CONCRETE FORM[ing]WORK:

Design, Fabrication, Simulation and Correlation of Parametrically Patterned Flexible Formwork and Concrete

ANNIE LOCKE SCHERER

KTH ROYAL INSTITUTE
OF TECHNOLOGY

Doctoral Thesis in Architecture

CONCRETE FORM[ing]WORK:

Design, Fabrication, Simulation and Correlation of Parametrically Patterned Flexible Formwork and Concrete

ANNIE LOCKE SCHERER

Stockholm, Sweden 2021

CONCRETE FORM[ing]WORK:

Design, Fabrication, Simulation and Correlation of Parametrically Patterned Flexible Formwork and Concrete

ANNIE LOCKE SCHERER

Academic Dissertation, which, with due permission of the KTH Royal Institute of Technology, is submitted for public defense for the Degree of Doctor of Philosophy on Friday, the 24th of September 2021, at 1:00 p.m. in Ångdomen (room 5209), Osquars backe 31, Stockholm.

Doctoral Thesis in Architecture
KTH Royal Institute of Technology
Stockholm, Sweden 2021

Concrete Form[ing]work:
Design, Fabrication, Simulation and Correlation of Parametrically Patterned Flexible Formwork and Concrete
Annie Locke Scherer

Main supervisor: Dr. Oliver Tessmann
Secondary supervisor: Dr. Jonas Runberger

This thesis is part of the Formas project titled “Concrete Performance - Towards digitally cement-bound material systems,” supported by the Swedish Research Council. The second half of this project was supported by Lars Erik Lundberg Scholarship Foundation.

Cover spread: Fredric Boukari

Doctoral Thesis in Architecture

KTH Royal Institute of Technology
Architectural Technologies
School of Architecture and the Built Environment
SE 100 44 Stockholm, Sweden

ISBN: 978-91-7873-962-2
TRITA-ABE-DLT-2132

Graphic design by author

Proofreading by David Boothroyd and Magnus Persson

Printed by: Universitetsservice US-AB, Sweden 2021

Abstract

Concrete is one of the most commonly used construction materials, yet industrial fabrication continues to default to established standards of planar formwork and uniform cross-sections for the sake of simplicity and predictability. The research conducted within *Concrete Form[ing]work* explored alternative methods of producing concrete formwork with a simple, technical re-imagination of material: exchanging the familiar, i.e., rigid wood, for flexible fabric.

A survey of state-of-the-art research in the field of flexible formwork identified extant challenges hindering a more widespread industrial adoption of this concrete forming method. The research presented in this thesis identified two fundamental challenges: the complex tailoring required to produce non-standard forms and the lack of accurate simulation tools to visualize and communicate the fabrication process. This researchs employed a recursive, process-based workflow to construct design research experiments that addressed both of these shortcomings.

The experiments were conducted within the fields of *smocking*, *flexible formwork*, *computational patterning*, *simulation* and *correlation*, and involved various levels of artifact development (*probe, prototype* and *demonstrator*). A review of relevant research revealed three significant characteristics of craft-based experiments: *procedural workflows*, *evaluation criteria* and the *externalization of tacit material knowledge*. These qualities served as a foundation for *Concrete Form[ing]work's* research methodology and how experiments were constructed. A circular workflow of simulation, fabrication and calibration was employed to negotiate the complex relationship between parametrically tailored fabric and concrete materiality. Experiments were conducted using various 'wandering' approaches (*serial, expansive, probing*) based on the presence or absence of a preconceived hypothesis; these various approaches allowed for valuable knowledge production while retaining notions of craft.

This research includes a comprehensive investigation of the potential of smocking as a means of tailoring complex formwork. Smocking is a centuries-old patterning technique of gathering and pinching fabric; its distinct feature is the ability to transform a flat sheet of gridded material into a complex surface without the extensive tailoring of custom pieces. By cataloging the related research fields of mesh unrolling, origami, kirigami origami, auxetic materials and conformal mapping in great depth, the research presented in this thesis has developed a digital tool, *OriNuno*, that deconstructs double-curved geometries into smocking patterns. *OriNuno* exemplifies the ability to program both local and global geometrical articulation with parametric smocking, allowing for the sustainable fabrication of complex forms from a single sheet of material.

Secondly, this research systematized tacit material knowledge in the field of flexible formwork and concrete through *communication* and *externalization*. This was achieved by highlighting not just the result but the process of experimentation and developing accurate simulation tools that correlated with the final fabricated counterparts. The simulation tool utilizes open-source plugins to construct particle-spring models, which negotiate the complex interconnections between concrete rheology, hydrostatic forces and textile elasticity. The digital tool was refined through an iterative feedback loop between simulation, computation, physical experiments and assembly to ensure high correlation with cast counterparts.

The contribution of the research conducted in this thesis can be viewed in terms of two aspects: the textile patterning of complex forms without an overabundance of unique elements and the expansion of accessible design and accurate simulation tools for flexible formwork. Addressing existing knowledge gaps and formalizing implicit knowledge improves the accessibility, utility and repeatability of flexible formwork fabrication methods for industry and designers with no previous tacit experience. This thesis takes significant steps to repair the once-fractured relationship between designer and fabricator through iterative material and digital experiments. In doing so, the research conducted within *Concrete Form[ing]work* has the potential to fundamentally change and streamline how the field of computational patterning and flexible formwork is approached and integrated within architectural design.

Keywords: **concrete, flexible formwork, geometry, parametric patterning, craft, smocking, simulation, correlation.**

Svensk sammanfattning

Betong är ett de flitigast använda byggmaterialen i världen, men trots detta begränsar sig de etablerade standarder som styr den industriella tillverkningen av betong för enkelhetens och förutsägbarhetens skull till rak formgivning och enhetliga tvärsnitt. Inom ramen för *Concrete Form[ing]work* utforskades alternativ till befintliga formsättningsmetoder genom en enkel teknisk omdaning av själva materialet: det välkända, rigida träet byttes ut mot flexibelt tyg.

I en översikt av det aktuella forskningsläget inom flexibel formsättning och gjutning av betong identifierades ett antal utmaningar som i dagsläget förhindrar införandet av flexibla formsättningssystem på bred front inom industrin. Den forskning som läggs fram i avhandlingen identifierade och sökte lösningar till två grundläggande utmaningar: a) den komplexa sömnad som krävs för att tillverka icke-standardiserade former och b) avsaknaden av konstruktions- och simuleringssverktyg som möjliggör visualisering och kommunikation av tillverkningsprocessen. Ett rekursivt, processbaserat arbetsflöde användes för att utforma forskningsexperimenten, vilka undersökte och sökte finna lösningar till ovan nämnda utmaningar.

Experimenten inriktade sig mot olika stadier av produktutvecklingsprocessen (*probe*, *prototype* och *demonstrator*) och genomfördes inom områdena *smockning*, *flexibel formgivning*, *datorstödd mönsterkonstruktion*, *simulering* och *korrelation*. En översikt av tidigare forskning rörande hantverksbaserade experiment påvisade att dessa har tre viktiga kännetecken: *procedurellt arbetsflöde*, *utvärderingskriterier* and *externalisering av tyst materialkunskap*. Dessa kännetecken utgjorde grunden för den forskningsmetodik på vilken forskningen inom *Concrete Form[ing]work* vilade och vilken var avgörande för experimentens utformning. Ett cirkulärt arbetsflöde bestående av simulering, tillverkning och kalibrering tillämpades för att hantera det komplexa förhållandet mellan det parametriskt skräddarsydda tyget och betongens materialitet. Beroende på om en hypotes förelåg eller inte genomfördes experimenten med olika typer av ”vandrande” tillvägagångssätt (*seriellt*, *expansivt*, *undersökande*) – detta arbetssätt möjliggjorde värdefull kunskapsproduktion samtidigt som forskningens hantverksmässiga aspekter bibehölls.

Forskningsansatsen första bidrag till forskningsfältet var utförandet av en omfattande undersökning av smockningens potential som tillverkningsmetod för skräddarsydda, komplexa formsättningar. Smockning är en månghundraårig

mönstringsteknik i vilken tyget dras samman och fästs så att rynkor uppstår. Tekniken utmärks främst av att den gör det möjligt att förvandla en plan, rutnätsmönstrad yta till en komplext krökt yta utan att behöva klippa till och sy ihop en mängd unika delar. Genom en systematisk genomgång av relaterade forskningsfält såsom utrullning av nätmönster, kirigami, origami, auxetiska material och konform projektion utvecklades inom ramen för denna forskningsansats ett digitalt mönsterkonstruktionsverktyg som dekonstruerar dubbelkrökta geometriska former och omskapar dem till smockmönster. Detta verktyg påvisade såväl möjligheten att programmera både lokal och global geometrisk artikulation i parametrisk smockning som möjligheten att på ett hållbart sätt tillverka komplexa former utifrån ett enda plant ark.

Studiens andra bidrag bestod i att tyst materialkunskap inom området flexibel formsättning och betonggjutning systematiserades genom att *kommuniceras* och *externaliseras*. Detta åstadkoms genom att inte enbart belysa resultatet utan även experimenteringsprocessen som helhet och utvecklingsprocessen av det simuleringsverktyg som möjliggjorde korrelation mellan simulering och fysisk slutprodukt. Det utvecklade digitala verktyget använder plugins med öppen källkod för att konstruera fjädrande partikelmodeller som kan hantera det komplexa förhållandet mellan betongens reologiska egenskaper, hydrostatiska krafter och textilens elasticitet. Det digitala verktyget vidareutvecklades genom en iterativ feedback-loop (simulering, beräkning, fysiska experiment och montering) för att säkerställa högsta möjliga korrelation mellan simulation och gjuten slutprodukt.

Sammantaget kan dessa båda bidrag till designforskningen anses utgöra två delar av en helhet: dels skapades möjligheten att konstruera textila mönster för komplexa former utan att detta innebär att en stor mängd unika delar måste klippas till och sys ihop, dels utökades antalet tillgängliga och tillförlitliga digitala verktyg för design och simulering av flexibla formsättningsystem. Genom att söka fylla i befintliga kunskapsluckor och formalisera underförstådd kunskap sökte denna studie öka tillgängligheten, användbarheten och repeterbarheten för de tillverkningsmetoder som används vid tillverkning av flexibla formsättningssystem både inom industrin och av designers som ännu inte besitter den tysta kunskap som krävs.

Genom de iterativa experiment med fysiska material och digitala simuleringar som genomförts inom ramen för *Concrete Form[ing]work* har betydande steg tagits för att återställa den splittrade relationen mellan designer och tillverkare.

Den forskning som presenteras i denna avhandling har potentialen att i grunden förändra och förenkla det sätt på vilket man närmar sig och integrerar områdena datorstödd mönsterkonstruktion och flexibla formsättningssystem inom arkitekturens gestaltning.

Nyckelord: **betong**, **flexibel formsättning**, **geometri**, **parametrisk mönsterkonstruktion**, **hantverk**, **smockning**, **simulering**, **korrelation.**

Acknowledgments

While there is quite an extensive list of those who have helped me accomplish this feat, I would like to mention a few in particular.

First of all, I would like to express my sincere gratitude to my main supervisor, Oliver Tessman, who invited me to Stockholm and the KTH Royal Institute of Technology. He gave me the opportunity to continue exploring my passion for constructing double-curved surfaces from flat sheet material. I appreciate the wealth of knowledge he possesses and shares, as well as the many opportunities I have been afforded while working with him. He is brilliant at knowing when to push and give tough love, and when to ease up. Thank you for your unwavering support during this process and for being a fantastic supervisor. I'd also like to extend my thanks to my secondary supervisor, Jonas Runberger, who has also been with me from the beginning of my PhD research. I greatly appreciate his input and he has given me invaluable feedback regarding my methodology and dissemination.

My deep gratitude goes to the foundations that kindly provided funding for my PhD. *Concrete Form[ing]work* is part of a research project entitled 'Concrete Performance - Towards digitally informed cement-bound material systems' funded by Formas, the Swedish Research Council. I am grateful for Formas funding the first two years of my research, in addition to the Lars Erik Lundberg Scholarship Foundation for funding the continuation of my licentiate into a PhD.

I value the help and feedback from experts at the CBI Swedish Research Institute of Cement and Concrete, namely Alexander Eriksson-Brandels and Patrick Rogers; the scripting assistance provided by Daniel Piker, Andrei Nejur and Jack Young; and the engineering consultation and modeling advice from Birk Granberg and James Solly. I appreciate Alex Larsen taking the time to translate my abstract, Hélène Frichot for serving as my quality reviewer and David Boothroyd and Magnus Persson for proofreading my thesis. Furthermore, I'd like to acknowledge the fabric formwork and geometry experts whom I have had the great pleasure of interviewing and consulting: Alan Chandler, Keenan Crane, Rohan Sawhney, Andrew Kudless, Tomohiro Tachi, Sandy Lawton, Anne-Mette Manelius, Arthur Mamou-Mani, Remo Pedreschi, Joseph Sarafian and Diederik Veenendaal. Writing this thesis during the COVID era was no easy feat, and I am grateful for the endless mangos from my roommate Kuldeep Pareek and the cuddly company of my cats: Trout and Charlotte. I'd like to acknowledge my

“work husband” Luis Orozco for his late-night proofreading, excellent academic advice and supportive friendship over the last (almost) decade.

Influential professors that have nourished me throughout my education include Melissa Goldman, Robin Dripps, Karl Daubman, Kirk Martini, Peter Waldman, Earl Mark, Francois Roche, Sean Ahlquist, Adam Fure, Malcolm McCullough, Wes Mcgee, Oliver David Krieg and David Correa. I would like to thank my university colleagues at KTH, who have always been a help during in-between moments over a coffee in the lounge: Bojan Boric, Janek Ozmin, Erik Sigge, Frida Rosenberg, Meike Schalk, Veronica Bröderman Skeppe, Cecilia Lundbäck, Daniel Koch, Helen Runting, Jennifer Mack, Christina Pech, Erik Stenberg, Vasily Sitnikov, Helena Westerlind, José Hernandez Vargas, Anna Eklund, Andreas Billing, Flora Bahram, Ana Brené, Carin Österlund and Birgitta Brunström. I am especially grateful to Pablo Miranda Carranza for his coding expertise and constructive dialogue throughout my PhD research as well as for creating a wonderful experience co-teaching KTH’s *Studio 09: Architectural Notations*.

I would also like to acknowledge the people who made the fabrication of my final demonstrator, *Wall Three*, possible. I am tremendously grateful for the fabrication support from Anton Dalsmo, Tobias Kiefer and Immanuel Rein. In addition I’d like to express my gratitude to Blivande and Frihamnstorget for lending their space and outdoor gallery, to the Concrete Canvas suppliers for their expertise and consulting, Layher Sverige for lending their scaffolding free of charge and Simon Cederquist and Fredric Boukari for professionally photographing *Wall Three*.

Last but not least, I am beyond grateful to my mother, Donna Stamps, and her partner, Daniel Noneaker, for their proofreading and emotional support. This ambitious endeavor would not have been possible without their unwavering encouragement.

TABLE OF CONTENTS

Abstract vii

Svensk sammanfattning xi

Acknowledgments xv

01. INTRODUCTION 1

1.1 Research Problem 5
1.2 The Paradigm Shift of Material and Form 6
1.3 Flexible Formwork & Cast Concrete 7
1.4 Research Questions 8

02. THEORETICAL FRAMEWORK 11

2.1 The Technocultural Shifts of Material and Form 13
  2.1.1 Workmanship of Certainty: The Fracturing of Material and Form 14
  2.1.2 Digital Workflows: Redefining the Architectural Design Process 15
  2.1.3 Digital Craftsmanship 17
2.2 The Experiment 18
  2.2.1 Experimental Workflows 19
  2.2.2 Evaluation Criteria of Design Research Experiments 21
  2.2.3 Communicating Tacit Material Knowledge 23

03. CONTEXT & STATE OF THE ART 27

3.1 The Genesis of a Novel Approach to Concrete Structures 29
3.2 Twentieth-Century Concrete Innovations 30
3.3 Flexible Formwork for Cast Concrete 33
  3.3.1 A Collaborative Turn 35
  3.3.2 Tacit Materiality in Architectural Teaching 36
  3.3.3 Related Fields Using Flexible Formwork 41
3.4 Digital Concrete Formwork 43
  3.4.1 Digitally Programming Variable Formwork Stretch 44
  3.4.2 Fabric-Formed Concrete Shells 49
  3.4.3 Mass-Customization and Tailoring 51

04. METHODS 55

4.1 Craft-Based Research Methods 57

4.1.1 Ways of Drifting: Highlighting the Process 57
4.1.2 Evaluating Experiments: Categories of Material Evidence 59
4.1.3 Externalizing Tacit Material Knowledge in Relation to Flexible Formwork 61

4.2 Design and Fabrication Methods 64

4.2.1 Flexible Formwork 64
4.2.2 Smocking 67
4.2.3 Double-Curved Surfaces from Flat Sheet Material 73
4.2.4 Simulation and Correlation 80

05. DESIGN RESEARCH DEVELOPMENT 85

5.1 Material: Casting in Smocked Fabric 91

5.1.1 The First Fifteen Hand-Smocked Probes 91
5.1.2 Concrete Mixture Development 97
5.1.3 Casting in Skewed Smocking Grids 100
5.1.4 Fabric Selection 103
5.1.5 Column 01 105
5.1.6 Column 02 105
5.1.7 Lozenge Panels 108
5.1.8 Externalizing Material Knowledge Through Exhibitions 111

5.2 Geometrical: Computational Pattern Generation 119

5.2.1 Coded Pixels: Translating Smocking Logic to Code 119
5.2.2 Breaking the Grid 126
5.2.3 3D to 2D: Synthesizing Pattern-Generation Findings 127
5.2.4 Cone and Torus 1.0: Origamizer and Strip Unrolling 129
5.2.5 Dome Probe Using Generalized Ron Resch Patterns 133
5.2.6 Synthesizing Ron Resch Patterns, Kirigami, BFF and Smocking 139
5.2.7 Column 3.1 142
5.2.1 Column 3.2 145
5.2.2 Torus 2.0 149
5.2.3 The Hyperbola Catalog 150
5.2.4 Wall Three 160

5.3 Digital: Simulation and Correlation 183
  5.3.1 Simulation ‘Goal’ Breakdown 183
  5.3.2 Simulating Flat Smocking Patterns 185
  5.3.3 Rapid Prototyping of Smocked Columns 187
  5.3.4 Dome Textile Simulation 192
  5.3.5 Externalizing Tacit Knowledge Through Simulation 193
  5.3.6 Accurate Correlation With Cast Probes 195

06. CONCLUSIONS & FURTHER RESEARCH 203

Selected Video Documentation 208

Selected Workshops & Exhibitions 210

Selected Lectures 213

List of Figures 215

Footnotes 221

APPENDED PAPERS 225

Concrete Form[ing]work:
Integrating Patterns in Flexible Formwork for Cast Concrete 227

Concrete Form[ing]work:
Designing and Simulating Parametrically-Patterned Fabric Formwork for Cast Concrete 243

Bibliography 255

01. INTRODUCTION

Preface: The World is Flat

After relocating from Los Angeles to study architecture at the University of Virginia in 2008, I found myself developing a love of computational design and digital fabrication. David Rutten had just released Grasshopper, the visual programming plugin for Rhino 3D, and architecture undergraduates dove headfirst into parameterization and the sinuous forms we could quickly and easily model. I enrolled in Melissa Goldman's course 'The World is Flat,' which anchored students' newfound fascination for parametric formalism and Voronoi diagrams within the practical constraint of utilizing standard sheet material. In this course, I discovered my interest in the complexities surrounding making double-curved forms from flat materials. Coupled with the influence of Melissa's hands-on and process-oriented teaching style, this passion has stayed with me throughout the past decade of my academic research and teaching.

After completing my M.Arch at the University of Michigan, I centered my post-professional thesis at Universität Stuttgart's ITECH program, *Programmable Folding*, around kirigami (a variation on origami that includes cutting paper in addition to folding). The research presented in *Programmable Folding* studied the geometrical rules of kirigami and developed computational folding patterns with programmed cuts (Scherer, 2015). These strategic cuts encoded flat patterns with a folding logic so that they could be assembled into double-curved three-dimensional forms. After I began my PhD research at the KTH Royal Institute of Technology in Stockholm, Sweden, my passion for geometry, parametric patterning and fabricating double-curved sheets from flat surfaces heavily influenced the course of my research. During the first years of PhD research, I came across smocking—a patterning technique of pinching and sewing fabric for tailoring clothes. Smocking has an uncanny geometrical relationship with kirigami, as both methods can be used to program curvature from a flat sheet of material. Geometrically, what kirigami achieves through cutting holes, smocking achieves through pinching fabric. In this context, I approached the research aim of my thesis: to investigate novel and sustainable alternatives to existing production techniques for complex concrete formwork.

1.1 Research Problem

Based on the high availability of raw materials and low cost of standardization, concrete is well-established in the construction industry and one of the most widely used building materials globally. Regrettably, with four billion tons of cement produced each year, concrete construction accounts for eight percent of the total carbon dioxide emissions worldwide (Barcelo et al., 2014). Furthermore, seemingly inexhaustible, essential resources such as sand are dwindling, resulting in export restrictions and illegal mining (Gavriletea, 2017). Rigid formwork of such constructions (**FIGURE 1.1**) ranges from 40 to 60% of the total cost of a concrete structure (Hanna, 1999; Lab, 2007). Nervi writes about this obstacle,

> *It may be noted that although reinforced concrete has been used for over a hundred years and with increasing interest during the last few decades, few of its properties and potentials have been fully exploited thus far. Apart from the unconquerable inertia of our minds, which do not seem able to adopt freely new ideas, the main cause of this delay is a trivial technicality: the need to prepare wooden forms* (Nervi, 1956, p. 95).

FIGURE 1.1: Traditional concrete formwork (Wikipedia Creative Commons).

Standard concrete production practices must be reconsidered in order to formulate sustainable, long-term solutions to these very present dangers. Concrete as a material is at a crossroads. While it is reasonable to encourage architects to consider alternative building materials, a radical overhaul of systems and scrutiny of existing manufacturing techniques is necessary. Given its prevalence and utility, concrete will likely remain a mainstay in construction; as a result, one of the focuses of this thesis is minor innovations that could significantly impact the future of this industry.

Concrete itself has a long history of continual reinvention. As Pedreschi reflects in a tongue-in-cheek manner, “[concrete] can be found in the pyramids of Giza, was perfected by the Romans and has been continuously developed through the centuries to the point where it can be used to make everything from canoes to vanilla-scented concrete” (2013). Mixes such as carbon-dioxide-absorbing concrete (Adil et al., 2017) and ultra-high-performance concrete (Schmidt & Fehling, 2005) are becoming more widely utilized as they have a lower cement ratio and higher strength than traditional mixes.

In addition to experimenting with more sustainable ingredients, it is also possible to reconsider the standard cross-section of industrial elements that typically result in the over-dimensioning of concrete structures. Research of novel fabrication processes must be prioritized so that when concrete is required as a material, it is used more thoughtfully and sustainably. The integration of digital fabrication and parametric design brings about new opportunities in sustainably fabricating non-standard forms. This thesis aims to propose sustainable, efficient and repeatable fabrication processes for bespoke concrete architectural elements.

1.2 The Paradigm Shift of Material and Form

This thesis surveys the evolution of architectural fabrication from the era of the craftsperson (pre-industrial) through standardization (1800s) and mass customization (1990s) to the present day. Industrialization focused on standardization and a ‘one-size-fits-all’ approach to architectural elements, which typically meant architectural elements were optimized for the greatest point load. This approach begets over-dimensioning of elements and ultimately high material waste. With the advancement of computer numerical control (CNC) machines in the 1990s, architectural design underwent a technocultural shift away from standardization and towards mass customization. Designers focused on exploring new formal geometries, often without considering material qualities and the cost of fabrication (Carpo, 2011; Garber, 2017).

The research conducted within *Concrete Form[ing]work* investigated the implications of this shift towards standardization in order to situate the research. The above-mentioned technocultural shift is first discussed in relation to a theoretical framework to understand the resultant fracturing of material and form and the evolving relationship between designer and fabricator. This framework sparks a discussion regarding materiality, digital craft, design research and the role of experiments in contemporary architectural design research. This thesis aims to situate itself directly at the center of this discussion, taking advantage of the technocultural shift as an opportunity to reunite materiality, craft, design and fabrication. The title of this research project, *Concrete Form[ing]work*, purposely features '*[ing]*': this denotes the active role that the materiality of concrete takes in the process of forming and signifies the interruption of conventional, linear design processes.

1.3 Flexible Formwork & Cast Concrete

This thesis discusses the implications of the technocultural shift toward mass-customization (discussed in the previous section) within the context of flexible formwork and concrete construction to situate its methods and research questions. While the era of mass customization has involved a formal shift from standardized cross-sections to bespoke geometry, this change in the context of concrete construction migrated the focus from material waste to formwork waste. Freeform geometries require either hours of milling or other custom formwork solutions which are discarded after each use; these complex formworks can account for up to 70% of the structure's costs (de Soto et al., 2018). Formwork made of non-recyclable materials such as expanded polystyrene (EPS) foam raises issues of sustainability and efficient fabrication techniques, doubling the embodied energy of concrete construction (Sitnikov, 2020, p. 55). While EPS formworks can offer high-resolution and custom forms, they are typically coated in non-reusable sealants, missing opportunities for a united design concept and implementation (Verhaegh, 2010, p. 25).

The issue of sustainability has led designers to explore alternative formwork systems. With fabric formwork, it is possible to form materially efficient concrete shapes without the need for labor- and material-intensive formwork. Furthermore, its permeability allows excess water to wick out through the material during curing, improving the strength of the resulting cast (Hawkins et al., 2016). While extensive research has been conducted in recent decades (Veenendaal, West, et al., 2011), industry has not eagerly adopted this formwork technique. Flexible formwork is typically deemed too complex to simulate accurately, leading researchers in the field to utilize full-scale form-finding in place of computer simulation (Chandler & Pedreschi, 2007; West et al., 2016). Unfortunately, this technique does not often offer the high degree of predictability or repeatability that is required to meet industrial standards. The tacit material knowledge typically required by the fabricator makes this approach particularly challenging for those with limited prior knowledge of the system (Chandler, 2015). Another hindrance of state-of-the-art fabric formwork projects is the intricacy of assembling complex fabric formwork (Sarafian et al., 2016; Warmann, 2010b). With increasing surface articulation and complexity of the desired form comes the need for more sewing and tailoring; this, unfortunately, renders the fabrication technique even less appealing to industry.

1.4 Research Questions

The theoretical framework (**CHAPTER 02**) and state-of-the-art (**CHAPTER 03**) sections surveyed specific gaps in architectural research which inhibit flexible formwork from permeating industry. These gaps relate to the patterning of complex forms, repeatability, simulation and accurate correlation which served as a springboard for the development of the following research questions:

- How can fabric formwork be re-envisioned using smocking to create novel concrete-casting techniques?
- How can smocking be parameterized and differentiated to articulate new methods of fabricating architectural elements?
    - How does one take a three-dimensional input surface and construct a two-dimensional smocking pattern which accurately approximates the input form when sewn?
- What are the possibilities and limitations of simulating flexible formworks and correlating them with cast counterparts?

These questions were addressed through a craft-based methodology of conducting research experiments. Building on an analysis of existing research methods, three characteristics of craft-based experiments were identified: *procedural workflows*, *evaluation criteria* and the *externalization of tacit material knowledge*. These characteristics were integrated in the experiments described in this thesis. *Ways of Drifting* were utilized to highlight the procedural workflow and 'wandering' approach, resulting in experiments with varying degrees of completeness. These outcomes are classified as *probes*, *prototypes* and *demonstrators*. These categories signify the manner in which the experiments were conducted (*serial, expansive, probing*) and the *evaluation criteria* of said experiments.

