statement "what cannot be programmed cannot be physics" constitutes a relation among the laws of physics an object is subjected to and its physical manifestation; the object's programming. This principle underscores a strong coupling between an object's manifestation and signification. If we can accept both architecture's computational turn and Fredkin's statement, the question surfaces whether Fredkin's notion can be subjected to an architectural interpretation? My understanding of Fredkin's idea relates to the advancement of the architectural model.

The promotion of the architectural model With architecture's computational turn, the model has changed in terms of both modality and denotation. The model has become the *absolute* project reference where it used to be a declaration of architectural intent, a *metaphor* for the project to build. That is to say, the architectural model was promoted; it has evolved beyond an expression of architectural intent, it has moved beyond representation towards a definition. This transgression of the model from a symbolic description to definition is making a dramatic impact on the practice, autonomy and economy of architecture. The digital model has been the catalyst in expanding the scope of architectural form and giving rise to computational architecture's "burlesque" of a quasi-biological form; though little has been said on the radical *epismetic* shift of the model.

This section is based on *J. Feringa. The promotion of the architectural model, Metaphors in Architecture and Urbanism* [103]

The shift from a *representational* to a *referential* model changed what an architectural model embodies. In terms of engineering, the model provides the interface that allows architects and engineers to assess how a building's performance from the model, paving the way for a performance oriented architecture. Legally, the IFC/BIM model will overtake the legal status over a drawing set [63]. The most striking impact the promotion of the model has had, is in the construction process, CAM[7] changed status of the architectural model to an *operative* model. Models and drawing sets have transgressed from a symbolic metaphor and have been promoted to become the project reference. CNC tool paths are a *derivation* of the project's model, an approximation of the original within a given tolerance, an interface between architectural intention and its manifestation. Has the model become a platonic original?

Functional, analogical and figurative discrepancy Jim Glymph only recently became partner at Frank Gehry when he introduced CATIA to the office, while working on the Fish sculpture at Port Olímpic, Barcelona, a seminal project that both explored the formal register and economical potential that CAM opened up. The Fish scultpure is one of the first projects exploring an organic architecture, while truly achieving this objective would be fishy indeed. The project underscores that while the model has become literal in terms of construction, Gehry's idea is conveyed by means of *connotation* not *denotation*. Nature has no concept of semiotics. Significance is embodied in matter, perhaps this vindicates what is appealing in biomimicry to architect's; matter and meaning in unison at the cellular level.

Figure 2.8: Frank Gehry, Fish sculpture at Port Olímpic, Barcelona, 1989/1992

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[7] Computer Aided Manufacturing

Can a critique of the model offer perspective on the ongoing epismetic shift in architecture? Only two decades later do the ramifications of this shift come within grasp. A remarkable aspect in the work of Gramazio & Kohler is that the model is dissolved in its architectural *modus operandi* therefore losing its abstraction. The assemblage of the bricks is simultaneously the architectural model *and* its architectural manifestation. A representation of the robotic assembly process would be merely illustrative. Therefore if CNC[8] based building methodologies are to be embraced fully, the promotion of the model also has to be internalized in the conception of architecture. There is a sharp contrast in the architectural application of industrial robots between the work of Gramazio & Kohler and that of R&Sie's "architecture des humeurs." The contrasting positions can be understood through the difference in understanding of the role of the model. In the project of R&Sie, the method of robotic construction is merely suggested;[9] the model of the project is part of an architectural narrative, where in the work of Gramazio & Kohler, the model has become the definitive reference. The fundamental difference is that the architectural model became *operative, literal* in the work of Gramazio & Kohler, fully dissolved in the realization of the architectural artifact, where it remains part of the architectural *narrative, figurative* in the work of R&Sie. When juxtaposed by another, the epistemic dichotomy becomes apparent. What is evoked when the barrier between the conception and realization is being torn down, when the means of fabrication are innate to the architectural project? What can be articulated when an architect's intent is no longer lost in translation?

Figure 2.9: R&Sie(n), Une Architecture des humeurs, Paris, 2010

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[8] A hypernym for fabrication methods under Computer Numeric Control

[9] It is important to point out that *Viab02* is a model for a robot, not a functional robot

Figure 2.10: Programmed robot building up the brick wall, Gramazio & Kohler, ETH Zürich

An understanding of the architectural ramifications of CAM in construction cannot be suggested, only demonstrated: "One should be aware that a major difference exists between the precise numeric design and the physical world – geometric and fabrication data do not contain information about physical conditions such as gravity or material properties per se. Conversely, this means anticipating physical requirements at the outset of the parametric design process and using material conditions as well as assembly logics as the basis for coding."[70]

It is precisely this *embedding of architectural knowledge within the model* that serves the autonomy of architecture. By altering the architect's deliverable from description to a definition that requires no further interpretation, the architect is placed at the heart of the construction process, consequentially taking up a central role in the realization.

More intricate designs can be realized. A substantial part of the cost involved in CAM is not the materialization itself, but rather the often involved programming the tooling[46]. Deeply integrated design & fabrication process will aid to further explore this potential.

These transitions give rise to a materialistic understanding of the role of the architect. Can architecture be valued as the difference between the market value of the assembly and the cost of raw construction materials plus cost of assembly? Will this realization open up the prospect of Design & Build oriented architectural practices, not unlike Jean Prouve's practice; an architect with the means of production. So far its undeceided whether this prospect is either nostalgic or part of an ongoing effort of architects reclaiming their industrial standing.

The work of *Designtoproduction* has been exemplary regarding the shifting status of the architectural model. *Designtoproduction* is a consultancy firm, focused on the post-rationalization of an architectural model. A capable *enabler*, even though not directly involved in the architectural conception. Has a false schism been brought about? While the model has become literal, it has not necessarily been regarded as such during its architectural conception. An interesting case of an outcome of this position is that of the Centre Pompidou in Metz. What the virtuosity of *Designtoproduction*'s post-rationalization underscores that this roof *is not a straw-hat*, the metaphor on which Shigeru Ban's roof design is based on. Which wouldn't be an issue if it wasn't built like one, and might be a legitimate position, had the architects' design achieved a level of suspension of disbelief. The roof was modeled in an overly simplistic way: a hexagonal pattern is projected from the ground plane and hence bears no relation to how the roof works structurally, which can be observed by the homogeneous thickness of the columns spread under the roof. The radius of the inscribed circle through the hexagon bares no relation to its structural load. As such the roof feels bulky, which sells Ban's initial idea short. Possibly the conceptual model should have been regarded as a declaration of architectural intent, where it mistakenly has been taken as a referential model. What's striking is that the skill and rigor demonstrated in the realization contrasts with the lack of it in terms of its conception. Where the model has become *literal* in fabrication it remains *allegorical* in terms of its architectural conception. The absoluteness of the architectral model as such is brought into view, and raises the question whether *Designtoproduction* should interpreted the CAD model from scratch based on S. Ban's concept, rather than to "post-process" a coarse conceptual model.

Where the Metz Centre Pompidou project struggles with an analogical discrepancy, the recently completed Qatar National Convention Centre by Isozaki[10] deals with a functional discrepancy. The shape of the building, or rather its structure, is the outcome of a topological optimization process, minimizing the volume required to distribute the loads of the roof. The irony here is that there is little load to distribute although the structure suggests the base of a skyscraper. The issue here is not the optimization process per se but rather its naive architectural application. The Centre is a pornographic building; a structure overdosed on Viagra without the hope of ever climaxing.

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[10] Originally Isozaki's competition entry for a new train station in Florence.

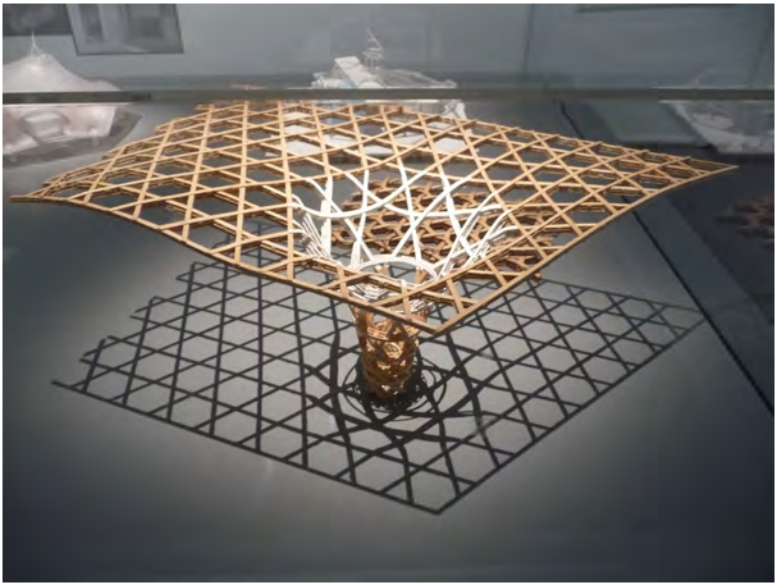

Figure 2.11: Shigeru Ban / designtoproduction - Metz Centre Pompidou, 2010

Figure 2.12: Arata Isozaki, Florence New Station, 2002, Competition model

Why settle for simile? Architecture's biophile infatuation is worrisome; with the literal turn of the architectural model, the burlesque of biomimicry will rapidly become a backward position. The promotion of the model is a pivotal moment in architecture, one that should not be lost on the callow act of mimises. *Why settle for simile?* Where Haeckel's images were adequate and imaginative in Berlage's era, here they represent a commonplace. Architecture is situated in a society fueled by genetically modified crops, where genetic material is routinely patented; mimicry as an approach seems an underdeveloped epistemic position, seen in the context of a radically technocratic society.

J.J. Tabor's research is a strong reminder that "physics runs on a kind of computer." To paraphrase Tabor: "We have re-programmed the genomes of living cells to construct massively parallel biological computers capable of processing two-dimensional images at a theoretical resolution of greater than 100 megapixels per square inch. First, we rewired a signal transduction pathway in E-coli to express a pigment-producing enzyme under the control of red light. We then use the engineered bacteria as pixels in biological film."[58]

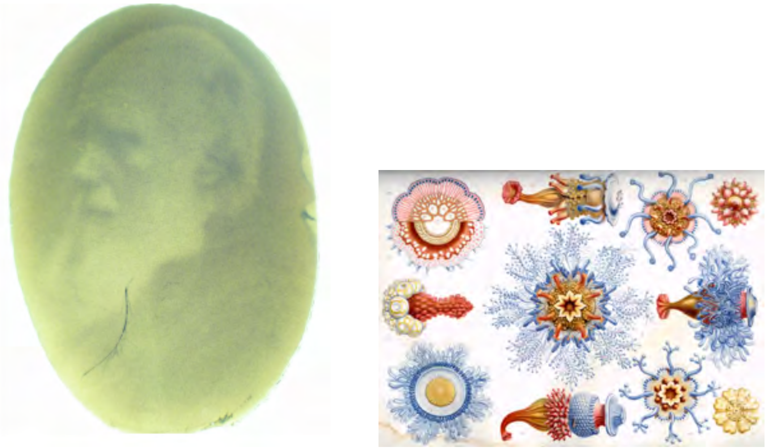

Figure 2.13: left:Bacterial portraiture, J. J. Tabor
right: Ernst Haeckel Kunstformen der Natur, 1899

As nature is sufficiently well understood – we are indeed able to re-program its gene expression –, architecture's superficial emphasis on *simile* reveals itself as a cold caricature of a retrograde epistemic position. If computing is the runtime of physics, that which precedes nature, than why the self-censorship? Conceptually, a biomimetic approach is one of *representing* an idealized, stylized nature, where GMO's[11] *yet substantiate* this idealized, stylized nature. Tabor continues: "Next, use the 'bacterial photography' technology as tool for the engineering of a massively parallel biological computer which uses cell-cell communication to compute the edges (lightdark boundaries) within images."[58]

Along with the advancement of the architectural model, architectural models should evolve; significance transcribed at the cellular level. What's sure about the explosion-formed anodized titanium cast vase by Greg Lynn is that it will neither rot, stink nor decompose, underscoring that it's not composed of cellulose tissue. Is the resulting artificial/organic hybrid *both, and* or *neither, nor*? Is the gorgeous anodized titanium piece antithetic to its conceptual ambition?

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[11] Genetically Modified Organism

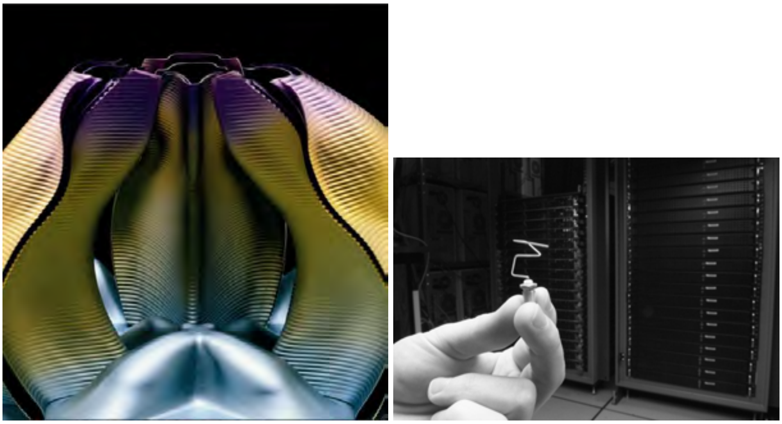

Figure 2.14: left:Greg Lynn's vase for Alessi
right:Hornby's antenna developed for NASA's Space Technology 5 Mission

How to close the epismetic rift? The epismetic crisis in architecture is underscored by radical shift in status of the architectural model. How can this rift be brought about? Perhaps Fredkin's notion of *Finite Natures* offers a clue; a close coupling of the laws of physics an object is subjected to and its physical manifestation. The antenna that Greg Hornby evolved for NASA's Space Technology 5 Mission offers perspective. The antenna is one of the components of a satellite that consumes most energy over it's lifespan, therefore it's worthwhile to spend considerable effort optimizing its design. The many non-linear radio-frequencies that an antenna has to be able to deal with make the design task one of great complexity. Different bandwidths interfere with one another, finding a compromise is therefore very difficult. What's stunning about the design is that it has pierced through the ceiling of design complexity of what a traditional designer can achieve. A designer who has limited design resources, limited hours to spend, has finite patience and knowledge of the intricacies involved. While current design approaches in architecture aim for complexification —rendering a straightforward design concept into something that is not—, here we are presented by a design approach that achieves the inverse; an approach of *condensation*. The antenna is so strongly coupled to the phenomena it has to deal with, that it lies beyond what's considered rational. To the untrained eye, Hornby's antenna looks like someone channeled their anger on a paperclip. While it is straightforward to complexify a design it takes massive computational resources and a great deal of knowledge to *sublimate* a design. Coupling evolutionary computing with simulation forms the toolchain of the design strategy of sublimation. When juxtaposed with Lynn's vase the opposing approaches are underscored; manifestation vs. materialization. What potential does the synthesis of the antithetical design strategies hold? The combined sophistication of Lynn's materialization and Hornby's manifestation offers great architectural promise.

Situated development John Rieffel developed the concept of *Situated development*: "the evolution of prescriptive representations requires simulating an object's entire assembly, rather than only its final shape, a process which we call 'Situated Development.' In this context, the environment in which evolution occurs is meant to be equivalent to some physical assembly mechanism, such as a rapid prototyping machine .”[50]

The architectural possibilities of such a design method holds striking potential; not a mere design is evolved, but a holistic building strategy, bridging what Rieffel refers to as the *fabrication gap*. Situated Development creates *motivated complexity*, tapping into the potential of moving beyond *digital craft*. CNC based fabrication methods remain a form of artisanal creation, since translation from a design to CAM code[12] is a highly involved process. The critical difference is that Situated Development gives rise to *implicit fabrication*, where generating a manufacturing code no longer is a post-rationalization of the project. Potentially this approach is a means of unlocking the true potential of CNC fabrication. The involved CAM programming is the reason why a mere fraction of the production potential of CNC fabrication is utilized, with craft, artisanship absolving the relative cumbersomeness of the process.

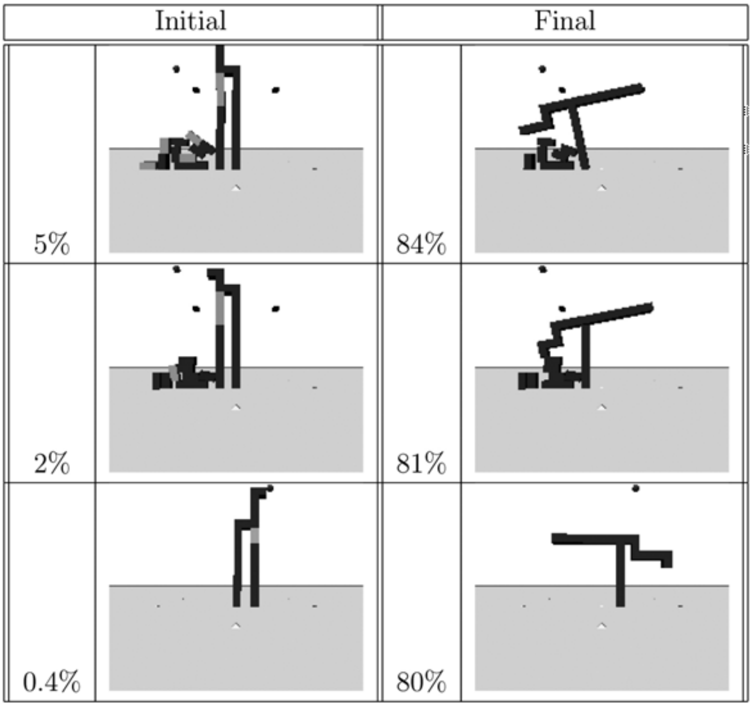

Figure 2.15: Rieffel's' concept of emerging ontogenic scaffolding; a structure is assembled, with the inclusion of gray, temporary scaffolding elements. When these are removed and the structure is subjected to its environment, the structure is altered until it reaches a point of stability

There is a real contradiction in terminology of the artisanship involved in automated manufacturing. While the design resolution is dramatically increased, the threshold to

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[12] Computer Aided Manufacturing; g-code, robot code

Figure 2.16: Michael Hansmeyer, Sixth Order installation at the Gwangju Design Biennale 2011

fabrication is taken away. Finally, it's worth pointing out that the design process itself is an important factor in production, of up to 70% [13]. Such a design approach is diametrically opposed to the formal, biomimetic design approach and raises the question of what can be considered *natural* in architecture. A natural progression towards materialization is exploiting technological propensities. In this light, it's interesting to juxtapose the research of Michael Hansmeyer and John Rieffel. While Hansmeyer achieves a great level of visual complexity, the process of manufacturing the imposing columns involves the patience and endurance of the students involved in manufacturing the project, where Rieffel relies on the effortless collapse of his structures for their final assembly. While the complexity of Rieffel's research is obfuscated by its seeming simplicity so is the elegant algorithmic simplicity of Hansmeyer's project obfuscated by the resulting visual complexity. It is the combined merit of either project which is most promising. The renewed centrality of fabrication in architecture evokes the idea that architecture perhaps can be considered to be the difference between the cost of the raw building materials and assembling subtracted from the market value of the build project. Even though this point of view is somewhat banal, I find it an optimistic idea. Those architects who will succeed to incorporate knowledge into the architectural model will be able to realize greater architecture quality within similar budget contraints. Design strategies such as *Situated Development* simultaneously embed and evolve knowledge about the architectural model, where materialization is no longer an afterthought, but at the heart of conception. It brings computational architecture towards materialization at a cellular level where advanced architectural conception methodologies are closely entangled with robotic fabrication strategies. If such specialized design methods will emerge, the level of expertise and efficiency involved will advance architecture's autonomy. Even though the visual complexity of the models evolved by both Rieffel's and Hornby's work is lacking, I cannot help but find the approach more radical and stimulating than the featherweight pseudo-complexity all too present in computational architecture. The exploration of condensation, is long overdue.

Figure 2.17: The scope of digital means of manufacturing. (Left) FreeD, developed by the responsive environment group at MIT: bot craft and automation, or neither craft nor automation? (Right) Lights-out manufacturing: FANUC plant near Fuji, Japan

2.1.3. IMPLICIT FABRICATION

FABRICATION BEYOND CRAFT: THE POTENTIAL OF TURING COMPLETENESS IN CONSTRUCTION

Over the last decades numeric control (NC) and robotics have become firmly grounded within architectural practice. While the hacking of CNC machinery, the development of production strategies specifically oriented toward architectural applications, and the development of robot end-effectors implementing new architectural fabrication processes are perceived as forms of craft, a salient contradiction surfaces. While robotics has essentially developed in the field of industrial automation, in architecture, NC is increasingly understood as a form of digital craft. This year's ACADIA conference is no exception; it refers to the increasing role of robotics in construction as robot craft. Is this a contradiction in terms? If so, what is the origin of this contradiction, and what consequences are implied? The state of the art in lights-out manufacturing (LOM) has plants operate unattended for a month, while on the other hand, handheld machining tools are being developed; the scope of NC has become so vast. The role of NC in fabrication is at a pivotal point in architecture; due to its widespread adoption, limitations of the approach have come within view. This article seeks to identify such limitations and bottlenecks and to develop a critical position for the coming decade of NC in manufacturing architecture.

INTRODUCTION

The Contradiction of Digital Craft A renewed perspective is developing on the notion of the architect as master builder; the concept of an architect such as Jean Prouvé with the means of production resurfaces. Numeric control (NC, used here as a hypernym for both CNC and robotic production methods) is the critical technology that makes reexamining this concept worthwhile. The horizon of the impact of *"The linguistic turn of architectural production"*—to paraphrase Philippe Morel [43]— on architectural practice is not yet in sight. Projects such as the Gantenbein of Gramazio & Kohler, practices

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This section is based on *J. Feringa. Implicit Fabrication, Fabrication Beyond Craft: The Potential of Turing Completeness in Construction , ACADIA 2012: Synthetic Digital Ecologies* [91] such as RokOffice and Snøhetta, and the emerging of specialized offices that bridge the fabrication gap such as designtoproduction and 1:One, convincingly demonstrate how a more central position within the construction process can be claimed — one where the architect ceases to be an interchangeable middleware between developer and contractor. Apart from the contradiction in terms of digital or robotic craft, the notion of craft seems to ignore its industrial potential, which is peculiar since the approach is rooted in industry. Given the potential for NC to renew the architectural profession, is framing NC as digital craft not Luddism, self-censorship? Or does the notion of craft merely point out that digital craft is an emerging field, or is it a consequence of an artisanal inclination toward manufacturing? The fact that NC is over half a century old argues against this, as do the economic implications of adoption of NC. The innovative FreeD handheld milling machine effectively explores the contradiction of digital craft; is it both craft and automation, or neither craft nor automation? Perhaps the contradiction —NC was conceived essentially as a form of automation— is conspicuous since these oppose some of the central concepts in computational architecture. I think of John Frazer's notion of an "army of clerks" [17]; computing's diminishing costs are significant. The same holds progressively true for fabrication; the cost of running for NC is low in relation to its production capacity and potential returns.

The disparity in approaches toward NC ranges from handheld milling devices to the extreme of LOM where robots assemble similar robots, a rudimentary form of self-assembly. The central issue here is that the notion of craft fails to acknowledge precisely this linguistic turn of architectural production; the practical problem of production has been transmuted into an intellectual problem. The dilemma of production is no longer managing hordes of workers, nor is it the mechanization of work; it has become the more abstract and intellectual ability to express the construction of an artifact as a set of executable instructions — as code. A decade after architecture's linguistic turn, the moment is here to reflect on NC's original intentions and the merits and shortcomings of the development, and to look forward to which possibilities still lie ahead of us.

LIGHTS OUT MANUFACTURING

Roger Smith, CEO of General Motors in the 1980s, subject of Michael Moore's film Roger & Me [11], is the person who invented and evangelized the term "lights-out manufacturing." Since then, the manufacturing of robots has become a rudimentary form of self-assembly; robots have been assembling robots in an LOM approach since 2001. "At this moment, in one of FANUC's 40,000-square-foot factories near Mt. Fuji, robots are building other robots at a rate of about 50 per 24-hour shift and can run unsupervised for as long as 30 days at a time. When they stop, it's because there's no room to store the goods. Trucks haul off the new robots, the lights are cut, and the process begins anew. "Not only is it lights-out," says FANUC vice president Gary Zywiol, "we turn off the air conditioning and heat too." [38]

WORKFLOW

The artisanal inclination of digital craft can be explained partially by the highly involved process of moving from form toward fabrication. Three degrees of code are implied in what is best described as a canonical workflow in computational architecture. First, design intent is formalized in code that produces geometry.

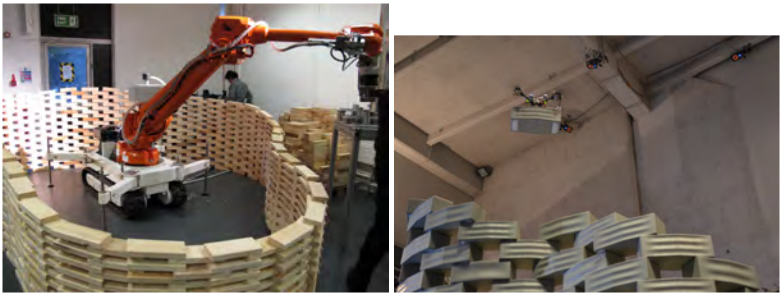

Figure 2.18: Remote sensing applied in the work of Gramazio & Kohler, ETH Zürich. (Left) Robust assembly by integrating computer vision at FABRICATE 2011. (Right) Flight assembly exposition opening at FRAC Centre, Orléans

Secondly, code is developed—custom fabrication processes require custom software to generate fabrication code (super-Tools, HAL, Kuka|prc, Lobster)—or existing tools (among the usual suspects are Mastercam, Robotmaster, RobotStudio, and RhinoCAM) are deployed for geometric interpretation and code generation for fabrication. Finally, the outcome of the geometric interpretation once again is code: a g-code dialect or robot code, such as RAPID for ABB robots or KRL for Kuka robots. In other words, moving toward fabrication is a highly indirect, transliteral, and cross-domain process.

Semantics The circuitous and unidirectional nature of this approach is problematic for the semantic integrity of the generated fabrication code. If code is so central in manufacturing, shouldn't we pay more attention to the way fabrication instructions are structured? Clearly, semantics will not affect tooling precision, but it is important to realize that the limitations of production are increasingly framed as intellectual rather than mechanical limitations. I argue that such limitations are ever more embedded in the semantic structure of fabrication code. These programs represent fragments of a building, frustrating an integrated approach. Once fabrication code is generated from the model, the umbilical cord is cut off, with no way to adapt such fragments to late-breaking changes. These various fragments are described individually in an absolute coordinates system rather than in relative coordinates, which is semantically more meaningful, since this encodes how the fragments relate, allowing for online correction during production. This ability is especially important in relation to additive manufacturing processes, where material dispersal generally is less exacting than in subtractive processes. The merits of such an approach were aptly demonstrated by dFAB (School of Architecture, Carnegie Mellon University) at the *"FABRICATE: Making Digital Architecture"* conference through the integration of computer vision (CV). Stacking the discrete elements one on top of another leads to buildup of tolerances and as such cannot be captured in an absolute coordinate system. When the stacking operations are described in a relative coordinate system, compensation for eventualities can be accommodated in the continued assembly. If this technique is already a prerequisite for the assembly of a folly with a diameter that equals the robot's reach, then the ability to generate fabrication code in a relational or

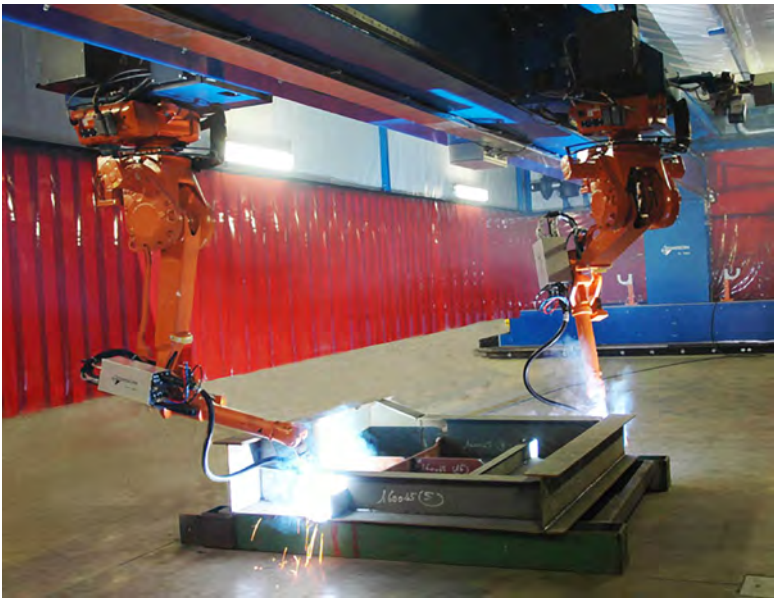

Figure 2.19: Robotic welding of stiffeners incorporating force-feedback control

relative manner is an essential technology for architecture.

Turing Completeness in Construction Turing completeness is the ability of a computer to simulate the most primitive computer (while the ability to simulate the simplest computer equates to simulating the most complex); in practical terms, it implies the ability of conditional branching, the power to execute if and goto statements. As such, a CNC controller cannot be considered Turing complete, while a robot is. During production a robot has the ability to compute, to execute a software program, to sense its environment and respond to these signals, and to make decisions while the code is run. Turing completeness is essential in order to describe fabrication code at a higher, semantically more meaningful level than the mere motion instructions that a CNC controller is able to execute. What explains the merit of dFAB's demonstration is that the fabrication instructions are described in relation to one another, and the feedback is employed to adapt the instructions and as such explores Turing completeness in construction.

An interesting application of the exploration of environmental feedback to develop robust and scalable construction methods is how force feedback is employed in welding ship hulls. Rather than assuming that a steel stiffener follows a perfectly straight line, the process has to be able to adapt to deviations. The robot is equipped with a force-feedback sensor; during the welding process, the tooltip locates both the horizontal plate and the stiffener; and given a measure of force feedback, the right welding spot is considered to be located. Rather than executing a stream of instructions, the robot is executing a program, a semantically meaningful construct other than the stream of explicit instructions. In order to move beyond craft, to develop original construction technologies that are both robust and scalable it is essential to embrace Turing completeness in construction. In an email exchange with the author, Jan Kranendonk argues that CAM operators routinely produce code for a hundred robotic welding hours within an hour. An important realization is that the economics of robotic imply that if you are able to program robots in a meaningful manner, you will. On the other hand, the relatively modest cost of robots in view of their production potential and the ability for processes to run 24/7/365 robustly pave the way for construction processes that are of greater resolution or relatively inefficient, where the relative inefficiency is offset by the capacity to produce around the clock robustly. What kind of architectural design will give rise to a production process where a dozen robots run continuously for half a year? I am not arguing for robotic water dripping to form stalactites, but the possibilities that this perspective opens up are intriguing, while the cost involved is not prohibitive per se.

Limits of the Current Approach The merits of numerical control have been well known for over half a century. Interestingly, the widespread adoption of computer-aided manufacturing (CAM) has brought attention to the limitations of the approach. The Foundation Louis Vuitton (FLV) project of Gehry CAM takes place at an unprecedented scale and level of complexity. The baroque project is a true building information modeling (BIM) tour-de-force with "over 100,000 versioned iterations of the BIM model, nearly 100Gigs of BIM data, 19,000 unique CNC-molded glass-reinforced concrete panels, 3500 unique CNC-molded curved glass panels." While these figures speak for themselves, never before had such an immensely detailed CAD model ever been developed. The project by itself is driving the French construction industry forward more than any other project in this decade, though the approach is not without issues. While the challenges of the project's adoption of CAM fabrication is unprecedented, so is the rumored ratio of architects to construction workers. Architecture seems light-years away from embracing LOM, but perhaps the approach offers a number of hints:

- In LOM, there is an extreme degree of integration

- Robots poll the state of other robots on conveyor belts and are orchestrated to respond in a global, synchronized state of production. The process is local and deeply integrated. That is the opposite of how CAM is applied in architecture, where production is dispersed over a number of subcontractors, lacking both synchronicity and locality, and frustrating integration between the various phases of construction

- This diaspora of production does not allow the fabrication code to be defined in a relational manner.

- Almost exclusively, the fabrication processes applied in computational architecture are driven by toolpaths. Toolpaths have become the lingua franca of CAM production, a unidirectional kitchen sink through which the project has to pass, where slowly but surely the horizon of what can be communicated effectively within this protocol comes into sight.

- Paradoxically, NC has reduced the margin of error to a problematic point, since the room left to correct eventualities has been proportionally reduced simultaneously. The margin for error is marginalized, paving the way for a tolerance rat race where the tolerance of component A inherits the tolerances of component B, since assembly is an unforgiving process in which error easily builds up.

TOOLPATHS

APT There is no doubt that a huge leap was made with the formalization of production processes by NC. Conceptually the process is no different from when the concept of CAM arose, by the end of the 1950s at MIT. It is worth pointing out that APT (automatically programmed tools) is considered one of the first programming languages, invented shortly after Fortran, considered the first high-level programming language, and LISP [19]. Interestingly, these three languages still are in widespread use today. It is striking how CAM as a language has hardly evolved since, certainly when seen in the light of many great breakthroughs, revolutions, and evolutions in the development of programming languages. Douglas Ross, the inventor of APT, describes the design process of the APT language in detail in "Origins of the APT Language for Automatically Programmed Tools". What is striking is that to an extent, ongoing efforts to modernize machine tool programming in the STEP-NC effort share a similar ambition as early uses of the APT language. A central aspect of APT was its subroutine library. One can think of this library as a set of functions nowadays performed by CAM software. Ironically, rereading the ambitions of the APT languages [8], in the early days of machine tool programming, such operations were described in a more high-level manner than what is common today. The STEP-NC effort follows a similar approach; machining operations—pocketing, drilling, roughening, contouring, tapping, swarfing—are associated to the CAD geometry. A library of subroutines then computes the toolpaths from this description—a considerable abstraction, since g-code is machine specific, while the STEP-NC approach is machine independent. So even while Ross took great care with regard to the semantic structure of the APT program and was deeply aware of the necessity of a clear semantic structure in order to achieve a high level of automation, his article starts with a wonderful and telling citation:

> *"(From THE NEW YORKER) Cambridge, Mass., Feb. 25, 1959. The Air Force announced today that it has a machine that can receive instructions in English, figure out how to make whatever is wanted, and teach other machines how to make it. An Air Force general said it will enable the United States to 'build a war machine that nobody would want to tackle.' Today it made an ashtray."*
>
> Douglas T. Ross [8]

Pointing out that the *"linguistic turn of architectural production"*, to paraphrase Philippe Morel [43], has been insufficiently realized, the lack of semantic structure stalls the fulfillment of CAM in the context of architecture.