Several design methods and techniques were employed to examine the previously introduced research questions: flexible formwork, computational fabric patterning, simulation and correlation of fabricated experiments. These methods were utilized throughout the three subsections of design-led research development:

- **Material:** Casting in Smocked Fabric.
- **Geometrical:** Computational Patterning.
- **Digital:** Simulation and Correlation.

Each of these **CHAPTER 05** sections catalogs the investigation in relation to each corresponding research question. These sections are organized based on the themes of experiments (*Material*, *Geometrical*, *Digital*) rather than chronologically in order to offer a more meaningful reflection of the relevant aspects of each experiment. While many experiments in this thesis were produced to answer specific research questions which pertain to a single subsection, as the project progressed more complex investigations addressed aspects that were relevant across multiple subsections. Experiments such as these (the *Column* series and *Wall Three*) are discussed across multiple subsections in order to coherently synthesize the three section themes with their corresponding research questions.

02. THEORETICAL FRAMEWORK

In order to contextualize the research presented in this thesis, a historical overview which describes a paradigm shift from craftsmanship to standardization is provided. This shift is examined through a contemporary lens to understand the role of craft in the context of the digital era. A series of craft-based workflows are presented which demonstrate that digitalization is not a threat to craftsmanship, but rather an opportunity for a designer to be involved in all aspects of the design process, which in the process reunites the roles of the designer and the fabricator. The second half of this chapter examines the concept of 'the experiment' and its relationship with craft-based research. By examining existing research methodologies, three distinct characteristics are identified: *procedure-based workflows*, *evaluation criteria of experiments* and *communication of tacit material knowledge*. These characteristics are unpacked in the chapter as they were the basis upon which the experiments presented in this thesis were formulated (**SECTION 4.1**).

2.1 The Technocultural Shifts of Material and Form

Prior to the industrial revolution, objects were crafted by "'the Smiths': the blacksmith, the silversmith, the locksmith, and the gunsmith" (Resch, 1973, p. 643). Generations passed on their knowledge, resulting in a distinct communication and fabrication synergy between user, object and maker (Resch, 1973, p. 643). This once-close relationship between the technology and anthropology of art is apparent in the etymology of the words 'art' (*artem* or *ars*) and 'technology' (*tékhnē*). Although these words in the present day have differing connotations, they were once interchangeable, referring to the type of skill identified with craftsmanship (Ingold, 2002).

With the industrialization of the eighteenth century came an impulse to differentiate intellectual labor from manual labor. 'Art' and 'technology,' once almost indistinguishable, became "somehow opposed" (Ingold, 2002, p. 349) due to the "debasement of the craft to the 'merely technical' or mechanical execution of predetermined operational sequences… [and the] elevation of art to embrace the creative exercise of the imagination" (Gell & Hirsch, 2020, p. 350). Industrialization also brought about a need for larger production quantities; the idea of "the Smiths" and their strong relationship to fabricated objects, craft and the surrounding environment was forsaken for average generalizations and standardization of consumers' needs (Resch, 1973, p. 643). The once-intimate relationship between materiality and production, as well as between the designer and the fabricator, began to fracture.

2.1.1 Workmanship of Certainty: The Fracturing of Material and Form

The Jacquard machine of the early 1800s revolutionized the textile industry and fabric production. Thanks to a series of punch cards and automatic patterning through a control mechanism, the weaving of complex textiles no longer required significant manual effort by weavers and nearly eliminated the need for human labor. Simultaneously, the fields of programming and computer science emerged. The mathematicians Babbage and Lovelace proposed the Analytical Engine, a mechanical device for calculating mathematical functions, in 1837. Though never completed, this device developed conditional and branching loops that would later advance the discipline of computer science that we know today (Green, 2005).

By the twentieth century, programming and automation had heavily displaced tradespeople, artisans and their craft. Standardized building systems popularized by Fuller (Ananthasuresh, 2015), Haller (Stalder, 2013) and Wachsmann (Herbert, 1984) highlighted the benefits of automation. Modular assembly kits such as Mengeringhausen's *Mero Node* (Deplazes, 2005, p. 136) and USM Haller's furniture systems (Relph-Knight, 2014) echo Wachsmann's agenda to shift focus away from craftsmanship and individual authorship (Tessmann, 2008). The technological advances of machines during the Industrial Revolution offered an increased certainty and predictability with which craftspeople could not compete. This standardization, or "workmanship of certainty" as it is referred to by Pye, arose through a refining process of tooling techniques which amounted to a quantifiable level of repeatability and control of the product (1978, p. 24). Comparatively, the result of the craftsperson's work cannot inherently be predetermined as it relies on the experience, judgment and skill of the particular individual fabricating the object, i.e., tacit knowledge. "Craftsmanship," dubbed the "workmanship of risk" by Pye, could not compete with the precision and replicability of industrial making processes (1978, p. 24).

Within the *workmanship of certainty* (i.e., mass production and standardization), cross-sections of elements are uniform; the dimensions of which are optimized for the greatest point load regardless of force distribution (Burry et al., 2005). This standardization brought about the oversimplification of building materials, inevitably breeding "oversizing and wasted material" (Carpo, 2011, p. 104). From an economic standpoint, the cost of excess material is negligible compared to the savings of mass production. Within the field of industry and standardization practices, material irregularities and changes due to environmental conditions were viewed as “undesirable, problematic, and to be avoided at all costs” (Hensel et al., 2008, p. 36). The “constraint of matter by ideal geometry” espoused by modernists such as van der Rohe neglected the opportunity of working with materiality to inform form (Reiser, 2006, p. 88).

Without thoroughly examining the opportunities of material properties, this separation of structural and material logic is unwarranted. Hensel et al. note “there are no inferior materials, but only inappropriate and unimaginative use and an insufficient understanding of how properties deemed inferior can be looked at and utilized in a more opportunistic manner” (2008, p. 38). Materials should be reflected in architectural tectonics, both geometrically and through the expression of internal force. Rather than “transcend the accidents of matter,” designing with materially-informed tectonics opens a new realm of possibilities within the field of architecture (Benjamin, 2003). In contrast to idealism, integrating materiality affords opportunities to address material efficiency, adaptability and resilience within architectural design.

2.1.2 Digital Workflows: Redefining the Architectural Design Process

The advent of computational design can be interpreted as threatening the connection between the roles of designer and craftsperson. The architect Felix critiques this rise in technological methods, arguing that it would result in a situation in which “each action is less consequent than it would be [on] paper […] each will be less carefully considered” (2005). Similarly, Sennett scrutinizes computer-assisted design (CAD), sharing a concern that the architect will lose the ability to “draw bricks”, resulting in a “disembodied design practice” (2008, p. 42). While it is important to be aware of these potential repercussions, the digital workflow processes afforded by computational design provide valuable opportunities within architectural design (Aish & Bredella, 2017; Carpo, 2011). The adoption of digital technologies in architectural design reframes the role of the architect and while the role of the drawing is challenged, it is for the better; computational design tools reshape the once-linear design process. The introduction of g-codes and digital fabrication allows the architect to specify all design and fabrication aspects within a procedural workflow. This workflow, coupled with the externalization demanded by the explicit nature of logic, suggests compelling opportunities for the architect to reinhabit the role of the craftsperson.

Carpo recognizes this critique of CAD-CAM technologies and the fear that the 'tacit knowledge' of a craftsperson cannot be verbalized because it derives from a mystical union between the body of the artisan and the materials they are crafting (2012, pp. 101–102). He argues that while this is a concern worthy of consideration, the iterative nature of these technologies "can make or break in no time more models than a physical craftsman could in a lifetime" and should be regarded as a "powerful ally" (2012, p. 102). Provided that computation goes beyond mimicking analog processes of architectural design, Carpo sees these digital tools as an opportunity to reconnect the worlds of design and fabrication. Therefore, the integration of digital tools in contemporary architectural design research should not be feared but instead utilized to its full potential and embraced as a methodology.

Computational tools, digital fabrication and mass-customization—"the non-standard paradigm", as referred to by Carpo (2011, p. 105) is an opportunity to reinvent materials' relation to form. Designers can once again have higher precision and control over the execution of their intended final product; this change allows architects to take on "new forms of digital artisanship" and ensures a reunion of craft and materiality with the design process (2011, p. 117). This shift from linear to circular design workflows can revolutionize how technology is embedded in architectural design and take full advantage of its novel capabilities. By involving the architect in all aspects of construction, from design to optimization and fabrication, this cultural shift reunites the designer with fabrication, repairing a rift created by the industrial revolution.

Aish and Bredella echo this optimism with regard to the opportunities afforded by the evolution from building modeling to design computation, and focus on dissecting how computational tools relate to the design processes of architects (2017). Prior to computation, two-dimensional drawings are generally created in the initial design phase; throughout the evolution of a building, these drawings are iterated by different actors, resulting in a lack of communication during these progressions, further resulting in consequent construction errors. By integrating what they refer to as "Building Modeling assumptions," the architects' design process was reversed, in that the components were selected before the general form was investigated (2017, p. 4). In their opinion, the full benefits of design computation can only be seen when an end-to-end workflow or "information flow system" permeates the entire design logic. While possible, this requires a subtle re-wiring of architects' design methodology; an iterative feedback loop replaces the formerly linear process of design to fabrication. This shift in workflow requires a more significant initial investment of time and energy, as the designer must specify the logic and interdependencies of input parameters (2017, p. 13).

2.1.3 Digital Craftsmanship

The opportunities afforded by the above-discussed new digital workflows blur the distinction between the roles of the architect and the craftsperson (Aitchison, 2011; Garber, 2017; Kolarevic & Klinger, 2008; Loh et al., 2016). In the traditional sense, 'making' implies the presence of tacit material knowledge rather than explicit knowledge (McCullough, 1996; Sennett, 2008). Sennett refers to this knowledge as "corporeal anticipation" of how a material may behave (2008, p. 175). The overall development of computational design and CNC machines led to newfound terms such as "digital craft" (McCullough, 1996) and "digital making" (Kolarevic & Klinger, 2008), leading to questions about where the role of craftsmanship lies when fabrication is automated.

Loh et al. add nuance to the definition of 'craftsmanship', defining it as the relationship between the "intent of the designer and the execution of the work" and "completeness of process from design to production" (2016, p. 190, 195). This distinction offers the possibility of retaining craftsmanship in the digital era, even when the designer has no personal experience with a material or fabrication process. They argue that the "authenticity" of craft is not necessarily the result of tacit knowledge alone, but instead comes from the "integrative workflow process" (2016, p. 201). Craft is, therefore, a self-referential and incremental innovation that, over time, results in the formation of a repertoire (2016, p. 202). These ideas are similar to McCullough's, which ascribe intellectual property not to the fabricated object but to "the tradition by which it is made—such was the stuff of apprenticeship" (1996, p. 94). Garber relates this workflow modeling shift to the "craftsman," who was once involved in all aspects of a finished design. This paradigm shift supports the "architect's return to the role of master builder," which ensures accurate translation from design notations to physical fabrication (2009, p. 93). Garber acknowledges how the shift which occurred during the late 1990s was "truly experimental in terms of formal exploration, but led to a sort of excess geometry that was seen as disconnected from a social agenda" (2017, p. 8). New digital workflows afford new opportunities for architects to understand the functionality of their proposed design on-site, which combats fears that architects use digital tools only to "advance their interest in novel architectural formalism" (2017, p. 8).

The research conducted within this thesis builds upon the existing research methodologies which pertain to digital craft, making and procedure-based workflows (Aitchison, 2011; Garber, 2017; Kolarevic & Klinger, 2008; Loh et al., 2016). The "authenticity of craft" is no longer solely centered around having tacit material knowledge; it has evolved to also pertain to the dialogue between craft and digital fabrication (Loh et al., 2016, p. 188). This shift underlines the relationship between the designer, the material and the process in which it is constructed. The literature review conducted during the process of writing *Concrete Form[ing]work* investigated the development and utilization of digital tools while retaining the notions of craftsmanship afforded by these tools. When these digital workflows were integrated into design research experiments, a thoughtful evaluation of experiments was valuable in terms of how they are conducted, evaluated and communicated. By precisely determining these parameters, design research experiments reunited the designer and fabricator as well as craft and digital fabrication.

2.2 The Experiment

Integrating this design feedback loop discussed in the previous section into architectural design requires a broader rethinking of how designers conduct design research. Typically, scientific research experiments are performed with the intention of producing knowledge and disseminating it to others, the veracity of which is demonstrated by its repeatability. These are usually undertaken with a highly constrained set of parameters, and conclusions are deduced based on given criteria. A hypothesis is posited and subsequently tested through observation and experiments to verify or falsify the theory.[1]

The difference between scientific research experiments and design research experiments is that the focus in the former is placed on the outcome and in the latter on the process; thus, design research experiments are not always set up to have the end goal answer a specific question. Sennett notes: "Every good craftsman conducts a dialogue between concrete practices and thinking; this dialogue evolves into sustaining habits, and these habits establish a rhythm between problem solving and problem finding" (2008, p. 9). This balance

---

[1] Karl Popper notably demarcated science from non-science with 'the Falsification Principle', arguing that theories must be falsifiable to be scientific (Popper, 1959, p. 6).

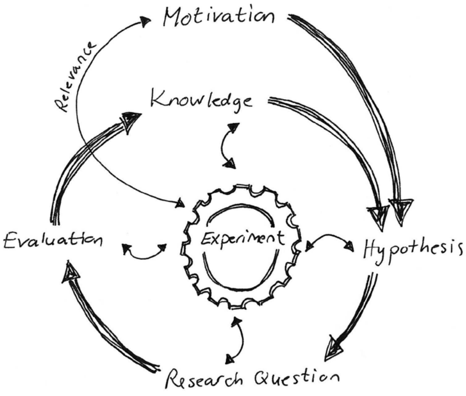


FIGURE 2.1: “Drive wheel” model: constructing a hypothesis (Bang et al., 2012)

between solving and finding problems has developed in the digital context of experimental practice, evident in the recent resurgence of prototyping; this can take the form of installations, pavilions and other full-scale demonstrators (Burry & Burry, 2016). As digital tools allow architects to take a more active role in the design, simulation and calibration process, a thoughtful evaluation of the formulation, evaluation and communication of design research experiments is required.

2.2.1 Experimental Workflows

In contrast to traditional scientific workflows, a series of alternative approaches have developed in the field of design research (Bang et al., 2012; Brandt & Binder, 2007; Koskinen et al., 2011; Zimmerman & Forlizzi, 2008). Koskinen et al. unpack the term ‘constructive design research,’ proposing *the lab*, *the field* and *the showroom* as means of understanding the methodology (2011). These concepts are elaborated on by Bang et al., who identify a methodological gap between constructive design research and practical research activities, adding the nuance of “motivational contexts” (2012, p. 4). This nuance investigates the relationship between hypotheses, experimentation, evaluation criteria and production of knowledge. In this model, the hypothesis plays a central role as a “drive wheel” (**FIGURE 2.1**), continuously influencing and evolving throughout the research (2012, p. 6). Zimmerman and Forlizzi similarly distinguish two types of constructive design research (referred to as “research through design”) based on motivation (2008, p. 2). These types can either take the form of a “philosophical” approach (formulating a research question from an existing theory) or a “grounded” approach (focusing on real-world problems to achieve an intended outcome) (2008, p. 43). Emphasizing the experiment over the hypothesis, Brandt and Binder refer to ‘designerly ways of knowing’ (Cross, 2006) as practice-based research, situating their discussion regarding the interdisciplinary, collaborative nature of knowledge production (2007). The underlying message within all of these works is that, while it is more conventional to formulate a research project with a specific question in mind, it can also be developed with a ‘wandering’ approach to experimentation in the absence of a clear strategy.

This approach can be related to the craftsmen and their relationship to thinking and making. Ingold distinguishes between the theorist, who “makes through thinking,” and the “craftsman,” who “thinks through making” (2013, p. 6). During this process of creating, everything produced by a craftsperson can be considered an experiment; these experiments are not conducted to fabricate a preconceived design or validate a hypothesis, but to openly investigate an inquiry (2013, pp. 6–7). Goal-based workflows can result in those conducting experiments imposing preconceived notions upon what is not yet known. An open-minded approach shifts the focus from the fabricated artifact to the process of making. In doing so, this constructs an active, responsive dialogue between the maker and their materials and surrounding environment (2013, p. 7).

Architects such as West and Krogh et al. have utilized this approach when formulating craft-based experiments, stressing the importance of an open mind when the result is not always known when beginning to work (Krogh et al., 2015; West, 2011). West, a leading figure in the field of flexible formwork and cast concrete, argues for a post-rationalization approach prevalent in his design research. Rather than having prescribed notions of what an experiment’s outcome may be, he encourages “playing” and seeing what compelling results occur:

> *It's not like having a bullseye that you try to shoot the center of with a rifle; it's more like shooting a shotgun against a wall and drawing bullseyes around the holes. You never miss. Always find something. And the intellectual problem is to identify what it is you found and to see its use-value in some way or not. So by playing, we can find.* (West, 2011)

Krogh et al. describe a similar 'wandering' approach with regard to their concept of *Ways of Drifting* (**FIGURE 2.2**) which, when viewed in the context of established scientific methods, is "regarded as bearing the touch of randomness, the uncontrolled, illogical and inconsistent" (2015, p. 5). However, within the context of design research, "pursuing alternative opportunities in the vicinity of one's work is an embedded way of arriving at relevant and high-quality work" (2015, p. 3). Given that design research has different experimental goals as compared to scientific research, this touch of playfulness and randomness is not only tolerated but encouraged. One does not construct an experiment that behaves isomorphically to a phenomenon observed in nature, but synthesizes something new through exploration. This experimental workflow connects the metaphorical 'dots' that might not have been initially anticipated and brings about a novel means of experimenting in design research.

2.2.2 Evaluation Criteria of Design Research Experiments

While the traditional, 'passive' production of proofs is valuable in scientific research, observing the process of experimentation can prove to be as valuable as the results themselves (Hacking, 1983). Compared to scientific experiments that form a hypothesis and conclude it to be 'true' or 'false,' craft-based experiments can find value in the wealth of knowledge that exist between these ends of the spectrum. This approach is unique in that potentially any outcome can provide valuable learnings, even if a hypothesis is not necessarily validated.

Tamke et al. address the differences between architectural and scientific experiments, specifying four characteristics of experiments: *speculation*, *reflection*, *evaluation* and *interface* (2017, pp. 4–5). These cover a wide range of experiment types, including those for which the outcome is known beforehand, those that guide the re-formulation of design criteria, those that are conducted with the sole purpose of calibrating results and those that spark interdisciplinary collaboration and knowledge-sharing. These categories allow the experiment's purpose (and consequently evaluation criteria) to inhabit a plurality of forms. Given that design is creative and constructive in nature, architectural experiments may consist of many sub-experiments which explore a wide variety of trajectories and adjacent fields (2017). This experimental setup establishes a fusion of technologies and domains, fostering a nurturing environment for interdisciplinary design research.

Table 1 Table of typology

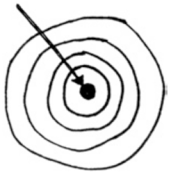
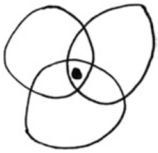
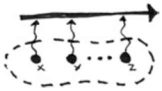
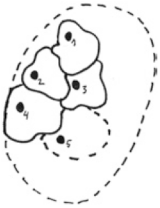
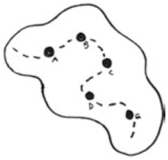
Method	Graphic model	Keywords
Accumulative		Depth, stacking
Comparative		Acknowledging complexity
Serial		Systematising local knowledge
Expansive		Broadening, extending
Probing		Illogical, artistic, impact oriented

FIGURE 2.2: Krogh et. al's *Ways of Drifting* (Krogh et. al, 2015)

A fruitful research contribution does not require answering a 'yes/no' question, nor the invention of a new methodology. Instead, the contribution itself can be a synthesis or hybrid of existing methodologies. While a vague research question may be articulated from the start, it is essential to monitor how the hypothesis evolves and remain aware of the existing triangle between the artifact, the research interest and communication of tacit knowledge (Krogh, 2016). This restructuring of evaluation criteria is key to determining how a design research experiment will contribute to existing fields.

Krogh et al. note that *how* experiments are carried out is rarely communicated, and researchers instead generally highlight the outcome of investigations (2015). He stresses the importance of not only including but elevating how a researcher arrives at this outcome, "how the design project drifted through and gained insights unintended by its original pursuit—and what knowledge one developed in doing so" (2015, p. 4). Norell builds on this view, similarly migrating the main focus from the outcome. Grounded in the ideas of Murray (2013, p. 96), Norell builds on the notion that knowledge produced by architectural design research can result in a plethora of forms. Norell argues that neither the process nor the effect should be exclusively highlighted (2016). In his licentiate thesis, *Taming the Erratic*, Norell puts forth the construction of a alternative approach to exhibiting work: exhibiting models, drawings and simulations together to convey the entire process of making, yet purposely refraining from any linear design narrative (2016, p. 57). In addition to exhibiting demonstrators, the process is highlighted and becomes, in itself, an unpolished knowledge contribution. The research presented in this thesis aligns with this research methodology in that part of its contribution is considered to be the continuous testing of technical and theoretical investigations rather than a specific end goal.[2]

2.2.3 Communicating Tacit Material Knowledge

A reflection on the communication of tacit knowledge produced is valuable during craft-based experiments to ensure a valuable contribution to design research. Murray builds on Frayling's notions of design research (*into*, *through* and *for*) (Frayling, 1993) and highlights the difficulty of concretizing tacit findings

---

[2] This research methodology was also carried throughout the instruction of the Master's-level program *Studio 09*, taught by the author and Pablo Miranda Carranza (for more details see (Scherer & Miranda-Carranza, 2019).

(2013). Murray differentiates between the prepositions ‘for,’ ‘into/about’[3] and ‘through,’ noting the significant yet not fully explored value of research *through* design. He ascribes the difficulty of forming a knowledge base to the cumulative nature of tacit research, noting that most craft-based knowledge is personal and not typically disseminated. In order to take advantage of the enormous projective qualities of design research, Murray stresses a thorough and rigorous explanation of research practices to establish legitimacy (2013). Those conducting research *through* design must recognize this difficulty and actively question how tacit knowledge is communicated to other research fields. Though Murray acknowledges this hindrance, methods of avoiding this issue are not elaborated upon.

Outside of the design research context, the philosopher Polanyi (1958, 1966) and knowledge-management theorist Nonaka (1994) categorize knowledge as *explicit* or *tacit*. While *explicit* knowledge can be codified, generated through logical deduction and stored objectively, *tacit* knowledge is built up through experience and is more difficult to communicate: “We always know more than we can tell” (Polanyi, 1966, p. 4). Ingold disagrees with Polanyi’s distinction between ‘telling’ and ‘articulation,’ arguing that “The figure of the silent craftsman who is struck dumb when asked to tell of what he does, or how he does it, is largely a fiction” (2013, p. 109). While he defines ‘telling’ as “the practice of correspondence,” ‘articulation’ is differentiated as “knowing from the inside;” noting that scholars active in fields that work with tacit knowledge (i.e., anthropology, archaeology, art and architecture) have no issue in “telling,” yet they cannot “articulate” these implicit nuances without significant difficulty (2013, p. 111).

Nonaka and Takeuchi developed processes for this meaningful articulation and conversion methods when navigating between tacit and explicit knowledge (1995). The Nonaka-Takeuchi SECI model (**FIGURE 2.3**) details four modes of knowledge conversion (*socialization*, *externalization*, *combination* and *internalization*) and distinguishes between codifiable and uncodifiable tacit knowledge (Nonaka & Takeuchi, 1995). *Externalization*[4] is a process of translating

---

[3] Research *for* design focuses more on understanding pertinent architectural precedents. Research *into* or *about* design sets a specific goal of what design ‘should be’ and seeks to improve upon it (for further discussion, see (Downton, 2003).

[4] The research conducted within this thesis recognizes the other, more common conception of the term *externalization* which is chiefly psychological. The use of this term throughout this thesis follows Nonaka et al.'s understanding throughout.

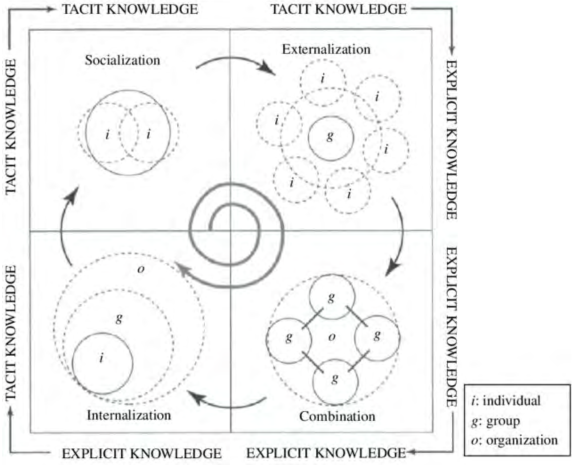


FIGURE 2.3: Spiral evolution of knowledge conversion and self-transcending process (Nonaka and Konno, 1998).

tacit knowledge into explicit knowledge, which can be achieved through the combination of explicit *articulation* (concepts, metaphors, words, images) and the commitment to translate this knowledge into forms understandable by others (Nonaka & Konno, 1998).

Understanding and implementing this external knowledge conversion process can be valuable when applied to craft-based research experiments. These can take the form of sketches, diagrams, hypotheses, models, manuals and prototyping and can occur across a wide variety of research fields that intersect both tacit and external knowledge bases. This interdisciplinary approach of *externalizing* encourages individuals to reflect on and codify their work through articulation, promoting interaction between a larger field of researchers with various tacit knowledge. While this might not inherently guarantee successful communication of all tacit knowledge, examining how craft-based experiments are conducted, evaluated and communicated has the potential to invent new forms of creating knowledge and solidify their relevance within design research.

03. CONTEXT & STATE OF THE ART

“Materials…are active participants in the genesis of form.”
(DeLanda, 2001, p. 132)

This chapter examines the history and development of techniques for fabricating concrete structures. This includes model-based design processes which produce form-found structures, the genesis of the use of textiles as concrete formwork and the integration of digital tools within flexible formwork construction processes. The survey of state-of-the-art research identified two knowledge gaps in flexible formwork research: firstly, the complex tailoring required to fabricate bespoke forms and secondly, the lack of accurate, accessible simulation tools in which to visualize and correlate concrete cast in flexible formwork. The research presented in this thesis aimed to contribute toward bridging these two knowledge gaps.

3.1 The Genesis of a Novel Approach to Concrete Structures

The growing interest in experimenting with novel fabrication techniques and systems has shifted focus away from standardization and towards the reciprocal relationship between materials, forms, tools and techniques (Loh et al., 2016). This paradigm shift, as noted by Kwinter[5] (2003) and De Landa[6] (2001), distinguishes the ‘possible' and the ‘real' from the ‘virtual' and the ‘actual' (Garber, 2009, p. 93); what this opens up is a space for unpredictability and open-ended experimentation. While the previous half-millennium has been characterized by the former (in that architectural drawings are interpreted by the builder, thus rendering design and execution unrelated), the latter reflects a philosophy of design with an inextricable relationship between design and materials (Garber, 2009).

Challenging the prevailing modernist tendencies of the twentieth century, the development of form-finding techniques represented a renewed interest in the relationship between material and form. This type of experiment signified designers' willingness to surrender formalistic autonomy and defer to the natural resolution of forces within a given experiment (Isler, 1994, p. 142).

---

[5] Kwinter distinguishes between “poor formalisms” (or “unextended formalisms”) as “a sloppy conflation of the notion of ‘form' with that of ‘object'” while defining “true formalism” as systems which relate form, object, material and expression (Kwinter, 2003, p. 96).

[6] De Landa takes note of this paradigm shift by contrasting two philosophies of design (of particular relevance is his idea of "genesis of form"; (De Landa, 2001, p. 132): one being conceptual and assuming material homogeneity while the other portrays materials as active, heterogeneous, and integral to the design process.

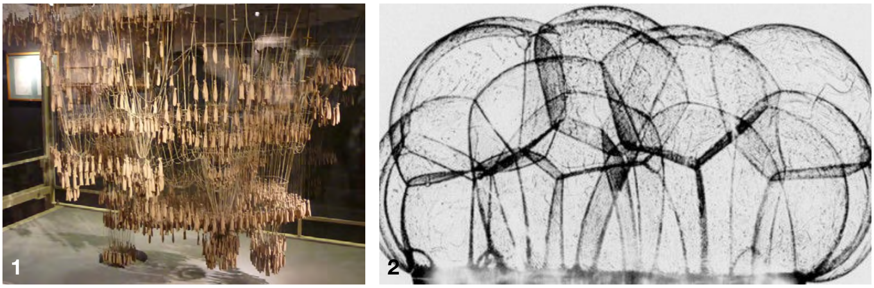


FIGURE 3.1: (1) Gaudi's *hanging chain model* (Zexin & Mei, 2017).
(2) Otto's *soap bubble experiment* (Zexin & Mei, 2017).

The hanging chain models of Gaudi (1852–1926; Huerta, 2006) and soap-bubble and cable-net experiments of Otto (1925–2015; Boller & Schwartz, 2020) are notable examples of interactive design explorations. Gaudi's well-known hanging chain model (**FIGURE 3.1 (1)**) utilized a series of linked chains and weights that resulted in a catenary curve that, when inverted, formed optimized arches. When these models were constructed with masonry, the curves 'found' the optimal shape of the compression forces within an arch and allowed Gaudi to design the organic and fluid curves of the *Sagrada Familia* (Huerta, 2006). Otto developed his own form-finding techniques with his soap-bubble experiments (**FIGURE 3.1 (2)**). Dipping looped cords into a soap solution, he was able to visualize minimal surfaces[7] before digital computation of such forms was possible. These experiments were characterized by self-organization between fixed points, demonstrating the dialogue between forces and resistance (Boller & Schwartz, 2020). Today, these forces can be computed digitally in Rhino 3D with parametric and live physics plugins such as Grasshopper and Kangaroo.[8]

3.2 Twentieth-Century Concrete Innovations

The form-finding techniques discussed in the previous section inspired a new

---

[7] In mathematics, a minimal surface is one in which the surface area is minimized and has vanishing or zero mean curvature (Pottman et al., 2007, p. 647).

[8] Kangaroo, a plugin for Grasshopper 3D, is a spring-based Live Physics engine which uses Dynamic Relaxation (DR). The Kangaroo/Kangaroo 2 plugin provides a catalog of 'goals,' which are predefined functions which act on defined points, lines and meshes. These goals can include geometry constraint, curve bending or elasticity or applying loads and other forces. The goals are aggregated in the 'solver,' which dynamically applies the specified goals based on user-input 'strengths.'

generation of designers to investigate the relationship between shape and structure in the context of concrete. Architects and engineers such as Isler, Candela, Nervi and Musmeci (**FIGURE 3.2**) experimented with structural forces in material systems, deriving optimized and materially efficient forms (Boller & Schwartz, 2020; Garlock & Billington, 2008; Leslie, 2018; Marmo et al., 2019). These designers emphasized the process of construction, continuously refining techniques through iteration across multiple projects.

The proliferation of concrete reinforcement enabled the development of structures such as Isler and Candela's thin concrete shells (Boller & Schwartz, 2020; Garlock & Billington, 2008). Candela (1910–1997) experimented with double-curved *hypar* shells (known as *cascarones*), well-known examples of which include *Los Manantiales* (1958) and *L'Oceanogràfic* (2003; **FIGURE 3.2 (1)**). These hyperbolic paraboloids (*hypars*) are ruled surfaces, derived through geometrical investigation and constructed using straight wooden beams (Garlock & Billington, 2008). Similar to Gaudi, Isler (1926–2009) utilized hanging models, pioneering thin-shell synclastic concrete designs. Rather than impose preconceived notions of form on structures, he worked with form-found models, in particular shells[9] (Isler, 1959). As part of the process of documenting his experimental modeling and fabrication of these shells, he was able to structurally validate the concepts while simultaneously "subordinat[ing] himself to the supremacy of form" (Boller & Schwartz, 2020, p. 565).

Nervi (1891–1979) relied on experimentation when exploring materially efficient concrete construction methods in an age in which complex structural calculations were not possible. Utilizing design mathematics and material intuition, Nervi developed novel construction techniques in response to the limited availability of steel during Italy's Mussolini era (Leslie, 2018). Examples of his lightweight corrugated vaults and structural ribs include Orvieto Aircraft Hangar (1935; **FIGURE 3.2 (3)**), Gatti Wool Mill (1953) and *Palazzetto dello Sport* (1958). Constantly reinventing methods of production during his career, he eventually amassed over 40 patents, including ferrocement (1944), wave segments (1948) and rhomboidal elements (1950). These patents specified novel combinations of cement mortar and metal armature, materially efficient concrete elements and custom 'shape elements' to construct complex stay-in-place formwork. Musmeci, a former employee of Nervi, was inspired by the

---

[9] These include the rubber membrane method, hanging textile method, foam flow method and shaking method (Baghdadi et al., 2019, p. 493).

FIGURE 3.2: (1) Candela's *L'Oceanogràfic* 2003 (Wikipedia Commons).
(2) Isler's *Klicherschale,* 1965 (Wikipedia Commons).
(3) Nervi's Orvieto Airport Hangar, 1935 (Leslie, 2018).
(4) Musmeci's *Viadotto dell'Industria,* Basento 1971–1976 (Marmo et al., 2019).

FIGURE 3.3: (1) Fisac's *Casa Pascual de Juan,* 1975 (Veenendaal, Coenders, et al., 2011).
(2) Fisac's *Hermanas Hospitalarias Social Center, Ciempozuelos* 1985–1986 ("Fundación Miguel Fisac").

cultural context of these concrete innovations, utilizing physical models and experimentation to investigate minimal surfaces of reinforced concrete shells. His most notable work is the *Viadotto dell'Industria* bridge (1971–1976; **FIGURE 3.2 (4)**), which includes four spans of 70 meters (Marmo et al., 2019).

Although various techniques were utilized in the construction of these structures, each employed a strong relationship between form and model to envision and construct these minimal surface structures. Their artists, architects and engineers resisted the debasement of craft that resulted from industrial mass production, not only accepting Pye's "workmanship of risk" but embracing it so as to innovate.

3.3 Flexible Formwork for Cast Concrete

Until the late 1960s, the use of flexible formwork for concrete casting was relatively uncommon and primarily a functional, cost-effective alternative to more traditional formwork. Fisac (1913–2006) was the first to look past the utilitarian aspects of flexible formwork and explore both the architectural and aesthetic implications of this technique (Veenendaal, West, et al., 2011). Like Candela, Fisac graduated from the Higher Technical School of Architecture in Madrid, Spain. Fisac "rebelled" against the use of traditional shuttering formwork with cast concrete, "decid[ing] to discard this incorrect texture" of wood grain left in the material (Fisac, 2010). In his work (**FIGURE 3.3**), Fisac experimented with polyethylene sheets and ropes to provide a 'pillowy' softness to the otherwise cold and hard material of concrete. Fisac gained a reputation for pushing the

FIGURE 3.4: (1) Unno's *URC House* (2003) (Veenendaal, West, et al., 2011).
(2) West's C.A.S.T. research, *Bone Beam* (West et al., 2016).
(3) ArroDesign's *Black Tree House* (2007) (Veenendaal, West, et al., 2011).

boundaries of formwork during the 2000s with the prefabricated elements he created for the *Teatro Municipal* (Veenendaal, West, et al., 2011).

During the 1990s, Fisac's ideas of architectural expression with textile formwork were further explored and developed by Unno, who developed a system known as Unno Reinforced Concrete (URC) for in-situ casting of load-bearing concrete walls using fabric (West et al., 2016). After the Kobe earthquake in 1995, Unno moved to designing earthquake-safe houses using simple, low-waste construction methods (Veenendaal, West, et al., 2011). His quilt-point approach can be seen in some of his work in Tokyo, such as the *URC house*, the *Eiji Hoshino Residence* and the *Stone Renaissance House* (**FIGURE 3.4 (1)**).

3.3.1 A Collaborative Turn

A significant shift which formalized fabric formwork as a research field occurred in the 1990s (**FIGURE 3.5**), when West founded the first fabric formwork research lab: the Centre for Architectural Structures and Technology (C.A.S.T.) Until this point in time, architects such as West, Fearn and Unno had worked independently. The creation of C.A.S.T. enabled a knowledge exchange between those leading the field of fabric formwork. Subsequently, the International Society of Fabric Forming (ISOFF) was founded, which led to increasing awareness of and knowledge regarding issues in the emerging field (Veenendaal, West, et al., 2011). This change prompted increased collaboration, which led to the development of fabric formwork as a research discipline to accelerate.

Blurring the line between pure formal applications and structural efficiency, C.A.S.T focuses on the use of simple profiles and the same principles as Gaudi's hanging chains to create structurally and materially optimized non-uniform section beams (**FIGURE 3.4 (2)**). Amidst their research into bending moment structures, double-curved shells and aesthetics such as wrinkling in cast panels, the primary method of experimentation and prototyping retains a focus on fabrication and full-scale mockups. This approach relies on a strong understanding of the relationship between forces and material. In addition to expressing the natural forces and bending moment, West's non-standard beams opened a dialogue relating to reduced material usage; in comparison to traditional panelized molds, material usage is drastically reduced when fabricating these elements. The column formwork for West's *Casa Dent* was easily transported in checked luggage from Canada to Puerto Rico. The 13 unique formworks were cast and flown back to Canada for reuse in further projects (West et al., 2016,

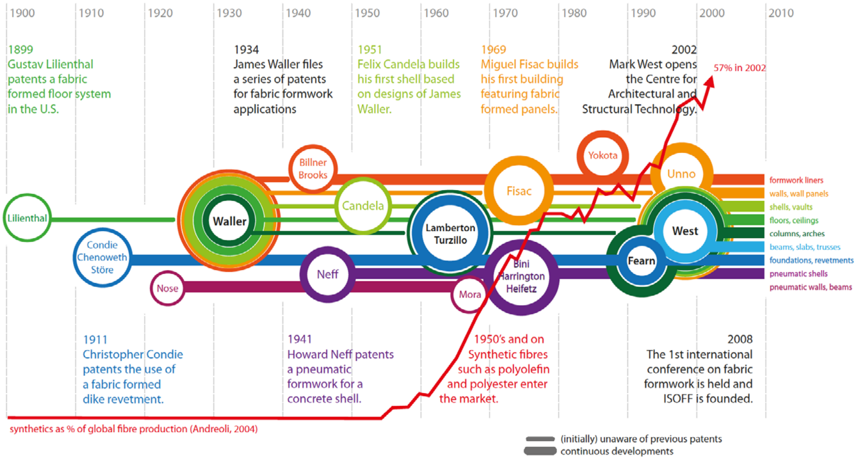


FIGURE 3.5: History of fabric formwork (Veenendaal, West, et al., 2011).

p. 46). The research in this thesis builds upon West's techniques for retaining material efficiency while adding enhanced customization and tailoring.

Projects such as *Black Treehouse* (**FIGURE 3.4 (3)**) were developed based on the increased collaboration between those leading the flexible formwork field. Though previously unfamiliar with textile formwork, Lawton of ArroDesign integrated techniques from Fab-Form Industries' Fearn (FASTFOOT Fabric Formed Footings, n.d.) and developed a frame-support method for vertically casting 30 feet (~9 meters) of concrete using a textile mold. ArroDesign specializes in constructing concrete homes and investigating sustainability and structural expression (Veenendaal, West, et al., 2011). This active exchange of ideas demonstrates that with increased communication and dissemination of tacit material knowledge, it is possible to rapidly develop new fabrication strategies and innovations.

3.3.2 Tacit Materiality in Architectural Teaching

Architects such as Chandler and Pedreschi have examined standardized construction paradigms for concrete through the lens of tacit materiality. They have tested efficient fabric formwork for beams, columns and shells, countering the stereotypical perception of concrete as a grey, massive, cold or aggressive material. Pedreschi postulates that these characteristics are not those of the material itself, but rather the consequence of the construction process (2016). The importance of design responding to technology, rather than forcing the technology to comply with the designed form, is a central thesis of their work. Chandler and Pedreschi use their academic teaching positions at the University of East London (UEL) and the University of Edinburgh (UoE), respectively, to examine the philosophy of engagement between architectural teaching and practice, and run studios that critically examine how and why buildings are made (Chandler, 2004).

One result of fabric formwork researchers' newfound awareness of each other in the 2000s was the series of 1:1 construction workshops that produced *Wall One* and *Wall Two* (**FIGURE 3.6**). These were conducted as a collaboration between architecture and engineering students at UEL and instructors from the UoE and C.A.S.T in Manitoba, Canada (Chandler, 2004). The goal of these workshops was to investigate repeatable fabric formwork techniques while simultaneously engaging fabricators to take an active role. Chandler stresses the importance of making 1:1 prototypes to educate students to actively respond to an evolving full-scale construction process. The sine-wave form was directly inspired by Dieste and the jig frame allowed flexibility for adjustment during the entirety of the casting process. This flexibility allowed ad-hoc fabrication of variably sized circular retaining disks during the casting process (Chandler, 2004).

Prototype constructions such as Chandler and Pedreschi's *Wall One* and *Wall Two* subversively question formal predetermination and risk-adversity in industrial concrete construction. Inspired by Pye's "workmanship of risk" concept, Chandler utilized these workshops to educate students on how to focus on and actively manage (rather than avoid) risk. By developing this intuition and new working practices, architecture students are educated to navigate risk with responsive judgment and dexterity when developing bespoke production processes. These workshops are state-of-the-art examples of reuniting the architect and the fabricator and embracing Pye's "workmanship of risk." The research conducted within *Concrete Form[ing]work* was inspired by these approaches and built upon this premise, investigating issues of repeatability and risk through the production of full-scale prototypes.

Pedreschi continued to develop his teaching methodology throughout his decade-long Master's-level studio Disruptive Technologies. Repeated prototyping, responsive production and collaborative learning were emphasized at the studio (Pedreschi & Lee, 2014). Two theses of note emerged from there:

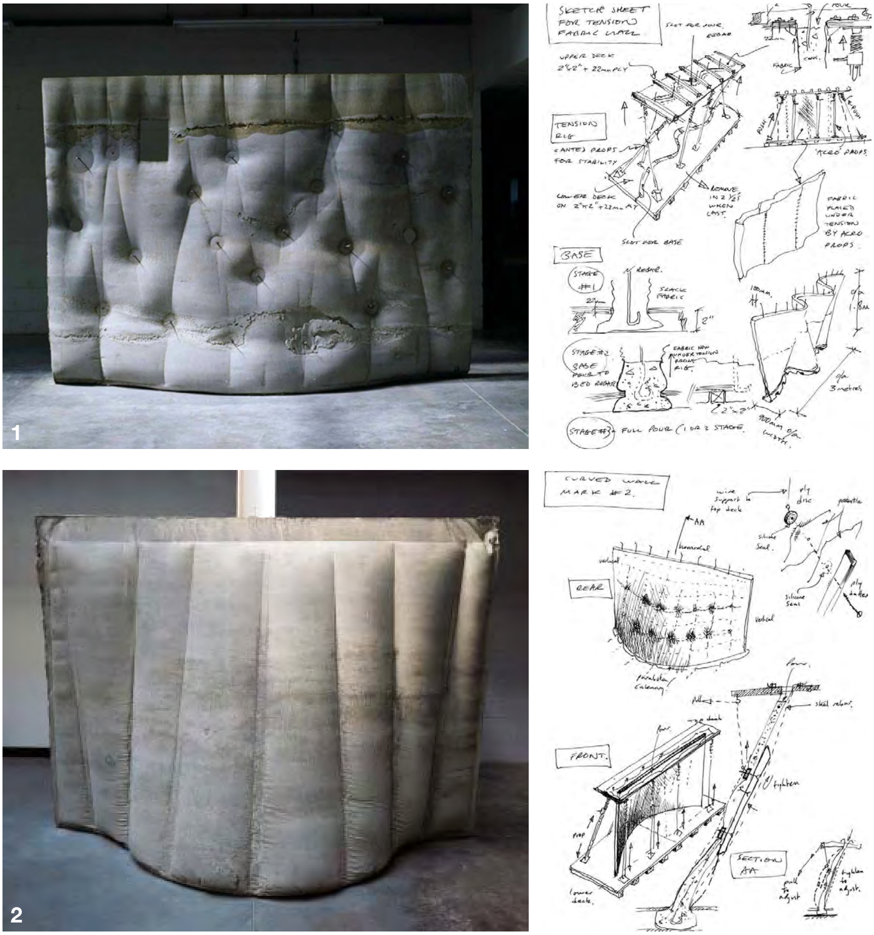


FIGURE 3.6: Chandler, Pedreschi and C.A.S.T. student workshop collaboration (1) *Wall One* (Chandler, 2004) and (2) *Wall Two* (Chandler & Pedreschi, 2007).

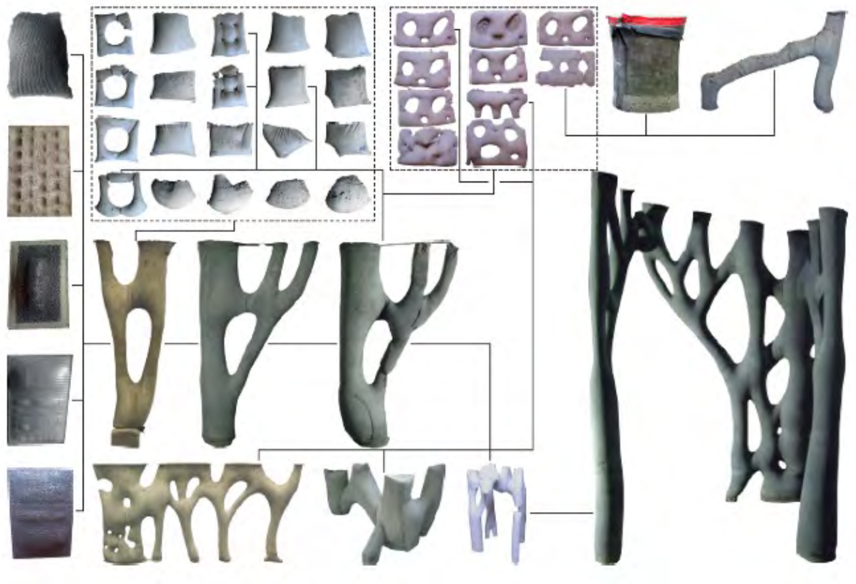


FIGURE 3.7: Chan et. al.'s UoE Disruptive Technologies Master's Thesis: *Single Cast Wall* (Milne et al., 2018).

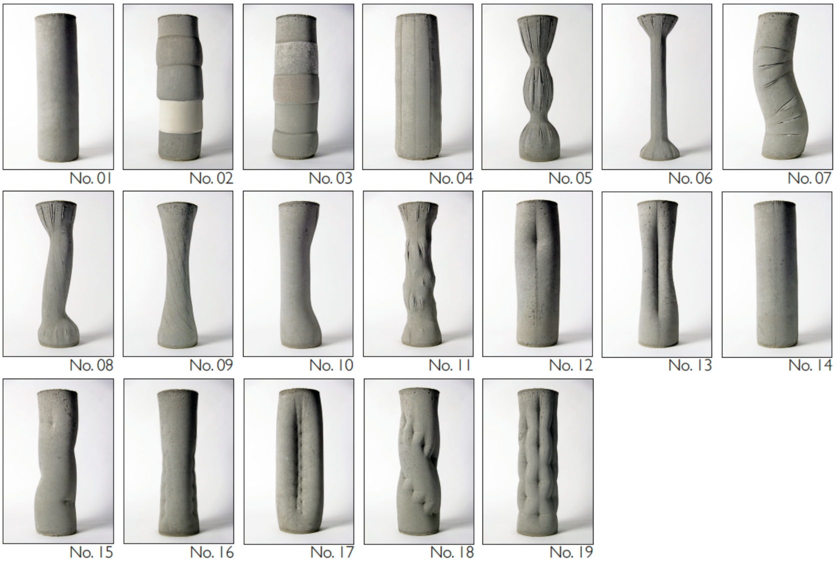


FIGURE 3.8: Milne's MScR UofE thesis, *Tailored Fabric Formwork* (Milne, 2017).

Single Cast Wall (**FIGURE 3.7**; Chan et al., 2011) and *Tailored Fabric Formwork* (**FIGURE 3.8**; Milne et al., 2015). As the name implies, the former utilized single-cast fabric formwork, and built upon West's techniques. Iterative prototyping on progressively larger scales allowed students to build up material intuition regarding the pressures of concrete, casting sequence and fabric response (Milne et al., 2018). The studio participants chose to forgo digital and simulation tools, placing a strong emphasis on "discovery through doing" (Bush, 2012). This practice allowed reliance on inherent knowledge of the material to design and fabricate the space frame. Utilizing the wealth of experience gained by exploring techniques from the past, the students hand-drew the chalk outlines of the mold directly onto the black cotton fabric—a simple yet effective way of allowing materiality to guide the overall design.

Milne's thesis follows a similar iterative prototyping logic, developing a library of variable columnar forms through fabric manipulation (2018). With an emphasis on showing materiality, this project questioned the migration of responsibility for form-giving from the designer to the material. The above-discussed projects showcase the possibilities of simple, affordable customization while highlighting the "tacit" or "sticky"[10] knowledge base required from a variety of related fields: architecture, construction, textiles, tailoring and fashion (2018, p. 2). *Concrete Form[ing]work*'s research methodology utilized similar methods of blending adjacent fields of knowledge and relying on a process of 'discovering while doing.'

Pedreschi and Chandler's academic workshops and studios demonstrate the increasingly collaborative nature and knowledge exchange within the field of flexible formwork. By collectively centering the design and making methodology around the interface between materials, social practice and design, these projects urge a reformulation of fabrication processes, with materiality as a guide. The qualities of concrete allow for the material behavior to engage with and influence the building process itself, questioning the limitations of industry's planar formwork and mass-production sequences. Through investigation of this process, there comes an understanding of responsiveness, adaptability and readability on various levels. While this emphasis on 'learning by doing' is ideal

---

[10] Milne et al. note that designers "often develop their own approach to particular solutions differentiated from conventional or traditional processes." They refer to this tacit material knowledge as "sticky" given that it is "difficult to transfer to those not experienced in the relevant techniques" (Milne et al., 2018, p. 2).

for hands-on studio work, effectively executing these techniques relies heavily on intuitive prototyping and a tacit knowledge base acquired over the academic year. Pedreschi and Chandler emphasize the accumulation of procedural knowledge more than evaluating how this knowledge is communicated. As elaborated on in **SECTION 4.1.3**, this prioritization can act as a limitation when the methodology is translated to full-scale applications (due to the large quantity of implicit knowledge and lack of simulation and consistency with regard to forms). The development of the research conducted in this thesis aimed to contribute to the rendering of implicit knowledge into an explicit form.

3.3.3 Related Fields Using Flexible Formwork

Given this cross-pollination referred to in the previous section, the research conducted in this thesis surveyed related fields that develop flexible formwork processes to pursue continued synergy. In line with Chandler and Pedreschi's philosophical methodology, artists have been intrigued by the dichotomy of seemingly hard, cold concrete and the expressive, soft gestures of casting in fabric (**FIGURE 3.9**; Etherington, 2010a, 2010b; Manelius, 2012). Manelius echoes this discontinuity between expected and experienced tactility when describing users' experiences of her constructions (2010). *Ambiguous Chair*, *Concrete Chair* and *Mass III* seek to explore this duality on the scale of furniture, and Manelius repeatedly cites the process of making as a methodology with regard to her pieces. Schmid's *Stitching Concrete* and Gustavsson's *Concrete Easy Chair* (2014) also explore the expressiveness of concrete and fabric. Rather than casting in a formwork, these chairs were fabricated using concrete-impregnated canvases, allowing the user to freely shape the cloth and then hydrate the textile to cure the concrete component of the canvas.

While these projects artistically combined the malleability of fabric with the durability of concrete, the explorations were on the scale of furniture. The size of these pieces could be attributed to the artists' unfamiliarity with fabric-formed concrete or the idea that casting on a small scale allows for material investigations (without the risk of formwork tears and other complications that accompany pouring extensive amounts of concrete). Furthermore, this scale is useful for experiments fabricated by a single person or small team outside of the context of a professional fabrication lab. Despite being small in scale, these artistic investigations successfully showcase the potential of combining concrete, textiles and material expression which hints at the possibility of larger-scale applications.

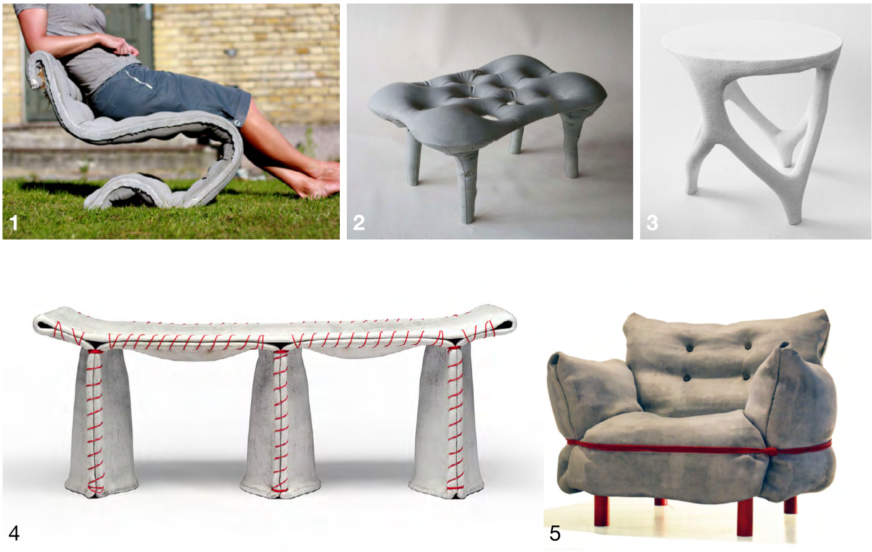


FIGURE 3.9: (1) Manelius's *Ambiguous Chair,* 2009 (Manelius, 2009).
(2) Remy and Veenhuizen's *Concrete Chair,* 2010 (Etherington, 2010a).
(3) Van Maele's *Mass III Chair*, 2010 (Etherington, 2010b).
(4) Schmid's *Stitching Concrete*, 2011 (Schmid, 2011).
(5) Gustafsson's *Concrete Easy Chair*, 2011 (Gustavsson, 2013).

FIGURE 3.10: (1) Fab Form Fast-Tube^{TM} (Fab-Form, n.d.).
(2) Concrete Canvas® *Disaster relief shelter* (Concrete Canvas, n.d.).