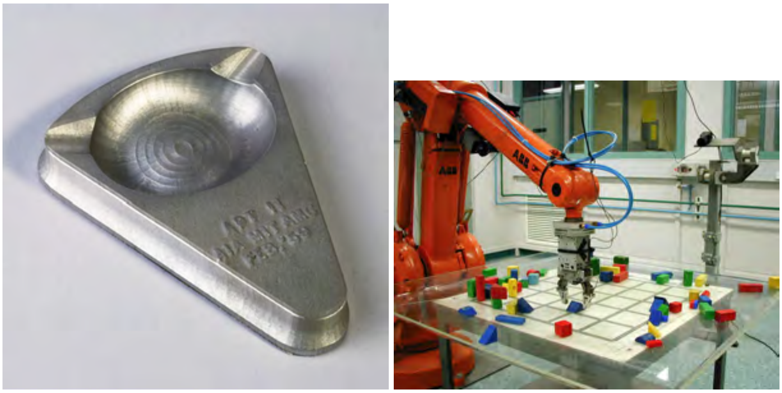

Figure 2.20: *Left* MIT ashtray *Right* Stigmergy revolves around the idea of embedding construction instructions in the environment and reading the instructions from it.

Post-Script John Warnock and Charles Geschke founded Adobe in 1982 and invented the page description language PostScript in 1984. In 1985 an interpreter for the PostScript language was developed by Adobe for the Apple LaserWriter. The coupled invention of PostScript and the LaserWriter gave way to the acronym WYSIWYG (what you see is what you get) and established desktop publishing.

What made the approach revolutionary is that the technical complexities involved in printing are abstracted by the PostScript interpreter. The CAM equivalent is to load a CAD file tagged with machining operations into the CNC controller and produce it, while the interpreter on the controller deals with the cumbersome process of generating the toolpaths. This is the ambition of the STEP-NC [67] effort and is a much-needed evolutionary step in machining. Though CAM and concepts not dissimilar to WYSIWYG printing were established 26 years ago, it has taken over 27 years to catch up; even when taking into account the considerable greater complexity of machining vs. printing, this is striking. I cannot stress enough that the differences in approaches here are first semantic, then technological. Ross had in mind a process that is closer to what PostScript achieved than what APT gave rise to. Machining code is regarded too much as data rather than as programming language. The close integration of the PostScript interpreter and the fact that PostScript is an adequate programming language led to experiments that suggest how manufacturing processes can be described in a more high-level manner.

Possible solutions: an outlook

Semantics in Fabrication Code Just van Rossum—brother of Guido van Rossum, creator of the Python programming language—and Erik van Blokland together form LettError. A key project of the duo is the Beowulf typeface. The font is a small piece of software written in PostScript, as discussed in this interview: *"Wired: You made the first "random" typeface, called Beowulf, by replacing the commands "lineto" and "curveto" in the PostScript code with your own command "freakto." The new command calls up a random generator that makes the character outlines irregular. When you created Beowulf, were you trying*

Figure 2.21: Applications of computer vision coincident in design and production. (Left) Hironori Yoshida: hybrid materiality explored by means of computer vision algorithms. (Right) Bolefloor: integration of advanced nesting algorithms and computer vision results in increased yield and adds design value

to prove something, or was it just a joke?" "van Blokland: It was quite a joke. We were both into programming—or would you call it hacking? What came of that interest was a very cool-looking thing. We wanted to make a typeface that looked very smooth and rounded off, but instead it became spiky, with little pointy bits sticking out from the edges of each character in a most unpredictable way. And what's the most fun about Beowulf is that every time you print it, those spiky bits take on a slightly different appearance." [18] What's of interest is that the design and its resulting products are self-contained in the Beowulf PostScript font, exploiting the elegant language/interpreter in a creative way. Interpreting PostScript equates to design production. The Beowulf font can be interpreted as a critical reflection of how design is encoded. The realization that PostScript is not merely a file format, but also a Turing complete programming language is far-reaching. The production of unique characters is an impossibility in (tool)paths, though trivial to implement in a programming language.

Perspectives: Computer Vision Is there an architectural analogy to the approach evoked by *LettError*? Implementing a design in a robot language like RAPID, where interpreting robot code on the controller equates to design production, offers perspective. A project of Hironori Yoshida [100] suggests such an approach and demonstrates the potential of remote sensing / computer vision for manufacturing procedures. The project exploits wood-grain patterns observed by a camera; imaging routines are applied to interpret g-code from it, mapping perception to production.

These procedures can be implemented in a high-level robot language with relative

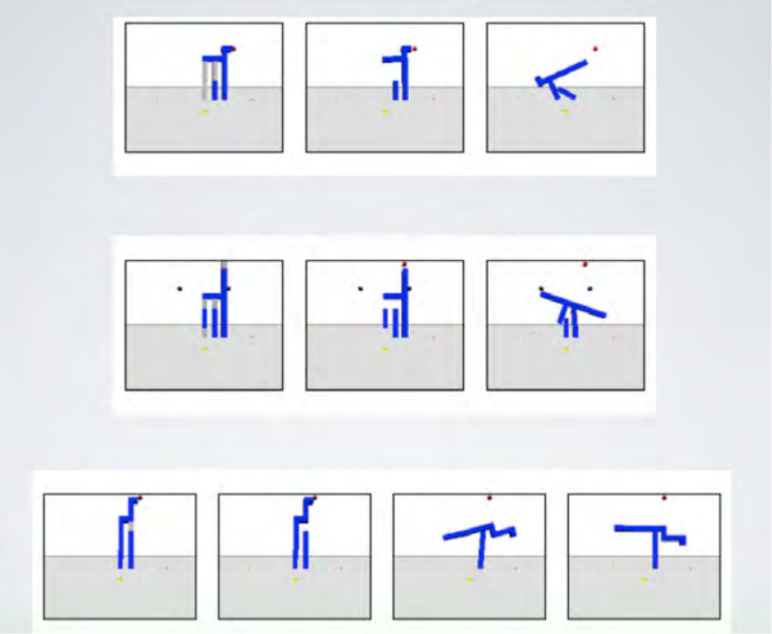

Figure 2.22: Simultaneous optimizing of design and assembly plan

ease. Picking and placing wooden panels is a routine job as well. Therefore, such a process—even while yielding intricate artifacts—can be fully automated with relative ease, which essentially has to do with how the design was encoded. Certain processes are considerably easier to implement and will scale up in terms of production. Being able to recognize this early on in the design process increasingly is an essential ability, while geometric intricacy of the design is a diminishing factor. A product and process that exemplifies this idea is *Bolefloor*, developed by the Institute of Cybernetics at Tallinn 2.21 University of Technology. The approach integrates remote sensing and applies advanced nesting algorithms. Data from a laser scanner is fed to nesting algorithms that both maximize lumber yield while adding value in terms of design. To paraphrase Kevin Kelly: *"in fact, in the technium, self-generated positive constraints are more than half the story; they are the main event"* [72]. An important realization is that increasingly the generation of fabrication code is a process that potentially is more costly and/or more time-consuming than executing it, which vindicates the relevance of processes that are described in higher abstractions such as remote sensing, which lead to an automated generation of production code.

Considerable production potential is left largely unexplored where this is not an issue of costly materials, nor man-hours, but the intellectual problem of developing fabrication approaches that explore the 24/7/365 production capacity of the machinery. This realization leads to a field of research that can be described as implicit fabrication, where fabrication code is implied from the design process. What approaches can be

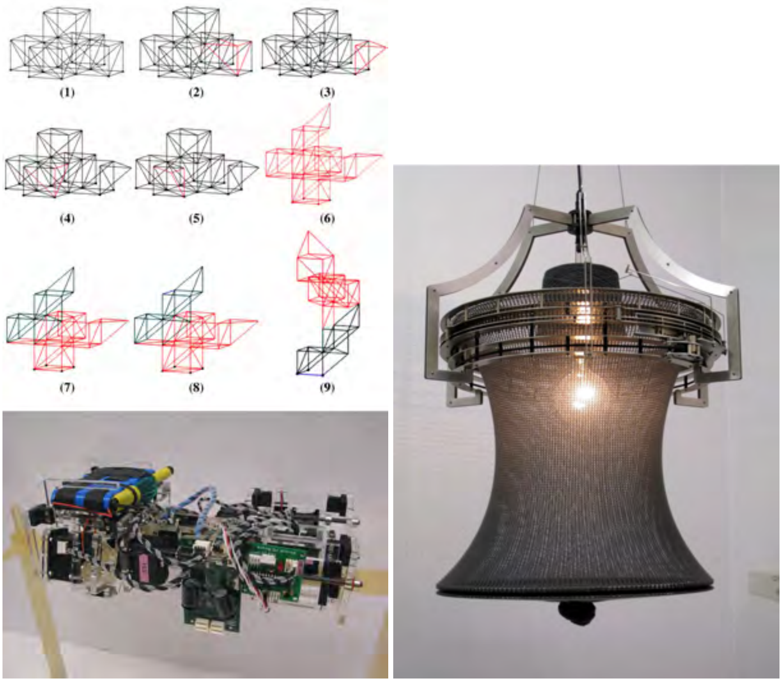

Figure 2.23: The means of production and its consequent outcome have formed an indiscernible whole; fabrication is fully implicit to the artifact itself. (Left) Cornell Creative Machines Lab's robotically manipulatable structures. (Right) Sleeping Beauty, Nadine Sterk.

identified that exemplify the future of this angle of research?

PROCESSES OF IMPLICIT FABRICATION

An important step up the ladder of abstraction that computer vision provides is the idea of stigmergy. Stigmergy [52] revolves around the notion that work evokes work; a change in the environment embeds information encoding the continued development of that environment. As such, the process can be categorized as a form of autopoiesis. The action of assembling elements encodes instructions on how to further continue the assembling process; a subassembly becomes a symbol that implicates the further advancement of that assembly—a form of positive feedback.

Stigmergy does not equate self-assembly, nor is self-assembly necessarily a process that exemplifies implicit fabrication. "Implicit" here means that the generation of the code required for construction is implicit to the design process, whereas the self-assembly process often is explicitly defined.

Evolutionary Fabrication The field of generative robotics offers a number of important ideas for the development of implicit fabrication. The grail of this emerging field is the concept of self-reproducing robots. An early and critical realization is the concept of embodiment [22]. The research suggests that to evolve robots, simultaneous evolution of brain/body is required; otherwise one might end up with a body that cannot be controlled or a brain that cannot control its body. The concept of evolutionary fabrication emerged as a consequence of the idea of embodiment. The pivotal realization is that buildability is a central concept in generative robotics. There is little meaning in the ability to produce design blueprints if these cannot be executed/self-reproduced. *"Approaching Fully Automated Design and Manufacture from this perspective requires a new formulation of Evolutionary Design, one that replaces descriptive blueprints with prescriptive assembly plans. In this approach, the formation of an object can no longer be taken for granted; we must realistically simulate not only the behavior of a finished object, but its entire assembly as well"* [52] This is what Rieffel refers to as the fabrication gap: by merely specifying the form of an object, this approach leaves unanswered the vital question of formation. Rieffel's concept revolves around the idea of situated development. The assembly process is a part of the evaluation criteria of the fitness function for the evolutionary design process; how cleverly a structure is built is part of the evaluation criteria while the structure is being optimized. Evolutionary computing is used not only to arrive at a global optimum of a design given a set of constraints, but also, in this approach, to simultaneously generate an optimized assembly plan. Fig.2.22 demonstrates the potential of Rieffel's coupled approach; here the objective of the design is to maximize the shading area. The poetic term ontogenic scaffolding refers to the temporary elements used while assembling the structure. The dynamics of the assembly are simulated and subvert the assembly constraints. As a result, integrating and exploiting the assembly constraints bring about an interesting notion: where the unfinished structure is effectively used as a tool, raising the idea of self-referential fabrication; where the construction of a structure implies this unfinished structure as an essential means of production until it is completed, when it progressively ceases to be a tool. Nadine Sterk's lamp design Sleeping Beauty suggests such an approach. Can a pavilion be a tool for the production of that pavilion until it is completed and effectively stops being a tool? An approach developed by the Cornell Creative Machines Lab research on robotically manipulatable structures [66] moves toward such procedures, where robots continuously disassemble and reassemble a constant number of structural elements to facilitate an ever-changing architectural program, an approach inspired by metabolism.

Evolutionary fabrication holds great architectural potential. Both the design and building processes are simultaneously optimized, which inspires the realization that—much the way the evolution of a robot's body requires the evolution of its brain—exploiting the true capacity of robotics in architecture requires the simultaneous evolution of building and construction processes.

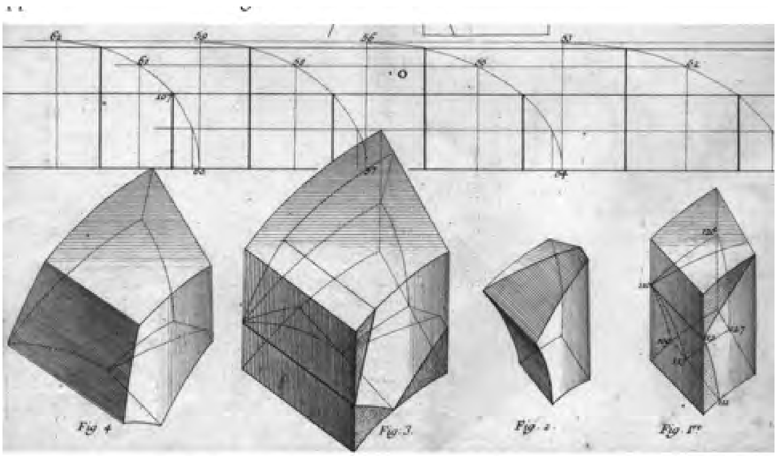

Fig. 10. De La Rue, *Traitè de la Coupe des Pierres* [1728], pl. XXX (detail)

Figure 2.24: De la Rue, Traite de la Coupe des Pierres

2.2. ARCHITECTURAL GEOMETRY

2.2.1. PROCESSES FOR AN ARCHITECTURE OF VOLUME

This paper addresses both the architectural, conceptual motivations and the tools and techniques necessary for the digi- tal production of an architecture of volume. The robotic manufacturing techniques of shaping volumetric materials by hot-wire and abrasive wire cutting are discussed through a number of recent projects. A comparative analysis between milling and hotwire cutting is presented and a number of case studies and tool development studies are considered. Finally, the specifics of toolpath generation for robotic wire cutting are introduced.

INTRODUCTION

There has been a growing interest in material processes that can support an architecture of volume, investigating materials which are unconstrained by the limitations of sheet based materials. Our initial investigations in processes for an architecture of volume explored the lightest and least expensive volumetric material available, EPS foam. This material has seen many applications in the mold making, highway and construction industry, as it is cheap, recyclable, extremely light and easy to shape. This material is typically carved using large CNC routers, and for double curved geometries this is still a requirement. The material can also be cut with a hotwire, which provides a method whose historical precedent can be associated with stereotomy and the developed surface of traditional stone masonry [2] Fig.2.24.

Architectural production has been systematically compressed into ever thinner layers by the constraints of industrially processed materials. CNC fabrication processes, initially heralded as liberating the designer from the disconnect between drawing and making,

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This section is based on *W. McGee, J. Feringa. Processes for an Architecture of Volume, RobArch 2013* [104]

Figure 2.25: Subdivided columns, M. Hansmeyer (left); Metropol Parasol, J. Mayer (right)

have accelerated the process, packaging components into the discrete 4’ x 8’ work envelope of the typical 3 axis router. In addition, streamlining the workflow from design software to fabrication processes (while this has many positive benefits), has in some ways allowed this “flattening”, slicing, slivering and wafering of building construction methods to go unquestioned. Openly available scripts allow 3D surfaces to be ribbed, unrolled and nested into common sheet sizes, ready for production. Contemporary digital fabrication techniques continue to proliferate this limitation, producing a stream of contoured, folded, notched and otherwise surface-driven projects.

This scope - that of a representational model - is sufficiently nebulous in terms of scale to abstract architecture from its realization. The irony of the proliferation of CNC methods such as 3D printing, 2D laser cutting, and routing is that its obscures the industrial potential of the close coupling of design and manufacturing methods. This becomes problematic when these false or self-imposed constraints become the aesthetic of the building, where the approach of building a representational model has been projected to its full size, as observed in the “Metropol Parasol” project by Jürgen Mayer Fig.2.25. An interesting example that simultaneously illustrates the merits and limits of this approach is the work of Michael Hansmeyer. His “subdivided columns”, a series of 2.7m high columns, built from 1mm layer grey cardboard Fig.2.25. While the intricacy and elegance of the work is not questioned, the project is antithetical in terms of fabrication; columns are load bearing structures that aren’t made of cardboard, and the intricacy can be subscribed to the strong will of architectural students, rather than architectural engineering. A consequence of exploring methods of construction that have little or no manifestation in building practice can be construed as a form of technological self-censorship. With the mechanics, tooling and technology available, it is paramount to focus research on those modes of production that do scale, hence are of value to the construction industry.

While advanced manufacturing methods have traditionally been associated with costly manufacturing methods, robotic hotwire cutting (hereafter RHWC) breaks with this trend given that complex formwork can be delivered for the approximate cost of normative formwork. As such RHWC is both an enabler, technically, in terms of forms that can be produced, and economically since this can be achieved at little or no additional expense. With the many ongoing predicaments in the construction industry, and the modest cost of delving into robotics, this is an important aspect that is open to further exploration.

Hyperbody’s robotics lab is equipped with two second hand ABB S4 robots, that were both acquired for less than what a makerbot costs Fig .2.26. Brand new robotic manipulators typically cost less than half the price of a typically capable dedicated CNC machine. Robotic fabrication presents a development platform for such considerations, given the trade-off of precision, ease of integration and programming, robustness, and market availability. As the technology has begun to gain acceptance in the building fabrication industry (admittedly it remains a very small fraction), these methods have started to challenge what type of construction can be delivered within a given budget.

ROBOTIC HOTWIRE CUTTING

Hotwire cutting holds a number of advantages when used to create formwork for casting. At an architectural scale, traditional approaches such as CNC milling become prohibitively time consuming. At the sheer volume demanded for full scale architectural in situ casts, such as bridges and commercial buildings, the incremental removal of material offered by the milling technology necessitates considerable machining time and results in production fees unacceptable to most building budgets [86, 88]. Machining hours may be reduced by tolerating a rougher surface, however, production times remains prohibitively high, and the rough tooling paths simultaneously frustrate the demoulding process. This limits the application prospect for CNC-milling technology primarily to detailing tasks, exclusive high-end building budgets and repetitive casts, where formwork may be reused. RHWC offers a number of advantages. The removal of material in this process is essentially volumic; the cutting process processes a surface in a single sweeping motion, whereas in milling the volume is removed layer-by-layer, constrained by the limited depth of the milling bit. Per surface, the length of the tooling path is parameterized over the radius of the milling bit, where often a roughening milling bit is used with a large diameter to approximate the shape quickly, while a milling bit of a smaller diameter is required to achieve a smooth surface. In addition, the RHWC leaves a surface considerable smoother than that of the milling process, producing a better surface finish on the cast product, while reducing demoulding adhesion. For extremely finished surfaces the mold can still be coated with polyurea, requiring less coats than a typical milled finish. The difference in production speed is easily understood geometrically; whereas milling essentially removes a sphere, RHWC removes a cylinder of material at an instance in time Fig.2.27. That amounts to a difference of 1 to 2 orders of magnitude, as the following comparative study shows, approximating the differences in production time for either production technique Tab.2.1.

Table 2.1: Machining metrics comparing the CNC milling with RHWC

Method	ex. A	ex. B	ex. C	ex. D	ex. E
CNC rough.	3h 34m	5h 5m	3h 44m	4h 22m	6h 31m
CNC finising	6h 44m	7h 42m	7h 01m	7h 31m	12h 14m
RHWC	0h 01.8m	0h 02.4m	0h 02.3m	0h 02.7m	0h 03.1m
Area cut	2.66m^2	2.95m^2	2.86m^2	4.01m^2	3.49m^2
Removed vol.	1.44m^3	2.06m^3	1.44m^3	1.72m^3	2.41^3

It is important to mention that, while the increase in production speed is dramatic, the

Figure 2.26: Production of the RDM Vault at Hyperbody's robotics workshop in Rotterdam

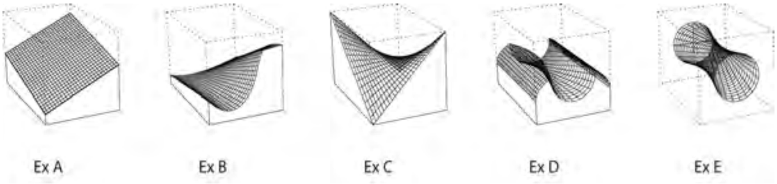


Figure 2.27: Comparative scheme of sample geometries

additional effort of rationalizing geometry to ruled surfaces — a key topic of architectural geometry — is not factored into this comparison. While RHWC is remarkably efficient, the geometric grammar that can be produced is a subset of what can be produced by milling. However, it is important to realize that architectural scale works in favor of RHWC. First of all, in the sense that forms which traditionally would not be manufactured by CNC methods can now be produced. Secondly, due to scale, the limitation to ruled surfaces becomes less of an issue, since a greater surface area makes constructing a satisfactory approximation less problematic.

PROJECTS

A number of case study projects have been performed to validate the capabilities of RHWC. In "Periscope", by Matter Design Studio, the hotwire process provided the means for the rapid production of a 50 foot tower of foam Fig.2.28. The economy of time and material was of paramount importance, due to the pressures of a two week construction window and limited budget. The RHWC process was used to generate a large array of mass customized masonry units, which were assembled in a running bond to approximate the original, doubly curved column. In an effort to establish a characterization of the various approaches to working with volumetric materials, one could consider this a "slab based" process, whereby components are cut from a slab of material, preserving some portion of the slab surface on the top and bottom of the part Fig.2.29. In this case the preservation of the parallel top and bottom surface is important to support the assembly technique. A more recent project by students at the University of Michigan uses the slab cutting process to shape AAC sheets into voussoir units to form a thickshell compressive vault. In this case the prototype uses abrasive waterjet cutting to cut the 4" thick AAC block. Previous work at the University of Michigan saw the application of this technique to process 2" thick sandstone (in slab form), uniquely cut to form thin-shell vault components. Wire cutting becomes more efficient and precise at larger material thicknesses, and opens up the possibility of structural systems that respond to additional factors beyond the material efficiency of the thin shell vault [102]. Clifford describes this as a shift from form-finding to form-responding, and uses it as an approach to develop structurally viable forms requiring relatively thick sections. The ability to work with volumetric materials is critical to the success of the process Fig.2.28.

An alternative approach to "slab cutting", which adds an additional level of geometric freedom, is the "solid" based cutting process as explored in recent projects by Hyperbody Fig.2.29. A recent collaboration between Hyperbody, ROK Office and the Block Research Group ETH Zurich, the RDM Vault Fig.2.32, explores a joint approach to the design and fabrication of vaulting structures, as evoked in Rippmann and P. Block[142]. RhinoVault[96] provided intuitive tools for the design of a vaulting structure, while PyRAPID enabled the transliteration of the resulting geometry to robotic motion, cutting the "traites" out of EPS foam. The pavilion was erected at Hyperbody's robot lab which will host the RobArch workshop in Rotterdam Fig.2.31.

In this case the components are nested completely within a volumetric block of

Figure 2.28: Periscope completed

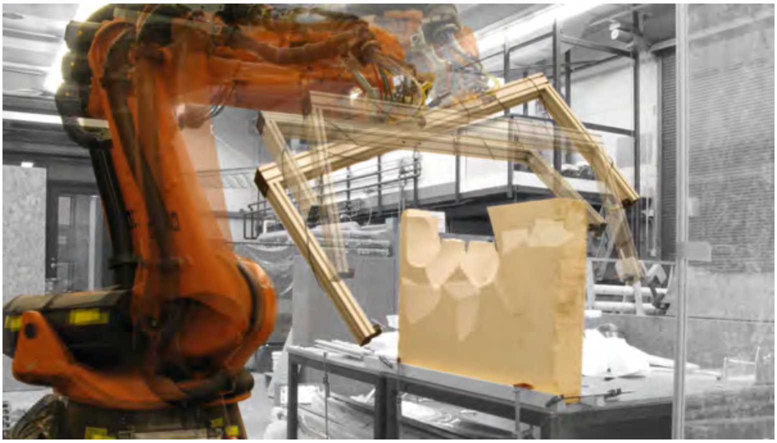


Figure 2.29: Slab cutting EPS

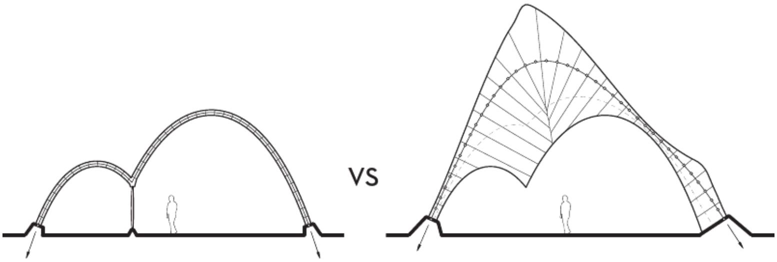


Figure 2.30: Thick funicular solver

Figure 2.31: Solid based cutting process, as explored in the RDM Vault

Figure 2.32: RDM Vault

material. All faces of a component are wire cut, as opposed to the slab cutting process, which relies on a parallel top and bottom face. While the cut surfaces are still limited to ruled geometries, by shaping the entire exterior of the component the aggregation can more accurately approximate a freeform surface, while producing joint faces which are normal to the thrust vectors. Component sizes and shapes will still be governed by their ability to fit within an available volume of material.

FROM HOTWIRE TO ABRASIVE WIRE

Building upon the work with EPS, there have been a number of investigations using more permanent volumetric materials, such as AAC (autoclave aerated concrete) and natural stone. It is against this background that several projects were undertaken using robotically manipulated abrasive wire cutting equipment. While numerous projects have investigated the geometric potential of hotwire cutting EPS, considerably fewer have dealt with developing the end of arm tooling to mount abrasive wire saws to robotic equipment for the purpose of cutting more rigid materials. While wire cutting harder stone materials remains a very slow process, there are several advantages when compared with CNC milling or multi-axis bridge saw cutting. The capital cost of the equipment is considerably less (one third to one half), with the generic robotic manipulator costing far less than a stone capable CNC, even after factoring in the cost of integration and tooling. In addition, the implication of the process as a semi-finishing operation makes it more appropriate to the tolerances possible using robotic manipulators, as opposed to more precise CNC equipment. There are also potential material efficiencies that can develop, given the much smaller kerf of the segmented wire compared to milling and sawing, although these

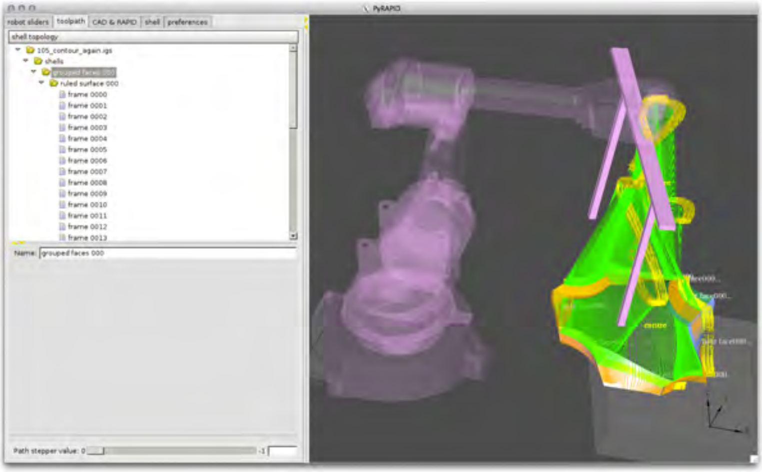
Figure 2.33: 6 axis CNC diamond wire saw (left); Wire sawing end-effector developed at the University of Michigan Taubman College (right)

will be highly geometry dependant.

Segmented diamond wires are well known for their ability to cut harder materials like natural stone (marble, granite) and reinforced concrete. Typically, the wire sawing process is used for either semi-finished flat slab cutting applications, or large scale demolition. There are exceptions, of course, such as this large 6 axis CNC wire profiling system by Pellegrini Meccanica Spa Fig.2.33. The machine clearly illustrates the possibilities for multi-axis wire cutting, but it also presents opportunities for a more flexible, portable approach to fabrication.

Dedicated CNC approaches are likely to always possess an advantage in terms of accuracy and overall capacity, but there are potential applications where the flexibility and portability offered by industrial robotic manipulators can fill a unique role in fabrication. Several researchers have tested applications for robotic wire sawing, but the capabilities of a robotically guided wire cutting operation to yield complex units in a finished/semi-finished state has not been studied extensively. It is worth pointing out that just over a decade ago “nearly eight hundred full-size DIN A0 templates were required to guide the stonemason’s hand” in completing the translation from model to workshop[32]. Shutao Li, et al.[48] developed a proof of concept production line to machine AAC slabs directly from BIM data. The tooling developed utilized a segmented diamond wire circulating in a rectangular frame. This approach has also been used in combination with a spiral cutting steel wire, cutting ruled geometries out of cured plaster [93] Fig.2.33.

The authors are currently engaged in developing end of arm tooling for robotic diamond wire cutting (hereafter RDWC), with a number of areas targeted for study. Robotic applications will require the tooling to be considerably lighter than the CNC applications highlighted above. This is not a trivial task, as even a typical manual profiling diamond



Name: grouped faces 000

Figure 2.34: PyRAPID, custom RHWC software develop on top of PythonOCC

wire saw can weigh 500 lbs[13]. In a typical wire cutting operation, as in band sawing, there are guides which support the blade opposite the travel direction. In the case of 3D wire cutting, the wire is capable of moving in any direction. The guide system needs to support this, and potentially will require a servo driven solution for positioning relative to the cut direction, similar to the CNC equipment described previously.

SOFTWARE

It can be argued the generic robotic manipulator utilized in this research is only incrementally different to it ancestors which were in continuous use in mass production for decades. Without a doubt, one of the driving factors behind its growing adoption in the architectural fabrication industry is the use of open source and bespoken software applications. While robotic manipulators provide incredible flexibility, this comes at the price of developing tools which suit both the designer and fabricator. Compared to CNC equipment, which has clearly also benefited from the developing culture around scripting and algorithmic design methodologies, robotics has the added benefit of compatibility with an open framework for fabrication. Closed-loop process feedback and the “ease” of integration into a multifaceted production process are relatively complex to perform using traditional CNC equipment; with robotic manipulators these capabilities are integral to the design. Such open frameworks are superMatterTools, developed by Wes McGee and Dave Pigram, Daniel Piker’s lobster, Robots-inArchitecture’s KUKA|prc, PyRAPID by Jelle Feringa and HAL by Thibault Schwartz.

A key motivation for the development of open frameworks is how existing approaches such as contour cutting can be adapted to the solid cutting process Fig.2.31, which are considerable more demanding in terms of toolpath generation, motion planning and collision avoidance. An interesting aspect is how the software developed for the exploration

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[13] See the Pellegri catalogue

of RHWC maps with modest adaption to RDWC. Hotwire cutting is a comparatively safe production method compared to the brutality of the diamond wire sawing process, so the evolution of RHWC naturally paved the way for RDWC. Whereas the development of RHWC was demanding in terms of software development and trivial in terms of the required tooling, these roles are reversed in the continued development of RDWC, where building a practical wiresaw is demanding.

The potential of RHWC and RHWD was explored with PyRAPID a software application was developed in Python with PythonOCC, a wrapper of the OpenCASCADE CAD kernel as it main dependency Fig.2.34. The application automatically clusters the faces so that they can be cut in a single sweeping motion, and generates a toolpath optimized for extending the reachability of the end-effector, and computes the inverse kinematics from that pose. As the tool orientation has a degree of freedom over the axis of the wire, the key is to exploit this, as it allows for considerable optimization of the reachability of the robot.

After clustering the faces the software tests whether an additional roughening step is required. The roughening step is specific to robotic hotwire cutting, while with a traditional hotwire cutting machine no clashes between the tool and workpiece occur. The downside, however, is that to cut large blocks, a considerably larger machine is required, while a robot is a fairly compact machine, certainly in view of its reachability.

Ongoing efforts include logistics, such as the integration of picking and placing, in order to facilitate a production workflow that minimizes operator attendance. The added flexibility and process integration of this setup is a topic of further research. An important argument why robotic hotwire cutting has considerable merits over a classic CNC hotwire machine is specifically the issue of process integration.

2.2.2. AN EXPERIMENTAL DEVELOPABLE-TRANSFORM BASED ON THE LEVELSET METHOD AND TOPOLOGICAL SKELETON

Segmentation of a free-form surface to a set of panelizable elements is a quintessential problem of Architectural Geometry. The developable-transform is a manifestly architectural problem since it involves aspects that are geometrical, industrial, economical, structural and of aesthetics. Much of the current work is focused on either of these aspects; however, an ideal approach would synthesize a number of these. In this paper an attempt is described on such a multivariate approach. A project for the design of a roof of a factory hall is presented that seeks to integrate both geometrical, industrial and structural aspects. Our approach evolves a front propagated by the levelset method over an anisotropic distance field, where the distance is adjusted according to local gaussian curvature. The front originates from local maxima within the distance field, consequentially traces the topological skeleton of the free-form surface.

INTRODUCTION

The developable-transform lies at the heart of Architectural Geometry[55]. Seminal work has been done in this domain has been contributed by architect D. Shelden [35] and mathematician H. Pottman et al [61], important contributions coming from computer scientists such as A. Sheffer et al [56] architect A. Kilian [36]. The developable-transform is a classical architectural topic, dating back as far as Philibert de L'Orme's design of the trompe of Château Anet of 1559 [14]. The developable-transformation is a multi-variate problem; it touches upon criteria that are geometrical, structural, industrial, economical and involves aspects of manufacturability and of aesthetics.