On the other end of the spectrum, the field of industrial fabric formwork is limited to a small set of refined, predictable fabrication techniques, which starkly contrast with the artistic explorations described above (**FIGURE 3.10**). Concrete Canvas Ltd (Concrete Canvas, n.d.) and Fab-Form Industries Ltd (FASTFOOT Fabric Formed Footings, n.d.) are two noteworthy companies and both have focused on larger-scale, repeatable applications of flexible formwork and concrete. Concrete Canvas® is primarily utilized in the development of low-cost disaster-relief shelters and erosion containment. This concrete-impregnated fabric is widely used in industry as an efficient, 'just-add-water' concrete textile that hardens in less than a day. Their Concrete Canvas® Shelters (CCS) are marketed as "a building in a bag" (Concrete Canvas, n.d.), which are optimized for compressive forces and only require inflation to erect the modular structures (Jindal, 2018). Concrete Canvas Ltd has successfully situated itself in an industrial context by limiting the applications to a small set of pre-defined variables. Fab-Form Industries Ltd operates similarly; company founder Fearn began developing flexible industrial formwork in the 1980s, and has centered his company around commercialized and sustainable fabric-formed cast-concrete foundations. Among Fab-Form's contributions are Fastfoot® and Fastbag® (fabric-based footings) as well as Fast-Tube™ (piers and columns; Schmitz, 2014). While Fab-Form has consulted on projects such as ArroDesign's *Black Treehouse*, in general there are scant examples of flexible formwork in industrial applications.

When comparing the artistic and industrial applications of flexible formwork and concrete, there is an apparent disjuncture. Artistic applications are limited to smaller-scale pieces; artists often focus solely on material expression and single-use cases rather than an investigation of full-scale, easily replicated fabrication processes. On the other hand, flexible formwork's industrial functions are limited to simple and easily reproducible forms, affording fast delivery to a client at a maximum profit margin with minimum effort. Despite its promise of efficiency and sustainability, a significant portion of the field of flexible formwork remains unexplored. With industry's risk-aversion and high demands with regard to predictability and repeatability, it is vital to develop standards and guidelines that make the adoption of flexible formwork both appealing and practical (Schmitz, 2018). Unless the gap between academia, art and industry is addressed, flexible formwork may very well remain a novelty.

3.4 Digital Concrete Formwork

The state-of-the-art fabric formwork examples discussed thus far were created using little to no digital design and simulation tools. This is a stark contrast to the field of 3D-printed concrete, which has seen significant development in the past decade (**FIGURE 3.11**). Several construction companies, such as Contour Crafting Corporation (Zareiyan & Khoshnevis, 2017) and WinSun [Ltd] (Sun, 2015) have invested heavily in the development of gantry systems to produce 3D-printed concrete houses. ETH Zurich's *Concrete Choreography* (Anton et al., 2020) and the printing company XtreeE (Gaudillière et al., 2019) couple toolpath planning with the material behavior of concrete, exploring vastly diversified geometries while maintaining efficiency and fabricability. Kapoor's *Cement Room* (2009) and Westerlind's *Choreographing Flow* (2021) approach the 3D-printing of concrete from a different angle, preferring to combine the accuracy of industrial robotics with the unpredictability of concrete rheology. Similarly, rather than combating natural slumping forces, Mohite's *Speed-Based Additive Manufacturing Technique* embraced the unpredictable and integrated materiality as a design driver (2021).

Despite the vested interest in developing 3D printing technology, the digital realm did not begin to permeate the field of flexible formwork research until the last decade. As digital tools for designers became increasingly accessible, flexible formwork investigations began to reflect this advancement; the following sections describe state-of-the-art works that have experimented with the integration of digital tools within this otherwise tacit (and non-digital) fabrication process. These developments take the form of programmable stretching through parametric textile manipulation, state-of-the-art fabric-formed concrete shells and highly customized spatial investigations.

3.4.1 Digitally Programming Variable Formwork Stretch

Compared to the projects presented thus far, which emphasize tacit material knowledge, the projects discussed in this section utilized digital tools during the design and fabrication process of flexibly-formed concrete structures. These tools enable computationally generated fabric formwork patterns, programmed stretching and variably cast forms. Despite the integration of digital tools, it is noteworthy that the following computational explorations were limited to flat pattern manipulation; while the final form was intuitively imagined, it was not precisely predetermined.

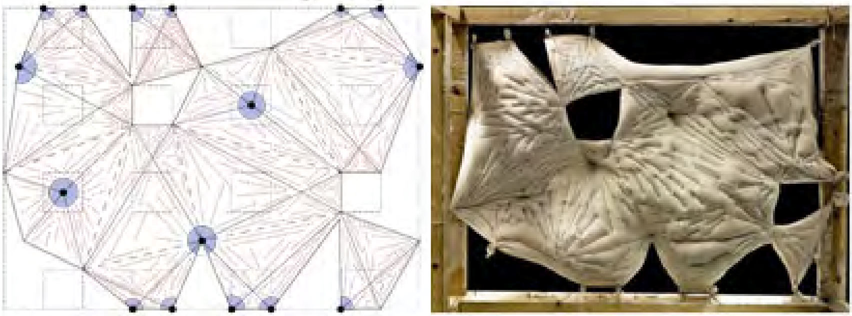
Student work such as *Grompies* (Warmann, 2010a) and *[Fabric]ation* (Able et al., 2012) experimented with the combination of computational patterning

FIGURE 3.11: (1) Winsun's *Concrete 3D Printed Houses* (Blain, 2014).
(2) XtreeE's *Post* (Gaudillière et al., 2019).
(3) ETH's *Concrete Choreography* (Anton et al., 2020).
(4) Kapoor's *Cement Room* (Kapoor et al., 2009).

and hand-sewing as a method for programming variable stretch within flexible formwork (**FIGURE 3.12**). *Grompies* is the result of a collaborative workshop, 'Matter as Computation,' held at the AA Design Research Laboratory. After the pattern of the lycra mold had been digitally generated through behavioral rule sets, it was translated to the textile and sewn by hand. When filled with plaster, the stitched areas inhibited the stretching of the fabric, and the digital pattern was readable in the fabricated model. *[Fabric]ation* programmed fabric stretch by overlaying two sheets of fabric with varying elasticities. The more rigid exterior fabric had laser-cut slits, allowing the more flexible fabric on the inner layer to bulge and stretch when filled with concrete. Despite being relatively small, these projects hint at a clear relationship between the designed pattern and the resulting cast, which showcases the material possibilities of manipulating fabric formwork digitally.

Kudless and Nan et al. (**FIGURE 3.13**) further unpack these principles of digitally programming flexible formwork stretch within the context of their research (Kudless, 2011; Nan et al., 2017). The *P_Wall (2009)* and *P_Wall (2013)* projects by Matsys (cast with plaster and concrete, respectively) challenge the notion that scripting a design should produce a deterministic form (Kudless, 2011, p. 102). *P_Wall (2009)* aggregates four types of hexagonal module. The construction process involved the use of a base framework that holds a series of vertical dowels, suspended above which is a horizontal piece of elastic fabric stretched in a frame. When cast, the fabric stretched and bulged based on the packing density and height of these dowels. The dowel density, placement and length were determined by a script and translated from user-input pixel gradient fields. The maximum dowel length corresponded to the maximum possible stretch of the material, which was determined during the making of previous prototypes (2011, p. 102).

1



2

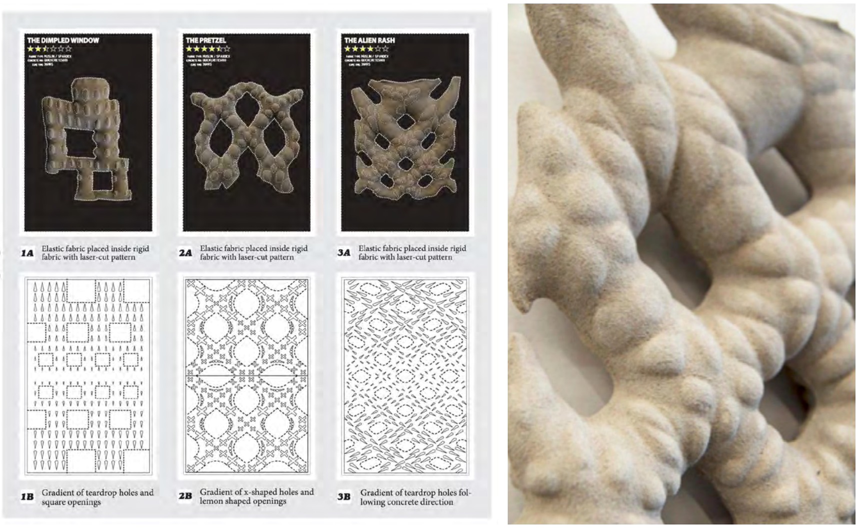


FIGURE 3.12: (1) Carlin et al.'s *Grompies*, student workshop, 2010 (Warmann, 2010a).
(2) Able et al.'s *[Fabric]ation* Master's thesis prototypes, 2012 (Able et al., 2012).

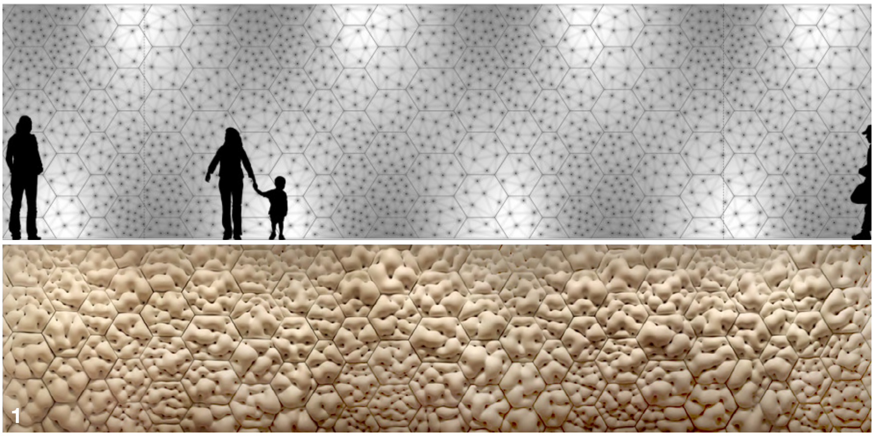


FIGURE 3.13: (1) Matsys' *P_Wall*, 2009 (Kudless, 2011).
(2) Nan et al.'s *Fabric Waisted Column & Twisted Column*, 2017 (Nan et al., 2017).

Despite the lack of simulation and an elementary fabrication process, Kudless notes that the constraining dowels allowed a “certain amount of generalized control […] while still allowing forms to organize at a more local level” (2011, p. 102). This installation allowed for the expression of both materiality and computationally programmed design, without subscribing to precise, preconceived notions of the final form; the user’s scripted gradient patterns were clearly readable within the organic bulges. The research presented in this thesis adopted a similar aggregation of methods, focusing the bulk of the design ingenuity on the design and patterning rather than the fabrication process itself.

P_Wall (2013) built on Kudless’ design and fabrication processes with a series of innovations. Practical constraints required the plaster cast and fabric formwork to be upgraded to shotcrete and rubber mold, losing some of the unpredictable material essence of *P_Wall (2009)*. While the casting method differed from that used for the 2009 wall, the noteworthy innovations used for the 2013 wall included rough digital simulations of the formwork structure. Using the Kangaroo 2 plugin for Rhino 3D/Grasshopper, Kudless noted the increase in the number of design iterations and testing before fabrication as compared to previous projects (Kudless, 2013). Unfortunately, no documentation has been published detailing the construction of these models in any detail.

Other methods of programming formwork stretch include hybrid formwork systems composed of fabric and 3D-printed silicone (Nan et al., 2017). Nan et al. acknowledge that while the generation of complex forms no longer constitutes a challenge in the field of architecture, the ratio between cost and benefit when fabricating these geometries remains disproportionate. Their *Fabric Waisted Column* and *Twisted Column* projects experimented with printing silicone ‘ties’ on a textile formwork, varying the size and placement of the silicone to restrain fabric stretch selectively during the casting process. Although a base approximation of the desired form was constructed in Rhino, Nan et al.’s research did not address precise simulation of hybrid textiles’ responses to the hydrostatic pressures or rheology of concrete. Even though most of the authors’ development focused on the technical aspects of 3D printing, Nan et al.’s columns are contextualized within a broader, process-driven methodology regarding the relationship between digital tools, the maker and the material. They specify that an initial experimentation phase was required to build up tacit knowledge before integrating the digital aspects of this work (2017, p. 11). With the continuous refinement of the digital crafting process (much like the

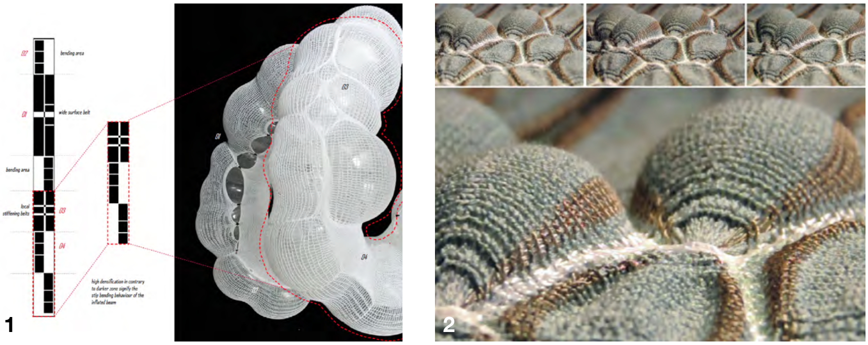


FIGURE 3.14: (1) Šinke Baranovskaya's *Knitflatable Architecture*, ITECH Master's thesis, 2015 (Baranovskaya, 2016).
(2) Ramsgaard Thomsen's *CAD CAM Knitting* (Tamke et al., 2012).

research methodology described in this thesis, introduced in the next chapter), this manner of experimenting leads to a holistic experimentation strategy in which there is an intersection of craft, tacit material knowledge, digital tools and materiality.

In investigating the process of programming formwork stretch, adjacent fields of textile manipulation must be acknowledged. In the context of fabric formwork, Ramsgaard Thomsen's *Listener* (Ramsgaard Thomsen & Karmon, 2011) and Šinke Baranovskaya's *Knitflatable Architecture* (2016) both utilize similar techniques of programming fabric to create sinuous bumps and bulges (**FIGURE 3.14**). When either hydrostatic or pneumatic pressure is applied to this differentiated material, the once-flat pattern is transformed into a complex, differentiated volume. By differentiating areas of varying elasticity, these techniques can be coupled with flexible formwork and concrete, allowing the hydrostatic pressure of the material to act as both a form-finder and form-giver. While CNC knitting was not used in the research presented in this thesis (which instead focused on high-tech design and low-tech fabrication methods), it calls to mind the potential of pre-programming planar materials in order to achieve variable forms after construction.

3.4.2 Fabric-Formed Concrete Shells

Despite this interest in researching flexible formwork technologies within an architectural context, many projects continue to face issues of predictability and repeatability. Aside from a few examples, there is a lack of accurate simulation

FIGURE 3.15: (1) Popescu's *KnitCandela* (M. A. Popescu, 2019).
(2) ETH Zurich's *Nest HiLo roof prototype* (Stoughton, 2018).

methods. Most designers favor bypassing simulation, preferring to rely on tacit material knowledge and iterative testing to optimize fabric formwork. This decision, unfortunately, compounds the difficulty of *externalizing* tacit material knowledge, creating a steep learning curve for those without prior experience.

FIGURE 3.15 shows two projects that have successfully navigated these issues: *KnitCandela* (M. Popescu et al., 2020) and ETH Zurich's *Nest HiLo roof* (Echenagucia et al., 2019). *KnitCandela* (**FIGURE 3.15 (1)**) is an undulating concrete shell constructed from form-found cable-netting and prefabricated CNC-knitted textiles. While the construction itself weighs five tons and has a surface area of 50 m^2, the formwork weighs just 55 kg. The formwork was CNC-knitted off-site and easily transported to Mexico City, where it was installed. With a formal nod to Candela (**FIGURE 3.2 (1)**), Popescu breaks from standard, planar elements as formwork and demonstrates the sustainable and materially efficient fabrication of complex concrete shells (M. Popescu et al., 2020). The *Nest HiLo roof* **FIGURE 3.15 (2)** serves as a proof of concept regarding fabrication methods for thin concrete shells using a cable-net system and fabric shuttering (Echenagucia et al., 2019). This roof structure consists of 953 nodes and 2015 uniquely sized cables which were non-uniformly prestressed based on the weight of the concrete during fabrication and the desired final form. Through extensive collaboration involving design, engineering, fabrication, simulation and testing between specialized industry partners and ETH Zurich's state-of-the-art fabrication lab, the *Nest HiLo roof* demonstrates that double-curved concrete shells can be fabricated in a materially efficient manner.

These full-scale, technically complex precedents are both materially efficient and repeatable examples of concrete shells. The research conducted within *Concrete Form[ing]work* took a slightly different approach regarding the material expression of concrete within the fabricated form. Conducted without the resources of a large team of architects, engineers, sponsors or state-of-the-art machines, this PhD research utilized the opportunity to shift the focus from high-level design and fabrication to high-level design with low-tech fabrication. By investigating what can be achieved without using high-tech machines, this approach shifted the complexity so that it was inherent in the design rather than fabrication, resulting in an accessible fabrication strategy.

3.4.3 Mass-Customization and Tailoring

As designed geometric forms become increasingly intricate, the complexity of formwork for such casts increases accordingly. Flexible formwork projects for cast concrete such as *FattyShell* (Warmann, 2010b) and the *MARS Pavilion* (Sarafian et al., 2017) demonstrate such a disconnect between form and ease of fabrication. The *FattyShell* project, conducted at the University of Michigan and designed and built by Sturgeon, Holzwart and Raczkowski, was constructed using a double-layer EDPM rubber formwork. The form was modeled as a surface mesh, using Autodesk 3ds Max's relax function to achieve a minimal surface. In order to fabricate the formwork for this project, an industrial robot was used to cut the 45 unique elements. An industrial sewing machine was used to join the unique unfolded Pepakura components, shown in **FIGURE 3.16**.

The *MARS Pavilion* in Palm Springs, USA resulted from the research of Sarafian and Culver; it was initially conceived in Greg Lynn's Supra Studio (*Fabric Forms* project), then implemented on a larger scale. Sarafian and Culver designed a modular system for casting CTS rapid-set concrete into fabric formwork held in place by two robots. The overall geometry was based on a catenary, hanging chain model, and each of the 70 modules is unique. The tailoring for each unique element was fabricated by a garment tailor in downtown Los Angeles requiring

FIGURE 3.16: (1) Sturgeon, Holzwart & K. Raczkowski's *FattyShell* 2010 (Warmann, 2010).
(2) Sarafian & Culver's *MARS Pavilion* 2017 (Sarafian et al., 2017).

three days for completion (J. Sarafian, personal communication, March 27, 2018). Both projects have inconsistencies in their digital process chains, both of which were interrupted by large quantities of unique components or custom tailoring; as such, they demonstrate room to challenge more efficient means of realizing mass-customized fabric forms. The research presented in this thesis acknowledged the existing typology of these fabric-cast constructions and investigated a more streamlined approach to customized forms without intensive tailoring of unique components or sacrificing artistic intent.

04. METHODS

The following sections discuss the craft-based methods (*Ways of Drifting*, *categories of material evidence* and *externalization of tacit material knowledge*) and design methods (*flexible formwork*, *smocking*, *double-curved surfaces from flat sheet materials*, *simulation and correlation*) of the research conducted within this thesis. The starting point is the concept of research *through* design, as argued by Frayling, which is the generation of knowledge through the process of making (1993). This can take the form of various scales of artifacts and experiments, which, in turn, contribute to the *externalization* of implicit knowledge. Building on these notions, the research conducted within *Concrete Form[ing] work* highlighted both design and research methods to continue this dialogue surrounding craft-based research. The contributions of this thesis include both physical experiments and an emphasis on and discussion of *how* experiments are conducted. By integrating a research methodology based on an iterative, procedure-based workflow, this thesis situates its design-led experiments within the context of craft-based research.

4.1 Craft-Based Research Methods

SECTION 2.2 'The Experiment' surveys existing craft-based design research experiments and synthesizes three key aspects in which they differ from scientific experimentation. These include *procedural workflows* (process-focused feedback loops of experimentation), *evaluation criteria* (finding value within 'wandering' experimentation instead of validating a preconceived hypothesis) and *externalization of tacit material knowledge* (actively evaluating and communicating how tacit material knowledge is disseminated). This thesis hybridizes and builds upon these existing methodologies to conduct research experiments within the context of flexible formwork and concrete.

4.1.1 *Ways of Drifting*: Highlighting the Process

As discussed in **SECTION 2.2.1 'Experimental Workflows'**, architectural designers have developed various process-based workflows with which to construct craft-based experiments (Bang et al., 2012; Brandt & Binder, 2007; Koskinen et al., 2011; Krogh et al., 2015; Norell, 2016; Ramsgaard Thomsen & Tamke, 2009; West, 2011; Zimmerman & Forlizzi, 2008). These open-minded approaches to making, sometimes in the absence of formulated end-goals, allow for a more responsive dialogue between research and the experimental environment. This cyclical, 'wandering' experimental methodology contradicts Protevi's "architect/master/ruler" description of the ancient Greeks, where the artisan was relegated to a realizer of form and "unworthy of notice" (2001, p. 123). Instead, these processes allow more active involvement in the making process and blur the distinction between designer and fabricator. It is not only possible but essential for design research to vary experimental modus operandi and "allow for the plurality of forms" in order to respond to craft-based learnings (Krogh et al., 2015, p. 10).

Krogh et al.'s *Ways of Drifting* when conducting design research include five methods of experimenting: *accumulative*, *comparative*, *serial*, *expansive* and *probing* (2015). This thesis utilizes the latter three methods to emphasize the experimentation process in addition to the outcome. Similar to the methodology of Bang et al. (2012), *serial* design experiments are conducted chronologically, with relative logic shared between related experiments (2015, p. 8). This research methodology was utilized for the *Column* Series, *Lozenge Panels* and *Wall Three*, wherein each experiment built on the previous, working to "systematize local knowledge" (2015, p. 8). These experiments deepened the knowledge of working with concrete and smocked fabric.

Krogh et al.'s *expansive* method is characterized as "extending," lacking strict linearity and having high diversity (2015, p. 9). This type of experiment explores from a broader perspective, seeking to widen the knowledge of the research domain. This particular method is beneficial for constructing novel links between related fields and characterizes the global research method of the research presented in this thesis. *Expansive* drifting was utilized in this research when investigating the adjacent fields of mesh segmentation, surface unrolling, origami, kirigami, auxetic materials and conformal mapping, searching for potential connections. The findings from the *Cone*, *Torus 1.0* and *Dome* probes were synthesized and served as the foundation of the pattern generation tool *OriNuno* developed during this research. By *extending* the knowledge of these specific domains in a circuitous fashion, this research situated itself in these related, yet previously unlinked fields.

The final manner in which the research presented in this thesis was conducted was *probing*. Similar to West's previously discussed shotgun metaphor, the *probing* method is characterized by "exploiting opportunities, [...] exploring design ideas as they emerge through design work," and allows the selection of exploration avenues based on personal, "artistic" motivations (2015, p. 9). These *probing* traits foster curiosity and do not imply a specific end goal of a research experiment. Such experiments are valuable in exposing new connections between related yet unconnected fields. Experiments such as the *First Fifteen Hand-Smocked Probes*, *Column 01* and *Skewed Grids* were conducted in this *probing* manner. These experiments were both inquisitive and intuitive, conducted without a clear vision of the result.

The research presented in this thesis emphasized the experimental process by incorporating Krogh et al.'s *Ways of Drifting*. Rather than constructing linear experiments with specific end goals in mind, the research was conducted using experimental 'wandering', continuously jumping between investigations of concrete, flexible formwork, computational patterning, simulation and correlation. By employing a feedback loop between these *Ways of Drifting*, this design research methodology resulted in a highly cyclical process to relate craft-based experiments to architectural practice (Scherer, 2017).

4.1.2 Evaluating Experiments: Categories of Material Evidence

As was established **SECTION 2.2.2**, the absence of end-goal-based experimentation in design research allows for a reformulation of experimental evaluation criteria that highlights knowledge accumulated throughout the process of making (Krogh et al., 2015; Norell, 2016; Tamke et al., 2017). Unlike their scientific counterparts, craft-based experiments are productive for *speculation*, *reflection*, *evaluation* and *interface* (Tamke et al., 2017). These characteristics have a foundation in Tamke et al.'s earlier work, differentiating between *types of material evidence* in design research. The modes of *probe*, *prototype* and *demonstrator* formalize the evaluation of *material evidence* and relate this evidence to the global design process (Ramsgaard Thomsen & Tamke, 2009). The research presented in this thesis built upon Ramsgaard Thomsen and Tamke's definitions to include additional nuances of these terms in the context of the experiments conducted.

Ramsgaard Thomsen and Tamke define *probes* as being design-led and speculative in nature. *Prototypes* are materially-focused and explore craft while developing the design criteria for *probes*. As digital design practices and simulation tools evolve to reflect material-driven fabrication processes, *prototypes* can also be used to cyclically validate digital models and establish consistency (2016, p. 51). *Demonstrators* are situated within real-world constraints, aiming to verify and communicate the efficacy of full-scale applications to a larger audience. Building on Allen's emphasis on the material nature of architecture, "working in and among the world of things" (Allen & Agrest, 2000, p. XVII), the use of *probes*, *prototypes* and *demonstrators* emphasize the importance of integrating physical making within various levels of experimentation. These categories serve as design research's counterparts to scientific "technology readiness levels,"[11] and guided the creation of the research methodology presented in this thesis, which was a means of finding value within all scales of experimentation.

In the research presented in this thesis, *probes* were also characterized by their 'wandering' nature. These experiments were sometimes design-led, but also sometimes conducted for the simple purpose of understanding how a system works (*thinking through making*). The latter served primarily to inform and build up a tacit knowledge base and were therefore 'intuitive.' Conducted for the purpose of *thinking through doing*, experiments such as *First Fifteen Hand-Smocked Probes*, *Column 01*, *Skewed Grids*, *Cone*, *Torus 1.0* and *Dome* were categorized as such. These *probes* could be evaluated based on the outcome (given that the outcome was not predetermined), and must instead be considered in relation to knowledge generation. By trying (and sometimes failing), these *probes* resulted in a wealth of material and geometrical findings, which later informed subsequent experiments. Given the absence of a hypothesis, the process of making was highlighted to communicate this developed intuition.

The *prototype* experiments conducted in the context of this thesis were not necessarily material-led, as is suggested by Ramsgaard Thomsen and Tamke. The term is generalized to include experiments that seek to answer more specific questions generated while fabricating *probes*. Similar to Chandler and Pedreschi's definition, *prototypes* assist in identifying "where to focus the activity of risk" (Chandler & Pedreschi, 2007, p. 18). *Prototype* experiments such as *Column 3D Prints*, *Column 02*, *Lozenge Panels* and *Column 3.1* were conducted after material and geometrical intuition had been built up and the fabrication techniques had been refined. A tacit intuition and knowledge base were vital to accumulate before formulating relevant hypotheses and successfully executing design intent.

Demonstrators were the results of experiments that synthesized the findings and techniques of the *probes* and *prototypes* developed during the research process. *Wall Three* is a straightforward *demonstrator* in the diction of Ramsgaard

---

[11] Technology readiness levels (TRLs) are a NASA-developed method of uniformly evaluating various types of technology from multiple fields based on their 'maturity' and development (Héder, 2017).

Thomsen and Tamke, as it applies material and computational findings to real-world contexts. This thesis argues that *demonstrators* inhabit a broader definition; in addition to addressing real-world constraints, *demonstrators* are characterized by rigorous testing, concretizing and the exhibiting of accumulated knowledge. As opposed to the more exploratory *probe* and *prototype* experiments, the *demonstrator* experiments were conducted with an accurate prediction of the outcome and served as knowledge confirmation. In this context, *Column 3.2*, *Hyperbola Catalog* and *Torus 2.0* are considered to be *demonstrators* as well. While these experiments did not necessarily address full-scale applications, they were conducted to confirm a precise end-goal and 'demonstrate' and verify a given technique.

4.1.3 Externalizing Tacit Material Knowledge in Relation to Flexible Formwork

The *Ways of Drifting* and *categories of material evidence* concepts further underline the complexities and iterative nature of craft-based experiments. By re-formulating the *evaluation criteria* of experiments, the oscillation between various scales of *material evidence* became an experimental method in itself.[12] The contribution of research experiments need not be solely polished images of a final installation, but can include a procedural catalog of successes, failures and findings. With this in mind, it is critical to reflect on how tacit material knowledge is codified and disseminated in the context of flexible formwork and concrete.

Effectively communicating flexible formwork techniques to industrial fabricators who are unfamiliar with the process remains difficult (Chandler, 2015; Milne et al., 2018). Chandler details his experience consulting with Heatherwick Studio for a 325,000 m^2, seismic-resistant, concrete-framed development in China. While their construction method had been rigorously tested in-house, it was "not detailed for the brutality of a fast-track building site" (Chandler, 2015, p. 6). The fabricators did not have direct tacit knowledge of the "feel" of fabric formwork and concrete and were thus unable to produce forms that were as successful as those cast by the researchers (Chandler, 2015, p. 5). Once Chandler's design team constructed and scanned a 1:1 proof of concept, the fabricators successfully reproduced the demonstrated technique with the required procedure and accuracy. Milne describes undertaking this process with an unnamed formwork producer for a 2 x 3 meter wall (Milne et

---

[12] For further discussion regarding this methodology, see Scherer (2017).

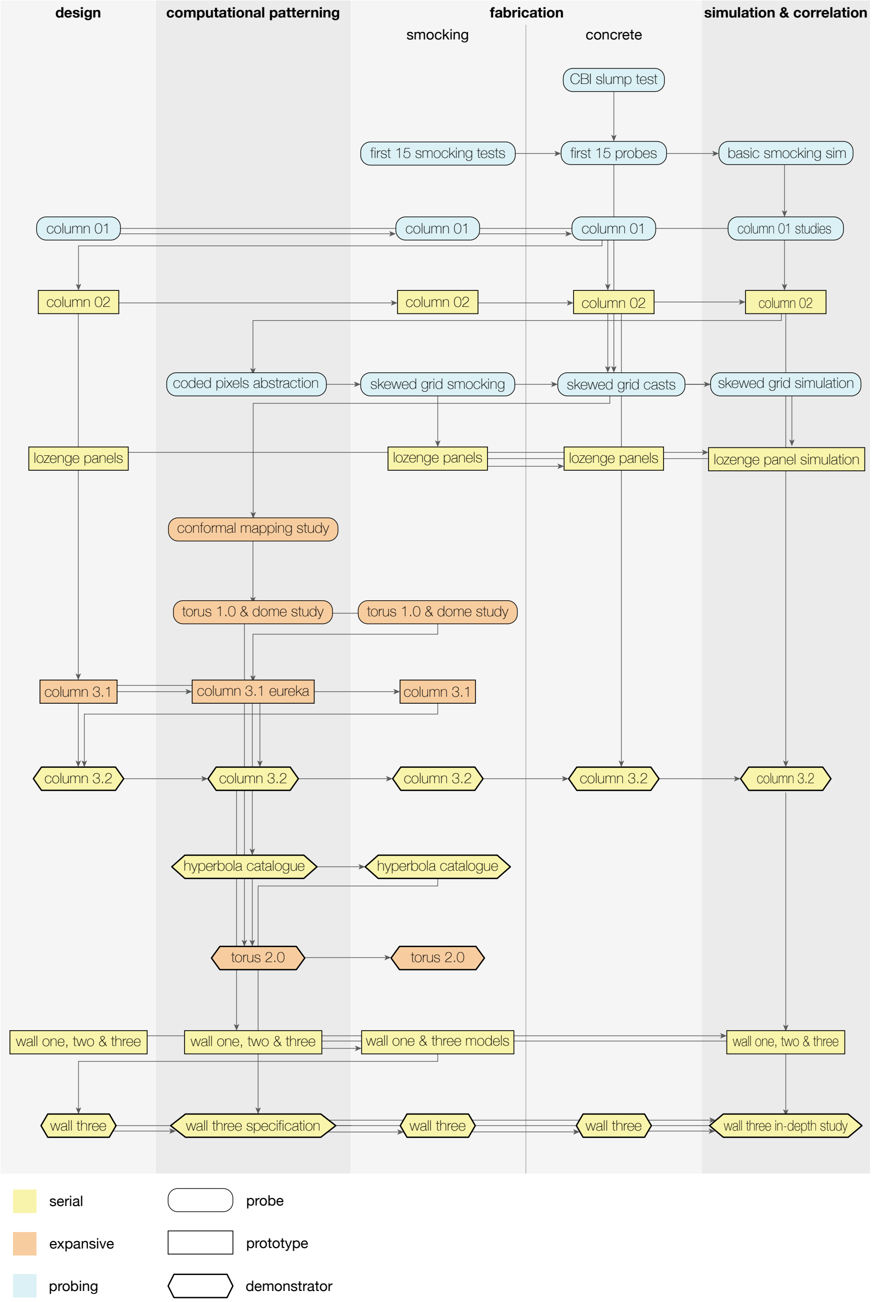


FIGURE 4.1: Chronological workflow of research experiments (Source: author).

al., 2018). Chandler and Pedreschi successfully fabricated the wall formwork and reinforcement mesh in six hours, yet the fabricators were unsuccessful in repeating the process, and the formwork failed.

These projects further underline the need to evaluate *how* first-hand tacit knowledge is communicated and translated to real-world applications. In order to more thoroughly permeate industry, the material expression of textile formwork must be balanced with the ability to fabricate predictable and repeatable forms. The research conducted within *Concrete Form[ing]work* explores the degree to which this tacit material knowledge can be integrated into the design process; this is done by reflecting on existing communication techniques in adjacent fields and identifying areas for improvement. Communication breakdowns in flexible formwork can be mitigated with more successful methods of *externalizing* tacit knowledge such as the integration of simulations, extensive detailing or documentation of the fabrication process.

To summarize, the experiments conducted during the research presented in this thesis were centered around a craft-based research methodology: a process-focused feedback loop that oscillated between various *types of material evidence* and modes of *externalizing tacit material knowledge*. This manner of working allowed the experiments to inhabit a plurality of forms while simultaneously retaining a sense of the importance of craft and contributing to design research. **FIGURE 4.1** details the chronological order of experiments along the Y axis, highlighting the constant feedback loop between design, experimentation and evaluation. While *probes* were conducted in a 'wandering' manner, prioritizing *thinking through making* and generating areas for investigation, *prototypes* further developed the research questions that were revealed by these *probes*. *Demonstrators* were executed with a specific end goal in mind and to show mastery of a technique and serve as knowledge-confirmation. As is stated above, the experiments are not presented in a linear order in this thesis; they are instead categorized into three sections ('Material', 'Geometrical' and 'Digital') that answer their related research question. By employing this craft-based methodology, the research presented in this thesis discovered previously unexplored links between related research fields (e.g., mesh segmentation, surface unrolling, origami, kirigami, auxetic materials, conformal mapping) in order to contribute to existing gaps in current flexible formwork research.

4.2 Design and Fabrication Methods

On the basis that concrete is subjected to both the formwork and the human hand that pours it, Forty asserts that "[c]oncrete, let us be clear, is not a material, it is a process" (2006, p. 35). Chandler and Pedreschi suggest a less absolute definition: when cast in flexible formwork, concrete is hardly an obedient or passive matter, which characterizes it as both a material and a process (2007, p. VII). Concrete bulges and strains against its formwork with apparent mass, pressure, rheology and texture. Fabric-formed casts reveal how concrete can be *both* a process and a material, actively imposing its material behavior during the forming process while simultaneously requiring engagement and response from the formworker. Process and materiality are not in opposition; their union brings a shift in possible architectural designs that vacillates between expressiveness and rationality (2007, p. 23).

When re-envisioning how fabric-cast forms are built within the context of parametric design and digital fabrication, it is possible to integrate both the process and materiality of concrete, with each reciprocally affecting the other. Coupled with a craft-based research methodology, the research presented in this thesis employed a series of design methods: *flexible formwork*, *smocking*, *computational patterning*, *simulation* and *correlation*. Circulating through these various design methods encouraged both the accumulation of tacit knowledge and the open exploration of novel concrete fabrication techniques for concrete structures. This research sought to address the industrial impediments of predictability and repeatability by identifying areas in which Pye's "workmanship of risk" can be safely applied so as to balance material expression and rationality of form.

4.2.1 Flexible Formwork

This thesis acknowledges Dieste's concerns regarding the concern that over-simplification of concrete construction generally results in the process defaulting to planar formwork (Scherer, 2017, p. 28). It further echoes his deep respect for the materiality of concrete, as well as his interest in the possibilities that a craft-based methodology brings to the architectural design environment (Dieste, 2004, p. 187). Natural hydrostatic forces and the materiality of concrete are viewed as opportunities for new innovations in architectural design. This research analyzed the unique qualities of flexible formwork and concrete,

FIGURE 4.2: (1) *Lozenge* cast probe sheathing and (2) *Skewed Grids* cast probe (Source: author).

accommodating a craft-based methodology and varying customization needs while simultaneously reuniting the design process with intrinsic material qualities.

Fabric was chosen in this research as a primary complementary material to investigate the dual sides of concrete as both a form-giver and a form-receiver (**FIGURE 4.2**). Flexible formwork highlights the rheological forces and materiality of concrete, contrasting the rigid constraint of the material with conventional wooden formwork. Painters imprint their mark in the design process, leaving behind imprints and brush strokes as a trace of how the piece was created (Andrasek, 2016). In the same manner, how a cast fabric form is constructed is easily readable. The creases, bulges and fabric texture imprinted on the hardened concrete hint at the process and hand that shaped it. A simple change of formwork material, e.g. from rigid to flexible, allows the concrete's inherent forces, hydrostatic pressures and rheology to become an active design driver in the constructed form. The fact that fabric is highly responsive to fluidity means that mass and surface material properties are engaged, encouraging the creation of more expressive cast forms. Given that forming during the casting process is active in relation to not only the designer but the fabricator, the distinction between the two becomes blurred; though this is reminiscent of the era of craftsmen, it is more of a rethinking of craft in the digital era.

In addition to enabling an expanded design space to produce non-planar shapes, flexible formwork addresses material consumption and sustainability issues. Compared to uniform-section members, fabric-cast elements utilize only the necessary amount of concrete with a ≈40% volume saving (Orr et al., 2011, p. 100). The costs of the formwork itself are also significantly reduced: conventional wooden formwork panels (being zero-deflection structures) require high stiffness, volume and weight to compensate for the forces imposed on the formwork (West et al., 2016, p. 46). Comparatively, ArroDesign's *Black Treehouse* fabric formwork project utilized ≈35% less material weight, translating to fewer pours and decreased energy use in transportation (Miller-Johnson, 2009). The portability of flexible formwork provides geographical freedom (see *Casa Dent*), meaning that it is optimal for use in locations with complex on-site logistics or when there is a lack of expertise in working with flexible formwork among laborers (West, 2004). Once cast, the formwork can be reused for future casts or lower-grade applications (Miller-Johnson, 2009).

Fabric formwork produces lighter elements and improves the surface quality of the cast (Abdelgader et al., 2018; Shah et al., 2018). Casting in permeable membranes allows excess moisture to wick through, simultaneously improving the strength and durability of the concrete while reducing surface defects. Surface quality can be further manipulated by utilizing patterned fabric (Manelius, 2012, p. 186), velvet (Morrow, 2017) and even bubble wrap (Bush, 2010). Construction practices primarily utilize woven geotextiles given their high strength, stiffness and tear resistance (West et al., 2016). The research presented in this thesis investigated and evaluated a wide variety of fabrics that range in elasticity, thickness and construction (see **SECTION 5.1.4 'Fabric Selection'**).

4.2.2 Smocking

In the context of the laborious custom formwork tailoring carried out within projects such as *FattyShell* and the *MARS Pavilion*, the research presented in this research investigated the potential of smocking as a method of simply manipulating single sheets of fabric to produce custom forms. Utilized since the Middle Ages, smocking is a practical sewing technique of gathering fabric and fitting garments with elasticity rather than tailoring. The process is derived from the word 'smock (**FIGURE 4.3**),' a farmer's work shirt, as this kind of fabric detailing was often worn by laborers (DeMarly, 1987). Smocked garments became less widespread at the end of the nineteenth century when agricultural workers moved to cities to work in factories; the clothing style was deemed too flowing and impractical when working with moving machines (Victoria and Albert Museum, 1893). At this time, the technique became popularized as a decorative status symbol, due to the time-consuming fabrication process. With the invention of pleating machines in the 1950s, smocking enthusiasts popularized the technique (**FIGURE 4.4**), integrating it into decorative projects such as pillows, aprons and children's dresses (Marshall, 1980).

Hand-smocking is undertaken by first marking either a grid or dots on the fabric. The smocking pattern follows these markers, and the endpoints of the pattern are gathered together with thread, resulting in folded pleats[13] (**FIGURE 4.5**).

---

[13] The two major traditions in smocking are the classic English and the later-developed North American. The former is a two-step procedure in which the fabric is first folded into regular pleats. After the smocking is complete, the threads holding the pleats in place are removed. Elasticity is a characteristic of this type of stitching (Wolff, 1996, p. 129). The latter, on the other hand, is based on a grid that is drawn on the fabric, does not involve pre-pleating and works entirely on the reverse side of the fabric (1996, p. 141). The research presented in this thesis focuses on the North-American technique; it has the most potential for grid abstraction and single-sided stitching, which is more suitable when combined with cast concrete.

FIGURE 4.3: (1) *Farmer's smock* (Victoria and Albert Museum, 1796).
(2) *Liberty Dress* (Victoria and Albert Museum, 1893).

FIGURE 4.4: Vintage smocked dress patterns (McCall Printed Pattern 1350, 1947; Simplicity Printed Pattern 1863A, 1956).

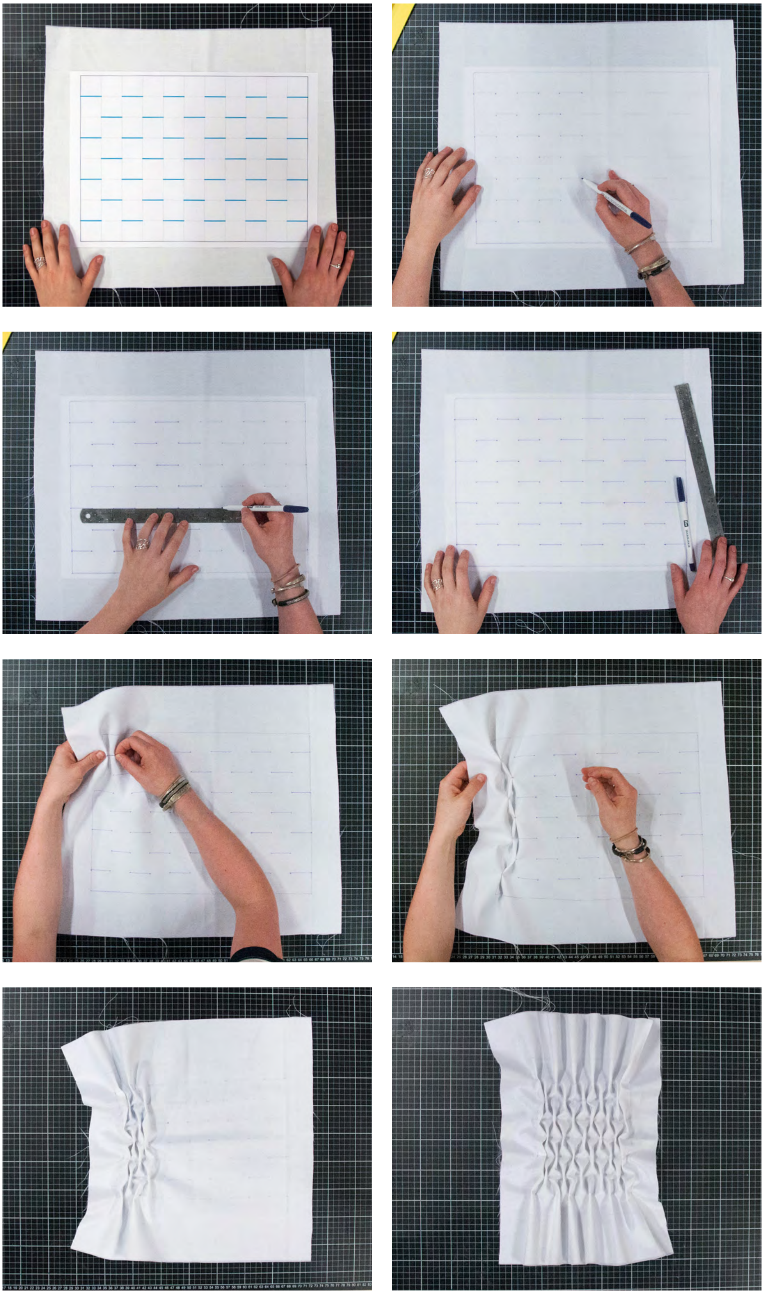


FIGURE 4.5: Hand smocking a basic 'Lozenge' pattern (Source: author).

Depending on the size and shape of the smocking, the size of the textile will be reduced by one third to one half of its original size (Scherer, 2017, p. 32).

Until the last decade, there has been little to no research on the potential of digitizing and computationally manipulating this patterning technique. This handicraft was again popularized in the 1950s,[14] and these pattern styles remain popular in handmade children's clothing to date. Despite the stagnation of smocking's evolution, the coupling of smocking with digital tools in the past decade has revived interest in the technique and revealed hidden potential in terms of the computational patterning of fabric.

Architectural smocking. Kuma's *Spacer Fabric Architecture* (2014) and Mamou-Mani's *Magic Garden* (2013) projects utilize the structure and thickness of spacer fabric to explore fabric manipulation and generate complex surfaces (**FIGURE 4.6**). Kuma's ITECH thesis project at the University of Stuttgart uses computational design to generate surface articulations and explore local and global manipulation of fabric. Infused with resin, it hints at the architectural applications of this technique. Rather than forcing material into a preconceived design, Kuma utilizes a similar methodology to the research presented in this thesis; the design is coupled with a feedback loop from extensive material experimentation.

In collaboration with RIBA and Karen Millen's atelier, Mamou-Mani's *Magic Garden* (**FIGURE 4.7**) is a state-of-the-art example of computational sewing and the use of materiality as a design driver. This 2013 project used smocking techniques on spacer fabric to activate the 30 meters of windows of Karen Millen's flagship store on Regent Street, London, UK. Mamou-Mani used full-scale mockups to test the kinds of geometry that could be made with the fabric, and directly interacted with the material from the start of the project. The project integrated various simulation tools, including the Kangaroo 2 and Grasshopper plug-ins for Rhino 3D, but these tools appear to have only been used for small-scale geometries. Global geometry was designed as an abstracted surface; a plexiglass skeleton was used as a substructure, and the flexibility of the fabric allowed a smooth interpolation between skeleton ribs (Mamou-Mani, 2013). While both *Spacer Fabric Architecture* and *Magic Garden* investigated the potential applications of smocking to architecturally shape space, both required

---

[14] This technique is an heirloom craft, primarily popular with older generations; perhaps this partly explains why there has been little interest in manipulating these patterns digitally.

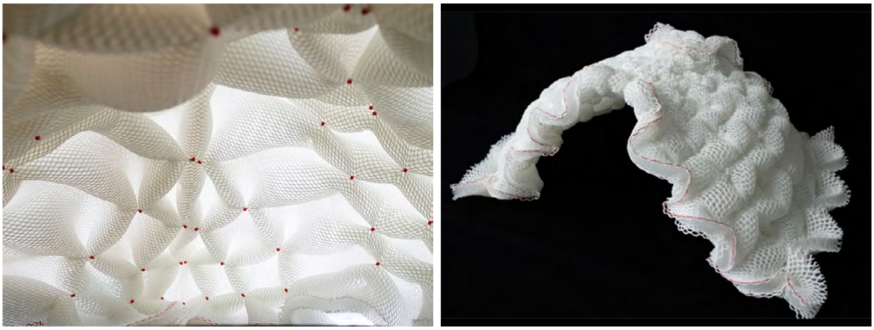


FIGURE 4.6: Kuma's *Spacer Fabric Architecture* Master's thesis (Kuma, 2014).

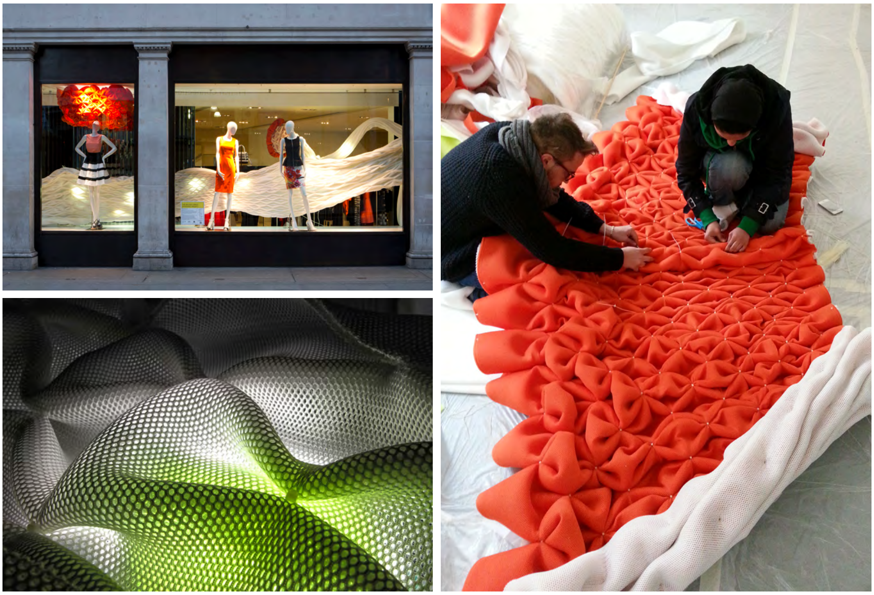


FIGURE 4.7: Mamou-Mani's *Magic Garden* (Mamou-Mani, 2013.).

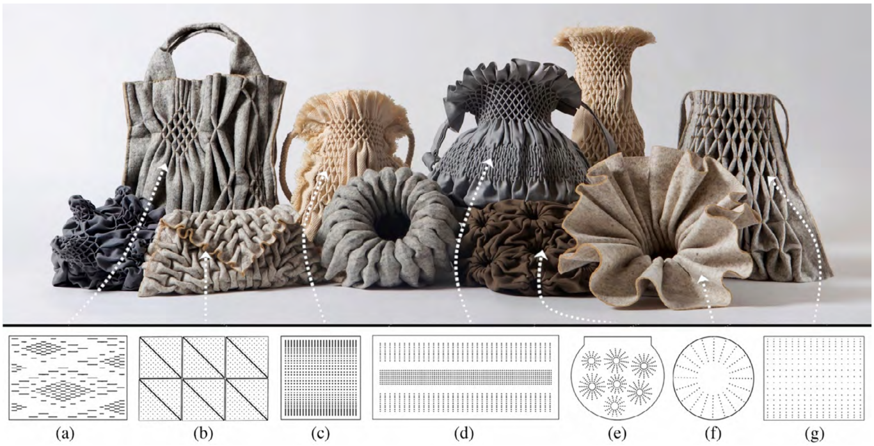


FIGURE 4.8: Efrat's *Crafted Technology* Master's thesis (Efrat, 2016).

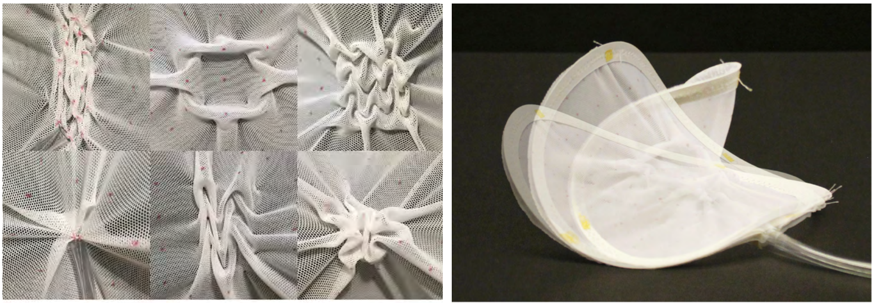


FIGURE 4.9: Millentrup's *Actuated Textile Hybrids* Master's thesis (Millentrup et al., 2019).

a second material as a substructure to support the global shape.

Smocking research. The designer Efrat explores the development of digital tools accessible to craftsmen. Her Master's thesis *Crafted Technology* (**FIGURE 4.8**) involved the conducting of mathematical research and digitizing of smocking patterns. The results were visualized in the fabrication of eight algorithms, demonstrated using 18 unique bags. These different patterns investigated various qualities of patterning, structural strength and elasticity (Efrat et al., 2016). It should be noted that while *Crafted Technology* rigorously tested a variety of digitally-generated flat patterns, it did not address the deconstruction of three-dimensional shapes as a means of generating smocking patterns.

Recent development focusing on the actuation of smocked prototypes has explored the 'in between' states of smocking rather than a simple bi-stable configuration of flat/smocked (**FIGURE 4.9**). These projects integrate textiles with active elements such as shape memory alloy (SMA; Hoitinik & Cabral, 2014) or pneumatics (Millentrup et al., 2019). These small-scale probes focus on actuation (utilizing mechanical machines to cause movement) of the samples rather than patterning development; given the context and scale of experiments in this thesis, actuation was deemed inappropriate for further investigation.

4.2.3 Double-Curved Surfaces from Flat Sheet Material

> *Flat pieces cost one dollar, single curvature pieces cost two dollars, double curvature pieces cost ten dollars. The good thing about the computer is that it allows you to keep a close control over the geometry and the budget.* (Gehry, 1995, p. 36)

Gehry aptly noted that the production and assembly costs of fabricating non-planar forms rise exponentially with increasing geometrical complexity. When developing novel design and fabrication methods, it is essential to address issues of feasibility and practicality. This section introduces seven existing approaches to the geometrical construction of three-dimensional surfaces from flat sheet material, which were explored with the aim of developing an efficient and cost-effective method of tailoring double-curved surfaces. These approaches include: geometrical surface unrolling, mesh segmentation, Ron Resch patterns, Origamizer, kirigami, conformal mapping and techniques adopted from the papers *Freeform Origami Tessellations by Generalizing Resch's Patterns* and *Programmable Auxetic Materials*. These techniques

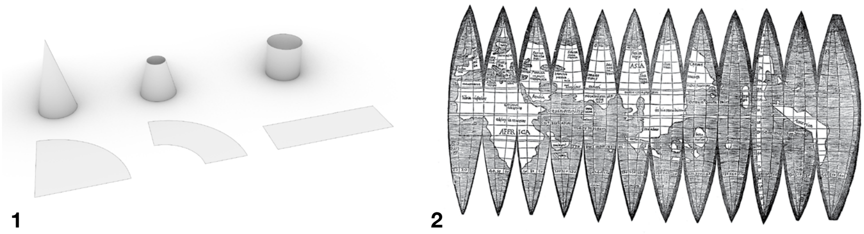


FIGURE 4.10: (1) Single curved surface unrolling (Source: author)
(2) Waldseemüller's 1507 globe segment map (Missinne, 2015).

were explored during the 'expansive' phase of the research conducted within this thesis (discussed in **SECTION 2.1.1**) which allowed for unforeseen links to smocking pattern logic to be identified; the limitations of current patterning tools were addressed and development was undertaken to combat these limitations. The findings of this survey of related fields served as a foundation on which the digital tool *OriNuno* (see **FIGURE 5.17**) was developed.