RELATED WORK

Only recently research aims to deal with this multitude of aspects [74]. The approach described here, as well of that described in this paper is aligned with an approach called Industrial Geometry [44], which seeks to integrate advances in the areas of CAD, CAM, Geometric Modeling, Robotics, Computer Vision and Image Processing, Computer Graphics and Scientific Visualization. For the problem of surface segmentation, the level set method [21] offers potential. The levelset is of interest since it uses an implicit approach rather than a parametric. If a shape optimization problem is formulated in terms of parameters or geometrical design variables, it usually does not allow for topological changes nor free-form boundary changes. Also, the design space of a parametrically defined shape is much smaller than that of a free-form surface locally parametrized by a b-spline function. Using the levelset method, this issue is resolved by representing the boundaries of a free-form surface implicitly in terms of a higherdimensional, time-varying hyper surface.

ASPECTS OF AN IDEAL SURFACE SEGMENTATION

What qualities define an ideal surface segmentation algorithm?

- Panels are bound within the constraints of industrial production.

This section is based on *J. Feringa. An experimental developable-transform based on the levelset method and topological skeleton, ALGODE 2011* [80]

- Geometric continuity; the angle between the various panels is minimized.

- Global orientation of the panels should be propagated smoothly.*visual* continuity; a continuity in the *orientation*; changes in the orientation of the panels should be propagated smoothly.

- Angular continuity; angles between diminimized, these should be as constant as possible.

- Structural continuity; ideally panels follow the structure of the building naturally. The load carrying structure and panels shouldn't be two disjoint geometric systems, but ideally originate from a *unifying* geometric principle.

- An *economy* of form; form is costly, therefore scarce. Panels are adapted to panels can be of a greater area, reserving detail for areas of the surface with greater fluctuation in curvature.

- Ideally, the surface segmentation a developable-transform produces augments the surface it approximates, therefore can be considered an integral part of the architectural design, rather than the product of a post-rationalization process. Hence the development of a surface segmentation algorithm is just a much design problem as it is a geometrical problem.

Description of the developable transform – anisotropic distance

The approach laid out in this section is based on image processing. Image processing toolkits such as VTK[14] and in particular ITK[15] offer a wide range of tools that are oriented towards segmentation. ITK, which offers state of the art image processing algorithms, is developed specifically for this purpose. Since a nurbs patch is a an embedding of $\Re 2$ in $\Re 3$, we can essentially deal with surface segmentation in $\Re 2$. Which allows our approach to be implemented in parametric space rather than cartesian space. A prototype of the software has been implemented in python[16]. The approach put forward in this paper seeks to integrate three aspects; that of the topological skeleton [7], the Daniellson distance transform [9], and curvature by means of the levelset method [21].

topological skeleton — daniellson distance transform The surface to be segmented is sampled for areas where the surface is trimmed, resulting in a binary image that represents the borders of the surface. From this image, the Daniellson distance transform computes an image where each pixel stores a displacement value to the nearest point on the border of the surface. Consequentially, the Daniellson distance transform computes the topological skeleton of the surface. The topological skeleton is the set of points in space equidistant to two or more points on the surface.

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[14] the Visualization Toolkit, an open source toolkit oriented towards scientific visualization

[15] the Image Segmentation & Registration Toolkit, an open source toolkit oriented towards medical visualization from MRI data

[16] The implementation was build upon the open source libraries VTK, ITK and PythonOCC.

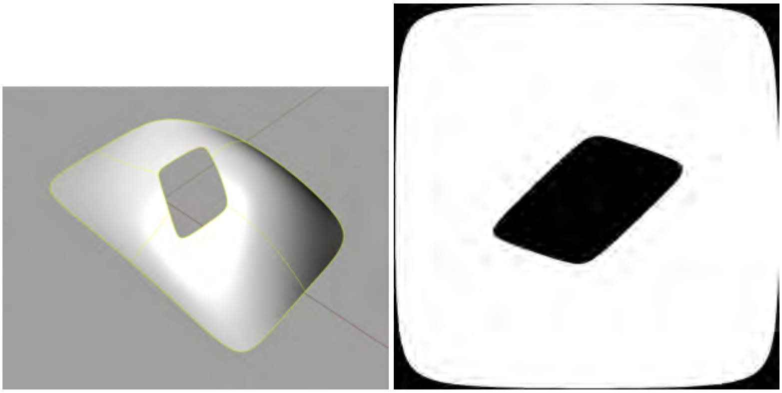

Figure 2.35: *Left:* The surface that will be segmented. *Right:* The first stage of the algorithm is scanning where the surface has been trimmed. This results in a binary field that delimits the surface

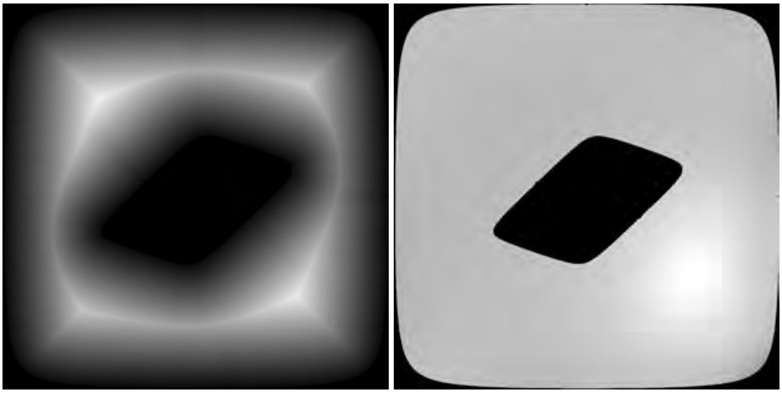

Figure 2.36: *Left:* From the trim field, the Daniellson distance field is computed. *Right:* The gaussian curvature of the UV domain is sampled

form - gaussian curvature Our approach towards form is essentially economical. Form is considered to be costly, therefore more should be distributed where there is greater fluctuation in curvature and used sparsely in areas of that have less deviation in curvature. In terms of the developable-transform; the width of the panels should be adapted to the local curvature.

anisotropic distance field An advantage of developing a segmentation algorithm based on image processing is that some operations become trivial. For example; combining the Daniellson distance field with that of the gaussian curvature field is a matter of normalizing the values in the fields and choosing a ratio between distance and curvature after which the two fields can simply be added. The resulting field is a anisotropic distance

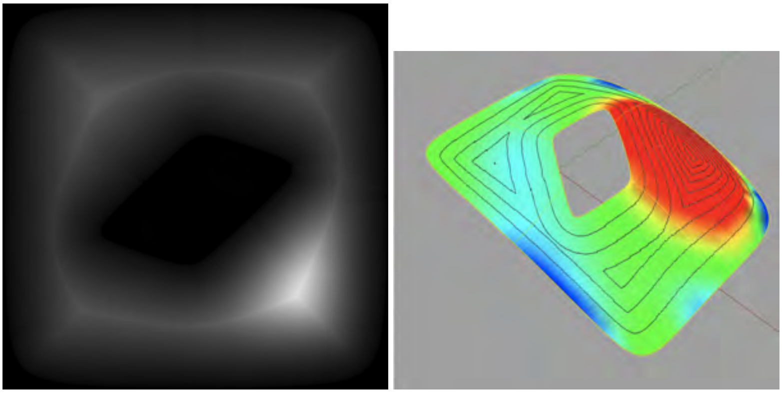

Figure 2.37: *Left:* After normalizing the distance and curvature field, the Daniellson distance field is scaled by the gaussian curvature field. *Right:* contouring of the combined gaussian curvature distance field, demonstrating how the field is adapted to the curvature

field. This field is used as a speed image through which a levelset will evolve. Areas that have locally greater variation in curvature will slow down the evolution of the levelset, resulting in a panelization that is adapted locally. The anisotropy of the field could be defined by any property; rather than choosing gaussian curvature the distance field could be augmented by the addition of a field that describes the local mechanical strain for example. The mapping of a property to the distance field could be further enhanced by a third field that describes the local relevance of the property in relation to the surface, such that the ratio between the distance field and curvature field can be locally defined. This approach allows one to strike a balance between distance and other properties that the segmentation strategy should accommodate.

contouring - levelset Initially, a marching squares contouring algorithm was used to segment the distance field Fig.2.38. However, where ever there is a local maxima in the field, a topological discontinuity is introduced. That would result in areas that are very challenging to build and break with the aesthetic principle of continuity in orientation of the panels. To overcome this issue, a levelset was propagated from the topological skeleton. The topological skeleton is a thin version of the shape equidistant to its borders. This results in a segmentation that are simple closed curves by construction; curves do not overlap, therefore no topological discontinuities are introduced. An interesting consequence is that this property results in a visually very continuous series of panels Fig.2.38. The fact that the levelset evolves perpendicular to the topological skeleton, could be of structural interest, for instance in roofing design; a canonical roof *is* essentially based on a topological skeleton[17]. Finally Fig.2.38 the levelset front is propagated from the local maxima of the distance field, which lie on the topological skeleton. These points are locally the furthest points from the surface border. The distance field then has

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[17] Roofing design can be easily generated by a so called straight skeleton algorithm. It shares similarities with the medial axis, but consists of only straight segments, where a medial axis can consist of more complex form

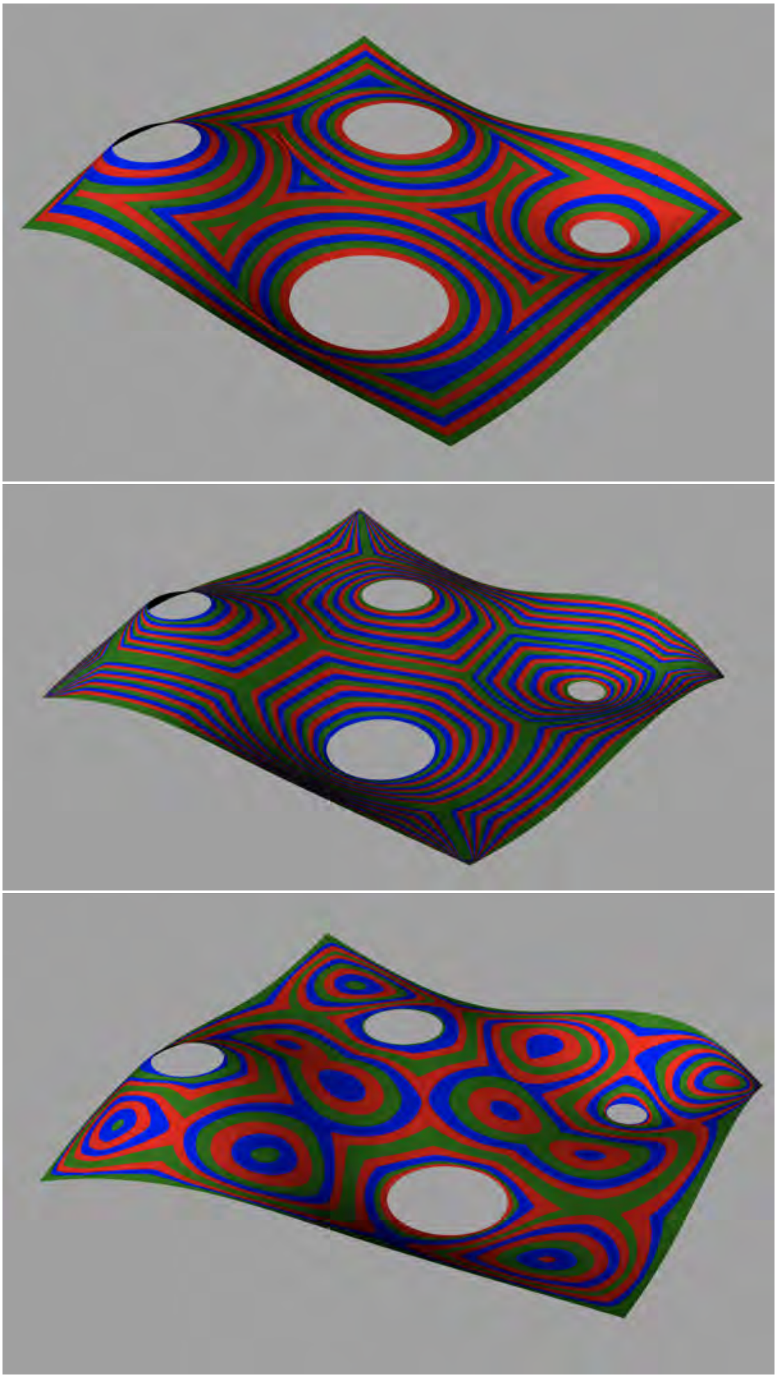

Figure 2.38: *top]:* a first, naive implementation where the distance field is contoured by a marching squares contouring algorithm *middle:* segmented using a geodesic active contour levelset; note the smooth transition from the topological skeleton towards the borders of the surface *bottom:* here the levelset departs from the local maxima in the distance field. The levelset evolves through anisotropic distance field, where the distance field has been augmented by a gaussian curvature field.

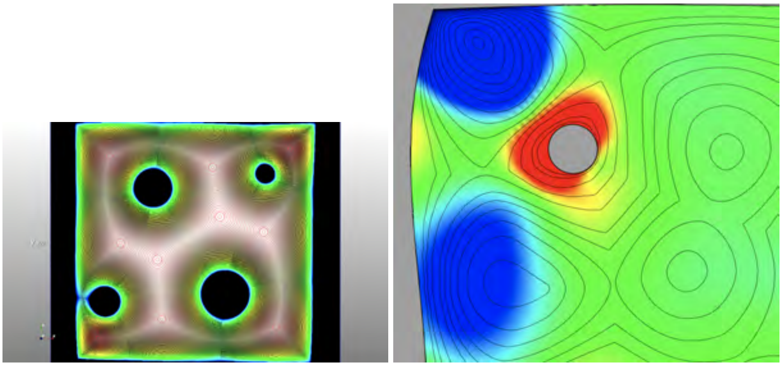

Figure 2.39: *Left* Contours of the levelset superimposed on the distance field *Right* Contours of the anisotropic distance field superimposed on a gaussian curvature field, underscoring the relation between the distance and curvature

been augmented by a gaussian curvature field, resulting in an anisotropic distance field. Because the levelset is propagated from a set of points, a saddle-point will be located at the middle point of the voronoi edge that connects a pair of seedpoints[18]. Fig.2.39 illustrates the relation between the distance and curvature in the anisotropic distance field.

Limitations of the approach A possible limitation of our approach is that with certain surface parametrization deviation between parametric and cartesian space might occur. In the experiments presented in this paper, this deviation was negligible. Geodesic distances from the topological skeleton to the surface border were found to be equidistant. Resampling the resulting curves such that a reasonable number of control vertices is obtained requires careful parametrization.

CONCLUSION

We have presented an experimental method for surface segmentation that bears resemblance with an approach outlines in [44]. We find that working with image data in combination with levelsets suitable for the application of surface segmentation. Due to the non-parametric, higher-dimensional nature of the levelsets one is able to generate patters that are remarkable accurate, given the limited resolution of the sampled fields. For the research presented in this paper, we found that using images of about 800 by 800 pixels is a good trade off. Using images of greater resolution results in curves that have such a large number of control points that these become difficult to post-process with CAD software.

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[18] A voronoi edge lies equidistant from the voronoi sites

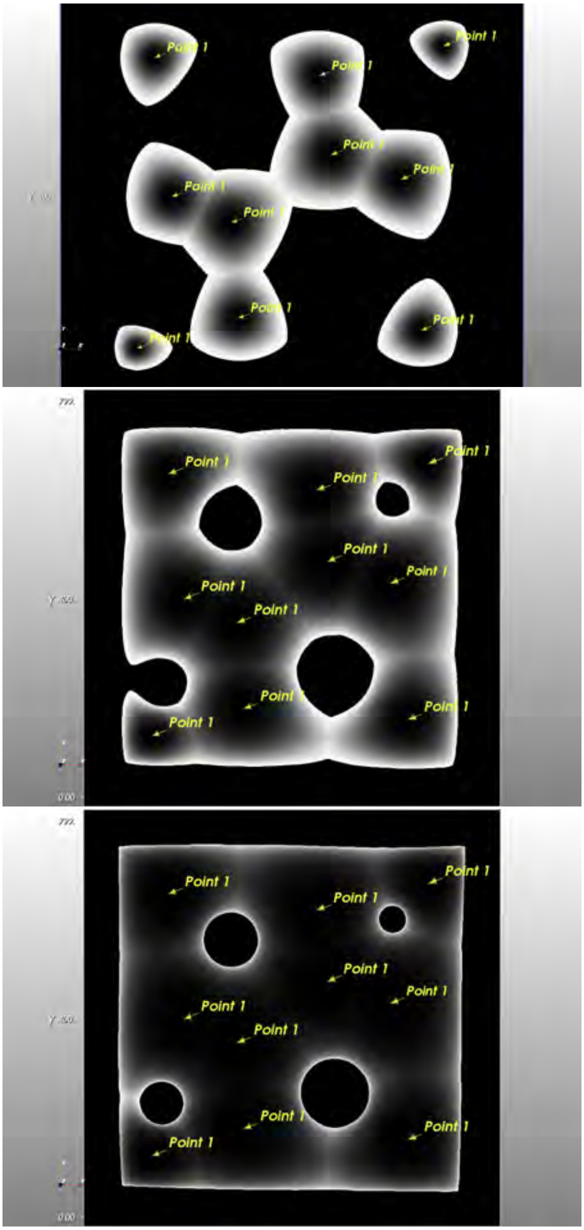

Figure 2.40: Various stages of how the levelset propagates through the distance field. The yellow arrows indicate the seedpoints from where the levelset departed from

Figure 2.41: RDM Vault

2.2.3. FABRICATING ARCHITECTURAL VOLUME

STEREOTOMIC INVESTIGATIONS IN ROBOTIC CRAFT

The 2011 edition of Fabricate inspired a number of collaborations, this article seeks to highlight three of these. There is a common thread amongst the projects presented: sharing the ambition to close the rift between design and fabrication while incorporating structural design aspects early on. The development of fabrication techniques in the work presented is considered an inherent part of architectural design and shares the aspiration of developing approaches to manufacturing architecture that are scalable to architectural proportions [68] and of practical relevance.

RDM VAULT

The RDM vault presents a collaboration between Matthias Rippmann[19] and Silvan Oesterle[20], initiated by Jelle Feringa[21]. Earlier work [88] Fig.71 suggested the necessity of dealing with structural design aspects early on in the design phase. An important constraint to building with expanded polystyrene (EPS) elements is their limited capacity to deal with tensile forces, while the material can cope with considerable compression forces. The project therefore sought to deal with both structural and fabrication constraints as the driving parameters of the design phase. RhinoVault, developed by the Block Research

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This section is based on *J. Feringa, A. Søndergaard. Fabricating architectural volume: stereotomic investigations in robotic craft, Fabricate 2014* [80]

[19] Matthias Rippmann is a member of the Block Research Group, ETH Zurich and a founding partner of ROK Office.

[20] Silvan Oesterle is a member of the Architecture and Digital Fabrication Group, ETH Zurich and a founding partner of ROK Office.

[21] Jelle Feringa is a PhD candidate at Hyperbody, TU Delft, co-founder of EZCT Architecture and Design Research and founding partner / CTO at Odico Formwork Robotics.

Group provides powerful and intuitive design tools for the design of compression-only structures. Earlier work was built with a custom-built and fairly improvised machine specifically for hot-wire cutting Fig.70. While that resulted in precise elements, both the software and design of the machine had a restrictive platform. Robotic hot-wire cutting[104] (RHWC) coupled with the development of the PyRAPID CAM software dedicated to RHWC, allows the application of a truly voluminous approach to the production of the trait[22] the RDM vault is comprised of Fig.2.41. At the time of construction, deploying RHWC for the first time at Hyperbody's Robotics Lab for the production of very large and geometrically challenging elements, the tolerance of the cut elements was unknown and therefore the design's shingles were accommodated for the eventual tolerances. As such, fabrication constraints become design drivers. In hindsight, margins for assembly were greater than the cutting tolerances (ranging from 1 – 2 mm). The project was designed and executed in the course of a month, emphasising the importance of experts having the opportunity to collaborate. The EPS elements were rendered with Acrylic One, a gypsum/acrylic composite material, and glass fibre. Resulting in a structural shell, a rendered finish and a fireproofing layer were applied to the EPS structure, increasingly the longevity of the fragile foam components. Though the approach has many practical merits, in the end, the project suffered from an architectural ambivalence that could be traced back to its materialisation. There is a precarious unease present whether one observes a 1:1 mock-up of an architectural intent (a representation) or the artefact as conceived. That apprehension extends to the inconclusiveness of whether the vault is an assembly of individual traites, or a monocoque glass fibre reinforced shell Fig.2.42. While efficient, practical and economical, the materialisation of the RDM Vault lacked a tactile and tectonic quality.

STONECUTTING

The concern of tectonics pushed the volumetric approach to fabrication further towards stereotomic tradition and towards a more permanent materialisation, fuelled by the development of a diamond wire saw. The powerful abrasive wire saw is powered by a 40 Kw hydromotor and allows the processing of stone at a very high speed. While stonecutting is a mechanically and time-intensive process, the effectiveness of abrasive diamond wire cutting, traditionally a demolition method, is easily proportionate to the speed up (an order of two) achieved by RHWC.

This research has precedents in the work of Shutao Li, et al[48], machining AAC slabs from BIM data and Bard, et al [93], where a spiral cutting wire was applied to process cured plaster, while the work presented here is focused on the lost art of stereotomy and processing hard mineral materials.

Elements shown in Fig.2.43 were fabricated in 20 minutes per piece. These initial experiments were conducted with an inexpensive material, engineered limestone. This experiment was conducted at Hyperbody's workshop for the first edition of the Robots-in-Architecture conference, taught by Wes McGee, Jelle Feringa and Lauren Vasey. The

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[22] The workers call the science of the trait, when cutting the stone, the science that teaches how to cut and separately construct more than one ashlar of stone so that, when they are put together (at the right moment), they create a piece of handwork that can be considered as a single object[2]

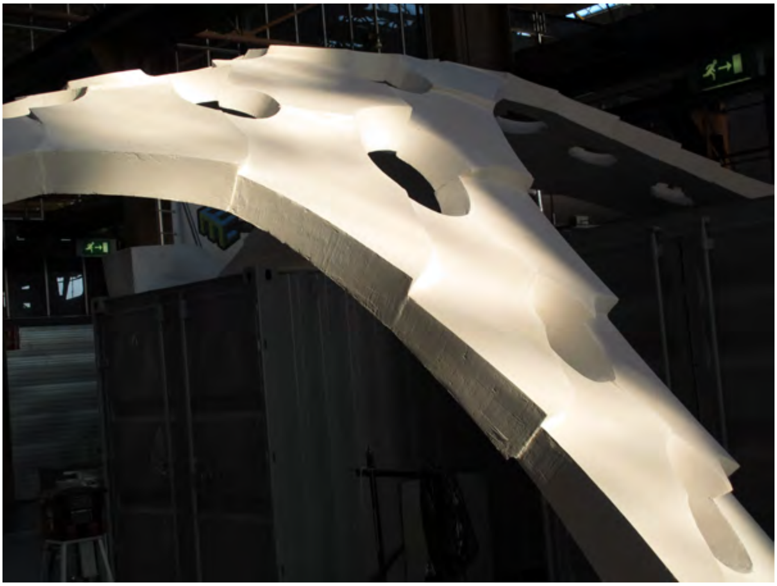

Figure 2.42: Discrete components merge into a continuous shell, lacking tectonics

Figure 2.43: Initial test cuts in engineered limestone

Figure 2.44: Experimental diamond wire saw setup

diamond wire saw was engineered and built by Jelle Feringa and Frank van Brunschot with the support of the industry partner Husqvarna. Further research took place in the summer of 2013 at the marble quarry of Carrara, in cooperation with industry partner Marmi e Graniti d'Italia, one of Italy's largest quarries Fig.2.44.

The work on robotic diamond wire sawing (RDWS) research is taking place right at the intersection between revisiting a long-lost ancient craft while employing state-of-the-art industry tools and bespoke software development. As such, the work is pleasantly equivocal; rooted in many centuries of a progressive architectural tradition while empowered by recent advances in industry and custom CAD software.

Stereotomy is resurfacing as a contemporary technique since Robin Evans formative book *Projective Cast: Architecture and its Three Geometries*[15] appeared in the early 1990s along with Bernard Cache's seminal work and writings in the late nineties[26]. Many recent projects, such as the MLK Jr. Park Stone Vault in Austin, Texas, by the Block Research Group[105], Brandon Clifford's recent publication, *Volume – Bringing Surface into Question*[107], and Matter design's *Voûte de LeFevre*[101] as well as Giuseppe Fallacara's many publications [79, 115, 139] and projects emphasise the relevance of the line of inquiry.

OPTICUT

During the Fabricate 2011 conference, the authors of this paper presented projects that dealt with topology optimisation (TO) and hot-wire cutting. It was instantly clear that while topology optimisation motivated the need for sophisticated formwork, hot-wire

Figure 2.45: Diamond sawing of excess marble

cutting could provide these in architectural proportions, at a modest cost, and, as such, offer substantial complementary advantages. With forces joined, the Opticut project launched to explore the architectural and performative potential for large-scale realisation of optimised spatial structures through the use of RHWC and casting concrete. A research partnership between Aarhus School of Architecture, TU Delft's Hyperbody's Robotics Lab, Odico Formwork Robotics and HiCon was mobilised.

Recent developments in topology optimisation of concrete structures has shown significant potential for form-finding and design of material-efficient structures, in which up to 70% of material consumption may be reduced in comparison to massive equivalents, while respecting normative performance requirements [62]. This material economy is achieved through the development of advanced structural morphologies, which minimise the required material volume to achieve structural performance through the densification of material in the trajectories of minimal deformation energy while maximising structural stiffness. As a consequence, new architectural shapes emerge, rendering the trajectories of structural force visible. Topology optimisation induces a significant moment of morphological unpredictability, as topologies emerge freely within an unconstrained solution space. The architectural specificity of these circumstances were initially investigated in the Unikabeton project, resulting in the realisation of a 12 × 6 × 3.3 m concrete structure using robotic CNC milling of EPS moulds . The project brought two conclusions:

- Topology optimisation's resulting structures, though structurally feasible, overstrain challenges in in-situ casting and formwork production.
- CNC milling of EPS formwork is prohibitively time-consuming and therefore costly to scale up to architectural proportions.

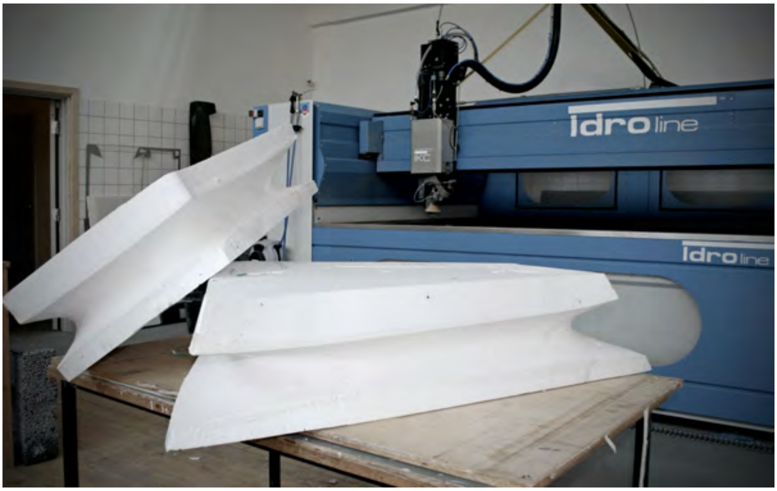

Figure 2.46: Opticut sample moulds

Concluding that a coupled design / fabrication process is key to achieving the merits and potential material savings offered by TO, Opticut initiated a dual investigation program to explore the capacity for an economically efficient production of advanced formwork for topology optimised spatial concrete structures using robotic hot-wire cutting (RHWC) of EPS formwork Fig.2.47. The first part of the project investigated the geometrical post-rationalisation of the mesh resulting from the topology optimisation process, by composing single- and double-ruled surfaces. In the second part, the necessary production procedures and software were developed. Currently, the construction of an over 20 m full-scale prototype structure on the coast at Aarhus is continuing and is scheduled for completion in February 2014. The design was formulated as a TO problem subject to wind and dead loads. Anticipating later post-rationalisation by ruled surfaces, the envelope was constructed from ruled-surface geometries, merging three typologies: the corner, the wall and the canopy.

Early experimentation found that translations using compositions of simple hyperbolic paraboloids from circular or ellipsoid starting geometries proved to be inadequate for approximating the TO's resulting mesh. Consequently, a procedure to create n-sided, irregular, hyperbolic paraboloids from non-parallel, double-ruled construction planes was devised. This approach allows for a parametric interpretation of the perforated topology while achieving surface curvature continuity. The prototype was designed for subdivision in six primary elements ranging from 10 × 3.5 × 1.7 m to 7 × 2.5 × 0.3 m. Casting the elements is achieved by using EPS plugs Fig.2.48 inserted in conventional in-situ shuttering systems, able to resist casting pressures on vibration tables commonly used in the prefabrication industry (figs. 9, 11–12).

The formwork is produced at Odico's production facility, utilising the world's largest

Figure 2.47: Post-rationalised prototype design

robotic hot-wire cutting machine, an ABB IRB-6400R industrial robot mounted on a 24-meter long linear axis Fig.2.49. While milling and hot-wire cutting cannot be directly compared, since cutting is geometrically a more restricted method, i.e. bound to ruled surfaces, architecturally it's arguably more liberating. To provide a perspective on how production capacity roughly compares, the cutting process presents a speed-up factor of 25 compared to milling. Given the intricate geometry, some efficiency of the process is lost, where in practice two orders of magnitude in speed-up are observed.

ODICO

The commercialisation of RHWC technologies was fuelled by the measured increase in production speed in comparison to existing procedures. While most architectural productions can feasibly be described by ruled-surface geometries, the tendering with partners NedCam and Dura-Vermeer for the production of formwork for a bridge spanning over 300 m (designed by Zwarts en Jansma), indicated a need for equivalent efficiency in doubly curved production. Following a grant received from the Danish National Advanced Technology Foundation, Odico now heads the 3-year research project, Bladerunner, which seeks to develop an economically efficient production of freeform doubly curved geometry through the development of robotic flexible-blade cutting with heated blades, in collaboration with the Development Department of 3XN Architects, GXN, the Technical University of Denmark and a number of building industry partners.

Although only founded in April 2012, production by means of RHWC is now in full swing at Odico. The company is providing services for companies such as Siemens Windpower and Spaencom[23].

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[23] Denmark's leading supplier of precast concrete elements

Figure 2.48: Opticut 1 : 1 sample cast, testing the casting quality of two adjacent, doubly ruled cells

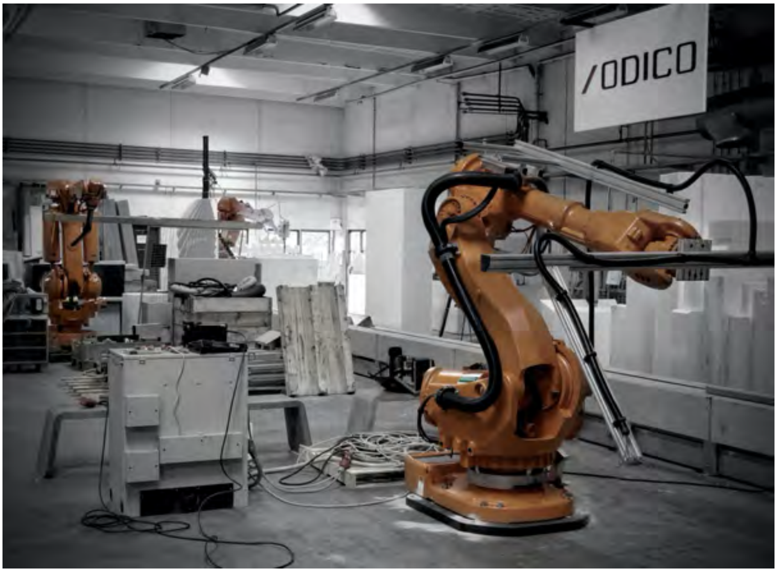

Figure 2.49: Robotic workshop at Odico

Figure 2.50: Y-joint sample cast constructed from three intersecting hyperbolic paraboloidal surfaces and six single-ruled extrusions

PYRAPID

The projects described in this article fuelled the development of custom software, dedicated to RHWC and RDWS, PyRAPID. PyRAPID is built on top of PythonOCC, with the open-source OpenCasCade CAD kernel as its main dependency (figs. 1314). The application automatically clusters the faces so that they can be cut in a single sweeping motion, and generates a tool path optimised for extending the reachability of the end-effector, and computes the inverse kinematics from that pose. As the tool orientation has two degrees of freedom (sliding and rotating) over the axis of the wire, the key is to leverage this freedom, as it allows for considerable optimisation of the reach of the robot.

ACKNOWLEDGEMENTS

Both the development of the diamond wire saw and the Opticut project were influenced and inspired by the work of Prof. Mark Burry.

The Hyperbody's collaboration with both the Aarhus School of Architecture and the Taubmann College of Architecture / Matterdesign took root from the 2011 Fabricate edition. The authors owe their thanks to the organisers of the first edition of Fabricate, which sparked the research reported in this article.

We owe thanks to Taubmann College, the Delft Robotics Institute and the Dutch Stimulation Fund for Architecture and to our industry partners Husqvarna and Marmi e Graniti d'Italia for their support for the research in RDWS. The authors thank the Aarhus School of Architecture for their generous support in funding the Opticut research project.

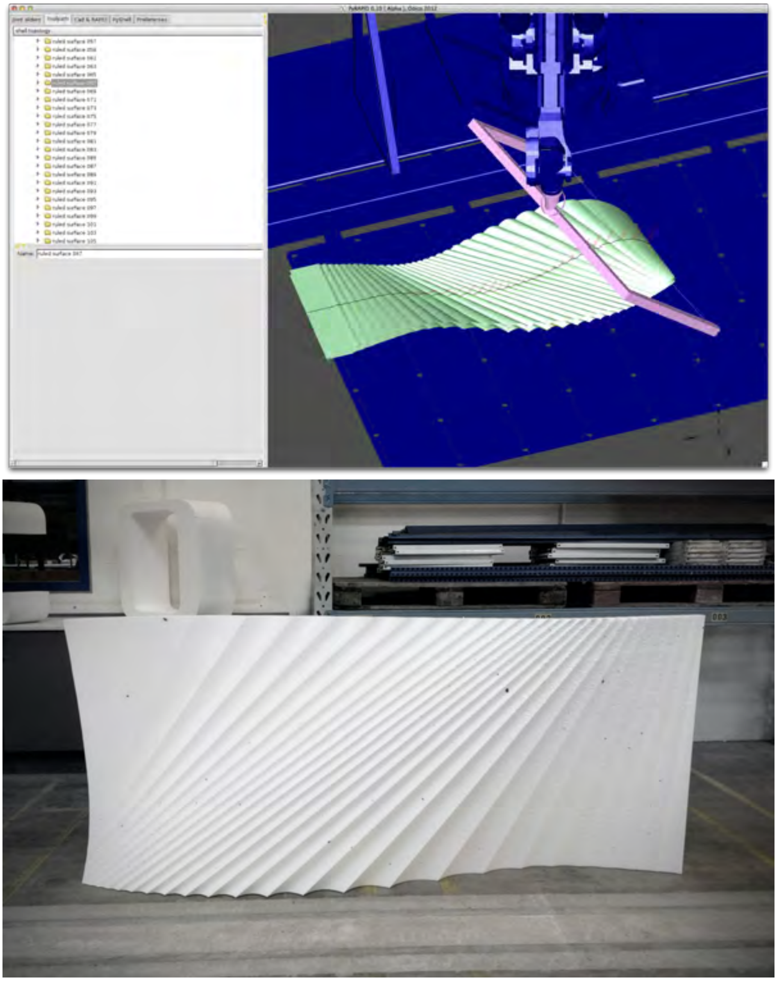

Figure 2.51: *top* PyRAPID coding of EPS mould cut with hot wire *bottom* Cut sample panel from PyRAPID coding

3

ROBOTIC FABRICATION

"It is for the architect to oversee the principle;
he can activate the resources of industry
husband its products
and avoid costly upkeep
he can augment the treasury
by means of the prodigal devices of art"

Nicolas Claude Ledoux

3.1. ROBOTIC HOTWIRE CUTTING

3.1.1. INVESTIGATIONS IN DESIGN & FABRICATION AT HYPERBODY

PROTOSPACE 4.0 MOCK-UP

Aiming to provide a new home to Protospace *4.0, a laboratory for collaborative design sessions, following the destruction of* iWeb, *(home to* Protospace *2.0) by a faculty fire, Hyperbody has completed a large mock-up using an innovative hot-wire cutting method. Fabricating the expanded polystyrene (EPS) prototype in this manner offers interesting potential for the realisation of non-standard architecture.*

Why hot-wire cutting? Early in the development of the *Protospace* pavilion it was clear that manufacturing components by CNC milling was prohibitively expensive. CNC milling was found to be sub-optimal for the intended design for the following reasons:

- Placing the hexagonal components on the table of a large milling machine would require many transformations to make the object accessible to the milling bit. This re-positioning of the object being milled delimits the effectiveness of the milling process
- Milling EPS foam generates considerable nonrecyclable waste, which is costly to dispose of
- Due to the fragility of the material it is necessary to protect the components when transported. Therefore, a partial negative shape of the component has to be milled as well

Cutting the EPS blocks by heat rather than a milling bit results in a smoother surface and better finish. When cutting through with hot-wire, the process singes through the cells rather than splicing them open, making finishing the EPS foam with a coating easier. In the final design stages, the geometry was rationalised to developable surfaces, since a hot-wire machine by construction is bound to this category of form. Shaping the large foam blocks with a CNC hot-wire cutting machine offered an effective and efficient solution.

What is the potential of hot-wire fabrication? Shaping volumes at an architectural scale in an accurate, cost-effective manner is a considerable challenge using any current digital fabrication methods. At Nedcam,[1] Hyperbody was able to evaluate machines that were sufficiently large for these applications. Their milling machines for example can remove a layer of 80 mm foam at a radius of roughly 15 mm at a speed of approximately 10 metres a minute, 0.012 cubic metres a minute, 0.72 cubic metres an hour. Rarely, however, will such rates be achieved, since these calculations assume maximal possible material removal, and no factoring in of the time it takes to position the milling bit. Other

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This section is partly based on *M. Verde, M. Hosale, J. Feringa. Investigations in design & fabrication at Hyperbody, Fabricate 2011* [88]

[1] NedCAM is a company based in the Netherlands that specializes in large-scale CNC fabrication and have worked on a number of interesting architectural projects. Its important to point out that NedCAM has been experimenting with hot-wire cutting for the roughening foam blocks that will be further milled.

potential issues to note are that the surface is only roughened and unlikely to be an acceptable final product. In practice a material removal in the range between 0.2–0.3 cubic metres can be considered optimal. For CNC milling such rates are screamingly fast, certainly when taking the accuracy of the machined components into account. Large CNC milling installations are expected to only improve marginally in terms of the speed of material removal. Therefore, it is worthwhile considering alternatives that scale well to architectural proportions and, by all indications, hot-wire cutting is a viable alternative method. An additional benefit of using hot-wire cutting is not just the effectiveness of the cutting process itself but also its coupling with expanded polystyrene. Building with EPS blocks is winning ground, but the approach has not filtered through to high-end architectural projects. EPS foam is both a very inexpensive material and perhaps surprisingly – a very eco-friendly material. It is not only friendly to the environment but also to the construction industry since it is lightweight. The advantage here is that building a large volume with EPS foam is easier and quicker for construction workers than traditional materials.

BUILDING THE MOCK-UP

During the construction of the *Protospace* mock-up, a number of observations regarding the intricacies of hot-wire cutting were made by Hyperbody. The following points identify a number of advantages in utilising CNC hot-wire methods:

- No waste. Material that was cut effectively provides packaging. The remaining pieces of foam can be recycled
- The cost of a CNC hot-wire machine is a fraction of a milling machine of comparable scale
- The hot-wire machine is relatively lightweight and simple to use, which means it could potentially be deployed on construction sites
- The components of the mock-up were produced in a cost-effective manner, representing about 20 per cent of the cost of producing the components by milling.

One significant problem encountered is that software tools currently available are primitive compared to milling software. Komplot Mechanics' in-house built hot-wire machine was augmented with portals on the front and the back of the table along with the portals on either side. As a result, the reach of the machine was improved, consequentially leading to fewer rotations of the components needed to fit the projected toolpaths onto the machine. To produce 3D rather than 2.5D (extrusion type forms) it is necessary to project the contours of the shape on two planes that represent the portals of the hot-wire machine. The temptation to script the projection of the toolpaths was avoided, since with each produced cell, Hyperbody gathered new ideas to improve the paths. There are a number of constraints that makes computing the projection of the toolpaths non-trivial. Rotation of the component on the machine has to be minimised. Both portals have to move at more or less the same speed: if a portal is standing still, the heat of the wire will burn a large hole in the foam block, or worse it could even enflame the material. Finally, toolpaths should cut top-down, such that the fumes from the melting foam can evaporate.

Figure 3.1: Komplot Mechanics's adapted hotwire cutting machine. Extra portal built to allow cutting both longitudinally and laterally

If not, the wire is cooled down and the polystyrene will start to stick to it. When cut, a block of EPS foam "sighs" and looses roughly a thousandth of volume. W ith a block of 2 metres, this "sighing" effect accounts for a tolerance of 2 mm. The final finished components deviated about 5 mm.

CONNECTION DETAILING

EPS components were reinforced with wooden inlays where the edges of the individually cut components met. ID tags and holes were milled into the 18-mmthick wooden inlays, providing the components with a connection detail. The components were finished by a 1-mm layer of poly-urea hot spray coating, which helps the distributions of stress in the structure over a larger area. The wooden inlays spread the point loads of each connection more evenly over the coating, preventing it from tearing. Moment forces in the structure are transferred over the sides of each component, resulting in mere tensile forces in each connection. The EPS material comfortably withstood the compression forces. Effectively the EPS 'mould' became an intrinsic part of the structure. Connections between components were tested on their strength in different conditions (supported on two sides, overhang, horizontally, vertically and so on) performing well. N o tearing or breaking occurred and the displacements due to bending stayed within tolerances. This can be largely attributed to the low weight of the components.

CONCLUSION

By working on the *Protospace* mock-up, Hyperbody have come to think of hot-wire cutting as a fabrication method with striking architectural potential. Apart from the hard geometrical requirements of developable surfaces there is a need for geometrical tools that can compute toolpaths that respect the aforementioned heuristics. There is a lot of ground still to cover, including in the detailing of expanded polystyrene. The Hyperbody Research Group continues to further develop these fabrication techniques, building upon the knowledge gained from the mock-up of the *Protospace* 4.0.

Figure 3.2: Connection detail of wooden inlays glued to the EPS block. Inlays are covered with a polyurea coating distributing stress over a larger area

Figure 3.3: The mock-up assembled in Protospace 3

3.2. ROBOTIC HOTBLADE CUTTING

3.2.1. ROBOTIC HOT-BLADE CUTTING AN INDUSTRIAL APPROACH TO COST-EFFECTIVE PRODUCTION OF DOUBLE CURVED CONCRETE STRUCTURES

This paper presents a novel method for cost-effective, robotic production of double curved formwork in Expanded Polystyrene (EPS) for in situ and prefabricated concrete construction. A rationalization and segmentation procedure is developed, which allows for the transliteration of double curved NURBS surfaces to Euler elastica surface segments, while respecting various constraints of production. An 18 axis, tri-robot system approximates double curved NURBS surfaces by means of an elastically deformed and heated blade, mounted on the flanges of two manipulators. Re-orienting or translating either end of the blade dynamically deforms the blade's curvature. The blade follows the contours of the rationalized surface by continuous change in position and orientation of the end-effectors. The concept's potential is studied by a pilot production of a full-scale demonstrator panel assembly.

INTRODUCTION

The vast majority of contemporary building designs are restrained to a formal language of planar surfaces and derivative geometric constructs; a constraint that stems from the practicalities of construction, which favors the use of mass-produced semi-manufactures and—for concrete in particular—modular, reusable formwork systems. An increasing number of high-profile project designs challenge the dominant paradigm. The challenge is posed by advanced building design projects, such as the Kagamigahara Crematorium (Toyo Ito Architects 2006) and Waalbridge Extension (Zwart & Jansma) Fig.74, which utilize manual production of formwork to achieve complex curvatures; and building projects which employ large scale CNC-milling to realize advanced structures, such as the Museum Foundation Louis Vuitton by Gehry & Associates (Paris 2014); the Nordpark cable railway by Zaha Hadid Architects (Nordpark 2007), and the Metz Pompidou by Shigeru Ban (Metz 2010). However, neither manual formwork production nor large scale CNC-milling provide a cost-effective option for general construction, and projects of this type therefore require extraordinary budget frameworks for realization.

Recent developments in architectural robotics by authors of this paper have demonstrated novel, cost-effective means of producing bespoke formwork with the constraint of being limited to ruled surface. The Robotic Hotwire Cutting (RHWC) approach is utilized to concrete casting in Expanded Polystyrene that has been developed to industrial scale [110], Fig.3.4. Currently, Odico Aps is putting forward RHWC in relation to a project design by the Danish artist Olafur Eliasson, for the Kirk Kapital HQ in Vejle.[2] Here, over 4000 m^2 of formwork are produced, achieving production speeds order of magnitudes faster than CNC-milling through the principal mechanics of the method[104]. In extension of these

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This section is based on *A. Søndergaard and J. Feringa, T. Nørbjerg, K. Steenstrup, D. Brander, J. Graversen, S. Markvorsen, A. Bærentzen, K. Petkov, J. Hattel, K. Clausen, K. Jensen, L. Knudsen, J. Kortbek. Robotic Hot-Blade Cutting, An Industrial Approach to Cost-Effective Production of Double Curved Concrete Structures, RobArch 2016* [126].

[2] http://www.domusweb.it/en/news/2011/12/01/kirk-kapital-a-s-by-eliasson .html

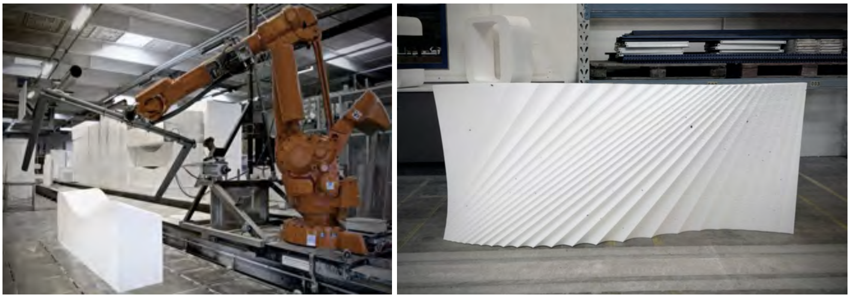

Figure 3.4: Large scale RHWC production at Odico (left), and hotwire cut production sample (right)

Figure 3.5: Robotic abrasive wire-saw cutting of marble blocks at Carrara, Italy (left); cut samples (right)

developments, experiments at Odico are performed in abrasive wire-sawing. Through this technique, the same digital control procedures—facilitated by the internally developed control software, PyRapid—is applied to direct processing of construction materials, such as industrial marble Fig.3.5 top. In further maturation of the concept, the method is being adapted in partnership development with Bäumer AG for industrial machining. Prototype production have revealed further significant reductions in machining times, in which full scale elements may be cut in matter of seconds Fig.3.6. However, for a number of projects, the realization of general double curved structures is imperative. Here, no effective methods currently exist for architectural scale in industrial production. In 2012, Odico Aps. tendered as part of a consortium for the realization of the aforementioned Extended Waalbridge project Fig.3.7. Here, the double curvature of the columns of the bridge elegantly blending with the bridge slab are dominated in a single direction. The considerable scale of the project implied large local radii (between 1 and 2 m) of the surfaces. Since, for this scale, CNC milling molds from EPS would have been a prohibitively ineffective method, digital manufacturing would not be economically competitive with the more traditional approach that was chosen. While developing the tender documents, Odico Aps. realized that the Hot-Blade cutting method discussed in this paper would represent a competitive solution.

Figure 3.6: Sample geometry cut in nonflammable acoustic foam under 16 s (left) Second abrasive prototype tool, developed in collaboration with Bäumer AG (right)

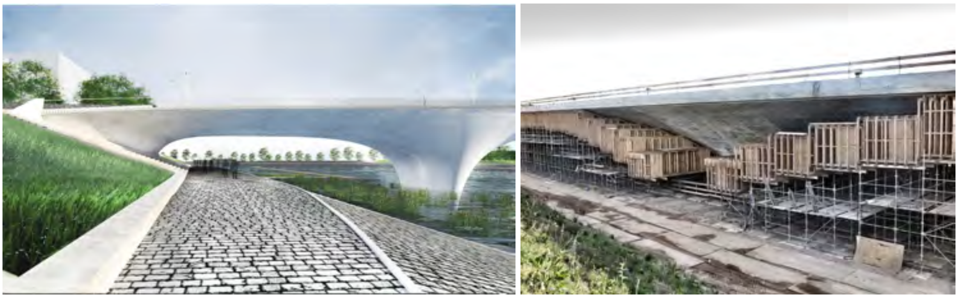

Figure 3.7: The Waal Bridge Extension Impression of the artist (left) (©Zwart & Jansma) Construction work using traditional formwork systems (right)

Figure 3.8: Design of the Concorde wing-section using physical splines, 1964 (©Bristol Archives)

STATE-OF-THE-ART

Contemporary construction currently employs either manually produced, bespoke formwork or CNC-milling of foam molds for the realization of complex concrete structures. In addition to these techniques, actuated mold systems have been explored by Danish Adapa and in the EU FP7 project TailorCrete [95, 92]. This technique employs actuation of a flexible membrane as a casting surface; however, the method is limited to concrete prefabrication; by the casting pressure the individual systems can take; and the need for multiple casting aggregates for large volume production due the curing time for concrete elements. In addition, dynamic slip-casting for column elements is being explored[112], as a variant of the additive manufacturing of concrete structures[40, 85]. These and related methods attempt avoiding the need for formwork altogether— however do so at the cost of significant degrees of freedom, such as the capacity to realize cantilevered designs. Finally, fabric formworks have been proposed and experimentally applied as an alternative technique for the casting of advanced designs[87]. This approach is challenged by the capacity of the fabric to achieve desired designs, as well as the unpredictability of the fabric behavior in combination with the required complexity of creating bespoke molds. A common denominator of the described developments is the requirement of shifting to entirely new modes of construction, which creates a high barrier for full scale implementation; or limits the degrees of freedom achievable compared to existing means of realization. In contrast, the method presented here proposes a production cycle which is fully compatible with current in situ and prefabrication in concrete construction, while achieving doubly curved formwork designs at machining times more than a hundred times faster than comparable CNC-milling, the most developed and applied strategy for industrial scale production. Double curved surfaces with positive Gaussian curvature can in a vast majority of cases be described via swept splines. The term “splines” nowadays refers to piecewise polynomial or rational functions used in CAD systems to model curves and surfaces. However, prior to the introduction of computers in the 1950s the term was used for thin wooden rods the shapes of which were manipulated by the placement of so-called “ducks” at various points to create a naturally smooth curve for drawing designs. These were used in ship building and, later, in the aviation and automotive industries. The placement of the ducks simulates the placement of ribs in the hull of the ship, and hence the curve drawn by following the spline is an accurate reflection of the natural shape adopted by the planks forming the ship’s hull. The use of splines for the storage and transmission of a design goes back to the Romans, in the form of physical templates for the ribs of ships[34]. Splines and ducks suitable for drawings of ship designs were developed later, perhaps in Hull in the 1600s. The mathematical shape of a physical spline can be described exactly, although it requires the use of so-called elliptic functions, which are nonlinear in nature Fig.3.8. The correct mathematical model for an elastic rod bent by a force at one end with the other end fixed was given by James Bernoulli in 1691[10]. In his approximation of the solution for the case that the ends of the rod are at right angles to each other, he recognized that the solutions would require non-standard functions. Later, in 1743, Bernoulli’s nephew, Daniel, suggested the problem to Euler, who then, in an appendix to his famous treatise on the calculus of variations found all possible shapes for these so-called Euler elastica[1, 3].

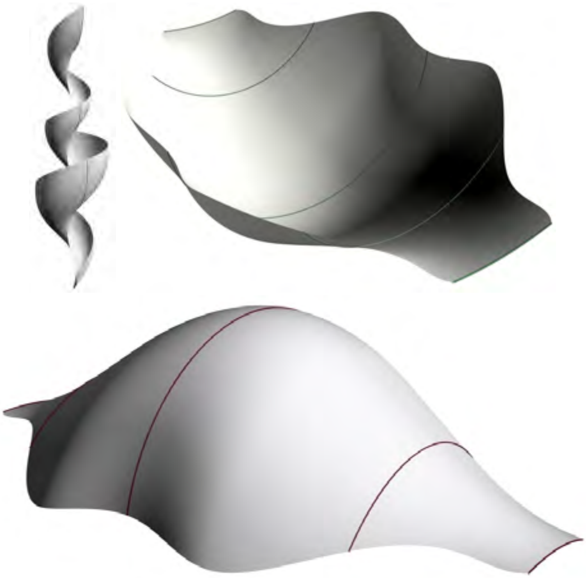

Figure 3.9: Elastica surfaces generated through implementation of the above formulation in Matlab

Geometry Rationalization

The presented geometry rationalization approximates the physical behavior of the the Hot-Blade in order to convert arbitrary input surfaces to producible geometry. The HotBlade is fixed between two robot arms, which enable us to choose the location and rotation of the blade's ends. The shape of the blade is the curve that, subject to the endpoint constraints, minimizes the elastic energy. These curves are the above-mentioned Euler elastica or elastic curves. Before discussing the approximation of a CAD surface, let us consider the class of surfaces defined by this cutting process, namely the surfaces swept out by continuously varying families of planar Euler elastica. A planar curve is geometrically determined by its curvature function $\kappa(s) = \theta'(s)$, where $\backslash\theta$ is the angle function of the unit tangent. One can show that the equation defining an elastica is the normalized pendulum equation $\theta'' = -\sin(\theta(s))$ and the solution is the curve:

$$C_2(s) = (2E(s,k)) - s, 2k(1 - cn(s,k))$$

where $cn(s,k)$ and $E(s,k)$ are standard elliptic functions depending on a parameter k. Applying all possible dilations, translations and rotations to $C(k)$, one obtains all possible elastic curve segments. Allowing all of these parameters to vary with time, and then generating the time sweep so defined, one obtains all possible elastica-swept surface patches. One can implement this numerically, to obtain examples Fig.3.9.

When rationalizing a CAD surface to Euler-elastica for Hot-Blade cutting, the surface is segmented into patches that can be approximated by surfaces of the type exemplified in Fig.3.9. We essentially do this simply by finding planar curves on the original surface and then approximating these by segments of planar elastic curves.

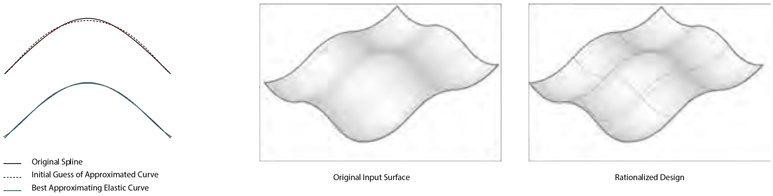

Figure 3.10: Original spline curve (blue) and initial guess for approximating elastic curve (red dotted), original spline curve (blue) and best approximating elastic curve (green, left). Input NURBS surface (center); rationalized surface (right)

Curve Approximation

Given a parameterized planar curve segment we wish to find a piece of an elastic curve which has the same shape. We do this via an optimization algorithm that minimizes the distance between two curves. By choosing a standard parameterization, we are able to describe any elastic curve segment by four control parameters, which determine the length and shape of the segment. Three more parameters determine the position and rotation of the curve in the plane. The distance between the given curve and any elastic curve is thus a function of the seven control parameters. The approximation algorithm has two steps: first, we analyze the geometry of the given curve in order to find control parameters for an elastic curve segment, which has the same overall shape Fig.3.10. Then, starting from this initial guess, we tweak the parameters, using the optimization tool IPOPT[51], until we get the closest fit. We can do this either with or without endpoints fixed.

3.2.2. Surface Approximation

We now consider a given CAD surface, and we want to approximate it by a surface that can be obtained by moving elastic curves through space. From the CAD design we extract planar curves on the surface and approximate each of these by an elastic curve. By interpolating the control parameters we obtain a rationalized design–a new surface, which is swept out by elastic curves moving through space. For larger designs we need to segment the surface into pieces that can be cut individually. Because we control the endpoints and directions of the blade, we can ensure smooth transition from one piece to another Fig.3.11.

Surface Segmentation

A number of segmentation procedures are developed, targeting three production constraints: (a) plane segmentation when exceeding the dimensions of the input EPS work object; (b) instability of the blade due to multiple inflection points, or (c) cutting the same area multiple times due to rotation of the blade profile. Fig.3.12 illustrates an example of a surface with too many inflection points. An inflection point is a point where the sign of the curvature changes; in other words the tangent at the point will cut the curve in

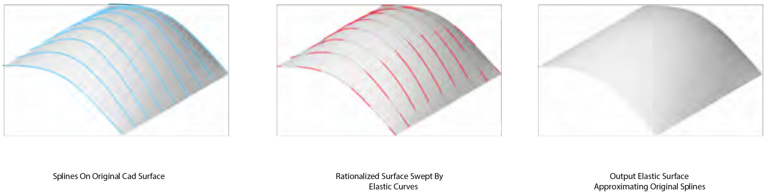

Figure 3.11: A selection of planar curves (splines) on the original CAD surface (left); The original surface with elastic curves that approximate the splines. Note that these curves do not lie exactly on the surface (center); Rationalized surface swept by elastic curves (right)

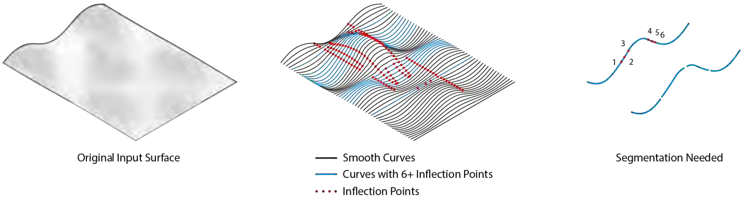

Figure 3.12: An input surface (left), Hot-Blade planar cuts with inflection points (center), and one of the cuts close up (right)

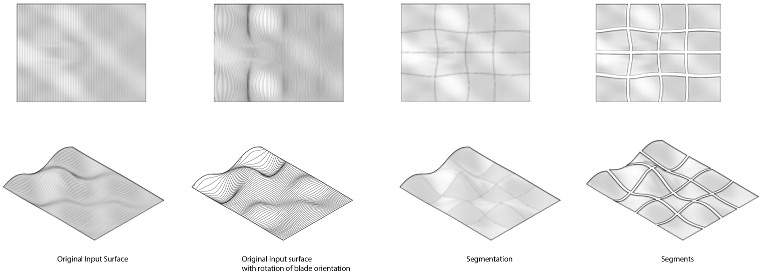

Figure 3.13: Segmentation schemes

two. We use a subdivision scheme to find the inflections. Analysis of one of the curves shows six inflection points and since many inflection points on the curve make the blade less stable, segmentation is required. Assuming the rationalization of each cut is curvature continuous, there will be the same number of inflection points on the cut and the rationalization. Two exceptions to this are inflection points near the edge of the cut that may disappear, and pairwise inflections close to each other, which may cancel out, just like pushing out a small dent. Taking the above into account, we propose the following algorithm.

1. Find the planar curves on the surface.
2. Calculate inflection points for each curve.
3. Segment the surface into a grid of blocks.
4. For each block test if there are more than two inflection points; if so try to
    - Move the block if there are overlaps to improve.
    - Remove inflection points close to each other. If there still too many inflection points continue to step 5.
5. Take two new blocks, each of the same size as the original block, and place them so that they overlap both each other and the two adjacent blocks in the row. Go to step 4.

In this algorithm we can control whether we keep the same number of blocks in all rows or not. This affects the aesthetics of the segmentation. In the overlap of the blocks we choose a cutting plane such that the segmentation follows the geometry. An example of the output of this algorithm can be seen in Fig.3.12 (right), showing the surface subdivision. The problem of cutting the same area multiple times arises when rotation of the blade in the cutting direction is allowed Fig.3.13 (column 2 from the left). We see here that the curves intersect each other, and thus part of the surface will be cut multiple times, which is undesirable. In most cases this problem can be solved by segmenting the surface, as described above. We only need to add a test for intersecting curves in step 4.

DATAFLOW AND ROBOTIC SYSTEM CONFIGURATION

The experimental setup consists of three robots. Robot 1 holds the EPS work object, which is to be cut, and moves the block linearly through space, thus acting in principle like a conveyer belt. Robots 2 and 3 control the ends of the HotBlade thereby determining its shape and its position in relation to the EPS block Fig.3.14. When the geometry rationalization is completed, we know a set of planar elastic curves on the rationalized surface. The curve segments which lie on the surface are shorter than the HotBlade cutting tool, but since we know not just the curve segments, but the entire curves we can easily extend the curves to the required length, i.e. the length of the HotBlade. These extended curves are the target shapes for the HotBlade during the cutting. We extract the relevant data for the extended curves, that is, we find the coordinates for the endpoints and the tangents at the endpoints. The endpoint coordinates determine the position of

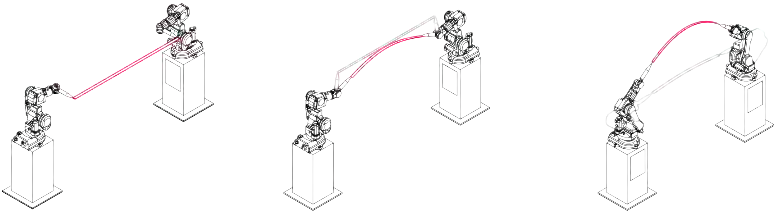

Figure 3.14: Deformation of the blade through orientation and positioning of the two end-effectors

the tools of robots 2 and 3 relative to the EPS block. The tangents determine the rotation of the tools, which in turn controls the shape of the blade.

For our experiments the robots were given 51 targets. That is, for each block that was to be cut, we provided 51 sets of positions and rotations for the tools of robots 2 and 3. The robot program then interpolates between these targets to follow a smooth path from the first to the last target, thus moving the blade while changing its shape, resulting in an EPS surface of the rationalized design.

BLADE MECHANICS AND CUTTING EXPERIMENTS

The main cutting tool used in the process is a thin metal strip—usually referred to as a blade—made of a nickel-chromium super alloy. The blade is pre-heated to a temperature of 300–400 °C by means of Joule heating and then it is slowly brought into contact with an EPS block to produce melting, and subsequently to form or cut the block into a desired shape (also referred to as thermal cutting). At such high operating temperatures, the blade has to be displaced (or bent) into an elastic shape with predefined curvature and at the same time maintain its elastic and flexibility properties. Using FEM simulations, the effect of mechanical properties on the target geometry was investigated and a particular material was chosen to ensure smooth cutting. The blade is attached to two robots, one at each end, by specially designed sandwich based holders to ensure strong and safe supports during all cutting operations. The physical displacement of the blade is achieved by moving the robots into an appropriate position, at the same time maintaining the elastica-strain-curvature relations. The temperature dependent variations of the blade shape are to be incorporated in the computational algorithm to secure proper shape representation Fig .3.15.

Two experiments were designed and performed in order to test the utility of the setup. In the first experiment a convex doubly curved surface was cut. The curvature of the blade was continually changing during cutting in order to test the limit of complexity that can be achieved and ensure proper geometrical representation. The presence of two inflection points on the discretized surface was considered as a possible problem, but the experiments showed that it does not make the blade unstable, since the robots compensate with the angles of the holders and the curvatures involved were moderate. Good surface quality was achieved at cutting with an absolute speed of motion of 7 mm/s. The EPS block to be cut had the dimensions of 600 × 600 × 600 mm.

The second test aimed to cut a number of EPS blocks and then assemble them into a

Figure 3.15: Tri-robot hot-blade cutting configuration

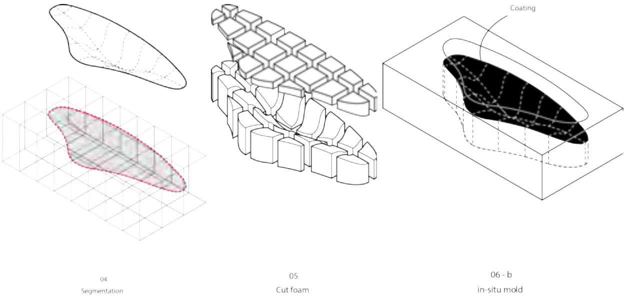

Figure 3.16: General production workflow diagram: segmentation (left); cut foam (center) and in situ mold (right)

single structure that should represent a ready-made mold for concrete casting. Different discretized pieces of doubly curved surfaces of both convex and concave types, as well as hyperbolic surfaces (negative Gauss curvature), were successfully cut with the setup. The size of each individual block was approx. 600 × 785 × 600 mm, resulting in an assembly of size 1800 × 2345 mm, comparable to the size of production frame molds. The cutting experiments are currently continued for production of doubly curved concrete panels with expected completion December 2015.

FORMWORK SYSTEMS AND PRODUCTION WORKFLOW

The efforts described in the previous chapters outline the general method for the cost-effective production of doubly curved formwork in Expanded Polystyrene. From this, the following process is developed Fig.3.16. The cyclical workflow links conventional CAD-modelling operations with the robotic Hot-Blade fabrication and standard concrete casting techniques. This requires the rationalization and segmentation of geometry types before rebuilding the geometry to the constraints of the blade, robot work envelope, work object dimensions and tolerances. After the input geometry has been translated to segments of swept Euler elastica surfaces and data deducted for tri-robot motion, EPS-mold pieces are produced. The mold pieces are subsequently used in combination with existing pre-fabrication and in situ workflows. For element pre-fabrication, molds are mounted on vibration tables and sides enclosed with metal or wooden frames. For in situ applications, mold pieces are used in combination with standard scaffolding modules for casting pressure support. These applications ensure a full compatibility of the end-products of the Hot-Blade with established industry workflows, critically ensuring a low barrier to adoption.

CONCLUSION

A general purpose robotic fabrication method for producing doubly curved formwork has been presented. The efficacy of the method has been demonstrated through geometry rationalization and pilot production of a sample formwork panel design. The method is being implemented for industrial scale fabrication by one of partners of the research consortium, and the identified challenges are being addressed through this work.

Acknowledgments The work presented in this paper is part of the larger 3-year research effort, “BladeRunner” established and generously supported under the program of the Innovation Fund Denmark for advanced technology projects. The project is conducted by the partners Odico Aps (project lead), the Technical University of Denmark, Department of Applied Mathematics and Computer Science and Department of Mechanical Engineering, the Danish Institute of Technology; GXN A/S and Confac A/S.

Figure 3.17: Final output

3.3. TOPOLOGY OPTIMIZATION

3.3.1. DESIGN AND FABRICATION OF TOPOLOGICALLY OPTIMIZED STRUCTURES; AN INTEGRAL APPROACH

Integral structural optimization and fabrication seeks the synthesis of two original approaches; that of topological optimization (TO) and robotic hotwire cutting (RHWC) [86] . TO allows for the reduction of up to 70% of the volume of concrete to support a given structure [78]. A strength of the method is that it allows to come up with structural designs that lie beyond the grasp of traditional means of design. A design space is a discretized volume, delimiting where the optimization will take place. The number of cells used to discretize the design space thus sets the resolution of the TO. While the approach of the application of TO as a constitutive design tool centers on structural aspects in the design phase [71], the outcome of this process are structures that cannot be realized within a conventional budget. As such the ensuing design is optimal in a narrow sense; whilst optimal structurally though, construction can be proved to be prohibitively expensive.