Geometrical Surface Unrolling. When investigating how to form bespoke architectural surfaces and shapes using flat sheet material, it is impossible to ignore architectural geometry and surface-unrolling techniques. There has been extensive research on assembling developable surfaces from flat sheet material (Pottman et al., 2007). Developable geometry denotes that a shape can be formed from a single sheet, i.e., a cone, truncated cone or cylinder, as shown in **FIGURE 4.10 (1)**. Double-curved shapes such as a sphere cannot be formed from a single sheet of material without either introducing singularities or simplifying into a tessellated mesh. A classic example of this problem is how to draw a map to represent the world accurately. As early as 1507, cartographers such as Waldseemüller ("Waldseemüller Map," 2020) addressed this issue, resolving the geometry into globe 'sectors' that abstracted the double-curved geometry into developable strips (**FIGURE 4.10 (2)**).

Mesh Segmentation. Mitani and Suzuki's work utilizes a modernized version of Waldseemüller's strip-based mesh unrolling technique, proposing a tool for unfolding approximated triangulated meshes (2004). This geometrical modeling technique (**FIGURE 4.11 (1)**) is realized by constructing various papercraft models, such as the Stanford bunny ("Stanford Bunny," 2020). Pepakura Designer (n.d.) is similarly geared towards hobby paper crafts and exists as a standalone program with an existing set of controllable parameters,

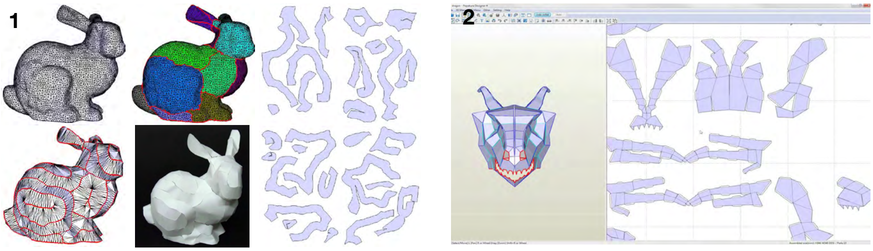


FIGURE 4.11: (1) *Strip Unrolling Method* of the Stanford Bunny (Mitani & Suzuki, 2004).
(2) Pepakura Designer (Pepakura Designer, n.d.).

unfortunately with minimal customization; **FIGURE 4.11 (2)**). Nejur's Ivy plug-in for Grasshopper/Rhino 3D (Nejur & Steinfeld, 2017) offers more sophisticated mesh-unrolling, allowing the user to specify various mesh graphs, segmentation and transformation in anticipation of fabrication. While all three methods are highly relevant to constructing parametric smocking patterns, none provided the requisite flexibility. Consequently, an entirely new tool, *OriNuno*, was developed to address the specific needs of this research project (described in **SECTION 5.2** and **SECTION 5.3**).

Ron Resch Patterns. Ron Resch, known for his origami tessellations and the *Vegreville Pysanka* (2000), developed a series of folding techniques in the 1960s and 1970s to investigate various kinematic folded-plate systems that could approximate a variety of shapes. His 1977 patent (1977) describes a geometrical, structural system characterized by equilateral triangles. These triangles are arranged in a hexagonal grid, with alternating hinged corners (**FIGURE 4.12**). Single-sheet foldings with such a pattern are characterized by a high diversity in terms of form, and can approximate a large variety of architectural surfaces (1973). This unique design system was facilitated by computer simulation and cutting-edge at the time; most ground-breakingly it proposed "the possible elimination of monotonous serial production in favor of mass production of non-identical shell forms" (Resch & Christiansen, 1970, p. 1). Resch's fundamentals contributed novel findings when combined with modern computation techniques; these significantly influenced *OriNuno*, the digital tool developed during the research presented in this thesis.

Origamizer and Freeform Origami Tessellations by Generalizing Resch's Patterns. Tachi is one of the leading experts in producing origami patterns for approximating surfaces. His research (**FIGURE 4.13**) encompasses Voronoi-based

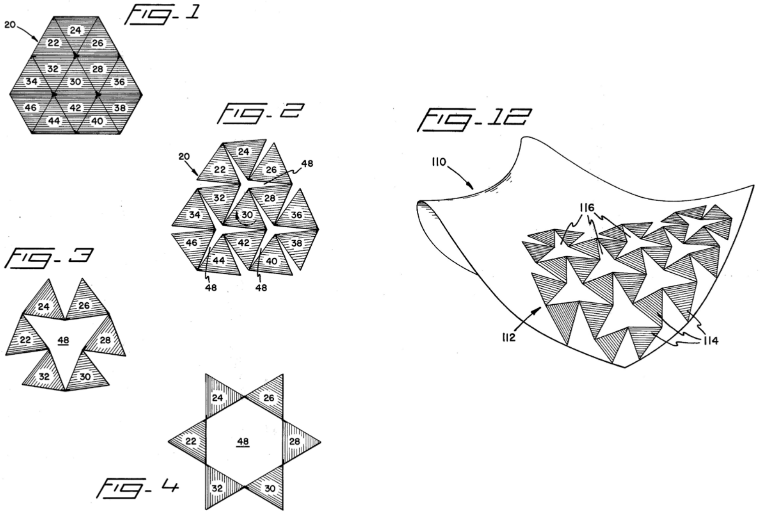


FIGURE 4.12: Resch's 1977 folding pattern patent (Resch, 1977) and paper studies (Resch, 1970).

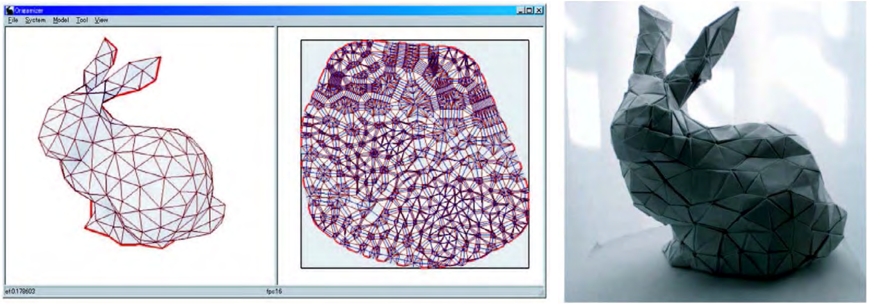


FIGURE 4.13: T. Tachi *Origamizer* desired polyhedral model, crease pattern and first origami Stanford Bunny (Tachi, 2010).

vertex-tucking modules (2009), the development of the Origamizer software package to "achieve arbitrary three-dimensional sheets from a single sheet of material" (2010, p. 310) and research into half-folded tuck modules based on Ron Resch's origami patterns (2013). Tachi's Resch-pattern generalizations build upon previous research which led to the creation of Origamizer and Freeform Origami software packages; half-folded state of the Resch patterns enables an even greater range of geometrical possibilities. Origamizer was explored within the patterning research presented in this thesis, and proved to be a highly robust program for generating flat patterns from freeform input shapes. Similar to Pepakura Designer and Ivy, Origamizer did not provide enough control over pattern manipulation to apply this to smocking. Although this tool did not suit the needs of the research presented in this thesis, it did serve as an excellent springboard for investigations into patterns and scripting as part of the research project.

Kirigami. While the geometry of folding origami has been thoroughly explored since the early 1990s by leading researchers such as Lang (Lang & Foer, 2014) and Demaine (Demaine & O'Rourke, 2007), that of lesser-known subset, kirigami, has only come to light in the past decade. Kirigami is a variation of traditional origami and involves the introduction of cuts (*kiri* meaning 'cut' and *kami* meaning 'paper'). While the folding and tucking used in origami do not easily translate to an architectural scale due to material thickness compounding, kirigami's strategically placed cuts result in a lack of self-intersecting faces, addressing the problematic combination of geometrical folding techniques and material thickness and providing promising possibilities relating to large-scale structures and flexibility of form. Castle et al. first began exploring the potentials of

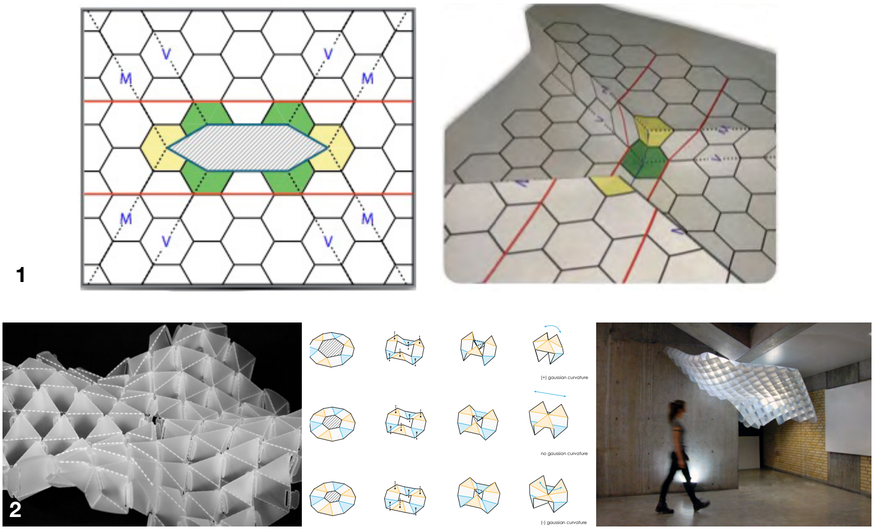


FIGURE 4.14: (1) *Folding Honeycomb* kirigami fundamentals (Castle et al., 2014).
(2) *Programmable Folding* Master's Thesis (Source: author).

kirigami, investigating folding honeycomb (**FIGURE 4.14 (1)** ; 2014) and algorithmic lattices (2016). Similarly, Baker's *Spin-Valence* space frame system fabrication logic developed the concept of structural space frames constructed through strategic cuts and rotational bending of steel (Baker, 2014; Sahuc, 2019). The geometrical principles of kirigami are applied on various scales ranging from thin graphene sheets (Blees et al., 2015) to foldable and deployable structures in space (Wang et al., 2021).

The pattern-generation research presented in this thesis utilized the author's kirigami-based 2015 Master's thesis, *Programmable Folding* (Scherer, 2015), as an intellectual springboard (**FIGURE 4.14 (2)**). By thinking beyond the flat goods themselves, parametrically derived folding patterns were created to be assembled into irregular, double-curved surfaces. This thesis analyzed the basic geometrical rules of kirigami folding, identifying which parameters are flexible and which are uncompromisable. The resulting computational pattern encoded a sheet material with an inherent assembly logic and provided the necessary information to fold the material into a complex, three-dimensional surface. This project built on research from the origami world, particularly referencing the work of Tachi (2013), Konaković-Luković (2016) and Castle (2016), and utilized Grasshopper and Kangaroo 2 for Rhino as the primary design tools to realize geometrical complexities within double-curvature folding. As part of the research process, tools for easy manipulation of areas and degrees of curvature, nimble generation of a 'cut and tabbing' pattern and simulation of the final folded geometry were developed. These techniques were the foundation for the development of *OriNuno* (described in **SECTION 5.2** and **SECTION 5.3**), which allows for the design of complex parametric patterning of and simulation of their final configuration. As with *Programmable Folding*, the research presented in this thesis explored and expanded the design possibilities of geometry and patterns on multiple levels and delivered a final product the design of which was embedded in the patterned flat sheet material.

Programmable Auxetic Materials. Konaković-Luković et al. (2016, 2018) investigate the applications of freeform surfaces via programmed auxetic materials (**FIGURE 4.15 (1)**). Their research investigates double-curved surfaces that are deployable through inflation or gravity. By programming the gaps between links, their research developed a method for computationally generating a pattern for auxetic materials to approximate positive-mean-curvature free-form surfaces. This 'personalization' of form has potential applications such as custom-curved heart stents (Tomita et al., 2015). Other methods using customized, deployable geometry include bi-stable 3D prints (Chiang, 2019) and *CurveUps*,

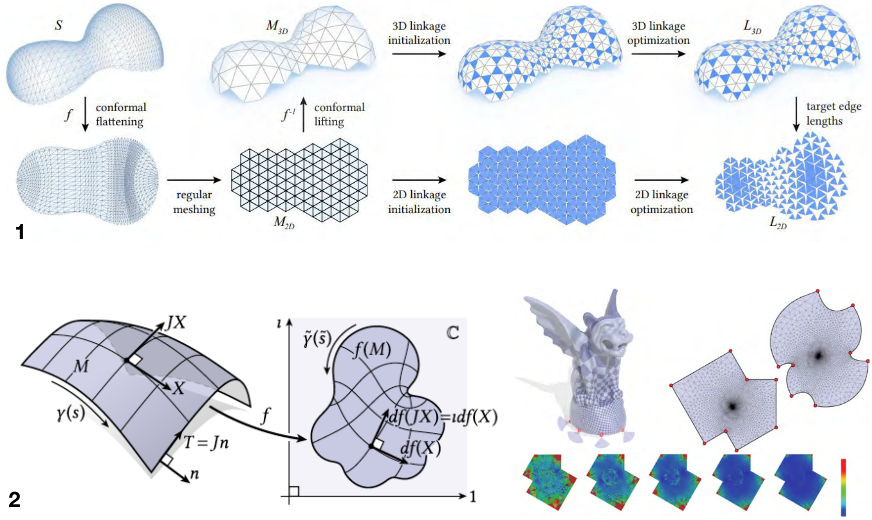


FIGURE 4.15: (1) *Programmable Auxetics* (Konaković-Luković et al., 2018).
(2) Conformal Mapping with *Boundary First Flattening* (Sawhney & Crane, 2017).

the elastic tension-actuated curved shells that form from an initially flat state (Guseinov et al., 2017). These mesh deconstruction techniques, which are used to unroll double-curved geometries, served as a significant inspiration in the development of the patterning techniques that was conducted as part of the research presented in this thesis.

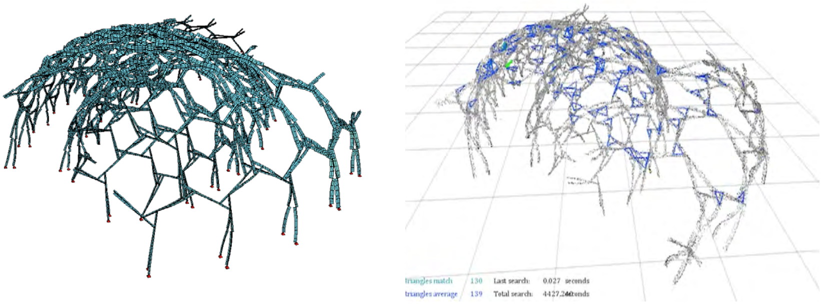
Conformal Mapping. Conformal mapping allows the translation of a curved surface to a planar one while locally preserving interior angles (though not necessarily size). While commonly associated with texture mapping (Desbrun et al., 2002; Levy et al., 2002), conformal mapping has been used in architectural applications to optimize sphere-packing (Schiftner et al., 2009) and hexagonal paneling (Rörig et al., 2015) on freeform surfaces. The recent development of tools such as Boundary First Flattening (BFF; **FIGURE 4.15 (2)**) has facilitated greater control over the shape of the flattened mesh and such tools allow for custom placement of cones to mitigate area distortion in mapping (Sawhney & Crane, 2017). Thus far, BFF is unique in its intuitive ease of use and utility; it can be easily combined with *OriNuno* to assist in cone singularity placement when working with more complex geometry.

The seven approaches outlined above were synthesized to develop the parametric patterning 'group' of the digital tool, *OriNuno* (**FIGURE 5.17 (2)**), generated during the research presented in this thesis. Geometrical surface unrolling, mesh segmentation and the Origamizer software package served as springboards for understanding the complexities of deconstructing three-dimensional surfaces. *Programmable Auxetics* developed Resch's cut pattern (1977), introducing gaps rather than folds to alleviate the geometrical constraints of origami. Both *Programmable Auxetics* and kirigami utilize similar methods, involving programming cuts in flat material to achieve double-curved forms; these holes, which geometrically remove material, were translated to the manner in which smocking gathers fabric. While BFF's conformal mapping software was explored during the initial stages of the research conducted in this thesis, the process of generating flat meshes from input shapes in the *OriNuno* tool was simplified to Grasshopper and Kangaroo 2 components.

4.2.4 Simulation and Correlation

Recent advances in computational tools allow designers to integrate and simulate materiality during the early stages of the design process (Tamke et al., 2012). The dearth of analytical models for flexible formwork significantly contributes

1



2

FIGURE 4.16: (1) Comparison of *Dermoid* FEA model with scan, CITA (Thomsen & Tamke, 2015).
(2) *Fatty Shell* comparison of digital model and fabricated form (D. Veenendaal & Block, 2012).

to industry's reticence to use such techniques (Veenendaal, Coenders, et al., 2011). By developing the integration of material workflows and digital tools within casting fabrication processes, it is possible to address industry's reluctance relating to concrete formwork innovation.

As Winsberg notes: "A simulation is any system that is believed, or hoped, to have dynamical behavior that is similar enough to some other system such that the former can be studied to learn about the latter" (2019 Section 1.3). Simulation can be used to predict future behavior and to ask the 'what if?' questions. Through simulation, one may infer some new knowledge about the system being simulated based on existing theory. The value of simulation is not to know more about something that already exists in the world but to know more about something that *could* exist (Nicholas, 2016).

Ramsgaard Thomsen and Tamke argue that material testing and physical experiments must be developed simultaneously with digital models (2016). Data from experiments is used to inform digital tools; in turn, digital models develop an understanding of material behaviors to generate structures not achievable by physical prototypes. A comparison between a finite element analysis (FEA) and laser scan of the final structure of CITA's *Dermoid* installation is shown in **FIGURE 4.16 (1)**. A reflection of the simulation's *verification* (mathematical exactness of the model) and *validation* (model appropriateness; Winsberg, 2010) is important in order to establish legitimacy.

Due to the complexities of simulating flexible formwork, most state-of-the-art research in this field is missing the link to simulation and correlation. Hydrostatic pressures, the rheology of concrete, the elasticity of the fabric and gravity are complex interconnected forces that are difficult to simulate as a group of intertwined variables. Existing methods of computing flexible formwork include the dynamic relaxation method (Barnes, 1994; Lewis & Lewis, 1996 used by Tysmans et al., 2011; Veenendaal, 2017) and the force density method (De Laet et al., 2010; Van Mele & Block, 2011).

West recognizes that fabric forming results in unpredictable forms which are often difficult to simulate accurately. He focuses instead on formwork end connections (or wherever the cast element will meet another architectural element) and allows the fabric areas between to form-find (West et al., 2016). Pedreschi, as previously discussed, prioritizes material intuition over digital simulations in his Disruptive Technologies studio. The *FattyShell* project (**FIGURE 4.16 (2)**) used three-dimensional modeling to visualize the spatial qualities of concrete forms cast in fabric (Warmann, 2010b). However, this model is a low-resolution, minimal surface mesh constructed for the purpose of unrolling the fabric pattern in Pepakura; these modeling techniques do not go so far as to simulate the casting process and are therefore only a general approximation of the cast form.

Using simulation and correlation as design methods, the research presented in this thesis aimed to formalize the tacit knowledge of materiality in order to produce forms that directly correlate to their simulated counterparts. Digital tools, in addition to verifying experiments, enabled rapid design prototyping and the production of digital information used during the process of externalization (as discussed in **SECTION 2.2.3**). The introduction of simulation within flexible formwork casting processes allowed for material behavior and rheological forces to be united without compromising predictability and repeatability. This combination of fabric, parametric patterning, simulation and correlation opened new avenues of design and the possibility to think outside the (fabric formwork) box.

05. DESIGN RESEARCH DEVELOPMENT

This chapter is organized into three sections, each corresponding to a particular research question. The 'Material' section focuses on the interaction between smocked fabric formwork and cast concrete. While some flat patterns were digitally manipulated, this section does not focus on pattern development but on the production of tacit material knowledge. The 'Geometrical' section describes the computational development of classic two-dimensional smocking patterns and investigation of the potential applications of this parameterization. An additional research question was formulated during this phase regarding the generation of smocking patterns from three-dimensional input shapes. Finally, the 'Digital' section focuses on aspects of the simulation of and correlation between flexible formworks and their cast counterparts relating to the experiments conducted during this research. These simulations included horizontally and vertically cast concrete as well as parametrically tailored concrete fabric. The sections and research questions are restated as follows:

- **Material:** Casting in Smocked Fabric
    - How can fabric formwork be re-envisioned using smocking to create novel concrete-casting techniques?
- **Geometrical:** Computational Patterning
    - How can smocking be parameterized and differentiated to articulate new methods of fabricating architectural elements?
        - How does one take a three-dimensional input surface and construct a two-dimensional smocking pattern which accurately approximates the input form when sewn?
- **Digital:** Simulation and Correlation
    - What are the possibilities and limitations of simulating flexible formworks and correlating them with cast counterparts?


WORKPLACE

MATERIAL:

CASTING IN SMOCKING

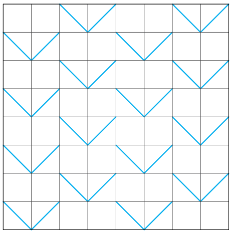
5.1 Material: Casting in Smocked Fabric

5.1.1 The *First Fifteen Hand-Smocked Probes*

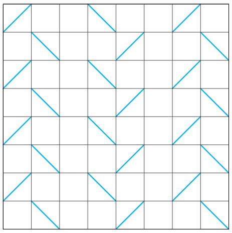
In the realm of flexible formwork and cast concrete, computationally generated non-standard forms typically result in impractical tailoring of multi-component formwork. The utilization of smocking introduces an alternative method for the shape manipulation of flexible membranes without the need to cut numerous individual components. By decreasing the complexity of fabrication without compromising form, the potential of smocked formwork was deemed worthy of investigation. The relationship between cast concrete and smocked fabric was of particular interest, raising questions regarding how individual patterns would respond to hydrostatic pressures.

During the initial stages of research, the *First Fifteen Hand-Smocked Probes* were developed. The patterns selected are available online from various sources (Edwin, 2020; Shore, 2013; The Sewing Directory, 2020) and are cataloged in **FIGURE 5.2**. An off-the-shelf jersey cotton knit fabric was used for these initial fabric formwork experiments. This highly elastic fabric (92% organic cotton and 8% spandex) was selected to investigate the contrast between the inelastic smocking tucks and the flexible space between them. A 35 x 35 mm grid was applied to an A3 sheet of fabric; the pattern was marked with a felt-tip pen and sewn together by hand (as in **FIGURE 4.5**). Earlier probes with smaller grids produced thin concrete elements that proved brittle upon removal of the fabric. The experiments with this grid size were intended to test the level of detail achievable with casting in fabric. The smocked fabric was stapled to a horizontal wood frame (**FIGURE 5.1**) and a semi-self-compacting concrete mix

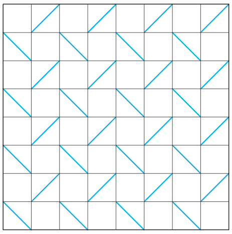
FIGURE 5.1: *First Fifteen Hand-Smocked Probes* casting setup (Source: author).



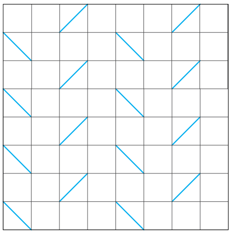
ARROW



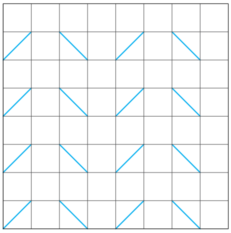
LEAF



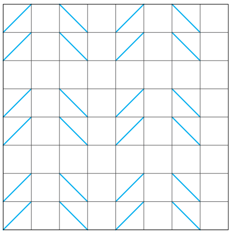
BASKET WEAVE



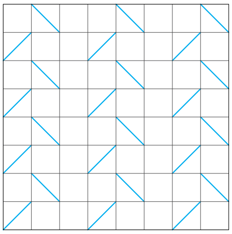
CRISS CROSS BONES



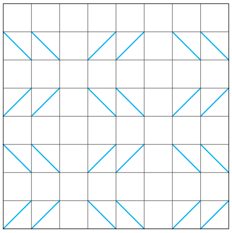
ZIG ZAG



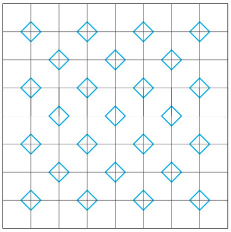
HEARTS



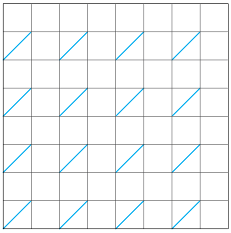
BRAID



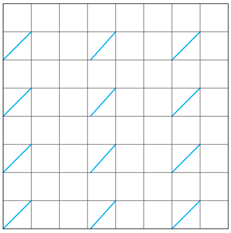
4 POINT STAR



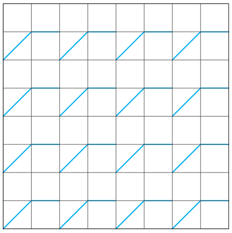
QUILTED DIAMONDS



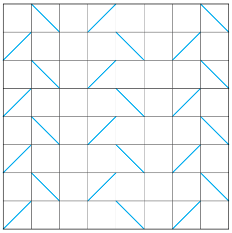
BONES



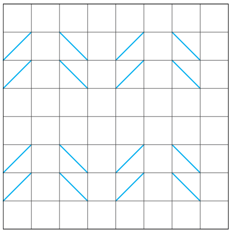
WAVES



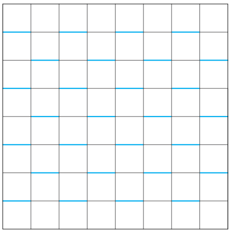
FISH SCALES



SHELL



DOUBLE ARROWS



LOZENGE

FIGURE 5.2: Existing smocking patterns tested in *First Fifteen Hand-Smocked Probes* (Source: author).

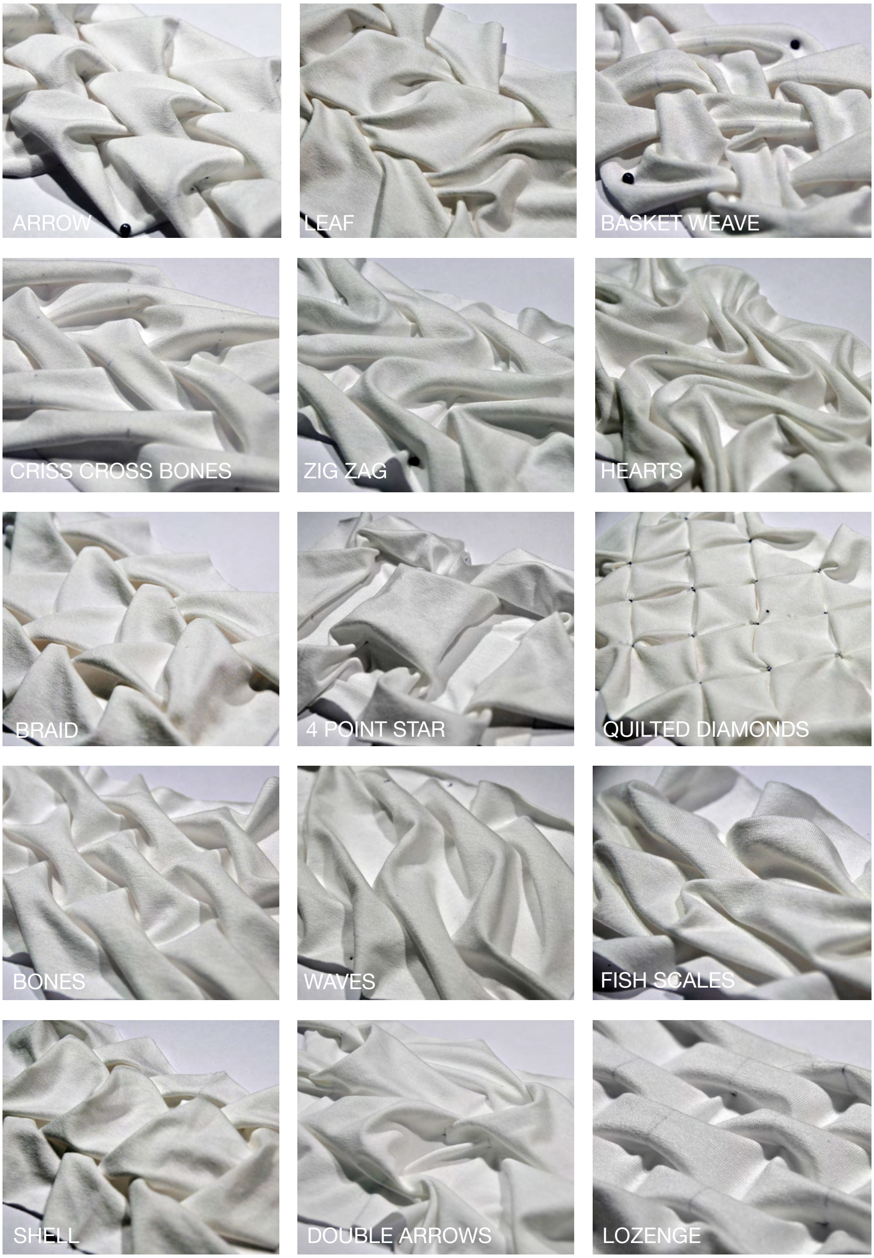


FIGURE 5.3: *First Fifteen Hand-Smocked Probes* sewn textile (Source: author).