INTRODUCTION

Earlier work on the Unikabeton project[78] suggests that the approach of milling the formwork offers little potential for large scale employment. Even when deployed on immense facilities specialized in the production of ship hulls and thus of the scale required for architectural production, material removal would not scale beyond about three quarters of a cubic meter per hour. This realization instigated a quest for finding a scalable, more economical approach to complex formwork. The notion of a coupled approach was brought about with the event of the conference Fabricate 2011, where the authors respectively presented work on TO and RHWC. It became manifest that a coupled approach would be mutually advantageous, increasing the relevance for both TO and RHWC simultaneously. The experience of building the protoSPACE project[81] Fig.71 learned that a material removal of 3 to 6 cubic meters per hour is achievable, even with an improvised, rudimentary set-up. The OptiCut project presented in this article inquires this potential. Earlier experience in the application of robotic milled formwork in the context of the Unikabeton project allows us to compare the two approaches. Our project suggests that hotwire cut formwork is considerably more cost effective, given that the approach is an essentially volumic.

ROBOTIC HOTWIRE CUTTING

The process requires a more extensive intermediary step of geometry rationalization. Constructing ruled surfaces from the double curved mesh generated by the TO process that adheres to specific constraints such as the styrofoam block size, dimensions of the hotwire tool and kinematic limitations of the robot. Interpreting the resulting meshes however is always an essential and unsurpassable step. Therefore it is only logical that aspects of realization, such as the demoulding of the formwork are taken into consideration. Ruled geometry is well suited to the task of casting concrete in particular demoulding the formwork is guaranteed to loosen more easily. While we experienced considerable

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This section is based on *J. Feringa, A. Søndergaard. Design and fabrication of topologically optimized structures; an integral approach, a close coupling form generation and fabrication, eCAADE 2012, Digital Physicality* [90].

unforeseen additional effort in demoulding the previous Unikabeton project, this aspect has been thoroughly integrated in OptiCut. Not only does the double curved geometry partially accounts for difficulties in demoulding, the formwork itself was milled with a milling bit of a large radius, since otherwise machining times would end up prohibitively long even for a project of modest scale (12 * 6 * 3.5 m) project. A side-effect of this is that 3 Cost aspects 4 the tracings left in the formwork frustrates the demoulding process. The costly formwork, the additional effort of demoulding offsets potential material savings gained by the TO process. By developing a closely integrated approach of TO and RHWC, we have been able to smooth out these obstructions considerably. As such hotwire cutting is a powerful enabler. Given our relative inexperience with the process we're optimistic that normative square meter price for high-end concrete work is achievable, considering advances made in terms of robot code generation, while assuming geometry is suitable to the process. Which implies that geometric sophistication potentially comes at little or modest additional expense.

COST ASPECTS

In comparison to the Unikabeton project we've been able to realize a reduction in formwork cost of 80%, where the decrease in expense roughly equates the shortened production span. The OptiCut project presents a six fold increase in terms of volume in comparison to the Unikabeton project, while the production of the formwork was of comparative cost.

GEOMETRY

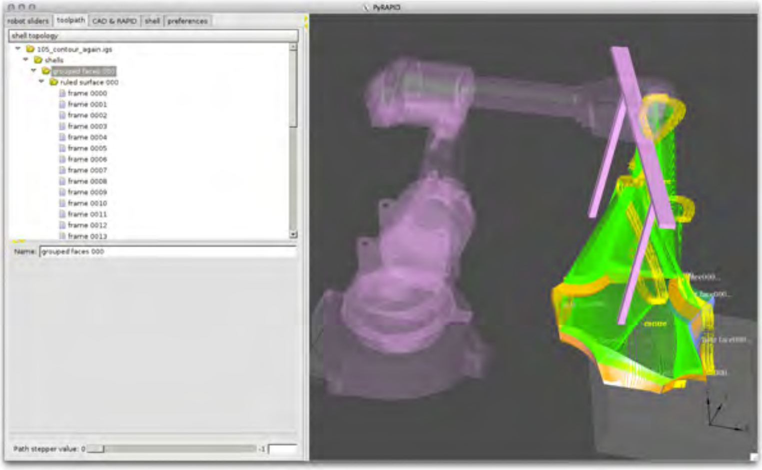
Initially some skepticism had to be overcome to what extent the meshes of the TO might be approximated by ruled surfaces. The process of geometry rationalization has gone through a number of increasingly canny interpretations of meshes resulting from the TO process where the constraint of the rulings became progressively less of an issue. An example of such developing insight in rationalization is the interpretation of the bone like columns typical for the TO process as hyperboloids, which are well suited for hotwire fabrication and matching the original TO results satisfyingly.

A more challenging part of production preparation involved producing puzzle pieces, the dovetails that join the various EPS foam blocks. While generating the dovetails is easily automated, resolving the right assembly order of the blocks posed a greater challenge.

TO and RHWC are remarkable coincident; in alliance either method gains in relevance. Savings in reduction of the volume of concrete is to a considerable lesser extent offset by the prohibitive expense of the required complex formwork. A custom software for the interpretation of the ruled surfaces to robot code was developed especially for the OptiCut project. The software specifically optimizes the toolpath for reachability; the tool orientation has a degree of freedom over the axis of the wire, it's important to take advantage of this freedom as it allows for considerable optimization of the reach of the robot.

The software nests the foam elements efficiently within the standard sized foam blocks and performs a topological sorting of the ruled faces of the geometry. This clusters faces that logically can be cut in a single sweeping motion that do not require re-orientation

Figure 3.18: *top* The Unikabeton Project *bottom* Structure from the milling process



Name: grouped faces 000

Figure 3.19: PyRAPID software facilitates the generation of robot code from introspecting the CAD model

of the foam block. After the topology sort the software tests whether an intermediary roughening step is required before grouping the faces. The roughening step is specific to robotic hotwire cutting, while with a traditional hotwire cutting machine no clashes between the tool and workpiece occur. The downside however is that to cut large blocks, a considerably larger machine is required, while a robot is a fairly compact machine, certainly in view of its reachability. Potentially a part-to-tool strategy, where the workpiece is held by the robot and moves towards one or several fixed hotwires is an option worth exploring for the most challenging pieces. An additional benefit is that since the workpiece is held by the robot, the picking and placing of foam blocksand cut products can be largely automated.

Checks are performed for clash detection between tool and workpiece. Finally, the lead-in and lead-out is computed. The tolerances achieved are approximately a millimeter. This factors in a sighing effect when cutting the block, but more importantly the robot is a machine that is both less stiff and precise than a gantry CNC machine. Compared to the earlier approach of milling with a large diameter for the Unikabeton project, RHWC is more precise with earlier mentioned considerable advantage of far smoother surfaces.

OUTLOOK

As a continuation of the presented project under development is the concept of "not-so- lossy-formwork". So far we've been dismissing the considerable capacity of the EPS material that an withstand ample compression forces. The approach suggests a parallel to half-timber structures, where channels cut in the formwork are used for casting, while a large part of the formwork remains within the cast concrete structure. As such the usage of EPS and concrete is devised as composite.

A considerable limitation of the current generation of off the shelf TO software is that homogeneous materials are assumed. Recent developments in TO [77] allows for

Figure 3.20: Ongoing production of the OptiCut formwork

heterogeneous materials and research projects have been formulated to investigate the amalgamation of EPS, concrete and reinforcement work. An approach under investigation is establishing a loss-less production cycle, building on the development of parting agents developed by BASF and the Danish Institute of Technology promoting the usage of EPS that can be recycled without down-cycling.

While creating prototypes for the presented project, we've started to investigate another take on hotwire cutting: hotblade cutting. Rather than using an end-effector mounted on a single robot, a blade is spanned across a pair of robots. When the distance between the TCP's of the robots is shorter than the length of the blade, an arc is formed, when either TCP shares a mirrored orientation. Both robots move synchronized with a rotary table, than double curved surfaces can be approximated. The merger of TO and RHWC paves the way for an economical, material efficient usage approach to realization of large scale TO structures. Even though TO is a fairly well established method within other disciplines[42], the integration of aspects of fabrication plays a critical role in driving forward the adoption of the approach. Undeniably there is a trade-off involved with hotwire cutting; apart from the obvious limitation of ruled geometry there are practical reservations to geometry where a large number of holes are involved. In such situations either a lead-in / lead-out is cut in the element that later on has to be mended, which comes at the cost of loss of precision and is more involved.

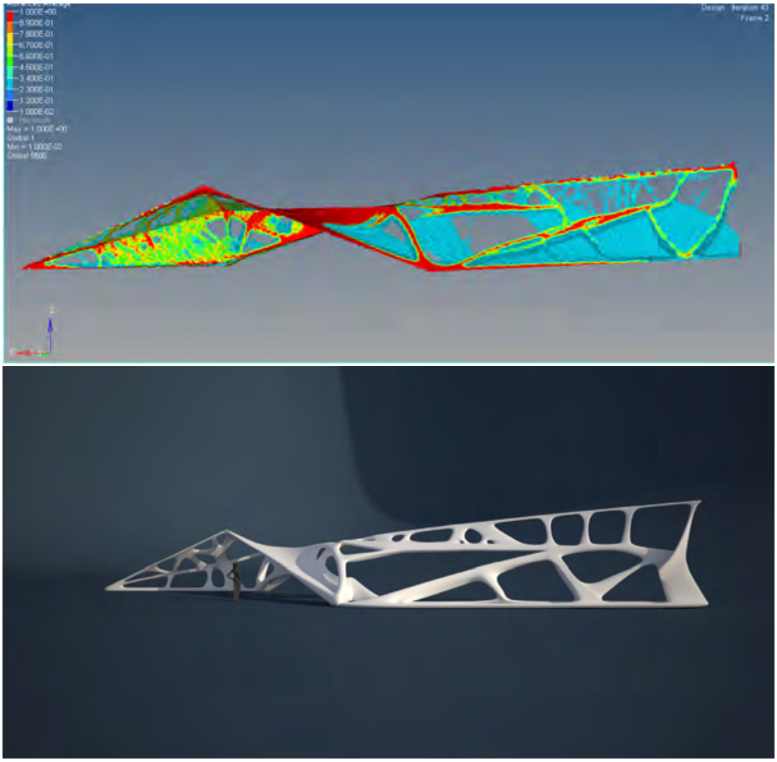


Figure 3.21: *top* Topological optimization result of the OptiCut prototype *bottom* Post rationalized optimization results

3.3.2. ROBOTIC ABRASIVE WIRE CUTTING OF POLYMERIZED STYRENE FORMWORK SYSTEMS FOR COST-EFFECTIVE REALIZATION OF TOPOLOGY-OPTIMIZED CONCRETE STRUCTURES

This paper presents a new method for industrial manufacturing of topology-optimized, ultrahigh performance concrete structures using robotic abrasive wire cutting of polymerized styrene formwork systems. Topology optimization is a wellestablished procedure within disciplines of aeronautic, automotive and naval engineering. However, while recent developments have highlighted a significant potential for structural innovation and reduction of material consumption in topologyoptimizing concrete structures, an effective method for large-scale manufacturing of such structures remains to be found. We argue that the prohibitive factor for large-scale adoption is the non-availability of mechanical processes capable of performing high-speed, high-volume manufacturing of advanced non-standard formwork and, consequently that this inhibition can be overcome through integrating ruled surface rationalization and robotically controlled abrasive wire cutting of three-dimensional formwork systems in polymerized styrene foams. The viability of the proposed method is demonstrated through the production of a 21 m spatial concrete structure, using abrasive wire cutting of EPS formwork via a containerized robotic work cell with an ABB IRB 6700 industrial manipulator, extended with external rotary axis.

1 BACKGROUND

Motivation Current consensus within the scientific community of meteorological and atmospheric sciences outlines several imperatives to reduce anthropogenic emissions of carbon dioxide, mainly the mitigation of anticipated risk of climate change. Within this frame, the emissions associated with construction contribute significantly to global emission levels. Within the construction sector, construction of concrete structures—in particular, the production and calcination of cement—represented in 2015 a combined 8% of global emissions[119], or more than four times the emissions generated by the global air traffic. This figure is projected to more than triple until 2050 due to the increasing global consumption of concrete for construction purposes.

It follows from this outline that a technology capable of reducing the emissions associated with concrete construction could have significant impact on global emissions, assuming industry-wide adoption. To address this challenge, several solutions can be considered: switching to alternative fuels to heat the calcination kiln, such as natural gas, biomass or waste-derived fuels [116]; replacing cement with a negative emission substitute; using engineered timber as substitute for concrete[29] or simply increasing the performance of concrete structures through optimization of the design geometry, thereby lowering general material consumption. The research effort presented in this paper is directed toward this last approach, while acknowledging the value of alternative strategies.

Hypothesis Several studies indicate that various means of structural optimization can substantially increase the performance of concrete structures, in ranges that allow for

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This section is based on *A. Søndergaard, J. Feringa, F. Stan, D. Maier. Robotic abrasive wire cutting of polymerized styrene formwork systems for cost-effective realization of topology-optimized concrete structures, Construction Robotics, Volume 2, pages 81-92* [134].

Figure 3.22: Topology-optimized concrete prototype from the Unikabeton project, produced via robotic CNC milling of EPS molds

reductions of material consumption [123, 97, 106]. Among the range of optimization strategies, topology optimization—commonly applied within the aeronautic and automotive industries—has recently seen an increasing interest as a form-finding strategy for architectural structures [130, 127, 98, 132, 118, 128]. While these studies indicate significant potential for increases in structural performance, this improvement is achieved through a simultaneous increase in geometric complexity, which challenges the current means of construction. For concrete manufacturing, the primary expense for non-standard structures is formwork costs, which represent 50–70% [54] of the total costs of the concrete works. Since the material cost per weight unit is comparably low, there is little financial incentive to deploy reduction measures for concrete material consumption at the expense of increasing formwork costs [25]. It is our hypothesis that the main constraint prohibiting large-scale adoption of topology optimization of concrete structures in the global construction sector is the non-availability of cost-efficient means of realizing advanced formwork.

FORMWORK MANUFACTURING

State of the art Current industry standard for manufacturing of non-standard mold systems falls generally in two categories: CNC milling of timber/EPS molds (typically, for designs of high complexity) and manually constructed formwork systems (typically, flexible modules with bespoke auxiliary supports or sheets of flexible material bent to match CNC routed edges).

These methods are well proven and capable of realizing complex structures, however, with two key disadvantages. CNC milling of advanced formwork is—while capable of producing designs of high complexity and high-end surface finishes—limited in production speed by its mechanical principle, which is defined by incremental subtraction of material from the work object, and thus speed is constrained as a function of the toolbit diameter relative to the target surface smoothness, defining the density of the toolpath and number of passes over a given surface. In practice, this typically translates to > 240 min/m^2 of machining time to arrive at industrial-grade surface smoothness. As such, the pricing per m^2 of milled formwork is predominantly defined by the required machining hours (as a function of the depreciation of the machining station), hence resulting in a premium pricing, available only to a low percentage of high-profile construction projects. Similarly, the construction of manual formwork systems is highly labor-intensive and constrained by the flexibility of the modular systems or formwork material applied.

To address the challenge of finding more cost-effective methods of realizing advanced concrete structures, a diversity of approaches has been suggested, including

1. actuator-based, flexible molds[83]
2. actuator-based slip casting[112]
3. 3d-concrete printing [40, 85]
4. hybrid wax extrusion and CNC machining[3]
5. robotically manufactured stay-in-place formwork[111]
6. robotic hot-wire cutting of EPS formwork[143]

A discussion of these proposals is given in [126].

Robotic hot-wire cutting of expanded polystyrene formwork has been pioneered in commercial deployment by Odico, who have demonstrated as an international first the realization of large-scale load-bearing structures using this manufacturing method. For production of ruled surface geometries, hot-wire cutting holds a significant machining time advantage over traditional CNC milling, as reaching the production surfaces can be achieved in a single pass operation, sweeping the entire surface. In practice this reduces production time of an equivalent surface to a few minutes Fig.3.23 compared to CNC milling. While the above developments demonstrates the viability of RHWC for construction purposes, the thermal cutting process of hot-wire cutting, in which polystyrene material is evaporated at 290–310 °C around an electrically heated wire, comes with a number of principal shortcomings: firstly, cutting speed is a function of the material density of the polystyrene work object and hence, at high density material types, production speed is significantly lowered, whereas for CNC machining it remains principally constant within the same classes of material. Second, the process is limited to thermally cuttable materials, which excludes a wide range of construction materials, including non-flammable foam types typically used in acoustic insulations, as well as common groups of solid construction materials, such as timber, natural and artificial stone and clay. Finally, the process is sensitive to maintaining a constant cutting speed across the entire length of the wire. This in practice excludes several classes of toolpath strategies, such as triangular sweeps and hyperbolic paraboloids, in which the Tool Center Point (TCP) remains relatively inactive, while the periphery of the wire moves at high velocity Figs.3.24, 3.25.

To address these challenges, Odico engaged in the development of a complementary process using a diamond threaded abrasive wire rotating on electrically propelled flywheels, fixed within an eight-rod carbon fiber frame structure. Over the course of four prototype end effectors, the process was refined to achieve an average cutting speed of 75 mm/s, hence reducing overall cutting time for the reference surface to < 15 s, while leaving a finished surface of very high smoothness levels.

The identification of machining time is conducted through a comparative study of the three machining methods on three similar robotic workstations, using, respectively,

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[3] http://www.freefab.com

Figure 3.23: The realization of the Fjordenhjem Kirk Kapital HQ, designed by Studio Olafur Eliasson, represents the first such commercial-scale application of RHWC

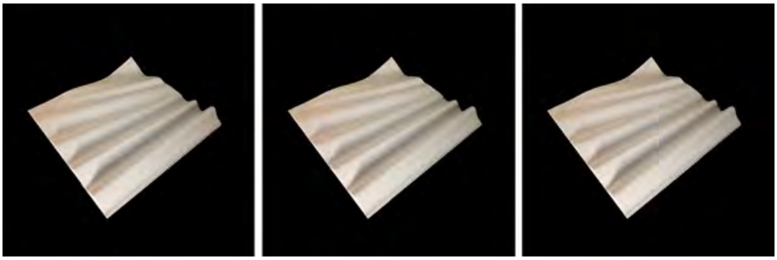

Figure 3.24: Comparative samples produced by: from left: RCNC; RHWC; RAWC)

IRB 6400R 2.8-200 (station 1), IRB 6400R 2.8-150 (station 2) and IRB 6700-300 (station 3) manipulators. Station 1 is equipped with an HSD ES-915a electrospindle with ø50 mm Schunk ball-end toolbit; station 2 with a proprietary RHWC end effector with ø 0.5 nickel–chromium wire suspended in a 2600 × 1600 × 150 mm carbon fiber frame. Station 3 is equipped with a proprietary RAWC end effector with electrically propelled ø1.5 mm abrasive wire Fig.3.24. The three stations produce a curved sample geometry of 1000 × 1000 × 150 mm, with total ruled surface area of 1187 m^3. We note that this effectively corresponds to a 9600% increase in production speed over robotic CNC milling, assuming product surfaces constructed from ruled surface geometries.

Table 3.1: Comparative chart for machining times of sample 1

Material	CNC	RHWC	RAWC
EPS S80	4 h 10 min 32 s	1 min 58 s	16 s
EPS S150	4 h 10 min 32 s	6 min 21 s	24 s
MX 300	4 h 10 min 32 s	19 min 32 s	36 s
Solid mat.	Yes	No	Yes

Figure 3.25: Top row, from left: Workstation 1, robotic CNC milling. Workstation 2, robotic hot-wire cutting. Workstation 3, robotic abrasive wire cutting. Bottom row: the corresponding machining result of sample 1 from each process

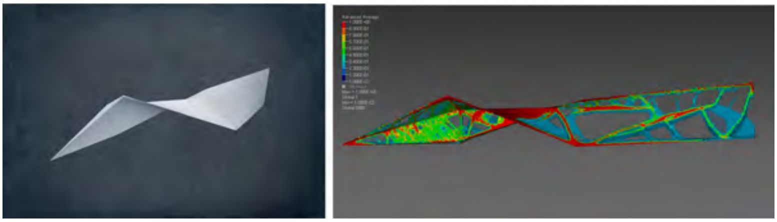

Figure 3.26: Left: design space before optimization. Right: topological optimization result

PROTOTYPE DESIGN

The design freedom enabled by the above developments provides a manufacturing framework for achieving rapid production of advanced formwork for concrete construction. To assess the potential for using this capacity in cost-efficient realization of topology-optimized concrete designs, a full-scale prototype study was undertaken.

With the motivation to test the extremes of the solution space, an optimization design space was developed, constituting a blend between three primary architectural configurations: a wall situation; a canopy; and a corner. The design space was optimized in Altair Optistruct for dead load and surface wind loads, using a volume constraint of 0.3. The resulting optimization provided the framework for the development and testing of a rationalization method and formwork system design capable of approximating the optimized mesh close enough to avoid compromising the reduction in material volume achieved through the optimization Fig.3.26.

RATIONALIZATION

As the mechanical principle of abrasive wire cutting is limited to the production of ruled surface geometries, a translation of the optimization mesh to compositions of ruled geometry is necessary to enable manufacturing through this method. Within this context, the main challenge is to approximate the optimized mesh close enough not offset the performance gains achieved through the optimization, while remaining within the solution space of the constraints of the fabrication method. To address this, a parametric rationalization scheme was developed, relying on (a) skeletonal tracing of the centerlines of the topology, and (b) a numeric approximation of the volume surrounding the centerlines through intersecting cells of ruled surface assemblies.

FORMWORK SYSTEM

Through the rationalization procedure, the formwork system is now determined. The system comprises three overall constituents, which is repeated for all six concrete components: (1) the main formwork system in expanded S80 polystyrene, split into two main parts to accommodate the later insertion of reinforcement bars; (2) a surrounding steel casing from assembled standard Peri scaffolding modules; (3) a parametrically generated timber support structure consisting of connected cassettes of (1) OSB plates ribbed with C24 coniferous beams to direct lateral pressure to the surrounding steel casing; (2) ribbed plywood panels to support directly the casting pressure exerted on the EPS formwork Fig.3.27. The EPS formwork design is determined by inverting the intersecting surfaces to volumetric formwork cell units, segmented per surface level. The boundaries of the formwork cell volumes are determined by extending the intersection lines of the cell surfaces. As the extension of the corner surfaces would collide with the volume of the linear extensions, the corners are separated as individual mold pieces, using the original intersection planes of the rationalization scheme. We have then an EPS formwork composition consisting of the following parts:

1. Corner segments, which hold the rounded hyperbolic paraboloid surface (highlighted red, Fig.3.28).
2. Main mold volumes, which hold the single-ruled extension surfaces between the corners (parts in white, Fig.3.28).
3. Boundary molds, which close the outer boundaries of the formwork cell assembly to the bottom and sides, with the top remaining open for pouring of the liquid concrete (marked gray, Fig.3.28).
4. An interface layer, which bridge the panelized segmentation of the timber support structure and part A–C of the EPS formwork, the depth of which is minimized to avoid self-intersection of the extension of the boundary surfaces.

To guide the subsequent assembly process, the interface layer is designed with linear waffle profiles aligned with the isocurvature of the global interface surface.

ROBOTIC PRODUCTION

With the rationalization and formwork design computed within a single workflow, we are now able to deduct the cutting motion for the robotic production cell. This system consists of (a) an IRB 6700-300 industrial manipulator, positioned inside a containerized transportable work cell frame and equipped with (b) a proprietary end effector with an electrically propelled abrasive wire, fixed within an auxiliary carbon fiber frame, and (c) a 1300 mm-high elevated work object fixture mounted on an external rotary axis Fig.3.29. Within this production cell, the surfaces are translated to the following cutting sequences:

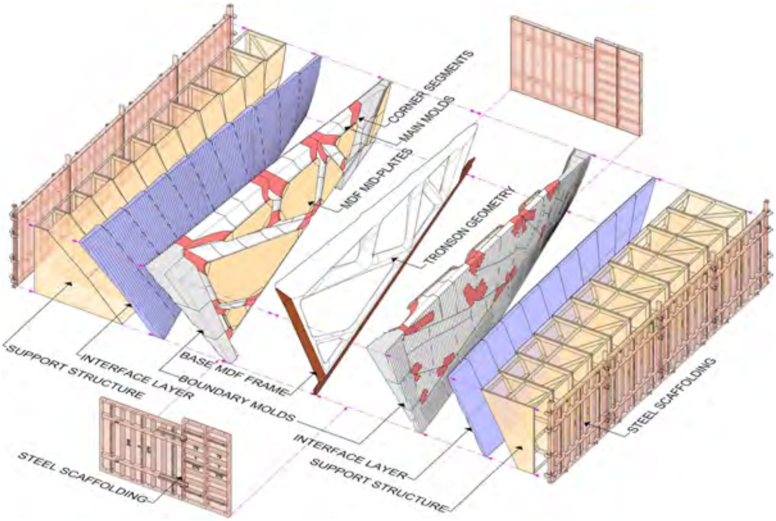

Figure 3.27: Formwork system, exploded isometry. From center going left, the system consists of: (1) the cast concrete component, (2) the EPS component formwork (white and red); (3) the interface layer (purple); (4) a timber support structure (yellow); and (5) standard DOKA in situ steel scaffolding

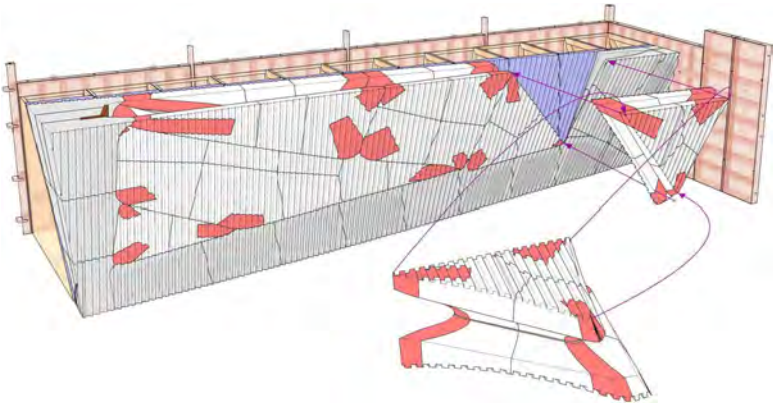

Figure 3.28: Corners (red) and main mold parts (white) inserted into the global system

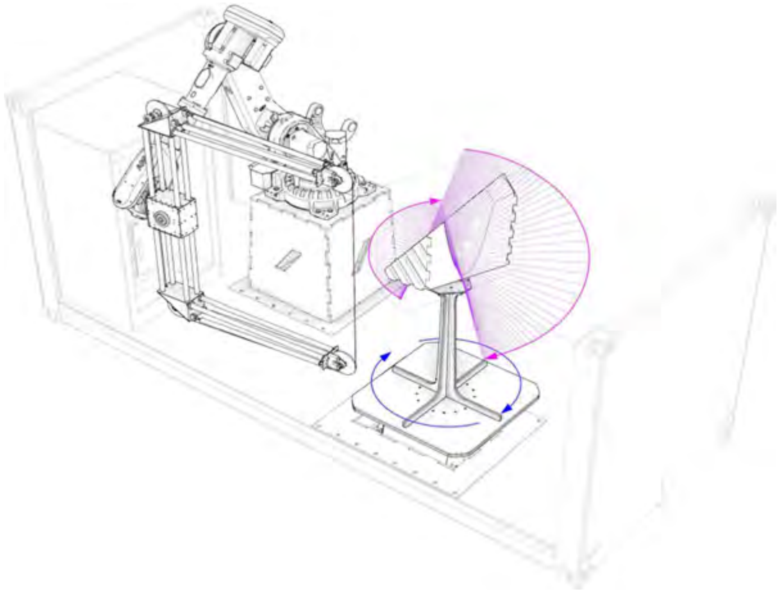

Figure 3.29: Diagrams of the cutting motion for, respectively, corner hypar

Corner mold parts The cutting sequence is initially discretized in (a) rotation of the work object on the external axis, and (b) surface cutting motion, with the tool center point (TCP) of the abrasive wire end effector following the line centers of the cutting surface isocurvature. While synchronized motion between external axis and end effector was initially applied, the simultaneity of rotational and linear motion resulted in distortion of the linearity of the wire, hence deforming the product geometry. By segregating the motion of the external axis and the end effector cutting in discrete time intervals, this problem is avoided. With this principal approach, cutting sequences are then computed in the following steps, describing all sides of the part in wire motion:

1. Top and bottom waffle profiling of the mold piece.
2. Side profiling.
3. Cutting of the hyperbolic paraboloid corner surface.
4. Backside cutting and splitting of the piece into two halves, finally releasing the piece from the stock material.

Main mold parts Similar to the corner parts, main mold parts are processes through the following sequence:

1. Cutting of the four extended side surfaces
2. Subtraction of the void for insertion of the corner part

3. Cutting of the single-ruled rib profiles
4. Cutting of the waffle profiling of the formwork cell top and bottom surface

The cutting motion is deducted from the rationalized geometry using the Odicut proprietary framework for robotic control in McNeel Grasshopper[4]. Due to the composition of the formwork geometries, end effector movement describes the extreme regions of the robotic work envelope, hence requiring both fine-tuned control of tool orientation and collision avoidance. For the initial establishment of this, cutting scenarios were tested for sets of ruled surfaces used in the rationalized design geometry. The tests were undertaken with the target of establishing a feasible path-planning approach. The conclusion of this pre-study showed that adding a rotary axis at a height > 1/2 wire length would offer an optimum path planning framework. Further, different robot poses were considered for maximizing end effector reach, along with different positions and orientations of cut pieces on the rotary table. From these studies, two “comfortable poses” were identified: (a) tool close to horizontal for top and bottom waffle profiling and single-ruled rib profiles with lead in–out approaching from above the cut piece, and (b) tool close to vertical and approaching from the side for side profiling and cutting the void for corner insertion Fig.3.29. In extension of each of the two main poses, the extremes of the cutting surfaces—defined by the start and end isocurves as well as the surface normal vector—were analyzed to compute a local average vector which is then compared to a pre-defined target orientation vector that serves as a guide for each type of cutting surface in conjunction to its corresponding robot comfort pose. This step is performed to compute the rotation value of the external rotary axis.

The most challenging procedure represents the generation of the robot path corresponding to the hyperbolic paraboloid for the corner surfaces. The center points of the isocurves—extracted from the original untrimmed corner surface—are initially used to set the correct piece orientation on the rotary tray. In a second step procedure, the actual toolpath trajectory is computed while using the active isocurves part of the trimmed body of the current piece. The aim is to ensure (a) a correct piece orientation (rotation) on the rotary tray and (b) keeping the center of the tool inside the trimmed geometry. The toolpath generated at this step translates to an up- and-over robot motion starting from a vertical tool orientation toward the right side of the current corner pieces toward a horizontal tool orientation and full upright robot posed in the middle of the cut and ending with a vertical tool toward the left side, robot pose being sideways.

This is achieved by generating a global rotational volume based on the stock block or, in extreme cases, using a local convex hull deducted from the current mold geometry at each specific external axis value. Collision avoidance is ensured by orienting the tool to match local tangent values computed from either horizontal or vertical cross sections of the above-mentioned rotational/convex hull volume and thus avoiding any tool–mold geometry collisions. This further implies that during each transition movement from one cutting motion to another, there is the above solution space, albeit specific to using a linear tool end effector, which can be used to generate valid and smooth robot motion between the end of one cutting motion toward the start of next one.

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[4] https://www.grasshopper3d.com

Due the large physical dimensions of the formwork segments and stock blocks against the 1600 mm width of the end effector, the manipulator's work envelope is used very close to its maximum boundaries. The operational work envelope is furthermore reduced during motion with close proximity to the robot base, due to the large scale of the end effector against the dimensions of the 6700 manipulator. In consideration of these factors, the general principle for collision avoidance deployed in this context is the generation of a collision volume (or safety bounding box) through one of two methods: in scenario 1 by establishing a three-dimensional rotational volume around the rotary table's axis by using the (a) the minimal bounding box of the actual piece geometry or (b) actual stock block geometry. The rotational volume is simplified for smooth robot pose and toolpath transitions to a cylinder shape with an extra half dome on the top. This ensures that each cross section computed for leadin, lead-out and transition moves (wire vertical/robot pose sideways toward wire horizontal and robot pose upright) will be a convex curve. Collision avoidance is ensured by orienting the tool to match local tangent values on the convex (transition) curve, which will always fall outside of the safety volume Fig.3.30.

In scenario 2 (extreme cases), a three-dimensional convex hull is deployed for (a) very large pieces or very large stock blocks or (b): formwork pieces exhibiting significant asymmetry in the length/width ratio of their minimal bounding box. For ideal cases, this ratio approximates 1:1—generating a small rotational volume—while for extreme cases, the ratio may constitute 4:1. Under such ratio, the default approach using a three-dimensional rotational volume fails, requiring a tighter approximation of the safety bounds to the target geometry. This is achieved through establishing a convex hull geometry. The convex hull is computed using a collection of sample points from the target formwork part geometry. In this case, the cross sections for lead-in, leadout and transition moves will constitute a convex polyline, which in a following step is translated to a smooth convex curve by interpolating through its vertex points with uniform knot spacing.

Formwork assembly and casting The corner and main mold parts are assembled into larger formwork cells using polyurethane adhesive and acrylic based surface coating. The timber support structure, produced through digital routing and processing on a Hundegger machining station and files derived parametrically from the global geometry model, is manually assembled in two main parts. The interface layer is mounted to the timber support and, subsequently, the formwork cells are mounted on the interface layer, using the waffle profiling as assembly guide. To mitigate the foreseen challenges of production tolerance in the prototype realization, several strategies are deployed throughout the construction phase. The primary foreseen sources leading to tolerance occurrence was the coupling of the in-built joint angle tolerance of the IRB 6700 manipulator, the large dimensions of both end effector and workpieces and finally the high level of formwork segmentation required by the chosen machining principle. These items are mitigated through the following measures: the formwork design is developed to include a timber-based and CNC-milled frame around all four main open edges of the polystyrene formwork system. This serves as guidance, to ensure that precision is obtained at edge level, despite any interior imprecision within the frame. Secondly, tolerance gaps occurring

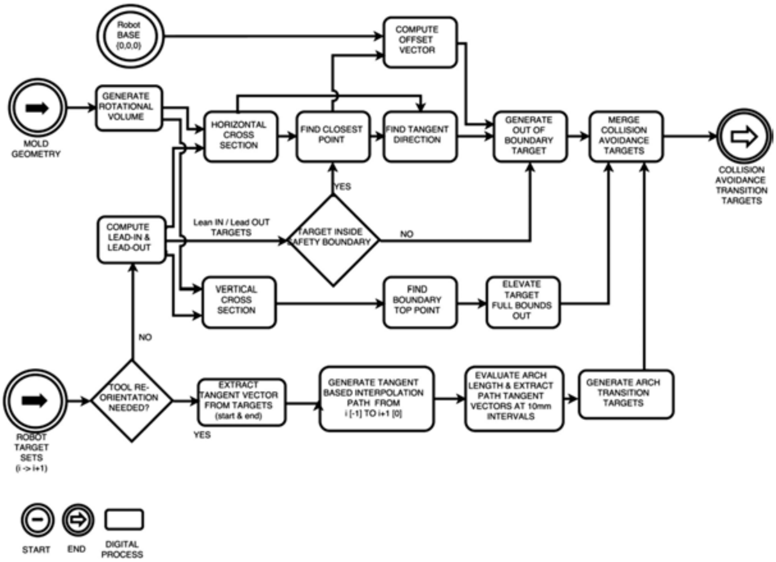

Figure 3.30: Function diagram of the collision avoidance scheme

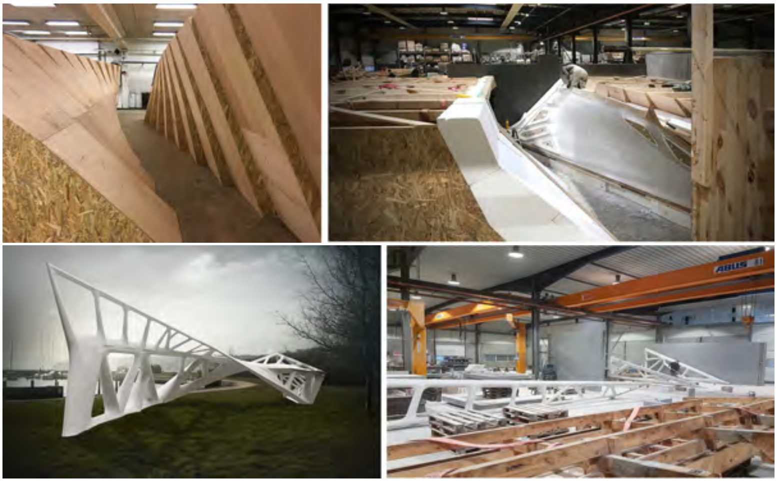

Figure 3.31: Timber support of element C1 prior to EPS assembly (left). Assembled mold and finishing of element B1 (right)

between styrene formwork parts are corrected through manual application of coating paste and general surface coating. Finally, tolerance compensation is built in through a 15 mm gap spacing between the six constituent concrete components, such as to enable adjustments in assembly Fig.3.31. Global coating is added, and reinforcement is inserted. Following the assembly of reinforcement, the two formwork sides are closed and concrete injected. After 24 h of curing, the formwork is demolded and demolished, completing the production of one structural component. The components are transported to site and assembled using a combination of temporary auxiliary supports and bolting.

CONCLUSIONS

We have presented a new method for high-speed manufacturing of topology-optimized designs for concrete structures using a dynamic ruled surface rationalization scheme to derive the parameterization of a fabrication integrated, three-dimensional EPS formwork design and associated abrasive wire-cutting procedures. The approach is found to enable significant reductions in machining time over current production methods, as well as facilitating the establishment of fully automated robotic production workflows for manufacturing of said formwork parts. The feasibility of the approach is demonstrated through the construction of the topology-optimized design for a full-scale UHPC prototypic structure, consisting of six prefabricated modules that's assembled on-site.

While overall viability of the method is demonstrated, we find that a number of workflow limitations, induced by the particularity of the prototype design, highlight significant improvements to be implemented before reaching feasibility of the method for large-scale adoption. These limitations relate to (a) the spatial nature of the prototype design; (b) the deployment of doubly ruled surface segments in rationalization; (c) the resulting formwork design scheme; and (d) the applied methodology for topology optimization. While these limitations, detailed in the following chapter, provided challenges for the implementation of the prototype, we find that through general simplifications on the global design level, such shortcoming can be overcome without challenging the underlying fundamentals of robotic abrasive wire cutting of EPS formwork systems, hence indicating general applicability of the method.

DISCUSSION AND FURTHER WORK

The presented research outlines an integrated method for cost-effective production of topology-optimized structure, using formwork machining time and design flexibility as the primary driver for the said cost-efficiency. In assessing the potential impact of this availability, we outline the following considerations. While the presented demonstration structure constitutes a non-comparative case for the most widely deployed concrete typologies, developing such designs would require less advanced measures of production than deployed through this pilot project and, hence, may be defined as safely within production range of the presented method. Pairing this basis with the indications of the potential for 65–70% reductions in material consumption outlined in preceding work compared to standard components, we may anticipate that cost neutrality of an optimized design over solid designs can be achieved through the cost reductions of the presented realization method and offset through lower material expenditure. On such basis, a rapid industry adoption may be anticipated. In the event of achieving widespread adoption, a reduction of 25% of global concrete consumption would equal the negation of approximately 600 million tons of CO_2 emission, comparable to removing all air traffic from the global emission scheme.

The design choice of relying on doubly ruled, hyperbolic paraboloid corner sections enables a closer approximation to the optimized mesh than achievable when relying on faceted, single-ruled geometries. However, it comes at the significant cost of needing to segment the formwork cells into corner and main sections. This adds substantial workload on the subsequent formwork assembly process, as well as increasing the room for production tolerance, in addition to requiring highly advanced motion planning and control of the part cutting sequences Fig.3.32.

The spatially advanced design of the formwork parts adds significant loss of formwork material, surmounting to an averaged 40–60% of the material stock block. As opposed to CNC milling, which would granulate the cutoff material directly, the cutoff, however, here doubles in function as protective casing, which significantly eases transport logistics as parts can be shipped as regular, rectangular bodies.

As a result of the segmentation scheme—determined by the geometry rationalization method—the overall volume of waste production is comparably higher with estimated 15–20% than achievable through CNC milling. However, for the general discussion of waste production, it should be noted that (a) the production and consumption of expanded polystyrene formwork material requires a fraction of the energy associated with concrete manufacturing. Hence, even significant increases in formwork waste production is fully offset by reductions in concrete material consumption enabled by the use of polystyrene formwork; (b) compared to conventional formwork systems in solid and laminated timber or construction metals, the overall energy footprint of formwork production is significantly less for expanded polystyrene systems; (c) the material properties of polystyrene enables a direct and energy light recycling process, in which cutoff parts are granulated and reused in forming of new stock block material. The spatially warping configuration of the global design—and the resulting complexity of the component formwork systems—required as noted the design and manufacturing of bespoke timber support segments on a per-element basis to reduce the general consumption volume. This step could be standardized in concrete component designs of less spatial and dimensional variability, and entirely avoided for component designs with small formwork volumes, i.e., panelized configurations as found in high-volume concrete prefabrication of general façade and structural components.

FURTHER WORK

With the prototype design intended to identify the practical boundaries and limitations of the proposed method, in addition to raising public awareness of the architectural possibilities of the merger of topology optimization and robotic manufacturing, the current work is focused on the development of revised workflows that will enable a cost range of production feasible within regular construction projects. The target is to achieve this through (a) the development of a slab component series within normative prefabrication dimensions; (b) a simplified production scheme that relies on nested, single-ruled formwork components to be used in combination with conventional prefabrication casting tables and (c) linear, parametrically produced reinforcement systems.

Figure 3.32: Reinforcement of element B1 (top, left) and element A1 after casting (top, right). Bottom: assembly of element A1 on A2, B1–B2

Figure 3.33: Final prototype structure

4

RESEARCH IMPACT ON PRACTICE

> *"Taking common sense into the holy realm of art*
> *is a shocking thing and most unpopular in academic circles…*
> *but, after all, architecture is a scientific art*
> *and the thinking basis will ever be for the architect his surety*
> *and the final courts in which his imagination sifts his feelings"*
>
> *Frank LLoyd Wright*

4.1. IMPACT

4.1.1. ENTREPRENEURSHIP IN ARCHITECTURAL ROBOTICS:THE SIMULTANEITY OF CRAFT, ECONOMICS AND DESIGN

> *If I was to realize new buildings I should have to have new technique. I should have to so design buildings that they would not only be appropriate to materials but design them so the machine that would have to make them could make them surpassingly well*
>
> Frank Lloyd Wright[4]

What do Odico Formwork Robotics, RoboFold, Machineous, ROB Technologies and GREYSHED share in common? They are all architectural robotics startups. Jelle Feringa, Chief Technology Officer at Odico, places the phenomenon of the architectural robotics entrepreneur in a historical and cultural context while highlighting the very practical role startups are poised to play in bridging the gap between academic research and industry, by providing the building industry with much needed new software tools.

This section is based on *J. Feringa. Entrepreneurship in Architectural Robotics: The Simultaneity of Craft, Economics and Design, Architectural Design, Volume 84, pages 60-65* [108].

What are the prospects of entrepreneurship in architectural robotics? Do forward-looking, entrepreneurial architects share kinship with the Renaissance architect Filippo Brunelleschi, who in the 1420s engineered a giant, three-speed, reversing ox-driven hoist, enabling him to span the massive crossing of Florence's cathedral with a dome? Is Jean Prouvé, an architect who ran a factory and who played a pivotal role in developing cutting-edge production technology and modular systems, a 20th-century analogy of how architects will operate in the 21st? Or will education tragically monopolise patronage of architectural robotics? Sharing the technological platform of robotics with industry encourages the transfer of knowledge from academia to industry. Researchers share the parlance of industry – code interpreted by the robot controller – with dialects differing from ABB's RAPID, Kuka's KRL or Staübli's VAL3 robot language. Operating on a similar platform challenges where technological innovation stops and industrial adoption starts; industrial robotics allows new manufacturing technologies to gradually evolve from initial experiments to industrial processes. The modest investment required to bootstrap a startup company,[1] given the cost of a new or refurbished robot seen in relation to its potential returns and production capacity, coincides both with a renaissance in manufacturing[94] and a need to renew the architectural profession.[65]

Startups A number of promising startup companies have been surfacing over recent years, leveraging architectural robotics beyond mere conceptual merit and stepping into the industrial arena – where startups play a pivotal role. While the robot research work is creating considerable interest, without the filter of practical adoption – technology you can buy – expectations go unfulfilled. This is why the startups presented over the following pages occupy an essential position in bridging the domains of academia and industry. Progress is affected by the cynicism sometimes observed in these domains, while institutionalism fuels the opportunity. The arguments are that from an academic or a computer science perspective there is little novelty. Inverse kinematics solvers and offline-programming software are sometimes considered to be 'known' problems.[2] Or from an industry point of view, the approaches developed in architectural robotics are far-fetched or perceived as too costly to develop, and as yet have an uncertain future in terms of their economic yield. The startups here challenge such long-proliferated misconceptions. The lack of software tools suited to architectural processes might explain the relative and creative dilettantism in developing robotics software for architecture, developed by architects. However, the robotics entrepreneurs featured here focus on pushing novel approaches beyond their conceptual infancy, bridging the gap between academic merit and industrial adoption, providing architecture and the building industry with an important new set of tools. Traditional robot integrators – often coming from a background in the automotive industry – are yet to step into this domain. The fabrication processes developed in architectural robotics differ considerably from the repetitive routines of industrial automation. For example, industrial processes are often programmed

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[1] The four ABB IRB 6400M94A robots that make up Hyperbody's robotics lab were acquired for the approximate cost of an entry-level 3D printer.

[2] In my opinion, mistakenly so. Only relatively recently have robots started to perform tasks such as milling and laser/plasma cutting. These tasks are highly demanding in terms of motion planning and optimisation, and require sophisticated, optimising inverse kinematics solvers. Such processes challenge the capability of existing motionplanning algorithms.

in-situ, where a robot programmer is explicitly jogging and feeding the robot with instructions. Once instructed, a robot is able to repeat this procedure. This mechanical approach does not extend to architecture, where the umbilical cord to CAD geometry cannot be cut.

Recovering Lost Ground This persisting CAD connection is why all of the startups presented here are so focused on software development – where the limits of where design stops *and* production starts are becoming increasingly intertwined. ROB Technologies and RoboFold develop both design and production tools. Are these companies forming a second wave after seeing the rise of the likes of designtoproduction, 1:One and CASE? Rather than making the most of the array of conventional CNC fabrication methods,[3] these companies take up the role of introducing novel fabrication processes, ranging from stacking bricks to folding aluminium panels and cutting massive blocks of foam. By making the software and design tools available to architects and industry, the threshold for market adoption is lowered considerably.

Is it possible that, when an earlier generation of architects ceded greater responsibility for the realisation of buildings to engineering offices, architecture lost some of its professional authority? The success of design rationalisation offices, file-to-factory processes and architectural robotics suggests so. Are the aforementioned companies and the robotic startups stepping into this void and recovering lost ground? If anything, the discrepancy between what is practically and economically feasible, in comparison to the daily routine of building production, is enormous; a shared thread is found in the ambition of closing this rift.

An economical perspective brings about the promise of novel fabrication methods and architectural robotics. However oversimplistic it is to consider architecture as the difference between the raw building materials and the cost of their assembly, it is here where the difference is made. Agriculture and construction are both the largest and least automated industries – where in the latter the cost of assembly essentially equates to the cost of labour. The economics of building have marginalised architectural ambitions, since craft is costly. However, as the cost of mechanised labour continues to drop dramatically, as automation and robotics become so ubiquitous, the moment has come to revitalise the architectural profession. Gramazio & Kohler's early Gantenbein vineyard facade (Fläsch, Switzerland, 2006) was seminal in this respect, simultaneously exploring the approach of automated bricklaying and its architectural potential. It is precisely this **simultaneity of craft, economics and design** that is so striking.

Design and Production The BrickDesign tool developed by ROB Technologies further blurs the false schism between design and production. BrickDesign is a Rhino3d[4] plug-in encapsulating the expertise required to design and plan large assemblies of discrete elements – bricks. To bring ROB Technologies' building process of automated bricklaying in non-standard formations to the market, it was necessary to facilitate the means of design. A lack of proper software tools means it is virtually impossible to design such a number of discrete parts without falling back into traditional bonding rules, which would not exploit the potentialities of the robotic process. As one of the pioneering

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[3] Such as laser, plasma and water-jet cutting, and milling

[4] Rhino3d

architectural robotics technologies, developed by architects for architects, BrickDesign is an important precedent of what is required before a fabrication concept can reach the levels necessary for application at the industrial scale. It has both democratised and opened up the approach to towards market adoption. This is a significant achievement, since traditionally industrial robot integrators have not been able to develop the required design tools, and as a result have only provided the required process automation.

The design and realisation of projects and prototypes built over the years by means of robotic bricklaying is an integral part of the push towards industrial readiness. For example, the client for a recent project – the brick facade of the Keller AG Headquarters (Ofenhalle, Pfungen, Zurich, 2012) – is in fact a central industrial partner of ROB Technologies, not only demonstrating confidence in the method developed, but also challenging the cliché of industry not being willing to commit to an investment in novel technology. Here is a partner that is pushing architects to reach new heights, both architecturally and in terms of technology, renewing the relationship between architect and industry. Regrettably, it is rare to see architects and their industrial partners changing the course of their industry in this way, hence the significant role startups such as ROB Technologies and the others featured here might play in progressing the field of architecture.

These startups are not just passively facilitating a construction method: an architectural ambition precedes an architectural technology. The recent Arum installation by Zaha Hadid Architects, RoboFold and Philippe Block, presented at the 'Common Ground' Venice Architecture Biennale in 2012, is insightful here. While a number of authors are credited, without RoboFold providing its own design software and fabrication process the constructive and aesthetic potential of the approach would not have been realised. The project was influenced by RoboFold's earlier developments, and as such this robotic startup company can be considered as both design *and* production partner. Their software tools aid in exploring the possibilities opened up by the robotic folding process – much like ROB Technologies' BrickDesign software allows exploration of the design space the manufacturing technique offers.

The question of economy, of developing an affordable approach to the fabrication of formwork, is addressed by Odico Formwork Robotics. The manufacturing of sophisticated formwork accounts for more than three-quarters of the costs associated with the realisation of sophisticated geometry in concrete. By upscaling wire-cutting technology to a robot with a reach of over 25 metres (82 feet), the company can produce intricate polystyrene moulds for sophisticated concrete structures in a short timeframe and within moderate budgets that challenge existing approaches to formwork. It provide solutions for the scaling of fabrication processes to architectural dimensions, developing technology that is congruent with the dominant building method – casting concrete. By moving beyond the limited production capacity of a CNC router, a cost-effective approach for the realisation of large sophisticated concrete structures becomes possible. Alongside its efforts for the building industry, Odico also produces formwork elements for a number of companies in the cleantech industry, such as Siemens Wind Power.

Recent explorations in stone-cutting technology by the Hyperbody research group at the Delft University of Technology underscore the interwoven relationship between manufacturing technology, economy and architecture.[5] Being able to process stone with

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[5] Hyperbody is directed by Professor Kas Oosterhuis. Its robotics lab was initiated and is directed by the author

the modest means of an industrial robot rapidly eludes the idea – an archaic notion – of building in massive stone elements. In addition, a salient realisation early on in the project is that the cost of marble has considerable scope. Since only up to 75 per cent of the stone quarried yields material that is of pristine quality, there is a large volume of second- and third-rate quality that is often ground down to a polishing agent used in toothpaste. The difference in quality is roughly based on the whiteness and homogeneity of the colour of the material, and translates into a factor of over 40 in the price per tonne. Given this economic bandwidth, an efficient way to shape the raw material into "*traits*"[6] suggests that building in stone may be a more viable option than is often considered.

This understanding has been one of the motivations driving the project, raising the question whether aspects of economy are an inherent element of design. Just as CNC and robotic technologies have made fabrication a more central design aspect, are such manufacturing technologies in turn bringing economic considerations into focus? ROB Technologies creates software, and RoboFold and Odico both develop software and produce building products. What will surface when the approach is extended to design?

Dutch designer Dirk Vander Kooij offers an interesting analogy. By mounting an extruder to an old FANUC robot, original and affordable chairs are produced by stacking contours layer by layer, much like an oversized 3D printer. What is interesting here is not only the quality of the end product, but that the designer is not relying on a third party to develop the process or produce the chairs, challenging the traditional boundaries of the profession, and certainly so from an economic point of view: "If he is lucky, the designer gets 3% ex factory. The brand adds 300% and the shop doubles that again. It's ridiculous how little of the cut a designer gets. If we used digital tools and changed the way stores work, the ratio would be able to favor creativity and the craftsman."[84]

Design and Build It would be misleading to mistake architecture for industrial design; even at the scale of the house, it is over-simplistic to think of architecture as a product. This said, the raw production capacity of industrial robotics does bring 'design and build' approaches to construction into view. Are the startups in architectural robotics revisiting the idea of an architect with a method of design *and* the means of production? In 1996, Bernard Cache's company Objectile set up a factory utilising CNC milling machines. In 2000, architect Bill Massie built the Big Belt house, and more than a decade later companies like Facit Homes are revisiting the idea of the house as a product, where CNC is the enabling technology. Do these projects suggest a reconsideration of the early objectives of Modernism, to provide affordable and modern houses of architectural ambition? To what extent the new-found vicinity of construction is desirable remains an open question. The emerging ecology of knowledge and new possibilities from which both the architect and contractor profit is good news for architecture. Combining architectural ambition with a sense of economical pragmatism, robotic entrepreneurship challenges preconceived ideas of what it is possible to realise given a building budget – an essentially architectural agenda is shared by these young companies.

Machineous is a fabrication and R&D company that has the most experience in this domain. Since its inception in 2008, the company has sized up its operation to five robot

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[6] A "*trait*" is a kind of drawing, usually drawn to scale, that contains the geometrical and constructive information needed to carry out the stone cutting for a specific work.

stations, and recently moved to a large 1,800-square-metre (19,400-square-foot) facility in Los Angeles, completing the transition from a robotic artisanal workshop to an industrial operation. The company's rapid expansion is matched by its increased scaling, from the production of bespoke furniture, installations and public sculptures to the production of building elements ranging from stairs to window apertures and facade panels. The crises of the American automotive industry between 2008 and 2010 made plenty of inexpensive but capable robots available at a fraction of the cost, and Machineous has adopted a number of these from a former Chrysler plant. The automotive industry's technological compost heap also fostered another startup: GREYSHED, a design-research collaborative focused on robotic fabrication within art, architecture and industrial design. GREYSHED's research has seen the integration of technologies such as augmented reality, gestural and sensor feedback in closely coupled design and fabrication processes. In its anti-institutional approach, experimentation and development of fabrication strategies are fuelled by the re-appropriation of affordable, off-the-shelf technological commodities ranging from smartphones and Kinects to chainsaws, cordless drills and refrigerator parts.

Given the current economic climate of the building industry, the momentum and market belief in the 'third industrial revolution', the impetus felt throughout the architecture, engineering and construction industry, the potential return on investments, and the low investment required to start developing architectural robotics, it is surprising that there are so few startups currently active. Are robotics and fabrication offering an apt bypassing of the maelstrom of architectural competitions, focusing on what is essential in architecture, or is there a derailing effect from taking up such a central role in the building process? Could it be Brunelleschi, the architect-engineer, versus Leon Battista Alberti, the intellectual architect, all over again?

4.2. CASE STUDIES

4.2.1. SCALING ARCHITECTURAL ROBOTICS: CONSTRUCTION OF THE KIRK KAPITAL HEADQUARTERS

At Fabricate 2011, the authors of this article encountered two new research trajectories [78, 81] , on, respectively, the design of topologically optimised concrete structures and hot-wire-cutting of expanded polystyrene (EPS) construction elements. Over lunch, the potential for a synthesis was gauged. In the years that followed, the intense collaboration that ensued resulted in a number of projects and articles[104, 108, 126]. The industrial merit of the approaches explored paved the way to further develop these at an industrial scale, leading to the founding of Odico Formwork Robotics in the spring of 2012[114]. At Odico, the challenges faced when deploying and building with robotics at scale are addressed. Over the years, a range of novel fabrication processes have been developed in an industrial context.

ARE QUANTITY AND QUALITY MUTUALLY INCLUSIVE?

Automation is often discussed in the framework of efficiency – of increasing productivity at lower labour costs. This is to say that robotics is discussed in a quantitative framework, rather than a qualitative one. The potential quality that robotics has to offer the building industry is central to its further development. Architectural robotics has been enthusiastically embraced by the design-led research community, exploring specific traits of machining processes for their intrinsic or tectonic potential. The cultivation of new manufacturing aesthetics, precipitated by the new degrees of freedom and material control offered by digital machining, has been a central motif over the past decade. Performance is rarely addressed, especially in direct quantitative terms.

So far, the literature lacks an accepted methodology and criteria to assess and contrast the relative merits of various existing technologies. Within internal technology research and development at Odico, quantity and quality represent the axes on which the merits of methods are plotted. The following criteria serve as guidelines to gauge the pertinence of technology:

- Transferability – does the approach translate across multiple applications, disciplines or material systems?
- Performance – does the approach offer a faster or more effective manner of producing results, compared to existing methods?
- Degrees of freedom – does the approach under consideration enable new opportunities in design, either by relaxing existing production constraints or by offering a way to explore previously uncharted design space?

This section is based on *A. Søndergaard, J. Feringa. Scaling architectural robotics: Construction of the Kirk Kapital Headquarters, Fabricate 2017* [134].

Figure 4.1: Robotic hot-wire-cut façade patterns and apertures for the in-situ cast concrete façade of the Sonnesgade 11 mixed use complex, Aarhus, by Sleth Architects
Photo: Rasmus Hjortshøj

Within these frameworks, quantitative and qualitative propositions are complementary – not conflicting – attributes of underpinning principles, with potential for large-scale impact in construction. Considerable attention has been directed within Odico to exploring the implications of one such technical approach and its derivatives – robotic hot-wire-cutting (RHWC) of expanded polystyrene (EPS) formwork for concrete casting. The following paper outlines the central developments within this effort.

SCALING PRODUCTION – KIRK KAPITAL HEADQUARTERS

The insight that underpinned the founding of Odico was that RHWC of expanded polystyrene formwork for advanced concrete casting could offer transformative advantages when deployed at industrial scale. When founding the company, the respective research projects by the authors of this paper allowed for the comparison of efficiencies between robotic CNC milling versus hotwire cutting of EPS moulds, which found that RHWC reduced machining times at a factor of between 10- and 100-fold [104]. This finding is particularly relevant in achieving feasible scalability within construction façade patterns and apertures for the in-situ manufacturing, where the throughput of large material cast concrete

Figure 4.2: Construction site overview: the robotically hot-wire-cut formwork is used in combination with standardised timber and steel modules to resist casting pressure, applied for creating the hyperbolic void openings of the cylindrical main walls
Photo: Kirk Property A/S.

Figure 4.3: Onsite prefabrication using a standard, rectangular scaffolding for formwork support against bespoke EPS infills.

volumes is a central concern. For robotic fabrication of such volumes, machining time replaces labour as the key cost factor and hence is a primary focus. While robotic CNC milling has long proven its versatility, its mechanical principle of incremental overview: the robotically material subtraction is inherently slow and thus not suited to scale economically beyond the exclusivity of used in combination with standardised timber and high-profile construction projects. As such, the capacity steel modules to resist of RHWC to cut through large volumes of expanded foams at significantly lower processing times, while for creating the hyperbolic void openings of the resulting in high-smoothness casting surfaces, can yield cylindrical main walls. considerable cost reductions in formwork manufacturing. Odico set out to engage the construction market for early-stage adoption and to mature the technology through input from the commercial pilot production. Production began at small-scale installations, with the objective of working towards construction-sized productions. These early efforts initiated a continuous cycle between the ongoing technology R&D and its commercial implementation. The experience gained in production informed the development of the technology required to meet industrial ambitions. Conversely, the production pipeline provides a continuous testbed for further advances in new technology that might be considered tangential to the objective of reaching an industrial scale in production. This milestone was reached in 2013 when Odico Formwork Robotics received the commission to produce over 4,500m^2 of bespoke formwork for the Kirk Kapital Headquarters (KKHQ) in Vejle, Denmark. KKHQ is a six-storey office complex designed by the Berlin-based Studio Olafur Eliasson and is architecturally Scandinavia's most ambitious office building. The project represents an international first in that it applies architectural RHWC for the production of critical load-bearing concrete structures Fig.4.2. The design comprises four intersecting cylindrical perimeter walls, which rise out of the harbour basin. With a height of 32.3m, the cylindrical walls are interspersed with 19 intersecting hyperbolic paraboloid void walls, spanning vertically across all storeys. With dimensions varying from 7.4 x 2.8 x 5.2m to 4.2 x 3.2 x 5.2m, the volume of formwork to be produced would surmount 70-110m$^($3) per storey section. While building a test mock-up, traditional wooden moulds were contrasted with the EPS moulds supplied by Odico. The EPS mould stayed more true to form under casting pressures, while a relatively low-density EPS material was selected for the test where the traditional formwork dealt with deformation. Through this critical finding, Odico obtained a vote of confidence from the building contractor Jorton to go ahead and produce the formwork for the project. The formwork system developed for the project entailed three primary variants. First, an in-situ prefabrication workflow, where polystyrene mould parts were inserted into a rectangular timber scaffolding box. This procedure was applied for onsite prefabrication of curved wall segments, which were subsequently hoisted into position Fig.4.3.

A second workflow was established for in-situ casting of lower-level hyperbolic walls. Here, the formwork was designed as a 110m^3 solid foam plug, orthogonally segmented relative to the size of the standard foam stock dimensions of 1,200 x 1,550 x 2,400mm. To minimise the volume of the plug, a single timber insert structure was produced and repeatedly used in all topologically similar cases, achieving minimisation of material as well as providing auxiliary support against the casting pressure, while imposing few geometric constraints on the formwork design itself. The final formwork system application was designed for parabolic endwalls to intersect the cylindrical perimeter walls. In this case, rolled steel repetitive-use formwork was used to create the main wall geometry, while foam inserts were used as vertical plugs to achieve the parabolic opening. This ability to utilise RHWC seamlessly within the existing casting workflows was decisive in adopting the process for the project. The above workflow required the organisation, design and manufacturing of around 3,800 unique RHWC formwork units. With the design not developed with the RHWC approach in mind, aspects of fabrication had not been a concern in the design and engineering development. As such, a considerable post-rationalisation effort was required. In order to segment the building to patterns that fitted stock material, a semi-automated CAD workflow was developed in McNeel Grasshopper and GH Python. While the project in principle would have sustained a shared, central BIM model, at the time the IFC 4 specification[7], which allows for NURBS[8] surfaces, was not available throughout the involved digital chain. The ability to exchange geometry in NURBS was a hard requirement, given the sophisticated ruled geometry of the project.

As a result, the model was sourced from a number of CAD platforms; and with the lack of software supporting IFC 4 at the time, this effectively disrupted a fluent interchange of modelling data, which compromised the geometric integrity of the model. As a result, a substantial effort in geometry pre-processing and optimisation of formwork design was required. Since then, Odico has provided support for IFC 4 for its offline robotics platform, PyRAPID[117]. Taking on a recently founded start-up to deliver a central feature of the project — the production of over 130 truckloads of unique formwork for realising the most prestigious office building in Scandinavian construction history -– was a risk offset by the disruptive properties of the robotic process. This enabled Odico Formwork Robotics to deliver at a considerably lower price point while handling all aspects involved with a small team.

INDUSTRY ENGAGES

Following the KKHQ project, Odico Formwork Robotics has seen a rapid expansion, completing over 200 projects in the four years since its formation, including several high profile commissions in the United Arabic Emirates, the United Kingdom, Norway and Denmark. One recent example was the design and production of EPS foam guides for the manufacturing of 2,000 uniquely bent aluminium profiles, targeted at the doubly-curved glass façades of Opus Dubai, an iconic premium hotel resort designed by Zaha Hadid Architects in Dubai, UAE. In this case, enabled by the geometric coherence of the design scheme, a complete automation of the workflow was established. This enabled the entirety of profile geometries to generate mould design and resulting robot code in a single batch operation. This optimisation allowed for an increase of output from 80 unique units per 24 hours to 200-300 units, helping to accelerate the production schedule.

High volume applications, such as stairs, panels and structural components — as well

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[7] "To support the best way to exchange rich geometry-preserving parameters, the resulting schema includes several additional geometry types, such as advanced B-rep (NURBS), faceted B-rep and surface models, constructed solid geometry (CSG) and advanced sweeps, including tapering and presentation styles, such as colours and textures, which can be added to these geometries."

[8] Non-uniform rational b-splines

Figure 4.4: The benches as installed in the Winton Gallery, December 2016
Photo: Luke Hayes

Figure 4.5: Production UPHC prototype of bench B5 for the Science Museum, Winton Gallery of Mathematics, design Zaha Hadid Computation and Design Group.

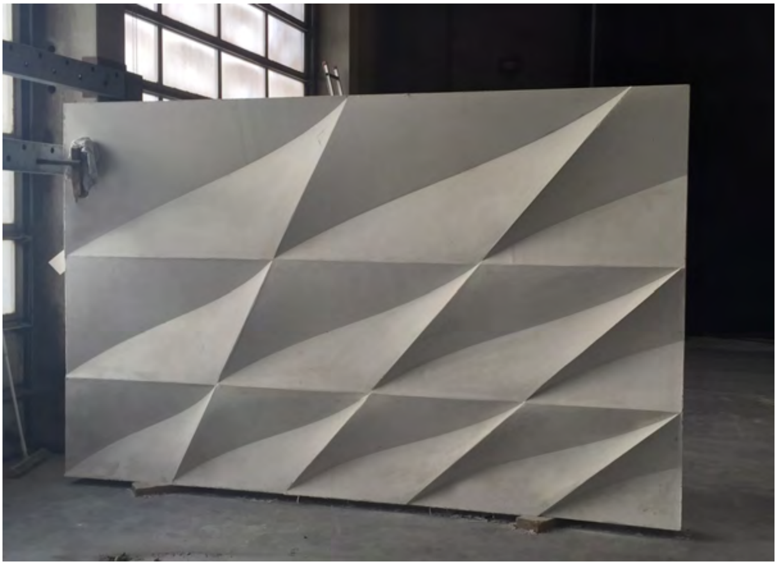

Figure 4.6: BladeRunner concrete panel demonstrator designed by 3XN Architects / GXN Innovation. The demonstrator is part of a series of explorations of design assemblies, seeking to capitalise on the aesthetic opportunities within the constraints of the hotwire cutting process.

as advanced infrastructural developments, where formwork expenditure represents a significant cost factor — form a testbed for the demonstration of the combined effects of the hotwire machining speeds, the degrees of freedom offered in robotic control and the cost-effective EPS material. Indeed, this represents a viable pathway for a dramatic offsetting of costs in industrial concrete production. The production of hotwire cut moulds for the KKHQ main structure corroborates that RHWC can act as a cost-effective method for the production of complex concrete moulds, applicable to a wide range of construction uses. In such cases, as is typical for the majority of Odico's production, the primary threshold is the successful demonstration that the technology can be effectively applied to designs that did not anticipate the use of advanced robotic fabrication – or RHWC specifically – in the conceptual design phase. Conversely, a growing interest from design partners in exploring the inherent vocabulary of RHWC concrete production is starting to complement these initial efforts. The architectural capacity of robotically controlled wire-cutting is being investigated as a constitutive premise for design, with the outline of capitalising on the specific degrees of freedom offered by the process, while maintaining the cost advantage demonstrated in practical applications Fig.4.6.

One of the first to address this potential in a commercial context, Zaha Hadid Computation and Design Group engaged with Odico to develop process-specific designs within various applications. An initial outcome of this effort was the design for 14 unique UHPC benches for the Winton Gallery of Mathematics at the Science Museum, London. For this project, a design scheme was developed within the constraints of wire-cutting moulds, enabling Odico to offer a production scheme favorable over existing fabrication approaches. The resulting benches were produced as 35mm high performance concrete shells surrounding a lightweight foam core Figs.4.4 and 4.5.