FIGURE 5.4: *First Fifteen Hand-Smocked Probes* casts (Source: author).

FIGURE 5.5: *First Fifteen Hand-Smocked Probes* (Source: author).

(discussed in the next section) was poured to fill the formwork. The cast probes are exhibited in **FIGURE 5.4** and **FIGURE 5.5**.

There were no preconceived notions of the final cast shape or attempts to simulate the outcome at the outset; the probes were conducted in a purely ‘wandering’ manner of trial and error. While the author was familiar with origami and kirigami folding patterns from previous work, no known precedents of combining smocked formwork and cast concrete existed to inform a more specific hypothesis. By understanding how to ‘read’ flat smocking patterns and visualize their final form before assembly, these initial probes provided a ’catalog’ of various textile patterns and began to formulate a tacit material knowledge base. Each pattern comprised horizontal, vertical and diagonal grid lines, and the variation in terms of combinations and relative placement significantly changed the outcomes:

- Single-dimension patterns (e.g., ‘Lozenge’) reduced the fabric size in only one direction while diagonal smocking patterns (e.g., ‘Basket-Weave’ pattern) reduced the fabric size in two dimensions (**FIGURE 5.6**).
- Patterns with relatively closely spaced smocks (e.g., ‘Arrow’, ‘Fish Scales’) produced varied tucks and folds.
- Patterns with relatively wide spacing or many blank grid squares (‘4-Point Star’, ‘Waves’) did not result in easily discernible details; the fabric was quite elastic, and the un-smocked fabric's stretching obscured most details.
- The ‘Quilted Diamond’ pattern (a smocking pattern with an even number of vertices to gather) was not viable when combined with cast concrete, as the smocking pattern isolated sections of fabric and did not allow concrete to flow into the fabric tucks.

Executing these probes without a predetermined end goal was both rewarding and intriguing from a material perspective. In addition to producing visually compelling forms, the probes resulted in a clearer understanding of the relationship between the weight, rheology and hydrostatic pressures of concrete cast using flexible formwork. While the research conducted in this thesis acknowledges that these experiments produce certain aesthetics, this aspect is not the primary focus as this research chooses to instead concentrate on the technical implications of casting in smocking.

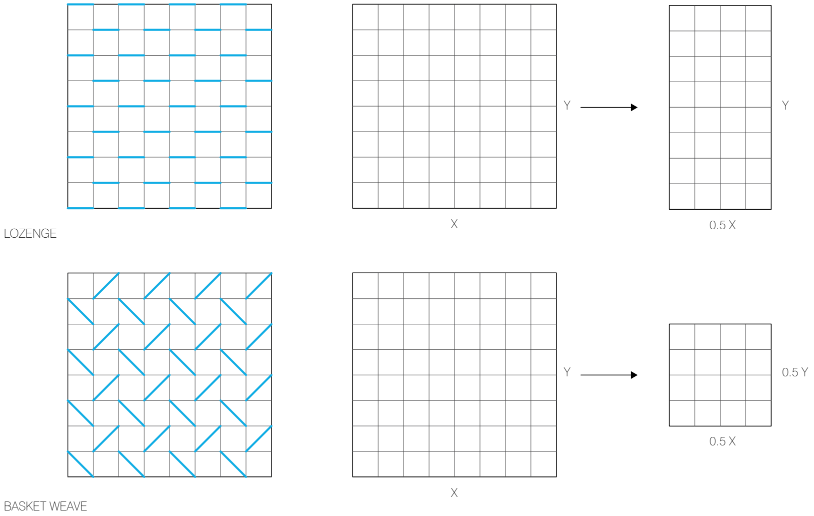


FIGURE 5.6: Diagram of pre- and post-smocked fabric size difference dependent on smocking orientation (Source: author).

5.1.2 Concrete Mixture Development

The mix of semi-self-compacting concrete (semi-SCC) utilized in the research presented in this thesis was developed as part of a larger research project conducted by the Swedish Cement and Concrete Research Institute (CBI) at KTH (**FIGURE 5.7**). This type of mixture allows for high fluidity without the need for additional water. SCCs, when compared to conventional mixes, are characterized by:

- Extreme fluidity.
- Comparable durability and material behavior to conventional mixes.
- Consistent performance irrespective of casting distance.
- High-quality surface finish (no bleed water or aggregate segregation, self-leveling).
- Improved working environment (no need for noisy vibrators to

compact the concrete).

- Sustainable casts (reduced use of by-products and need for repairs).

Initially conceptualized in Japan in the 1980s (Ouchi, 1999; Ozawa et al., 1992), SCC development quickly reached European countries such as Sweden (Billberg, 1999) and France (AFGC, 2000) in the 1990s, as well as North America (American Concrete Institute, 2007; Precast/Prestressed Concrete Institute, 2003). While initially regarded with hesitation due to its novelty, SCC has proven to be advantageous in a wide variety of areas, and currently comprises 2.4% of European concrete production (European Ready Mixed Concrete Organization, 2018). Given the recent market interest in reducing the environmental footprint of products and services, the compound annual growth rate (CAGR) of the market for SCC is expected to be 3.5% for the period 2021–2027 (The Express Wire, 2021).

The SCC mix developed by CBI differs from typical concrete mixes due to the inclusion of additional ingredients such as superplasticizer (SP) and viscosity-modifying agent (VMA) admixtures, as well as limestone (L40). SPs (in this case MasterGlenium® 51) enable high fluidity and workability of the mix while reducing the water content by up to 40% (Master Builders Solutions, 2015). The SP amount can be calibrated during mixing to adjust to the specific rheological needs of a particular cast. The VMA is added to increase plastic viscosity and limit segregation of aggregates (much like starch in gravy; Leemann & Winnefeld, 2007). L40, a readily available and inexpensive material in Sweden, was included to raise the quality of the mix and combat potential mixture separation caused by the SP. Finally, an aggregate diameter of 0–4 mm was specified to ensure a high-quality surface finish of the cast.

The mix outlined in the previous paragraph balanced a reasonable, workable consistency with high curing strength. The combination was beneficial when pouring was conducted in reinforcement areas with limited space, and was particularly suited to the small smocking details of fabric formwork experiments. Deferring to the expert recommendation of CBI, the author did not investigate alternate mixes (a topic that could be another PhD in itself). Minor adjustments to the amount of SP and VMA were made ad hoc and on-site for fluidity.

Self-Compacting Concrete (SCC) Mix

	Mass (kg)	**Parts**
Cement	0.330	1
Sand (0-4mm)	0.417	1.26
L40	0.175	0.53
VMA	0.00625	0.02
Water	0.148	0.45
SP: MasterGelenium® 51	0.003125	0.01
Total	~1kg	
Water: Cement ratio	0.45	

L40 (Limestone): Increases workability of the mix and keeps the sand and cement from separating. Also minimizes shrinkage cracking

VMA: Viscosity Modifying Admixture: Reduces the slump of concrete and prevents segregation of aggregates in mixes

Superplasticizer MasterGlenium® : High range water reducer; increases the workability and flow of the mix without the addition of more water

FIGURE 5.7: Concrete mixture ratio and slump tests (Source: author).

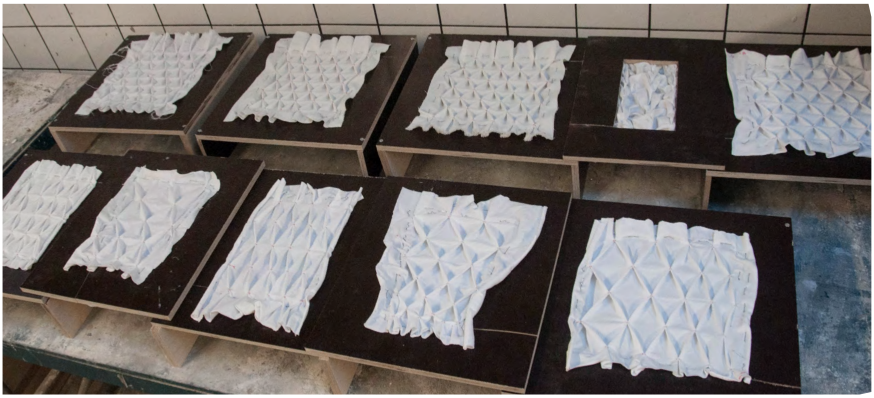


FIGURE 5.8: *Skewed Grids* casting setup (Source: author).

5.1.3 Casting in Skewed Smocking Grids

After familiarity with existing smocking patterns and their underlying logic had been obtained, the 'Lozenge' and 'Arrow' patterns were selected for further testing with skewed grids.[15] After isolating these variables, the next series of probes centered on basic pattern grid manipulation. At this stage in the research, little to no digital tools were used; the methodological approach remained 'wandering' and strictly 'hands-on.' With no available research of casting in smocking to learn from, a base amount of tacit material knowledge had to be acquired before formulating more specific research questions.

The square grid was skewed intuitively, varying the grid size and thus manipulating both smock length and spacing. Similar to the *First Fifteen Hand-Smocked Probes*, these patterns were hand-sewn and attached to rectangular wood frames (**FIGURE 5.8**). The 'Lozenge' (**FIGURE 5.9**) and 'Arrow' (**FIGURE 5.10**) *Skewed Grids* are represented next to their corresponding smock grid diagram and sewing pattern. Unfortunately, due to the amount of concrete used and the high elasticity of the jersey cotton fabric, the subtle variations in each of the smocking patterns were not as readable as anticipated. The details of the 'Arrow' pattern probes were slightly more readable due to the fact that pinching

---

[15] These two smock types are the simplest components of smocking patterns. 'Lozenge' and 'Arrow' smocks are made by gathering two or three points of fabric, respectively. As discovered during the creation of the *First Fifteen Hand-Smocked Probes*, other existing pattern bases are more complex in terms of either varying or combining these two base elements.

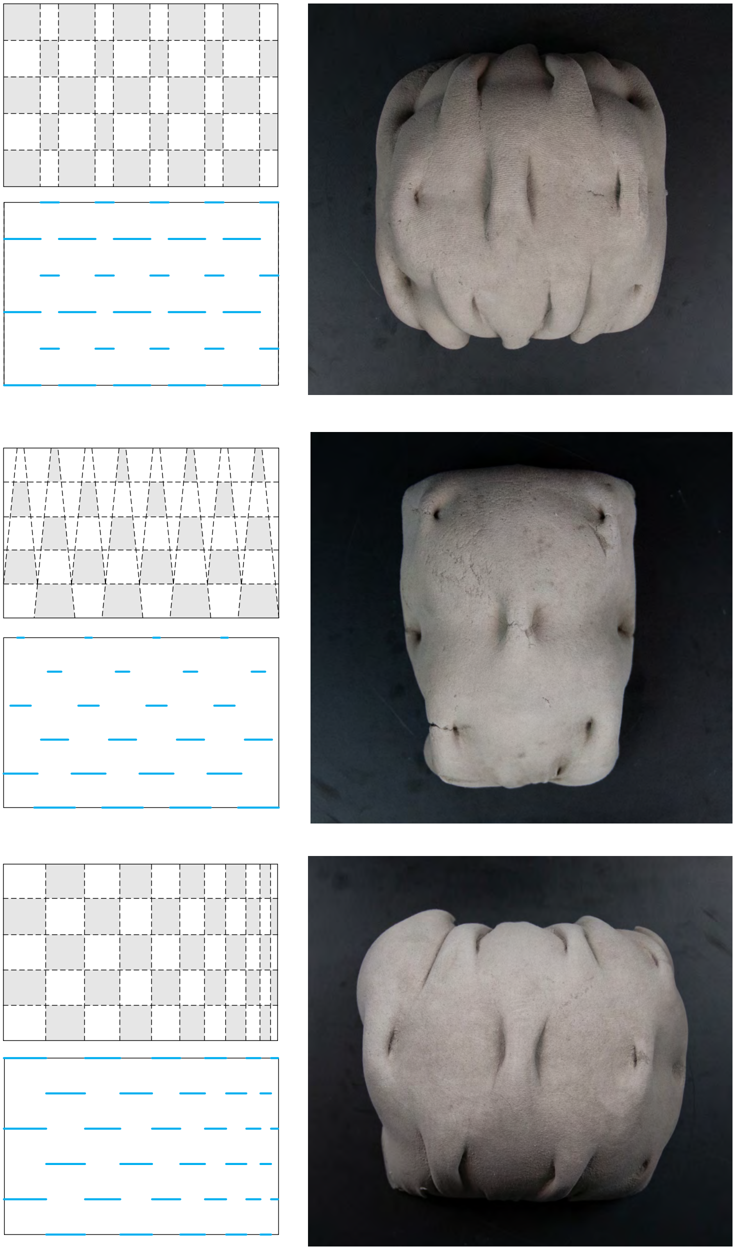


FIGURE 5.9: *Skewed Grids*: smocking grid alternately shaded to visualize grid manipulation, resulting ‘Lozenge’ pattern and cast probes (Source: author).

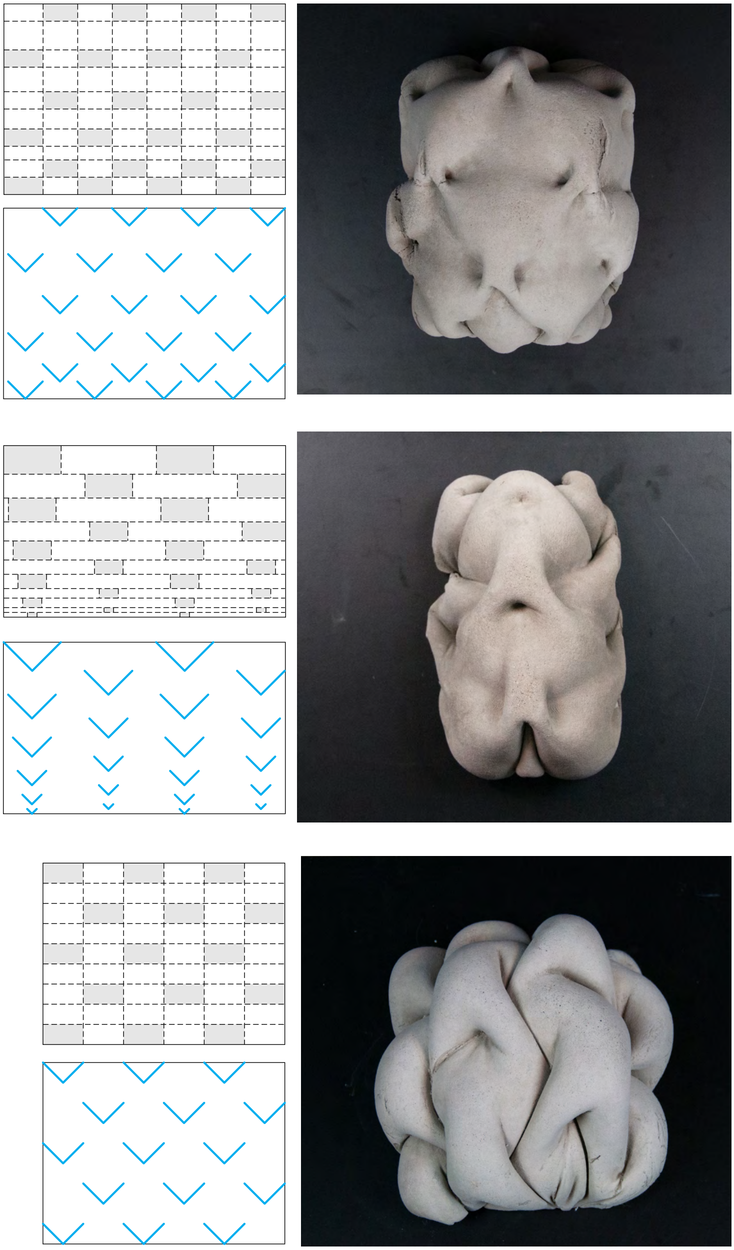


FIGURE 5.10: *Skewed Grids*: smocking grid alternately shaded to visualize grid manipulation, resulting 'Arrow' pattern and cast probes (Source: author).

fabric in two dimensions inherently minimizes stretch more than doing so in one dimension. Although the results of these casts were not as intuitively anticipated, these probes furthered the understanding of skewed smocking grids and their relationship to the weight of concrete. Subsequent probes explored the idea of improving pattern legibility by anchoring each smock to the casting plane; this small change isolated fabric stretching locally (between smocks) rather than globally (general ballooning of the entire probe).

5.1.4 Fabric Selection

In response to the undesirable ballooning of the *Skewed Grids* probes, the next series of probes focused on investigating a wider range of fabrics. These probes sought to ascertain what level of elasticity functioned best when used in conjunction with smock details and cast concrete. Up to this point, all casts had been fabricated in a highly elastic jersey cotton fabric. While this fabric choice was more successful for smaller probes, it was not suitable when casting larger amounts of material due to its high elasticity. A uniform 35-mm 'Lozenge' smocking grid was used to limit the number of variables for this probe. This pattern was applied to three types of fabric (**FIGURE 5.11**):

- High elasticity (organic cotton: 92%, spandex: 8%).
- Moderate elasticity (polyester: 62%, viscose: 32%, spandex: 6%).
- No stretch (polyester: 100%).

The highly elastic jersey cotton was quite successful; the closely spaced smocks of the fabric kept the form from filling with too much concrete (resulting in an amorphous blob) yet was elastic enough for the fabric to be easily removed from the cast form. The other two fabric probes cracked due to a combination of too little drying time before fabric removal and the high stiffness of the fabric, which resulted in a relatively high amount of force to remove the formwork. Generally, there is a trade-off to fabric elasticity: a more elastic textile, while easier to remove, is not typically strong enough to resist hydrostatic pressures and tearing. Thus, this type of fabric is ideal for casts that are small in size or highly detailed. Larger casts typically use a less elastic geotextile as formwork; while this is not as easily removed, it is workable and sturdy enough to retain integrity during casting. Consequently, fabric selection was closely related to the size of the cast and the smocking pattern arrangement.

high elasticity: organic cotton(92%), spandex(8%)

moderate elasticity: polyester(62%), viscose(32%), spandex(6%)

no stretch: polyester(100%)

FIGURE 5.11: 'Lozenge' smock pattern applied to fabric of various elasticities and resulting casts (Source: author).

5.1.5 *Column 01*

The first columns were cast horizontally, with the smocks perpendicular to gravity. Probes with closely spaced smocks resulted in minimal global stretching and more articulation between fabric pinches. This inspired a hypothesis that smock placement could be used in areas where stretching is less desirable in order to e.g. offset hydrostatic bulging. Before exploring more complex patterns and vertical casting, a simple 'Lozenge' pattern formwork was fabricated as a 'control' to accumulate further tacit material knowledge. A 5 x 5 cm grid was hand-marked with a pen and indicated the direction in which the smocking points were to be fastened in relation to the front and back of the textile (see **FIGURE 5.12**). The desired dimensions of the fabric after smocking were 30 x 35 cm, and as shown in **FIGURE 5.6**, the horizontal modules of the 'Lozenge' pattern caused dimension change on the X-axis but none on the Y-axis, and thus the fabric width was doubled to accommodate the dimensional change after smocking.

Column 01 had several failures, yet yielded valuable insights. Foremost, the smocking connections (industrial sewing thread) proved to be more robust than the fabric itself which tore during pouring. In response to this and in order to reduce the risk of further tearing, no additional concrete was poured into the formwork; the final height of this cast column was 23 cm rather than the planned 35 cm. Secondly, regarding the lower section detail of the column, the variable edge conditions were not easily readable as they were largely obstructed by the bulging of the fabric under hydrostatic pressure. This probe was an instrumental first step in gaining tactile knowledge of vertically-cast flexible formwork, and the lessons learned were carried into further probes.

5.1.6 *Column 02*

Based on the knowledge gained as a result of undertaking the previous castings, the second column was made with a thicker jersey cotton fabric. The smocking stitches (attached with industrial thread) were anchored to a carbon-fiber grid frame with zip ties. As it had been established that the number of variables was too great in the *Column 01* experiment, the top and bottom sections of *Column 02* were designed according to a simplified, circular profile. A 35-mm 'Arrow'

FIGURE 5.12: *Column 01* (1) pattern marking, (2) sewing, (3) formwork, (4) base detail, (5) cast column and (6) surface finish detail (Source: author).

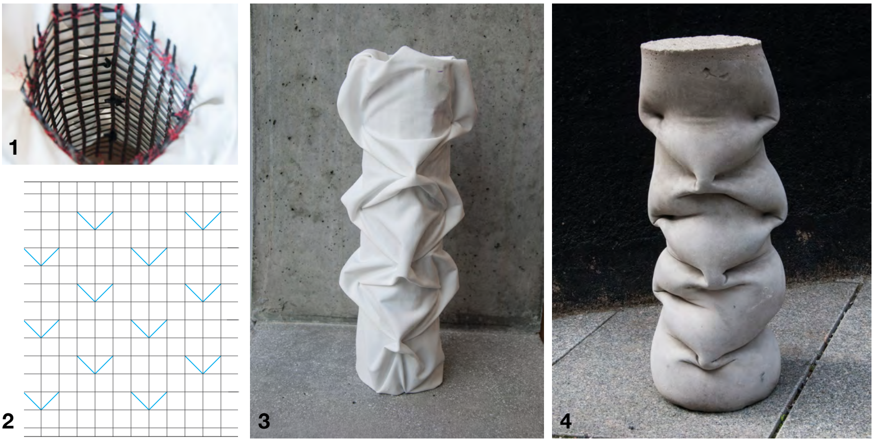


FIGURE 5.13: *Column 02*: (1) carbon fiber substructure to anchor smocks, (2) smock pattern, (3) formwork, and (4) cast probe (Source: author).

pattern[16] was selected to investigate the potential of smocking on both the X and Y axes in relation to vertical casting. Based on the geometry of the pattern (similar to **FIGURE 5.6**), it was possible to calculate the precise coordinates of the stitch locations and subsequently their anchor points on the carbon-fiber substructure (**FIGURE 5.13**). These locations correlated with the anchor points in the digital simulation, and were crucial to maintaining the global geometry of the column when subjected to hydrostatic pressures. The carbon fiber grid was a success and can be seen as a precursor to the metal reinforcement bars in the larger cast probes.

Column 02 highlighted the applications of a gridded substructure to anchor the smocking connections and maintain control over the global hydrostatic pressures of the column. While it was possible to fabricate *Column 02* using a 35-mm smocking pattern, a larger smocking module would have allowed the concrete mix to flow more easily into the details of the smocks. When coupled with a highly elastic material, the 'Arrow' pattern is not ideal for vertically cast elements, as the results tend to 'sag' in an unappealing manner. This experiment later led to further exploration of alternative textiles, a larger smocking grid, variation in the top and bottom section details and additional fabric types.

---

[16] This is roughly the minimum smocking size possible with this specific fabric and concrete mix combination (without causing cracking upon formwork removal), as determined through testing.

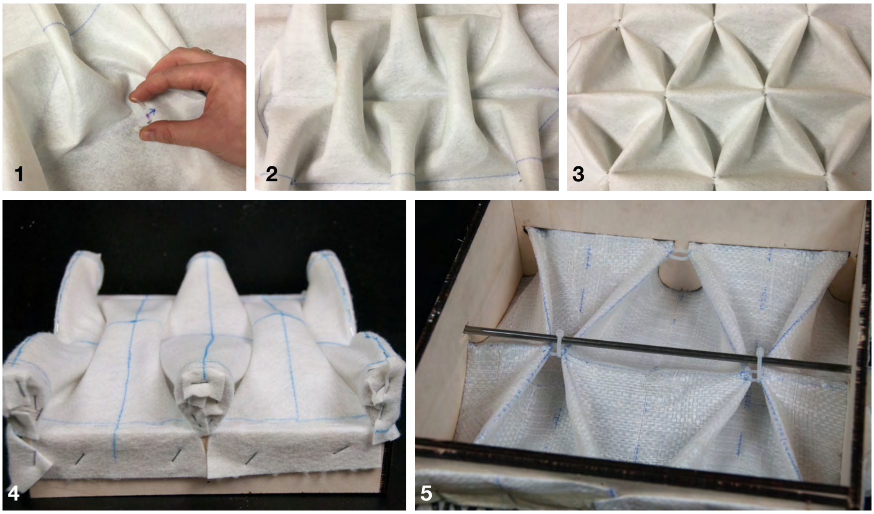


FIGURE 5.14: *Lozenge Panels* (1) smocking process, (2) front, (3) back, (4) formwork and (5) smocking anchor reinforcement (Source: author).

5.1.7 *Lozenge Panels*

Two large-scale *Lozenge Panels* (**FIGURE 5.16**) were produced with two aims in mind: to revisit past probe failures and integrate the accumulated knowledge, and to begin thinking about the larger-scale implications of smocking and concrete. With this in mind, the smocking pattern size, physical smocking connections and fabric selection were modified to reflect this.

Learning From Mistakes. Upon completing the *Skewed Grids* probes, the ballooning of the highly elastic fabric overwhelmed the global form so that local variation between smocks was not readable. The smocking points in the *Lozenge Panels* were anchored to a metal reinforcing bar to compensate for this ballooning (**FIGURE 5.14 (5)**). The *Column 01* probe successfully highlighted the edge conditions of the smocked formwork, the details of which were obscured due to the high hydrostatic pressure (**FIGURE 5.12 (4-5)**). The *Lozenge Panels* prototypes revisited this issue by including a wood cross-section to improve stability around the edges so as to retain the readability of the smocking details throughout the casting process.