While robotically controlled hot-wire-cutting of concrete formwork offers a distinct solution space in which novel design vocabularies can be explored, the mechanical concept per se can be extended across several domains of material processing and motion types. This line of thinking constitutes an important exploration within Odico's internal development efforts. Over the course of four tooling prototypes, robotic abrasive wire-cutting (RAWC) has been developed and implemented within Odico's production. While subjected to the same geometric and motion constraints as RHWC, abrasive wire-sawing enables the processing of hard materials such as marble[109], timber, non-flammable foams and ice Fig .**??**. This in turn facilitates a conceptual shift from producing the intermediate product of formwork designs to the architectural component itself. Adjacent to this strand of development, Odico recently began to explore the domain of ceramic brick fabrication. In collaboration with Strøjer Tegl, a leading Danish producer of ceramic bricks, a robotic system was devised for production of bespoke tile designs. Early work on the topic [89] indicated the architectural potential for bespoke ceramic tiles. Odico explored a different mechanical approach for processing the clay material due to the density of the clay utilised. By the development of an oscillating end effector, in which forward and quick lateral movement of a wire is combined, a rapid manufacturing process was devised, paving the way for rapid production while directly integrating with Strøjer's manufacturing process. As such, the installation enables the production of uniquely designed tiles. This quality was explored shortly after the initiation of the facility for an interior wall cladding of Odense Theater by Creo Arkitekter A/S, emulating the undulating motion of the theatre curtain.

DOUBLE-CURVED FORMWORK – BLADE CUTTING

Odico tendered in a consortium for the production of the formwork of the Waalbrug bridge extension project by Zwarts and Jansma Architecten. The design required many thousand square metres of double-curved formwork. The constraint of double curvature could not be met in a satisfactory way using ruled surface rationalisation and hot-wire-cutting, so that approach was dismissed in favour of timber formwork, which meant that Odico did not participate in the realisation of the project. However, the tender did inspire an idea: by bending a blade, double curvature could be closely approximated. This method allows the production of moulds at a new level of scale and efficiency, enabling the realisation of large-scale double-curved concrete structures. The cross-disciplinary research project BladeRunner was formulated, and two more years of development culminated in a patented technology where unique double-curved formwork no longer incurs an unreasonable cost penalty[121, 126]. This method is now under preparation for pilot production Figs.4.7 and 4.8, with expected construction scale roll-out over the course of 2017.

WHAT TECHNOLOGY WANTS

The past decade has seen the genesis of a range of specific robotic construction technologies and process concepts — some of which hold promise for adoption in construction.

Figure 4.7: Early doubly-curved hot-blade demonstrator produced at the Robarch 2016 Workshop, “SuperForm”, by the BladeRunner Research consortium and workshop participants

Figure 4.8: Experimental multi-robot cell deploying 3 ABB multi-move manipulators for production of doubly-curved geometries via sweeping of a flexible, heated blade along a surface.

Thanks to this accumulation of academic efforts, momentum is building. The critical test is whether architectural robotics can scale beyond the lab to the construction site and become a commercially sustainable industry, possibly breaking the current technological stasis. In *What Technology Wants*, Kevin Kelly offers a compelling perspective on the forces that drive technology: "The second great force pushing evolution on its immense journey is positive constraints that channel evolutionary innovation in certain directions. In tandem with the constraints of physical laws outlined above, the extropy of self-organisation steers evolution along a trajectory. While these internal inertia's are immensely important in biological evolution, they are even more consequential in technological evolution. In fact, in the technium, self-generated positive constraints are more than half the story; they are the main event"[73]. In the context of advanced architectural fabrication, we may characterise these positive constraints as methods and techniques that are tangential to the demands of a progressive architecture, having the capacity to scale architectural artefacts of a novel character, while coincidentally challenging the price point at which these can be delivered.

Due to the inertia of the building industry, there is still ample time to learn from other industries, especially when the former concepts of work and industry are changing. Considering the efficiencies of the vast, highly automated production lines in the automotive industry, automotive entrepreneur Elon Musk said: "The biggest epiphany I've had this year is that what really matters is the machine that builds the machine — the factory"[124] He noted that an increase in output orders of magnitude greater than today's levels was to be expected through the redirection of creative engineering efforts towards this target, rather than through the product itself. Does the same hold true for construction? Could a shift in design orientation from the object to the 'machine that builds the house' trigger unprecedented architectural innovation? Ironically, in the construction industry, the field of architectural conservation may offer us an insight. With the processing of natural stone becoming highly automated, has its manual handling evolved to become a punitive task, reminiscent of the image of Howard Roark working in the granite quarry in The Fountainhead[6]?

Architectural conservation is an area where novel fabrication methods involving robotics have been adopted early, resulting in industry-wide acceptance. Companies that have not invested in the past two decades in CNC or robotic fabrication will today or in the near future no longer be able to compete, given the cost of labour and the efficiencies gained by automation. The Sagrada Família has been architectural conservation's most enterprising project, and its expected completion date has been brought nearer by embracing robotic fabrication[53]. Today, the architectural merits of the past are being (re)built with state-of-the-art technology. Scanning sculptures and reproducing stone elements has become a default approach, as the recent recreation of Palmyra's Arch underscores[122]. The challenges faced by large-scale automation in construction could be the call to disrupt the present order: "Not alone have the older forms of technics served to constrain the development of the neotechnic economy, but the new inventions and devices have been frequently used to maintain, renew and stabilise the structure of the old order. . . Paleotechnic purposes with neotechnic means: that is the obvious characteristic of the present order"[5].

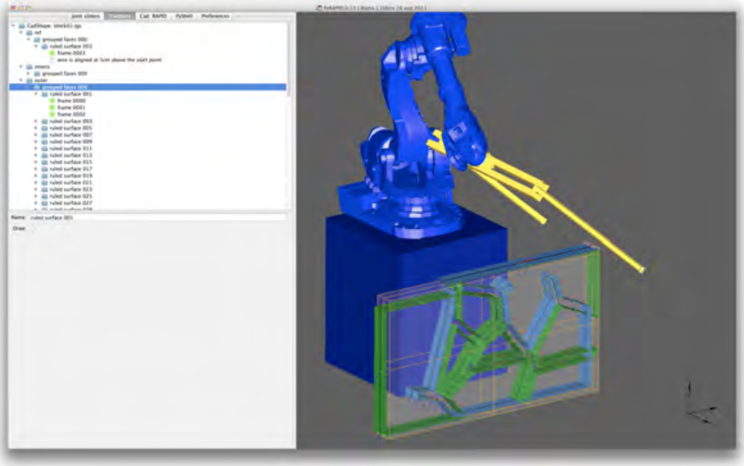

Figure 4.9: Recently completed mock-up of the Kirk Kapital HQ, for which the formwork was realized by robotic means by Odico formwork robotics

4.2.2. BIM AND ROBOTIC MANUFACTURING: TOWARDS A SEAMLESS INTEGRATION OF MODELING AND MANUFACTURING

In this paper the authors explore the potential of the IFC standard for robotic manufacturing. IFC, short for Industry Foundation Classes, is an open standard to describe Building Information Modelling data. IFC shares resemblance with its overarching technological foundation called STEP, short for STandard for the Exchange of Product model data. In the automotive industry, STEP is the de facto neutral CAD format facilitating interchange and from which manufacturing data, such as CNC toolpaths are routinely derived. These similarities inspire to look beyond the realms of what IFC is commonly utilized for and explores the relevance of STEP commonalities in the manufacturing domain. In particular, this paper addresses the need for valid Boundary Representations to model arbitrarily complex building elements and methods to assess their validity when transferring these representations from the modelling to the manufacturing domain. A preliminary implementation is sketched that ties open source components to a proprietary robotics environment to directly translate BIM geometry into manufacturing code.

INTRODUCTION

The Industry Foundation Classes (IFC) is an open standard and one of the central technologies that drive Building Information Modeling (BIM). It models a building as a decomposition of elements, which bind geometrical representations to semantic information and metadata. The use of IFC in the industry constitutes a radical transition from proprietary file formats and unstructured geometrical data into rich and open information models. So far that transition has yet to extend into the domain of manufacturing.

This section is based on *J. Feringa, T. Krijnen. Bim for robotic manufacturing, IASS 2015* [117].

IFC as a standard is not very restrictive, which made low-quality and needlessly tessellated geometry dictate its image in the industry in its early days. However, with IFC stemming from the geometrical underpinnings of ISO 10303-42, known as STEP CAD files, there is the potential to model arbitrarily precise geometry suitable for manufacturing. Whilst BIM evangelists have expressed the ambition of a central data repository to consolidate the construction effort, the authors have observed a rift between engineering and manufacturing efforts. Especially Computer Aided Manufacturing is a discipline that has not embraced BIM to its full potential.

Odico specialized in the robot fabrication of formwork for the construction industry. The approach developed supports the manufacturing of complex and curved formwork while the manufacturing approach and material utilized, expanded polystyrene foam, allows to produce complex formwork at cost that is an order of magnitude more cost effective than traditional means or CNC milling[104]. Currently Odico formwork robotics is producing complex formwork by robotic means for an architectural project being built in Vejle, the Kirk Kapital HQ by the Danish artist Olafur Eliasson. The project channels geometric data that originate from a number of sources participating in the project. The various competences required in the project map to a diversity of software platforms involved, including Tekla, Inventor and Rhino. Consolidating and normalizing the data from the various sources proved to be challenging. IFC 2x3 lacks the support for nurbs, required to describe the many curved areas of the project. However, in future projects interoperability from IFC is considered a key competence. This motivated exploring the potential of IFC 4 -offering nurbs support- for future projects.

A proprietary offline robot programming technology, PyRAPID developed by Odico is built on top of the OpenCASCADE CAD kernel[141], and accesses the API by means of the pythonocc module. This paved the way to experiment with IfcOpenShell[140], which in turn utilizes the OpenCASCADE kernel, and provides python bindings that are compatible with pythonocc. As such IfcOpenShell provides access to IFC files while giving access to an industrial grade CAD kernel by means of integration with pythonocc. As such the platform furnishes a low barrier environment to explore workflows based on current and developing IFC standards. PyRAPID's workflow is founded on vendor neutral CAD formats such as the aging IGES standard and the technically superior STEP standard[27, 28]. Hence, its anticipated that IFC is potentially an important source of robotic manufacturing data for the AEC indsutry. Possible increasingly so with the coming about of IFC 4 and the nurbs support it provides. Nurbs support is of considerable interest here, since the more challenging the geometry the likeliness of robotic manufacturing brought into service increases. Commonly the lack of support of higher order geometry delimits the rift between AEC/BIM software and CAD software used in the aeronautic / automotive industry . With IFC 4 support for nurbs geometry, possible this schism between these domains can be closed. The challenges experienced and the confidence and experience running production almost exclusively based on STEP data sparked the interest in exploring IFC for robotic manufacturing. STEP is an important precedent to IFC and shares many similarities. Potentially native IFC support lowers the threshold to barrier to entry to adopt such manufacturing processes, while providing a familiar workflow.

Figure 4.10: *Left* Recently completed mock-up of the Kirk Kapital HQ, for which the formwork was realized by robotic means by Odico formwork robotics *Right* Architectural elements produced by robotic means, deriving toolpaths from STEP data

Modeling for manufacturing with Boundary Representations

Modeling a building project is a laborious effort. Furthermore, the models represent a significant value that can be maximized by making optimal use in different contexts of the building industry, where currently IFC sees little or no usage. Reinterpreting data is not uncommon when moving from one industry partner to the other. It takes place for instance when the building model is transferred across incompatible software platforms or when different requirements are set to the data. This is a costly effort and, with the risk of introducing error, potentially contributing to the significant percentage of failure costs in the construction industry.

In this paper, the authors explore the hypothesis that an IFC files that encodes a higher level of data has the potential for greater impact and economic yield from the considerable modelling effort. To underscore this, the IFC elements used in the research work in this paper deal with geometric representation in the form of Boundary Representation (BRep) data, which is what enables the generation of manufacturing data from IFC data.

In a BRep model, a solid volume or shell is modeled as a connected set of faces. These faces are bound by edges. The edges themselves are bound by vertices. Faces, edges and vertices define the topology of the model, in short: the connectivity information, whereas geometrically, a face has an underlying surface, an edge follows a curve and vertices coincide with a point.

Other motivations for high geometric fidelity

This paper focusses on geometrical requirements for manufacturing, but at the same time other valid reasons exist to strive for a higher geometrical fidelity in IFC. These reasons include for example to facilitate a more precise mapping to structural or Finite Element Analysis tools. After all, a FEM with the required fidelity can be generated from a BRep model, with arbitrary precision and boundary conditions naturally derived from the faces, edges and vertices of a BRep model. Having to manually exact boundaries on a triangulated model are a considerable barrier to reuse of the data in across another context. Much like the FEM models, BRep data is a more natural model to define CAM operations on. A curved BRep face is potentially described by many hundred or thousand triangles. As such, like defining boundary conditions on FEM models, its becomes cumbersome or impossible to define CAM operations on triangulated geometry. For example, defining a pocketing operation on a BRep face rather than a large set of polygons. Finally, CAM operations require approximations of the BRep surface that are up to an order of magnitude below fabrication tolerances. Having the polygonol model approximate these would yield impractical data sets. The volume of data this requires, increases the inability to specify operations on the geometry while simultaneously hindering data exchange, simple due to its volume. Hence, in edge cases remodelling is required, which possible is required to be validated by the client, leading to even further -possible artificial- data exchange issues. Which is why geometric integrity and competence in data exchange is key to lowering the barrier towards manufacturing. Additionally, more precise clash detection and interference checking necessitates accurate boundary representations. Clash detection as a coordination tool is able to detect interferences after merging independently constructed aspect models of an edifice. Typically it is implemented as a series of triangle-triangle intersections, for example as in an implementation built upon the open source BIMserver.org[75].

Certain geometrical properties cannot be evaluated properly in triangulated geometry. For example, to assess whether a panel's minimal curvature radius is within the material's constraints, a geometrical model is necessary that enables to calculate surface derivatives, something which can not be done based on faceted, and therefore discontinuous, models. Lastly, a concise BRep model of curved surfaces is typically more efficient in terms of file size than its faceted counterpart, as it requires many more coordinates to approximate the curvature.

STATE OF THE ART OF GEOMETRY IN IFC

Similar to most STEP Application Protocols the geometrical definitions of IFC are by large extent taken from ISO 10303-42, what is commonly referred to as STEP CAD files. However, note that the entity names are matched to IFC's camelcase naming convention with an Ifc- prefix. As such, for example *IfcExtrudedAreaSolid* is a closely related to *extruded_area_solid* and identical except for an additional *Placement*and lacking a Name. The type of the *extruded_area* is different in IFC to allow IFC's parametric profiles as input for the extrusion. The parametric profile definitions in IFC are extended to include building-specific profile cross-sections, such as an H- or U- shape profile. Initially, STEP entities for NURBS have been left out of the Ifc2x3 standard, but have been included in the subsequent IFC4 release. Many IFC exporters of authoring tools have resorted to faceted representations as a lowest common denominator of exporter ambitions and viewer capabilities[64]. Especially for building products, such as windows or pipes, for which producer information can be embedded in the IFC file, and therefore the exact geometrical identity is of lesser importance, as the exact specifications can be read from producer's

Figure 4.11: Example of an IFC graph depicting a face with underlying BSpline surface bounded by four BSpline curves.

spec sheets. For products that needs to be manufactured specifically for the edifice, either prefab or in-situ, geometrical fidelity is more important. Partly, this is acknowledged in the IFC model as there are specific geometrical requirements for IfcWallStandardCase[9]. Note however, that these are on the level of textual recommendations and do not affect the semantic or structural validity of the IFC model. As such, Jeong et al[64] note that prevalent geometrical representations are of the type IfcFacetedBrep. The latter is a type of geometry that disallows curved surfaces and edges. Support for b-spline surfaces is a recent contribution to the emerging IFC4 standard and forms an important cornerstone for a complete BRep model. Initially using the IFC 2x3 data model, even if authoring tools would not resort to faceted representation and on the contrary write full-fledged boundary representations, there underlying surfaces would still be bound to a limited set of primitive surfaces, such as cylindrical and planar surfaces. With the recently introduced b-spline surfaces, the full free-form aspirations of the designer can be modelled in the IFC file with arbitrary precision necessary for direct manufacturing.

In addition, in IFC4 constructs to encode parametric relations between geometric entities are introduced that can be used to document design intent, embed knowledge on how forms are conceived and under what constraints they can be altered.

STEP AND IFC

In the automotive industry, we observe STEP AP 203 / 214 as the designated point of exchange between partners, while bridging the domain of CAD to CAM. Therefore it is implied that a similar strategy -due to the considerable overlap of IFC and STEP AP 203 /

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[9] buildingSMART, 2007, IfcWallStandardCase

Table 4.1: STEP application protocols

Part 213	Numerical Control Process Plans for Machined Parts
Part 222	Design Engineering to Manufacturing for Composite Structures
Part 223	Exchange of Design and Manufacturing DPD for Composites
Part 224	Mechanical Product Definition for Process Planning
Part 225	Structural Building Elements Using Explicit Shape Rep
Part 236	Furniture product and project
Part 237	Computational Fluid Dynamics
Part 238	Integrated CNC Machining
Part 239	Product Life Cycle Support

214- can be applied to the building industry, with recent additions IFC to help channeling these efforts. With IFC being an open standard the authors believe that it can formally document the tacit knowledge that lives in the industry. Knowledge and lessons learned from building models can transcend individual design projects and, as innovative efforts are no longer hindered by proprietary data, academic research and industry initiatives jointly contribute.

The STandard for the Exchange of Product model data (STEP) is an ISO standard, large ecosystem, environment, modeling language, serialization formats, integrated resources (geometry). IFC builds on top of this ecosystem and most notably relies on Part 11 for the schema definition, Parts 21 and 28 for the serialization formats, IFC-SPF and IFC-XML respectively. Lastly, the bulk of topological and geometrical representation items are drawn from Part 42.

IFC does not have this notion of complementary schemas for distinct purposes as can be found in the Application Protocols and Integrated Resource of the STEP domain. By example, the following STEP Application Protocols exist in STEP, that are tangential to the issues pointed out in this paper, and possible STEP AP's serve as a reference for the IFC community.

Conversely, there is a notion of Model View Definitions that impose additional constraints on an information exchange on top of the validity rules expressed in the IFC schema. As such, it is possible to constrain elements to a certain type of geometry and to ensure that certain attributes have values within a certain range. Automated tools exist to verify whether an IFC file conforms to such an MVD[120].

TRUSTING DATA

In order to implement automated manufacturing processes, trusting data, conversion and manufacturing processes is of vital importance. Repositories exist that collect publicly available IFC models[69] and assess their integrity. A detailed assessment of procedural and organizational implications are sketched in[99]. This is essential, this paper has drawn analogies to the automotive supply chain, where it has been acknowledged that alignment of organization processes is another important component besides file format interoperability[20].

One potential technical issue of data integrity stems from parametric history in IFC files. Typically, for example in case of a wall, the geometrical representation can be defined as an extrusion of a composite curve, trimmed by polygonally bounded halfspaces with cutouts specified in other coordinate systems. As such, the exact geometrical outcome becomes sensitive to tolerance and precision management and floating point precision truncation or rounding when reading the serialized numbers and successively applying geometrical operations. To circumvent potential issues that arise from this, in STEP AP 203e2 geometrical validation properties are introduced, which encode formal verification procedures on parametric models, for example to verify whether the centre of mass of the outcome is at the proper location, as well as fine grained tolerance management[45]. IFC only has one global precision indication on the representation context. As the parametric complexity of the model increases the need for this becomes more urgent, for explicit BRep data such considerations are less relevant.

Note however that parametricity is not necessarily something that stands in the way of automated manufacturing. Loading and verifying machine code is one of the dominant steps in this process. If this step can be done for a set of products that descend from a from a single parametric family, the overall process can be sped up even more. In STEP AP 203e2 the possibility exist to record static BRep snapshots of parametric geometry definitions[45] that fold parametric geometrical operations into a single precise outcome. A similar strategy can easily be adapted into IFC by adding another representation that describes a final BRep outcome of the entire parametric stack.

Lastly, analogous to STEP-NC traceability records [47] can be recorded. So that records of logistics, manufacturing procedures and measurements of the final product can be recorded.

CONCLUSION

One of the killer applications for BIM from its early days has been clash detection, in which neighboring elements are checked for geometric interference. This has proved to be successful when operating on approximate meshes, as the needed precision was lower than the error introduced by its approximation. Furthermore, operating on triangulated meshes reduced the algorithmic complexity. However, as described above, the authors foresee that increasingly sophisticated applications of IFC will further the demands of greater integrity for geometrical descriptions. Most notably, this applies to the manufacturing domain.

In this paper the advent of IFC4 is discussed, which offers the definition arbitrarily curved surfaces as NURBS. Similarly a technology stack is described in this paper, a Python and OpenCASCADE centric platform that ties IFC data input directly to the manufacturing process. With these two developments the feasibility of direct manufacturing from IFC data is proven. However, when geometrical data of the required fidelity will be exported by mainstream BIM authoring tools remains to be seen as the introduction of IFC4 is recent at the time of writing. Therefore, manufacturing based on IFC data currently still necessitates tinkering with custom software development. Similar to Model View Definitions that exist for coordination, facility management handovers and structural analysis, a Manufacturing MVD can be introduced that enforces precise non-faceted Boundary Representation suitable for manufacturing. Perhaps these can be defined as potential additional representations to more parametric ones. A notion similar to the ephemeral secondary representation that fold parametric sequences into explicit BReps as discussed in the previous section that discusses concepts from STEP AP 203e2 to augment the level of trust in geometrical data in IFC. The authors hope to underscore that, in order to make IFC an industry success and vertically integrated into the building sector, there needs to be a stronger understanding of what an IFC file constitutes when transcending to another domain, here fabrication, which poses strong demands on the integrity and precision of the geometry.

5

CONCLUSION

In this dissertation the question of how to bridge the divide between academic research and industry in the domain of *architectural robotics* has been addressed by investigating aspects of computational design, robotic fabrication and their impact on research and practice via a series of experiments and case studies. These showcase a fundamental change in design to production approaches that have been in the last decade advanced in academia and slowly started infiltrating architectural practice.

The first chapter 2 focused on *computational design* concluded that the literal turn of the architectural model has developed beyond representation, its significance transgressed from a representational conceptual model to a referential model from which manufacturing data is *derived* from. This development from symbolic description to definition has proven to have a dramatic impact on fabrication and therefore on the autonomy and economy of architecture as practice 16. With simulations by means of evolutionary computation, topology optimization, and CNC tool paths *derived* from the project's model, computational design has proven to establish an unprecedented link between conceptualization and fabrication.

If indeed the construction of architecture is robotised and the information derived from the architectural model, the longstanding Corbusian maxim *"architecture is not building"* is challenged. The question if construction the when robotised is the mere execution of manufacturing data or is it its generation is addressed along similar lines and comments as Retsin's elaboration on [131] how the practice of architecture will evolve. This position is advanced in projects implemented at Odico 61

With the literal turn of the model, the epistemic status of the architectural model is raised. The literal turn of the architectural model is explored in terms of its modality. Specifically, modality is explored in terms of semiotics and related to how the information instilled in the model is encoded. The epistemic shift – the transfer of architectural intent through connotation (G.Lynn's Alessi vases Fig.2.14, F.Roche use of robotics Fig.2.9) and denotation (J. Rieffel Fig. 2.15, G. Hornby Fig.2.14, Gramazio& Kolher Fig.2.10) is contrasted Fig.2.1.2.

The semiotics of the literal turn of the architectural model is explored in a design experiment. Here the physical manifestation of a model and its semiotics are paired. The design seeks to sublimate a design concept explored in the Seroussi project 2.1.1. Here —through the mechanism of evolutionary computing— daylight design is explored holistically, taking into consideration a highly detailed local climate model that takes into account all of the 4380 unique annual solar vectors

The project (*Analemma* Fig.5.1) seeks to construct a form such that a circular shadow is cast throughout the year, throughout the whole day. Here denotation is contrasted to connotation, where meaning is associated and inferred, denotational meaning is perceived through visible concepts, whereas connotational meaning stems from connotation to related phenomena[59]. As such the literal turn of the architectural model is explored in terms of its semiotics, by a pairing of conceptual intent (an object that casts a circular shadow, always) and the physical manifestation of the model Fig.5.1.

The generative potential of *multi-objective evolutionary computing* was explored in tie with advanced daylight simulation. The use of the Voronoi diagram as a genotype to

Figure 5.1: Analemma (2010), presented at the Club Transmediale 2011 explored the literal turn of the architectural model. Throughout the year, throughout the day, a circular shadow is cast. As such, concept and form are bound together in an undivided manner. Stubbornly renounces the earth's 29.783 km/sec velocity, arrogantly eschewing the Universe's perpetual motion

encode spatial designs is discussed and contrasted with binary matrices. The Voronoi encoding is found to be a considerable more effective approach, since the more powerful the abstraction is that encodes the evolving architectural design it is considerable more likely that the evolution will be effective. A general metric to qualify the effectiveness of a genotype/phenotype is missing. The significance of a powerful means of encoding design is drawn by analogy: the brain for instance consists of about a hundred billion connections, though only thirty thousands active genes describe the brain. Contrast this with the approach of binary matrices where a 1:1 ration between genotype and phenotype.

There is great interest to evolve an evolutionary developmental approach (evo-devo),as formulated by Stanley et al.[39]. Here development is the process of using the set of rules (codons) written in a genome to turn a single set (zygote) into a mature phenotype Yogev's thesis[76] provides relevant results in application of the evo-devo in a problem that addresses structural design. Rieffel extended the notion of the developmental approach to that of a *situated developmental* approach [50].

This work addresses the pivotal realization that buildability is a central concept in generative design, and a central concept that stems from the field of generative robotics[22]. Buildability is what Rieffel refers to as the fabrication gap 2.1.3: by merely specifying the form of an object, this approach leaves unanswered the vital question of formation. Rieffel's concept revolves around the idea of situated development. The assembly or construction process is a part of the evaluation criteria of the fitness function for the evolutionary design process; how cleverly a structure is built is part of the evaluation criteria while the structure is being optimized.

Robotic fabrication, has been identified in the second chapter as more effective than

CNC milling in relationship to specific designs. For instance, *implicit fabrication* enabled through the computational turn in manufacturing has been considered with respect to the *Turing completeness* in fabrication 26. The execution of CNC toolpaths is without any feedback loop or executing logic while running the toolpath. The dilemma of production has been identified as no longer relying on hordes of workers and mechanized systems but is transmuting to the intellectual problem of reporting construction as a set of executable instructions expressed as code driving a CNC machine or a robotic arm.

In this context, *architectural geometry*, involving volume- and surface-based approaches requiring the segmentation of an overall geometry to a set of components was identified a quintessential problem. For instance, the developable-transform –based on the medial axis analysis[7]– was recognized as a manifestly architectural problem because of its implications on geometrical, industrial, economical, structural and aesthetic aspects 48. The approach of applying *levelsets* in the context of architectural geometry / surface segmentation was an original one at the time. The article was first published in [80]. The merits of levelsets were early appreciated by Pottmann et al [74]. In 2014 the surface segmentation approach was explored in a pavilion for the STUK art festival Fig.5.3 Due to limited time and resources for the realization of the pavilion, not all of the RHWC voissoirs were cut with the highest precision. Across the pavilion the contours between the voussoirs were therefore emphasized with a shadowgap, which results in further accentuation of these contours. Even though an unwanted side-effect, this imprecision did underscore the segmentation logic, which was convincing in terms of design quality.

Although dealing with a dissimilar set of fabrication constraints, but sharing a preoccupation for natural stone, the work on segmentation was fuelled by the collaboration on the *RDM Vault* with Rippmann who's approach [105] manifested in the seminal *Armadillo pavilion* [125, 129].

Kohler pointed –in private conversation– out that the *RDM vault* 55 lacked a material quality, leaving it unresolved whether a pavilion in EPS was the ultimate embodiment, or whether it is a mock-up. Specifically, it lacked gravitas. The approach was expanded by cutting ruled geometry with an abrasive wiresawing of natural stone 44. Later the approach was generalized to overcome limitations of the RHWC approach 91

Recently, the intuition of exploring and exploiting the specific traits of the medial axis has been researched in a more complete manner in the thesis of Robin Oval (Block Research Group) [135]. Interestingly, the approach developed by Oval's syntheses the aforementioned approaches by use of the medial axis.

For instance, *Processes for an volume-based architecture* 37 identified one of the driving factors behind its growing adoption in the architectural fabrication industry regarding the use of open software applications. Specific case-studies 55 adapted existing approaches such as contour cutting to the solid cutting process. Where in the early days of digital architecture CNC and robotic milling were explored [16] as an interface to cross the virtual to the actual, hotwire cutting scales more gracefully to the dimensions architecture demands. In 2012, this realization manifested in the founding of *Odico*, where the research presented in this thesis provided the initial impulse and economic

Figure 5.2: Armadillo, presented at the Venice Biennale, 2016. ©Iwan Baan

Figure 5.3: A pavilion based on the research on the development transform49, presented at the STUK festival 2014

analysis of the approach. The robotic hotwire cutting process, as it yields a large portal tool is demanding in terms of toolpath and motion planning as motion required to take collision avoidance, the kinematic limitations of the robot manipulator, singularities and joint accelerations limits into consideration. As the hotwire tool offers a degree of freedom –the axis of the wire–, exploiting this freedom is essential in optimizing and constraining the reach of the robot within its kinematic domain and offers considerable potential to minimize the jerk of the joints of the robot, which result in the smoother motion which in turn yields higher quality results.

Recent work in the field of *topology optimisation* of concrete structure demonstrate

Figure 5.4: A pavilion based on the research on the development transform 49, presented at the STUK festival 2014

considerable potential for the design of structures that reduce the material consumed of up to 60%, while resulting in structures with a comparative structural capacity and that meet building code. This potential has been explored in the case-studies presented 85 while developing structural morphologies that minimize their constituent material volume, by condensing matter where minimal deformation energy is concentrated that simultaneously maximize structural stiffness. The resulting architectural grammer yields the course of structural forces perceptible.

With the *Robotic Hot-Blade Cutting* (RHBC) a general purpose method for producing doubly curved formwork has been presented. The efficacy of the method has been demonstrated through geometry rationalization and pilot production of a sample formwork panel design. The approach developed examines the challenges towards uptake of the approach on an industrial scale. RHBC presents, an economic outlook on the fabrication of double-curved formwork 72. Where hotwire-cutting has had an impact on the price level of formworks that are comprised of ruled surfaces, RHBC has a similar impact where double-curved formwork is required. Unintentionally, the developed approach to RHBC was limited to deforming the blade in co-planar fashion. Duenser et al.[136] generalised the approach and overcomes two key limitations of our approach:

1. the input model does not has to be segmented into sufficiently simple patches that can be cut with a single sweep
2. imposes no such co-planar restrictions, allowing the robot to auto- matically discover complex motions that exploit non-planar wire configurations.

The research challenges the boundaries of the architectural profession, in developing fabrication methods that challenge the economy of double-curved formwork. Whereas costly steel moulds or expensive 5-axis machine formworks stifle such formwork being employed In terms of research impact on practice, it has been identified that not only quality of the end product is an added value, but that the designer is not relying on a third party anymore to develop the process, which is challenging the traditional boundaries of the profession 107. In the presented case studies it is acknowledged that combining architectural ambition with a sense of economical pragmatism, robotic entrepreneurship challenges preconceived ideas of what it is possible to realisable given a building budget. Recently, Dennis Shelden edited a tangential AD issue [137]

BIM and robotic manufacturing In the early years of the adoption of BIM a key driver has been the facilitation of clash detection, where geometric entities are tested for interference. A case-study is presented 124 that in parallel identifies and motivates a demand for further advancement of geometric integrity. For the uptake of robotic manufacturing from IFC data, a deeper comprehension of what geometric integrity when crossing the domains of design to manufacturing is composed of. The latter imposes considerable constraints on the integrity and precision of geometry. Despite the building construction being slow in adopting new technologies, this thesis makes an attempt to identify challenges and opportunities for technology transfer from academia to industry in particular form the perspective that about 50% of all tasks will be automated while 45% rely on human-robot collaboration and only 5% remain in human hands [138]. This thesis identified a series of tasks that can be automated and presented ways to do so, while the challenge for the future remains to identify all tasks and develop automated and semi-automated procedures for next generation building processes. Following Ruttico from [133] the founders of EZCT Architecture & Design Research led to established two start-ups, *Xtreee* and *Odico*:

Academic research coupled with new industrial technologies in this area are spawning new companies, where design and fabrication occur simultaneously. There are several emerging start-ups committed to innovating production methods for serial repetition. In Switzerland, for example, ROB Technologies deals with engineering of non-standard applications for the assembly of brick blocks, wood, and ceramic elements. In Denmark, ODICO Formwork Robotics applies robotic cutting to molds for production of individual concrete elements (Jelle Feringa is now Chief Technology Officer within Odico). In France, XTreeE (ex-EZCT team and ex-students from Philippe Morel and Thibault Schwartz) is the first company to commercialize robotic large-scale 3D printing technology for the architectural design, engineering and construction sector.

BIBLIOGRAPHY

[1] Leonhard Euler. “Methodus Inveniendi Lineas Curvas Maximi Minimive Proprietate Gaudentes, Sive Solutio Problematis Isoperimetrici Lattissimo Sensu Accepti”. In: *Lausanne & Geneva: Marcum-Michaelem Bousquet* (Jan. 1744), pp. 1–322.

[2] Jean Baptiste de la Rue. *Traité de La Coupe Des Pierres*. Paris: Charles-Antoine Jombert, 1764.

[3] Augustus Love. *A Treatise on the Mathematical Theory of Elasticity*. Vol. 1. 1892.

[4] Frank Wright. “Frank Lloyd Wright: An Autobiography”. In: Toronto: Longmans, Green and Company, 1932, p. 149.

[5] Lewis Mumford. *Technics and Civilization*. Routledge, 1934.

[6] Ayn Rand. *The Fountainhead*. 1943. ISBN: 978-0-452-28637-5.

[7] Harry Blum et al. *A Transformation for Extracting New Descriptors of Shape*. Vol. 43. MIT press Cambridge, MA, 1967.

[8] Douglas T. Ross. “Origins of the APT Language for Automatically Programmed Tools”. In: *ACM SIGPLAN Notices* 13.8 (Aug. 1978), pp. 61–99. ISSN: 03621340. DOI: `10.1145/960118.808374`.

[9] Per-Erik Danielsson. “Euclidean Distance Mapping”. In: *Computer Graphics and Image Processing* 14.3 (Nov. 1980), pp. 227–248. ISSN: 0146-664X. DOI: `10.1016/0146-664X(80)90054-4`.

[10] C. Truesdell. “The Influence of Elasticity on Analysis: The Classic Heritage”. In: *Bulletin (New Series) of the American Mathematical Society* 9.3 (Nov. 1983), pp. 293–310. ISSN: 0273-0979, 1088-9485.

[11] Michael Moore. *Roger and Me*. Documentery. 1989.

[12] Edward Fredkin. “Finite Nature”. In: *XXVIIth Rencotre de Moriond* (1992), pp. 345–354.

[13] Geoffrey Boothroyd. “Product Design for Manufacture and Assembly”. In: *Computer-Aided Design* 26.7 (July 1994), pp. 505–520. ISSN: 0010-4485. DOI: `10.1016/0010-4485(94)90082-5`.

[14] Robin Evans. “The Projective Cast: Architecture and Its Three Geometries”. In: *The Projective Cast: Architecture and Its Three Geometries*. Cambridge, Mass: MIT Press, 1995, pp. 180–189. ISBN: 978-0-262-05049-4.

[15] Robin Evans. *The Projective Cast: Architecture and Its Three Geometries*. Cambridge, Mass: MIT Press, 1995. ISBN: 978-0-262-05049-4.

[16] Attila Foundation, RAM Gallery, and Nederlands Architectuurinstituut, eds. *Sculpture City: The Electronic Fusion of Art & Architecture*. Rotterdam: 010 Publishers, 1995. ISBN: 978-90-6450-229-3.

[17] John Frazer. *An Evolutionary Architecture*. Themes 7. London: Architectural Association, 1995. ISBN: 978-1-870890-47-2.

[18] Erik Spiekermann. "LettError[TM]". In: *Wired* (July 1995). ISSN: 1059-1028.

[19] Thomas J. Bergin and Richard G. Gibson, eds. *History of Programming Languages II*. New York : Reading, Mass: ACM Press ; Addison-Wesley Pub. Co, 1996. ISBN: 978-0-201-89502-5.

[20] Erick Haag and R. Vroom. "The Application of STEP in the Automotive Supply Chain". In: *Computers in Industry* 31.3 (1996), pp. 223–234. DOI: `10.1016/S0166-3615(96)00053-X`.

[21] J. A. Sethian. "A Fast Marching Level Set Method for Monotonically Advancing Fronts". In: *Proceedings of the National Academy of Sciences* 93.4 (Feb. 1996), pp. 1591–1595. ISSN: 0027-8424, 1091-6490. DOI: `10.1073/pnas.93.4.1591`.

[22] Pablo Funes and Jordan Pollack. "Evolutionary Body Building: Adaptive Physical Designs for Robots". In: *Artificial Life* 4.4 (Oct. 1998), pp. 337–357. ISSN: 1064-5462. DOI: `10.1162/106454698568639`.

[23] Greg Ward Larson and Rob Shakespeare. *Rendering with Radiance: The Art and Science of Lighting Visualization*. The Morgan Kaufmann Series in Computer Graphics and Geometric Modeling. San Francisco: Morgan Kaufmann, 1998. ISBN: 978-1-55860-499-5.

[24] Marcos Novak. "Next Babylon, Soft Babylon". In: *A.D.: Architects in Cyberspace II* 68.11-12 (1998), pp. 20–29.

[25] Kamal Sarma and Hojjat Adeli. "Cost Optimization of Concrete Structures". In: *Journal of Structural Engineering-asce - J STRUCT ENG-ASCE* 124 (May 1998). DOI: `10.1061/(ASCE)0733-9445(1998)124:5(570)`.

[26] Bernard Cache. "Objectile: The Pursuit of Philosophy by Other Means". In: *Architectural Design* 69 (1999), pp. 66–71.

[27] Mangesh P Bhandarkar et al. "Migrating from IGES to STEP: One to One Translation of IGES Drawing to STEP Drafting Data". In: *Computers in Industry* 41.3 (May 2000), pp. 261–277. ISSN: 0166-3615. DOI: `10.1016/S0166-3615(99)00052-4`.

[28] Mangesh P. Bhandarkar and Rakesh Nagi. "STEP-based Feature Extraction from STEP Geometry for Agile Manufacturing". In: *Computers in Industry* 41.1 (Jan. 2000), pp. 3–24. ISSN: 0166-3615. DOI: `10.1016/S0166-3615(99)00040-8`.

[29] Pål Börjesson and Leif Gustavsson. "Greenhouse Gas Balances in Building Construction: Wood versus Concrete from Life-Cycle and Forest Land-Use Perspectives". In: *Energy Policy* 28.9 (July 2000), pp. 575–588. ISSN: 0301-4215. DOI: `10.1016/S0301-4215(00)00049-5`.

[30] Hatem Hamda and Marc Schoenauer. "Adaptive Techniques for Evolutionary Topological Optimum Design". In: (Apr. 2000). ISSN: 978-1-85233-300-3. DOI: `10.1007/978-1-4471-0519-0_10`.

[31] John Mardaljevic. “Daylight Simulation: Validation, Sky Models and Daylight Coefficients”. Thesis. Loughborough University, Jan. 2000.

[32] Mark Burry, Jane Burry, and Jordi Faulí. “Sagrada Família Rosassa: Global Computer-Aided Dialogue between Designer and Craftsperson (Overcoming Differences in Age, Time and Distance)”. In: *Proceedings of the Twenty First Annual Conference of the Association for Computer-Aided Design in Architecture*. 2001, p. 11.

[33] K. Oosterhuis. “Variomatic”. In: *IFD-bouwen 1999*. Ed. by van M Braam Morris. Stuurgroep Experimenten Volkshuisvesting, 2001, pp. 118–121. ISBN: 90-5239-158-0.

[34] Gerald Farin. “A History of Curves and Surfaces in CAGD”. In: *Handbook of Computer Aided Geometric Design*. Elsevier, 2002, pp. 1–21. ISBN: 978-0-444-51104-1. DOI: `10.1016/B978-044451104-1/50002-2`.

[35] Dennis R. (Dennis Robert) Shelden. “Digital Surface Representation and the Constructibility of Gehry’s Architecture”. Thesis. Massachusetts Institute of Technology, 2002.

[36] Axel Kilian. “Fabrication of Partially Double- Curved Surfaces out of Flat Sheet Material Through a 3D Puzzle Approach”. In: *Acadia*. Indianapolis, 2003, p. 9.

[37] “Architectures Non Standard”. In: *Architectures Non Standard: Exposition Présentée Au Centre Pompidou, Galerie Sud, 10 Décembre 2003-1er Mars 2004*. Ed. by Frédéric Migayrou. Paris: Centre Pompidou, 2003, pp. 138–139. ISBN: 978-2-84426-231-8.

[38] C Null and B Caulfield. *Fade to Black: The 1980s Vision of “Lights-Out” Manufacturing, Where Robots Do All the Work, Is a Dream No More*. 2003.

[39] Kenneth O. Stanley and Risto Miikkulainen. “A Taxonomy for Artificial Embryogeny”. In: *Artificial Life* 9.2 (Apr. 2003), pp. 93–130. ISSN: 1064-5462. DOI: `10.1162/106454603322221487`.

[40] Behrokh Khoshnevis. “Automated Construction by Contour Crafting—Related Robotics and Information Technologies”. In: *Automation in Construction*. The Best of ISARC 2002 13.1 (Jan. 2004), pp. 5–19. ISSN: 0926-5805. DOI: `10.1016/j.autcon.2003.08.012`.

[41] John Mardaljevic. “Spatio-Temporal Dynamics of Solar Shading for a Parametrically Defined Roof System”. In: *Energy and Buildings* 36 (Aug. 2004), pp. 815–823. DOI: `10.1016/j.enbuild.2004.01.020`.

[42] Ole Sigmund and Martin P. Bendsøe. “Topology Optimization – from Airplanes to Nanooptics”. In: *BRIDGING from Technology to Society*. Ed. by Kristian Stubkjær and Tine Kortenbach. Kgs. Lyngby: Technical University of Denmark, 2004, pp. 40–51. ISBN: 978-87-990378-0-3.

[43] Philippe Morel. “N extensions à Extensions de la grille: Sur la production contemporaine et la notation à partir de Le Corbusier et Ludwig Hilberselmer”. In: *Multitudes* 20.1 (2005), p. 57. ISSN: 0292-0107, 1777-5841. DOI: `10.3917/mult.020.0057`.

[44] Helmut Pottmann et al. “Industrial Geometry: Recent Advances and Applications in CAD”. In: *Computer-Aided Design* 37 (June 2005), pp. 751–766. DOI: 10.1016/j.cad.2004.08.013.

[45] Michael J. Pratt, Bill D. Anderson, and Tony Ranger. “Towards the Standardized Exchange of Parameterized Feature-Based CAD Models”. In: *Computer-Aided Design* 37.12 (Oct. 2005), pp. 1251–1265. ISSN: 0010-4485. DOI: 10.1016/j.cad.2004.12.005.

[46] F. Scheurer, Christoph Schindler, and Markus Braach. “From Design to Production: Three Complex Structures Materialised in Wood”. In: *International Conference on Generative Art 2005*. 2005.

[47] Julio Garrido Campos and Martin Hardwick. “A Traceability Information Model for CNC Manufacturing”. In: *Computer-Aided Design* 38.5 (May 2006), pp. 540–551. ISSN: 0010-4485. DOI: 10.1016/j.cad.2006.01.011.

[48] Shutao Li et al. “CAD/CAM Integrated Building Prefabrication Based on a Product Data Model”. In: *Joint Internat.Conf.on Computing and Decision Making in Civil and Building Engineering*. 2006, p. 10.

[49] Philippe Morel. “Computatonal Intelligence: The Grid as a Post-Human Network”. In: *Architectural Design* 76.5 (Sept. 2006), pp. 100–103. ISSN: 0003-8504, 1554-2769. DOI: 10.1002/ad.330.

[50] John Rieffel. “Evolutionary Fabrication: The Co-Evolution of Form and Formation”. PhD thesis. 2006.

[51] Andreas Wächter and Lorenz T. Biegler. “On the Implementation of an Interior-Point Filter Line-Search Algorithm for Large-Scale Nonlinear Programming”. In: *Mathematical Programming* 106.1 (Mar. 2006), pp. 25–57. ISSN: 1436-4646. DOI: 10.1007/s10107-004-0559-y.

[52] Justin (Justin Keith) Werfel. “Anthills Built to Order : Automating Construction with Artificial Swarms”. Thesis. Massachusetts Institute of Technology, 2006.

[53] Antoni Gaudí, Mark Burry, and Deutsches Architekturmuseum, eds. *Gaudi Unseen: Completing the Sagrada Familia*. Berlin: Jovis, 2007. ISBN: 978-3-939633-78-5.

[54] Robert H. Lab Jr. “Think Formwork – Reduce Costs”. In: (Apr. 2007), pp. 14–16.

[55] Helmut Pottmann and Daril Bentley, eds. *Architectural Geometry*. 1. ed. Exton, Pa: Bentley Institute Press, 2007. ISBN: 978-1-934493-04-5.

[56] Kenneth Rose et al. “Developable Surfaces from Arbitrary Sketched Boundaries”. In: *SGP ’07 - 5th Eurographics Symposium on Geometry Processing*. Eurographics Association, July 2007, p. 163.

[57] Natalie Seroussi, Elias Guenoun, and Maison rouge - Fondation Antoine de Galbert, eds. *Pavillon Seroussi: biothing ; DORA (Design Office for Research and Architecture); EZCT Architecture & Design Research ; Gramazio & Kohler ; IJP - George L. Legendre ; Xefirotarch ; [les projets du concours ont été présentés à la Maison Rouge Fondation Antoine de Galbert du 31 mai 2007 au 9 septembre 2007, sous le titre de Pavillon Seroussi, Architectures de Collectionneur]*. Orléans: Éditions HYX, 2007. ISBN: 978-2-910385-49-1.

[58] Jeffrey J. Tabor. "Programming Living Cells to Function as Massively Parallel Computers". In: *2007 44th ACM/IEEE Design Automation Conference*. June 2007, pp. 638–639.

[59] R. L. Trask and Peter Stockwell. "Language and Linguistics: The Key Concepts". In: 2nd ed. Routledge Key Guides 66-67. Abingdon [England] ; New York: Routledge, 2007, p. 51. ISBN: 978-0-415-41358-9 978-0-415-41359-6 978-0-203-96113-1.

[60] Jelle Feringa. "Notes on the Potential of Simulation for Architectural Conception". In: *Silicon + Skin: Biological Processes and Computation, [Proceedings of the 28th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) / ISBN 978-0-9789463-4-0] Minneapolis 16-19 October 2008, 264-271*. CUMINCAD, 2008. URL: `http://cumincad.scix.net/cgi-bin/works/paper/acadia08_264` (visited on 06/08/2020).

[61] Alexander Schiftner et al. "Architectural Freeform Structures from Single Curved Panels". In: *Advances in Architectural Geometry*. Vienna: TU Wien, 2008, pp. 45–48.

[62] Per Dombernowsky and Asbjørn Søndergaard. "Three-Dimensional Topology Optimisation in Architectural and Structural Design of Concrete Structures". In: *Evolution and Trends in Design*. Ed. by Domingo Alberto and Lázaro Carlos. CMD Domingo y Lázaro Ingenieros SL, 2009, pp. 268–269.

[63] Dan Haynes. "Haynes, D. (2009). Reflections on Some Legal and Contractual Implications of Building Information Modeling (BIM)". In: *Construction Watch* 9 (2009), pp. 1–9.

[64] Y. -S. Jeong et al. "Benchmark Tests for BIM Data Exchanges of Precast Concrete". In: *Automation in Construction* 18.4 (July 2009), pp. 469–484. ISSN: 0926-5805. DOI: `10.1016/j.autcon.2008.11.001`.

[65] Amanda Kolson-Hurley. *Available: Immediately – the Recession Comes Home*. https://www.architectmagazine.com/practice/available-immediately-the-recession-comes-home_o. Feb. 2009.

[66] Daniel Lobo, David Alan Hjelle, and Hod Lipson. "Reconfiguration Algorithms for Robotically Manipulatable Structures". In: *2009 ASME/IFToMM International Conference on Reconfigurable Mechanisms and Robots*. June 2009, pp. 13–22.

[67] M. Minhat et al. "A Novel Open CNC Architecture Based on STEP-NC Data Model and IEC 61499 Function Blocks". In: *Robotics and Computer-Integrated Manufacturing* 25 (June 2009), pp. 560–569. DOI: `10.1016/j.rcim.2008.03.021`.

[68] Fabian Scheurer. "Size Matters: Digital Manufacturing in Architecture". In: *306090 Books*. Vol. 12. 2009, pp. 59–65.

[69] Robert Amor and Johannes Dimyadi. "An Open Repository of IFC Data Models and Analyses to Support Interoperability Deployment". In: *Proceedings of 27th International Conference on Construction IT*. 2010, p. 10.

[70] Fabio Gramazio, Matthias Kohler, and Silvan Oesterle. "Encoding Material". In: *Architectural Design* 80 (July 2010), pp. 108–115. DOI: `10.1002/ad.1114`.

[71] X. Huang and Y. M. Xie. *Evolutionary Topology Optimization of Continuum Structures: Methods and Applications*. Chichester, UK: John Wiley & Sons, Ltd, Apr. 2010. ISBN: 978-0-470-68948-6 978-0-470-74653-0. DOI: 10.1002/9780470689486.

[72] Kevin Kelly. *What Technology Wants*. New York: Viking, 2010. ISBN: 978-0-670-02215-1.

[73] Kevin Kelly. "What Technology Wants". In: New York: Viking, 2010, p. 119. ISBN: 978-0-670-02215-1.

[74] Helmut Pottmann et al. "Geodesic Patterns". In: *ACM Trans. Graph.* 29 (July 2010). DOI: 10.1145/1833349.1778780.

[75] P. van den Helm, M. Böhms, and L. van Berlo. "IFC-based Clash Detection for the Open-Source BIMserver". In: *EG-ICE 2010 - 17th International Workshop on Intelligent Computing in Engineering, 17th International Workshop on Intelligent Computing in Engineering, EG-ICE 2010, 30 June 2010 through 2 July 2010*. Nottingham, 2010, p. 1.

[76] Or Yogev, Andrew A. Shapiro, and Erik K. Antonsson. "Computational Evolutionary Embryogeny". In: *IEEE Transactions on Evolutionary Computation* 14.2 (Apr. 2010), pp. 301–325. ISSN: 1089-778X, 1089-778X, 1941-0026. DOI: 10.1109/TEVC.2009.2030438.

[77] Oded Amir. "Topology Optimization of Concrete Structures". In: *Euromech 522 Colloquium: Recent Trends in Optimisation for Computational Solid Mechanics*. Erlangen, 2011.

[78] Per Dombernowsky and Asbjorn Sondergaard. "Unikabeton Prototype". In: *Fabricate 2011: Making Digital Architecture*. Ed. by Ruairi Glynn and Bob Sheil. UCL Press, 2011, pp. 56–61. ISBN: 978-1-78735-213-1. DOI: 10.2307/j.ctt1tp3c6d.

[79] Giuseppe Fallacara et al. "The Vault of the Hôtel de Ville in Arles". In: *Nexus Network Journal* 13.3 (Oct. 2011), pp. 599–629. ISSN: 1590-5896, 1522-4600. DOI: 10.1007/s00004-011-0091-3.

[80] Jelle Feringa. "An Experimental Developable-Transform Based on the Levelset Method and Topological Skeleton". In: *Proceedings of the International Symposium on Algorithmic Design for Architecture and Urban Design*. ALGODE. Tokyo, Mar. 14, 2011.

[81] Jelle Feringa, M. Verde, and M. Hosale. "Investigations in Design & Fabrication at Hyperbody". In: *Fabricate 2011: Making Digital Architecture*. Ed. by Ruairi Glynn and Bob Sheil. UCL Press, 2011, pp. 102–104. ISBN: 978-1-78735-213-1. DOI: 10.2307/j.ctt1tp3c6d.

[82] Jørgen Hauberg. "Research by Design - a Research Strategy". In: *AE... Revista Lusófona de Architectura e Educacao* 5 (2011), pp. 46–56. ISSN: 1646-6756.

[83] Christian Raun Jepsen, Mathias Kræmmergaard Kristensen, and Poul Henning Kirkegaard. "Dynamic Double Curvature Mould System". In: *Computational Design Modeling* (2011). Ed. by Christoph Gengnagel et al., pp. 291–300. ISSN: 978-3-642-23435-7. DOI: 10.1007/978-3-642-23435-4.

[84] Gabrielle Kennedy. “Joris Laarman’s Experiments With Open-Source Design”. In: *Open Design Now: Why Design Cannot Remain Exclusive*. Ed. by Bas Van Abel. 1 ed., 2.print. Amsterdam: BIS, 2011, pp. 200–208. ISBN: 978-90-6369-259-9.

[85] Sungwoo Lim et al. “Developments in Construction-Scale Additive Manufacturing Processes”. In: *Automation in Construction - AUTOM CONSTR* 21 (Jan. 2011), pp. 262–268. DOI: `10.1016/j.autcon.2011.06.010`.

[86] Wes McGee. “Matter & Making”. In: *Fabricate 2011: Making Digital Architecture*. Ed. by Ruairi Glynn and Bob Sheil. UCL Press, 2011, pp. 74–85. ISBN: 978-1-78735-213-1. DOI: `10.2307/j.ctt1tp3c6d`.

[87] Diederik Veenendaal, Mark West, and Philippe Block. “History and Overview of Fabric Formwork: Using Fabrics for Concrete Casting”. In: *Structural Concrete* 12.3 (Sept. 2011), pp. 164–177. ISSN: 14644177. DOI: `10.1002/suco.201100014`.

[88] M. Verde, M. Hosale, and J. Feringa. “Investigations in Design & Fabrication at Hyperbody”. In: *Fabricate: Making Digital Architecture Riverside Architectural Press, Waterloo, CA*. 2011, pp. 99–106. ISBN: 978-1-926724-18-8.

[89] Stefano Andreani et al. “Flowing Matter: Robotic Fabrication of Complex Ceramic Systems”. In: *Proceedings of ISARC2012 – International Symposium on Automation and Robotics in Construction*. Eindhoven, 2012, p. 7.

[90] J. Feringa and A. Sondergaard. “Design and Fabrication of Topologically Optimized Structures; an Integral Approach, a Close Coupling Form Generation and Fabrication”. In: *Digital Physicality: Proceedings of the 30th eCAADe Conference, Prague, Czech Republic, 12-14 September 2012*. eCAADe. Prague: eCAADe, 2012. ISBN: 978-9-4912070. URL: `https://repository.tudelft.nl/islandora/object/uuid%3A1bd52cfc-ab2a-404f-be98-a6b71508f617` (visited on 06/08/2020).

[91] Jelle Feringa. “Implicit Fabrication, Fabrication Beyond Craft: The Potential of Turing Completeness in Construction"”. In: ACADIA 12: Synthetic Digital Ecologies. 2012, pp. 383–390. ISBN: 978-1-62407-267-3.

[92] P Hesse. “TailorCrete”. In: *Architekturteilchen. Modulares Bauen Im Digitalen Zeitalter*. Koln, 2012, pp. 126–127, 164–165.

[93] Steven Mankouche, Joshua Bard, and M. Schulte. “Morphfaux: Probing the Proto-Synthetic Nature of Plaster Through Robotic Tooling”. In: *Proceedings of the Acadia Conference*. San Francisco, 2012.

[94] Paul Markillie. “A Third Industrial Revolution”. In: *The Economist* (Apr. 2012). ISSN: 0013-0613.

[95] Christian Raun, Mathias K. Kristensen, and Poul Henning Kirkegaard. “Dynamic Double Curvature Mould System”. In: *Computational Design Modelling*. Ed. by Christoph Gengnagel et al. Berlin, Heidelberg: Springer, 2012, pp. 291–300. ISBN: 978-3-642-23435-4. DOI: `10.1007/978-3-642-23435-4_33`.

[96] Matthias Rippmann, Lorenz Lachauer, and Philippe Block. “Interactive Vault Design”. In: *International Journal of Space Structures* 27.4 (Dec. 2012), pp. 219–230. ISSN: 0266-3511, 2059-8033. DOI: `10.1260/0266-3511.27.4.219`.

[97] Asbjørn Søndergaard and Per Dombernowsky. “Design, Analysis And Realization Of Topology Optimized Concrete Structures”. In: *International Association for Shell and Spatial Structures. Journal* 53.4 (Dec. 2012), pp. 209–216. ISSN: 1028-365X.

[98] Lauren Stromberg et al. “Topology Optimization for Braced Frames: Combining Continuum and Beam/Column Elements”. In: *Engineering Structures* 37 (Apr. 2012), pp. 106–124. DOI: 10.1016/j.engstruct.2011.12.034.

[99] Bilal Succar, Willy Sher, and Anthony Williams. “Measuring BIM Performance: Five Metrics”. In: *Architectural Engineering and Design Management* 8.2 (May 2012), pp. 120–142. ISSN: 1745-2007. DOI: 10.1080/17452007.2012.659506.

[100] Hironori Yoshida. “Bridging Synthetic and Organic Materiality: Gradient Transitions in Material Connections”. In: *Biologically-Inspired Computing for the Arts: Scientific Data through Graphics* (Jan. 2012), pp. 81–88. ISSN: 9781466609433. DOI: 10.4018/978-1-4666-0942-6.ch005.

[101] Brandon Clifford and Wes McGee. “La Voûte de LeFevre”. In: *[En]Coding Architecture - The Book, Liss C. Werner (Ed.)* 2013.

[102] “Thicker Funicular: Particle-spring Systems for Variable-Depth Form-Responding Compression-Only Structures”. In: *Structures and Architecture*. Ed. by Paulo J. Cruz. Zeroth. CRC Press, June 2013, pp. 705–712. ISBN: 978-0-429-15935-0. DOI: 10.1201/b15267-95.

[103] Jelle Feringa. “The Promotion of the Architectural Model”. In: *Metaphors in Architecture and Urbanism*. Ed. by Andri Gerber and Brent Patterson. Bielefeld: transcript Verlag, Jan. 31, 2013. ISBN: 978-3-8394-2372-1. DOI: 10.14361/transcript.9783839423721.185. URL: http://www.degruyter.com/view/books/transcript.9783839423721/transcript.9783839423721.185/transcript.9783839423721.185.xml (visited on 01/21/2020).

[104] Wes McGee, Jelle Feringa, and Asbjørn Søndergaard. “Processes for an Architecture of Volume”. In: *Rob | Arch 2012*. Ed. by Sigrid Brell-Çokcan and Johannes Braumann. Vienna: Springer Vienna, 2013, pp. 62–71. ISBN: 978-3-7091-1464-3 978-3-7091-1465-0. DOI: 10.1007/978-3-7091-1465-0_5. URL: http://link.springer.com/10.1007/978-3-7091-1465-0_5 (visited on 01/21/2020).

[105] Matthias Rippmann et al. “Optimising Stone-Cutting Strategies for Freeform Masonry Vaults”. In: *International Association for Shell and Spatial Structures*. 2013, p. 7.

[106] Sigrid Adriaenssens. *Shell Structures for Architecture: Form Finding and Optimization*. First. Routledge, Mar. 2014. ISBN: 978-1-315-84927-0. DOI: 10.4324/9781315849270.

[107] Brandon Clifford. *Volume: Bringing Surface into Question*. Boston, MA: Matter Design Press, 2014.

[108] Jelle Feringa. “Entrepreneurship in Architectural Robotics: The Simultaneity of Craft, Economics and Design”. In: *Architectural Design* 84.3 (2014), pp. 60–65.

[109] Jelle Feringa and Asbjørn Søndergaard. "Fabricating Architectural Volume: Stereotomic Investigations in Robotic Craft". In: *Fabricate: Negotiating Design & Making*. Vol. 2. JSTOR, 2014, pp. 76–83. ISBN: 978-3-85676-331-2.

[110] Jelle Feringa et al. "Fabricating Architectural Volume: Stereotomic Investigations in Robotic Craft". In: *Fabricate: Negotiating Design & Making*. Vol. 2. gta-Verlag, 2014, pp. 76–83. ISBN: 978-3-85676-331-2.

[111] Norman Hack and Willi Viktor Lauer. "Mesh-Mould: Robotically Fabricated Spatial Meshes as Reinforced Concrete Formwork". In: *Architectural Design* 84.3 (May 2014), pp. 44–53. ISSN: 00038504. DOI: 10.1002/ad.1753.

[112] Ena Lloret et al. "Complex Concrete Structures: Merging Existing Casting Techniques with Digital Fabrication". In: *Computer-Aided Design* 60 (Jan. 2014), pp. 40–49.

[113] Pablo Marquez-Neila, Luis Baumela, and Luis Alvarez. "A Morphological Approach to Curvature-Based Evolution of Curves and Surfaces". In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* 36.1 (Jan. 2014), pp. 2–17. ISSN: 0162-8828, 2160-9292. DOI: 10.1109/TPAMI.2013.106.

[114] Asbjorn Sondergaard. "Odico Formwork Robotics". In: Architectural Design 229 (2014). Ed. by Fabio Gramazio and Matthias Kohler, pp. 66–67.

[115] Marco Stigliano and Giuseppe Fallacara. *New Fundamentals of Natural Architecture*. Roma: Aracne, 2014. ISBN: 978-88-548-7087-1.

[116] Roozbeh Feiz et al. "Improving the CO2 Performance of Cement, Part II: Framework for Assessing CO2 Improvement Measures in the Cement Industry". In: *Journal of Cleaner Production*. Special Volume: Support Your Future Today! Turn Environmental Challenges into Opportunities. 98 (July 2015), pp. 282–291. ISSN: 0959-6526. DOI: 10.1016/j.jclepro.2014.01.103.

[117] Jelle Feringa, Thomas Krijnen, and CTO Odico Formwork Robotics. "Bim for Robotic Manufacturing". In: *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium, 17-20 August 2015, Amsterdam, The Netherlands*. 2015, pp. 1–11.

[118] Salomé Galjaard, Sander Hofman, and Shibo Ren. "New Opportunities to Optimize Structural Designs in Metal by Using Additive Manufacturing". In: Sept. 2015, pp. 79–93. ISBN: 978-3-319-11417-0. DOI: 10.1007/978-3-319-11418-7_6.

[119] Jos Oliver et al. *Trends in Global CO2 Emissions: 2015 Report*. Nov. 2015.

[120] Chi Zhang, Jakob Beetz, and Matthias Weise. "Interoperable Validation for IFC Building Models Using Open Standards". In: *Journal of Information Technology in Construction (ITcon)* 20.2 (Jan. 2015), pp. 24–39.

[121] David Brander, Andreas Baerentzen, and Kenn Clausen. "Advances in Architectural Geometry 2015 - Designing for Hot-Blade Cutting: Geometric Approaches for High-Speed Manufacturing of Doubly-Curved Architecturel Surfaces". In: (2016). DOI: 10.3218/3778-4_21. URL: https://vdf.ch/index.php?route=product/product/download&eoa_id=9103&product_id=2001 (visited on 01/21/2020).

[122] Emma Cunliffe. *Should We 3D Print a New Palmyra?* http://theconversation.com/should-we-3d-print-a-new-palmyra-57014. 2016.

[123] Ashwini Kulkarni and Vijaykumar Bhusare. "Structural Optimization of Reinforced Concrete Structures". In: *International Journal of Engineering Research and* V5 (July 2016). DOI: `10.17577/IJERTV5IS070156`.

[124] Elon Musk. *Y Combinator*. 2016.

[125] Matthias Rippmann. "Funicular Shell Design: Geometric Approaches to Form Finding and Fabrication of Discrete Funicular Structures". PhD thesis. ETH Zurich, 2016, 374 p. DOI: `10.3929/ETHZ-A-010656780`.

[126] Asbjørn Søndergaard et al. "Robotic Hot-Blade Cutting". In: *Robotic Fabrication in Architecture, Art and Design 2016*. Ed. by Dagmar Reinhardt, Rob Saunders, and Jane Burry. Cham: Springer International Publishing, 2016, pp. 150–164. ISBN: 978-3-319-26376-2 978-3-319-26378-6. DOI: `10.1007/978-3-319-26378-6_11`. URL: `http://link.springer.com/10.1007/978-3-319-26378-6_11` (visited on 03/05/2020).

[127] Asbjørn Søndergaard et al. "Topology Optimization and Robotic Fabrication of Advanced Timber Space-Frame Structures". In: Feb. 2016, pp. 190–203. ISBN: 978-3-319-26376-2. DOI: `10.1007/978-3-319-26378-6_14`.

[128] Mania Aghaei Meibodi et al. *The Smart Takes from the Strong: 3D Printing Stay-in-Place Formwork for Concrete Slab Construction*. Aug. 2017. ISBN: 978-1-78735-000-7. DOI: `10.2307/j.ctt1n7qkg7.33`.

[129] Philippe Block et al. *Beyond Bending: Reimagining Compression Shells*. DETAIL Special. München: Edition Detail, 2017. ISBN: 978-3-95553-390-8.

[130] Per Dombernowsky and Asbjorn Sondergaard. "Unikabeton Prototype". In: *Fabricate 2011: Making Digital Architecture*. Ed. by Ruairi Glynn and Bob Sheil. UCL Press, Aug. 2017, pp. 56–61. ISBN: 978-1-78735-213-1. DOI: `10.2307/j.ctt1tp3c6d`.

[131] Gilles Retsin. "Teapots, Dresses and Chairs". In: *Architectural Design* 87.6 (2017), pp. 126–133. ISSN: 1554-2769. DOI: `10.1002/ad.2248`.

[132] M. Rippmann, A. Liew, and P. Block. "Structural 3D-printed Floor". In: *Digital Fabrication*. Ed. by A. Menges P. F. Yuan and N. Leach. Shanghai: Tongji University Press, Oct. 2017. Chap. 0.

[133] Pierpaolo Ruttico. "Robots in Architecture, Research and Development". In: *Informed Architecture*. Ed. by Marco Hemmerling and Luigi Cocchiarella. Cham: Springer International Publishing, 2018, pp. 65–76. ISBN: 978-3-319-53134-2 978-3-319-53135-9. DOI: `10.1007/978-3-319-53135-9_7`.

[134] Asbjørn Søndergaard et al. "Robotic Abrasive Wire Cutting of Polymerized Styrene Formwork Systems for Cost-Effective Realization of Topology-Optimized Concrete Structures". In: *Construction Robotics* 2.1-4 (Dec. 2018), pp. 81–92. ISSN: 2509-811X, 2509-8780. DOI: `10.1007/s41693-018-0016-8`. URL: `http://link.springer.com/10.1007/s41693-018-0016-8` (visited on 01/21/2020).

[135] R. Oval. "Topology Finding of Patterns for Structural Design". PhD thesis. Paris: Ecole des Ponts - ParisTech, Dec. 2019.

[136] Simon Duenser et al. “RoboCut: Hot-Wire Cutting with Robot-Controlled Flexible Rods”. In: *ACM Transactions on Graphics* 39.4 (July 2020), 98:98:1–98:98:15. ISSN: 0730-0301. DOI: 10.1145/3386569.3392465.

[137] Dennis Shelden, ed. *The Disruptors: Technology-Driven Architect-Entrepreneurs.* Architectural Design Profile no 264. Oxford: John Wiley & Sons, 2020. ISBN: 978-1-119-55509-4.

[138] Henriette Bier et al. “Dialogues on Architecture”. In: *SPOOL* 8.2 (Sept. 2021), pp. 105–110. ISSN: 2215-0900. DOI: 10.7480/spool.2021.2.6057.

[139] Giuseppe Fallacara and Marco Stigliano. “Stereotomy: Modern Stone Architecture and Its Historical Legacy”. In: (), p. 297.

[140] Thomas Krijnen. *IfcOpenShell.*

[141] *Open CASCADE Technology, 3D Modeling & Numerical Simulation.*

[142] Matthias Rippmann and Philippe Block. “Digital Stereotomy: Voussoir Geometry for Freeform Masonry-like Vaults Informed by Structural and Fabrication Constraints”. In: (), p. 8.

[143] Asbjørn Søndergaard and Jelle Feringa. “Scaling Architectural Robotics. Construction of the Kirk Kapital Headquarters.” In: *Fabricate: Rethinking Design and Construction*, pp. 264–271. ISBN: 978-1-78735-001-4 978-1-78735-000-7.

List of Figures

A

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