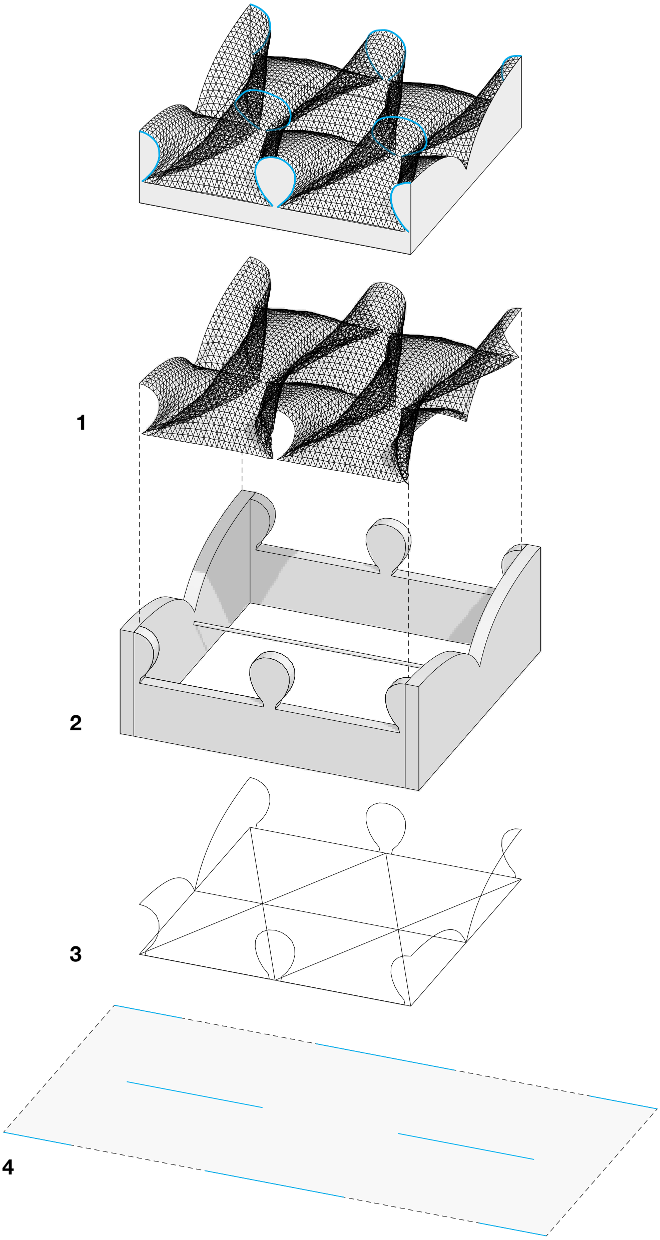


FIGURE 5.15: Axonometric diagram of *Lozenge Panels* (1) fabric formwork, (2) wood frame and smocking anchor, (3) simulation anchor points and (4) flat pattern (Source: author).

FIGURE 5.16: Cast *Lozenge Panels*. Left and right are felt and tarpaulin, respectively (Source: author).

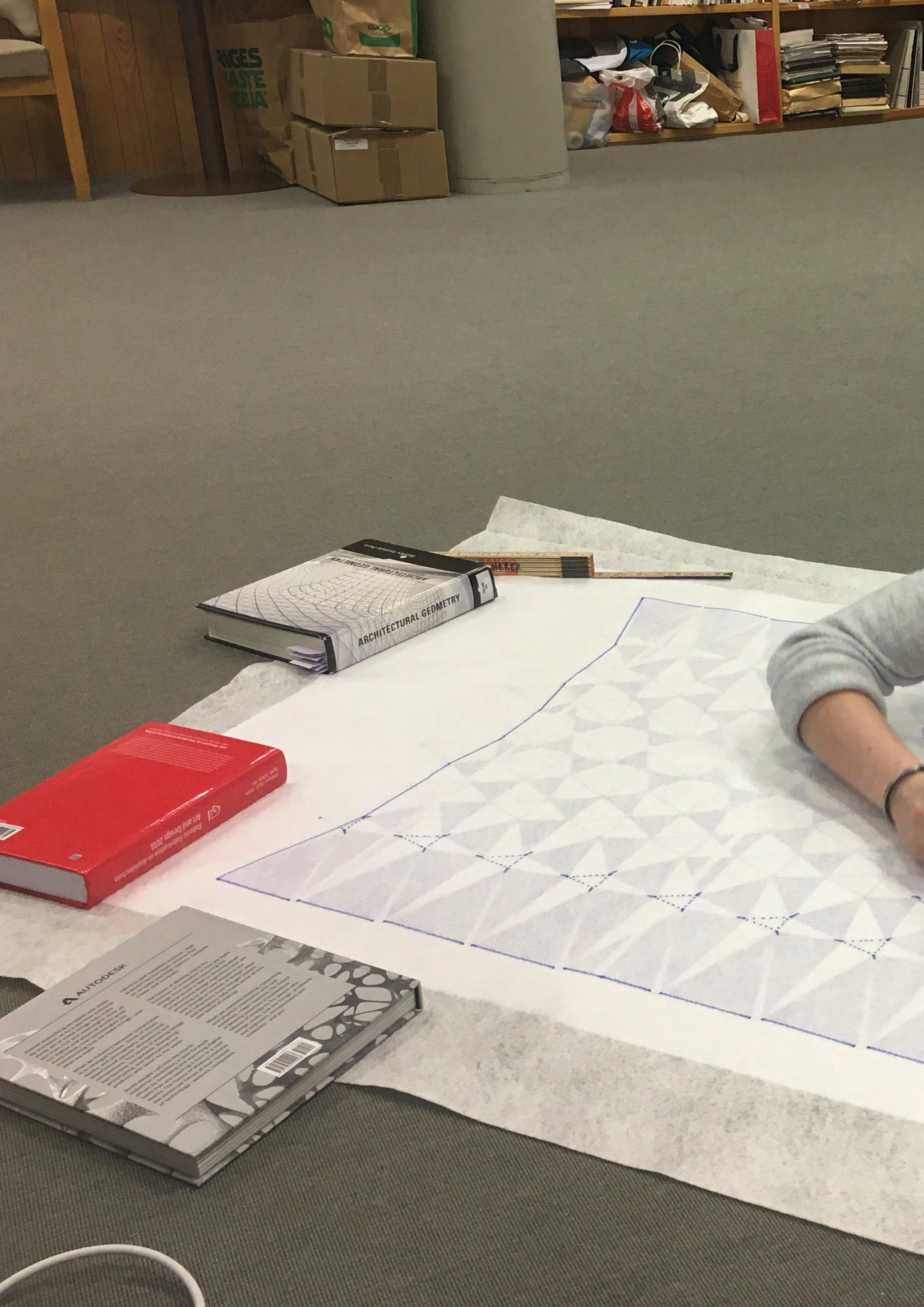
Thinking bigger. Tarpaulin and felt were selected based on the two fabrics' high inelasticity and sturdiness. Tarpaulin is a relatively common woven material, and felt was chosen to investigate the effects of matted materials (those that are neither knitted nor woven) on the casting. These adjustments addressed the ripped formwork of the *Column 01* probe and the ballooning of the *Skewed Grids* probes. *Lozenge Panels* used a smocking grid with 120-mm cells as this was the minimum detail achievable due to the stiffness of the fabric material. The industrial thread from previous probes was upgraded to large zip ties to test whether these would be appropriate connections when tailoring large-scale formwork. Two small slits, one above and one below the endpoints of the pattern, were laser-etched on the fabric to accommodate the modified zip-tie connection.

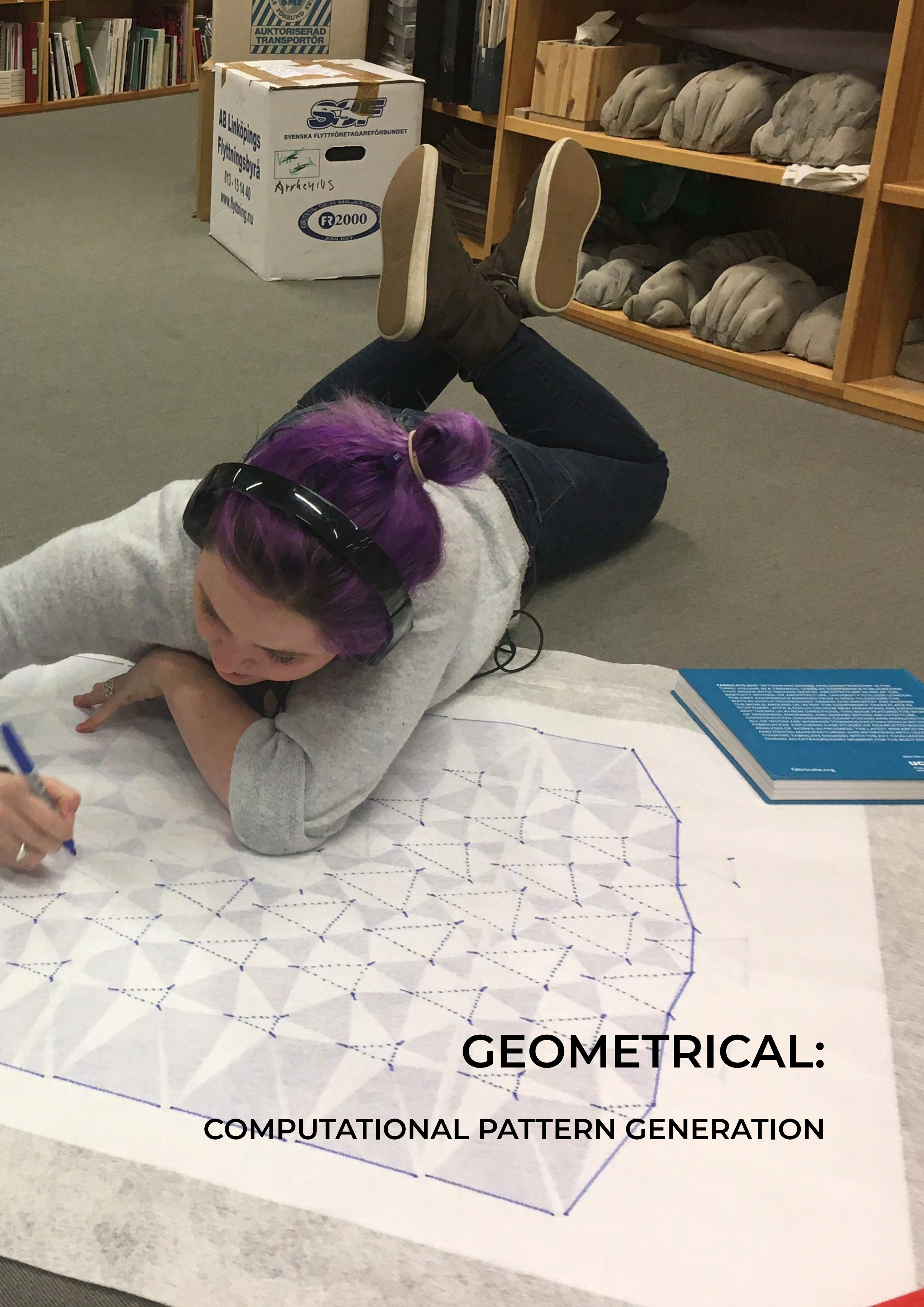
Reflections. The *Lozenge Panels* prototypes were quite successful in many respects, particularly regarding the fabric's strength and release properties. Both the felt and tarpaulin were strong enough to withstand the internal forces of the concrete without ripping. While coconut oil was applied as a form of release agent, its usage did not appear to be necessary when using materials such as tarpaulin, which is reasonably smooth and easily released from the cast concrete. While it did not have high elasticity, felt had a 'tooth,' which left a residue that would be very time-intensive to remove from larger prototypes; as a result, it was concluded that smoother materials such as tarpaulin were preferable for future experiments. The zip tie functioned as a 'full-scale' upgrade from the industrial thread and the assembly was quick; various sizes are commercially available, which suited the fabrication needs. The edges of the panels that highlighted the variable cross-sections of the smocks were appreciably more successful in this probe than those of *Column 01*. This experiment confirmed the possibility of a custom smock edge detail on a 1:1 scale; however, further investigation was required to fully realize the large-scale implications, and so this aspect was not explored further. Finally, the zip-tie anchoring of the smock points to the casting plane eliminated the problematic ballooning of the *Skewed Grids* casts. This subtle change allowed the fabric to stretch between the smock points (locally) without compromising the global, programmed shape.

5.1.8 Externalizing Material Knowledge Through Exhibitions

In an effort to address the communication and externalization of the process of making, the results of the experiments described in this thesis research were exhibited at Galleri Frihamnstorget in Stockholm, Sweden (see **'SELECTED**

WORKSHOPS & EXHIBITIONS'). The exhibition included physical probes of the research conducted in this thesis, documentation of the fabrication process, pattern-generation diagrams and videos of casting simulations. The exhibition included the permanent *Wall Three* installation (discussed in the **SECTION 5.2.4**) and presented a physical storyline of the cyclical and iterative process of craft-based experiments. The attendees had a wide range of backgrounds, including architects, engineers, academics and creatives from the nearby Blivande cultural center. Exhibitions such as this have a special role in terms of disseminating craft-based research outside of the field of architecture and design.

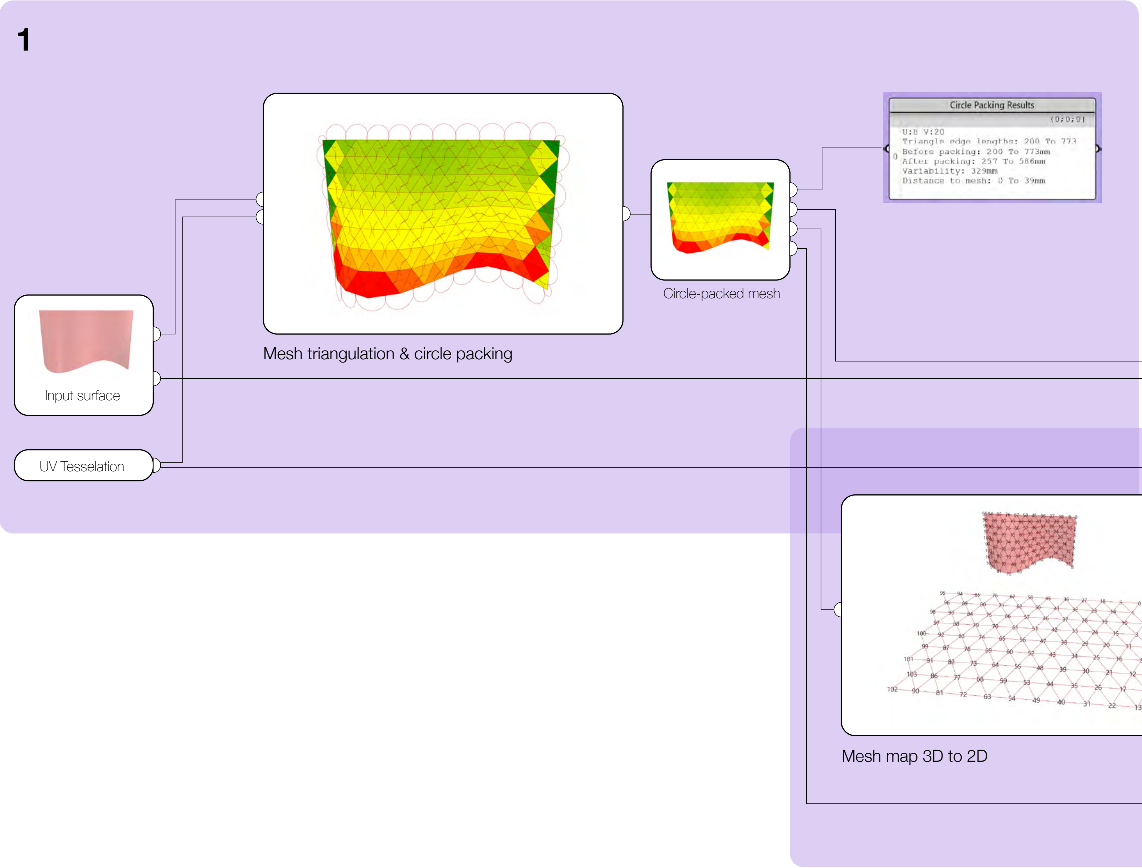

ARCHITECTURAL GEOMETRY
Robotic Fabrication in Architecture, Art and Design 2018
AUTODESK



GEOMETRICAL:

COMPUTATIONAL PATTERN GENERATION

Design

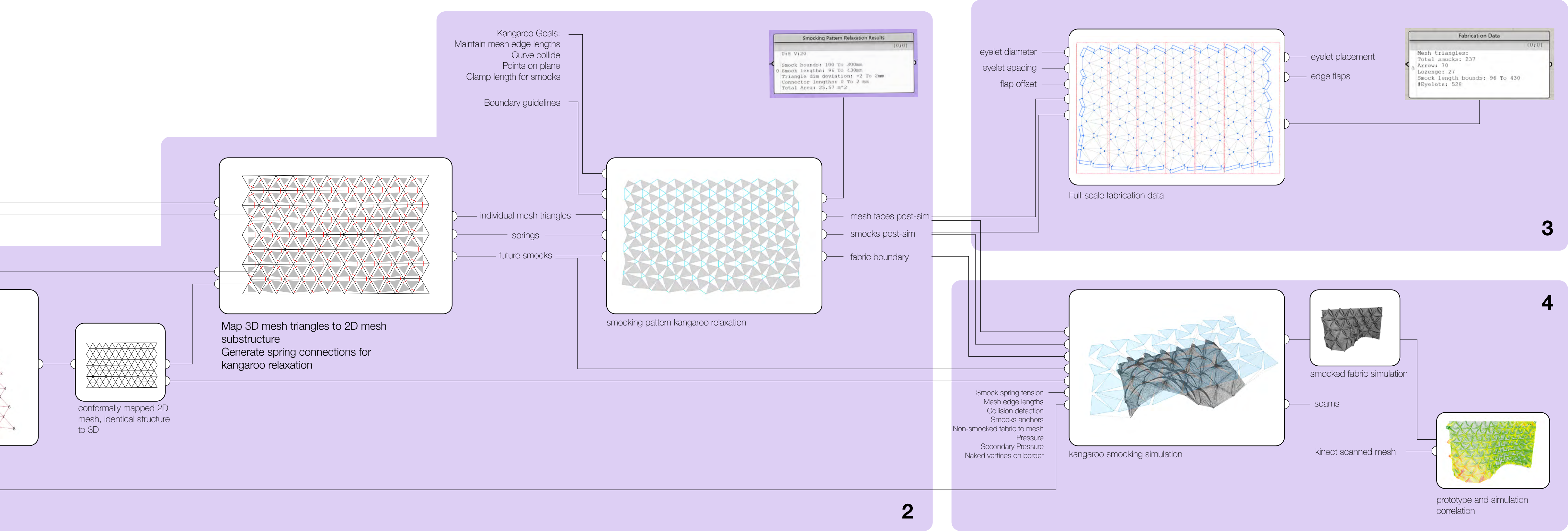


```
{0;0;0}
U:8 V:20
Triangle edge lengths: 200 To 773
Before packing: 200 To 773mm
After packing: 257 To 586mm
Variability: 329mm
Distance to mesh: 0 To 39mm
```

FIGURE 5.17: Diagrammatic representation of comprehensive scripting tool *OriNuno* with four 'groups': (1) design, (2) parametric pattern generation, (3) fabrication constraints, and (4) simulation and correlation (Source: author).

Pattern Generation

Fabrication Constraints



Smocking Pattern Relaxation Results

```
{0;0}
U:8 V:20

Smock bounds: 100 To 300mm
0 Smock lengths: 96 To 430mm
Triangle dim deviation: -2 To 2mm
Connector lengths: 0 To 2 mm
Total Area: 25.57 m^2
```

Fabrication Data

```
{0;0}
Mesh triangles:
Total smocks: 237
0 Arrow: 70
Lozenge: 27
Smock length bounds: 96 To 430
#Eyelots: 528
```

Map 3D mesh triangles to 2D mesh substructure
Generate spring connections for kangaroo relaxation

smocking pattern kangaroo relaxation

conformally mapped 2D mesh, identical structure to 3D

Full-scale fabrication data

smocked fabric simulation

kangaroo smocking simulation

prototype and simulation correlation

Simulation & Correlation

5.2 Geometrical: Computational Pattern Generation

During the course of the research presented in this thesis, a digital tool was developed using Grasshopper 3D and Kangaroo 2 (**FIGURE 5.17**). The name, *OriNuno*, comes from the Japanese words *ori* and *nuno*, meaning 'to fold' and 'cloth,' respectively. *OriNuno* contains four 'groupings' or sections of script, which each address the following 'groups': *design*, *smocking pattern generation*, *fabrication constraints* and *simulation and correlation* (**FIGURE 5.17 (1-4)**). The 'Geometrical' section of this chapter describes the development of the *smocking pattern generation* 'group' (**FIGURE 5.17 (2)**) of the *OriNuno* tool.

5.2.1 *Coded Pixels*: Translating Smocking Logic to Code

The first step in digitizing smocking patterns was to generate a pseudocode logic[17] of existing smocking patterns. Of the 15 patterns discussed in **SECTION 5.1.1**, 14 were more closely examined and deconstructed to generate a pseudocode logic and an interactive pattern-generation Grasshopper tool.[18] Each of the basic patterns was generated from a grid (regular tiles), allowing the repeating module to be identified. The patterns were tiled by translating each module without rotating or reflecting (also known as periodic tiling). The examined smocking patterns had various 'minimum grid size' requirements: these mandate the number of grid squares that must be grouped before being arrayed into a larger smocking pattern. These range from 1 x 1 grid ('Quilted Diamonds') to 6 x 4 grid ('4-Pointed Star').

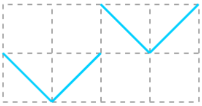
The smallest repeating module (labeled 'minimum grid size') was deconstructed into numbers (0, 1, 2), each of which denoted a corresponding smock orientation to fill the specified grid square (**FIGURE 5.18**). A tool was developed using Python and Human UI[19] in Grasshopper, where the user can select a smocking pattern from the available drop-down menu and set the X and Y extents of the pattern

---

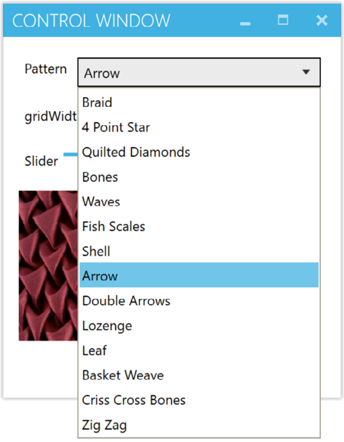
[17] In computer science, pseudocode is the informal 'translation' of an algorithm or programming language to plain language or diagrams; they are intended to be read by humans, rather than machines ("Pseudocode," 2021).

[18] Note that the 'Shell' and 'Leaf' patterns were later found to be identical, aside from a 180-degree difference in orientation and were thus consolidated.

[19] Human UI is a plugin for Grasshopper that facilitates the generation of custom user interfaces, developed by the Design Computation Leadership Team of the American architecture, planning and design firm NBBJ.



Minimum Grid Size: 4 x 2



Pattern Arrow

0	0	2	1	0	0	2	1	0	0	2	1
2	1	0	0	2	1	0	0	2	1	0	0
0	0	2	1	0	0	2	1	0	0	2	1
2	1	0	0	2	1	0	0	2	1	0	0
0	0	2	1	0	0	2	1	0	0	2	1
2	1	0	0	2	1	0	0	2	1	0	0
0	0	2	1	0	0	2	1	0	0	2	1
2	1	0	0	2	1	0	0	2	1	0	0

Pattern: Arrow
Mapped Grid Size:12 x 8

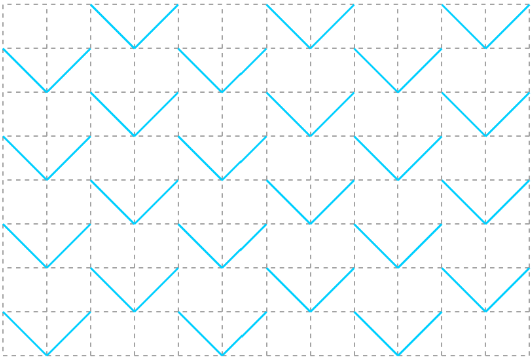
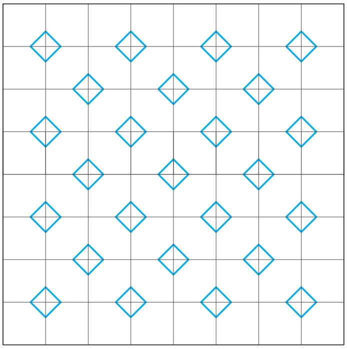
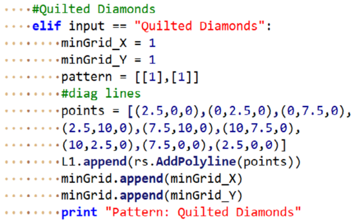


FIGURE 5.18: *Coded Pixels:* Human UI interface and sample smocking pattern generated with Python (Source: author).

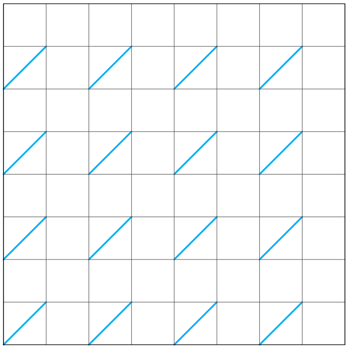


Quilted Diamonds

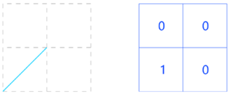
Pattern: Quilted Diamonds
Minimum Grid Size: 1 x 1



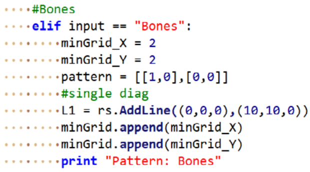
```
    #Quilted Diamonds
    elif input == "Quilted Diamonds":
        minGrid_X = 1
        minGrid_Y = 1
        pattern = [[1],[1]]
        #diag lines
        points = [(2.5,0,0),(0,2.5,0),(0,7.5,0),
        (2.5,10,0),(7.5,10,0),(10,7.5,0),
        (10,2.5,0),(7.5,0,0),(2.5,0,0)]
        L1.append(rs.AddPolyline(points))
        minGrid.append(minGrid_X)
        minGrid.append(minGrid_Y)
        print "Pattern: Quilted Diamonds"
```



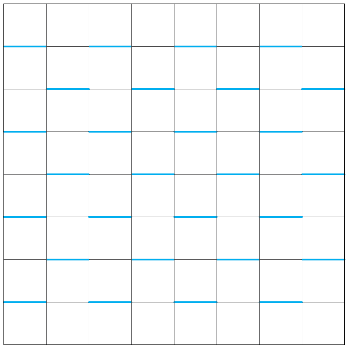
Bones



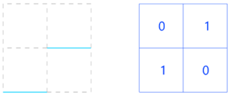
Pattern: Bones
Minimum Grid Size: 2 x 2



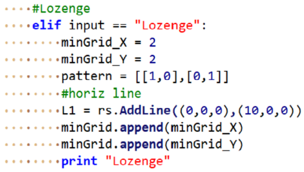
```
    #Bones
    elif input == "Bones":
        minGrid_X = 2
        minGrid_Y = 2
        pattern = [[1,0],[0,0]]
        #single diag
        L1 = rs.AddLine((0,0,0),(10,10,0))
        minGrid.append(minGrid_X)
        minGrid.append(minGrid_Y)
        print "Pattern: Bones"
```



Lozenge

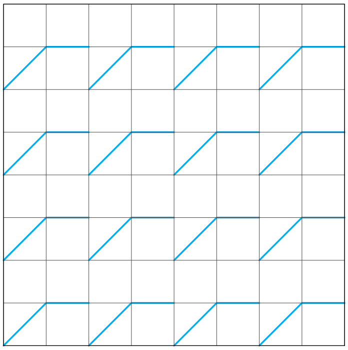


Pattern: Lozenge
Minimum Grid Size: 2 x 2

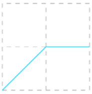


```
    #Lozenge
    elif input == "Lozenge":
        minGrid_X = 2
        minGrid_Y = 2
        pattern = [[1,0],[0,1]]
        #horiz line
        L1 = rs.AddLine((0,0,0),(10,0,0))
        minGrid.append(minGrid_X)
        minGrid.append(minGrid_Y)
        print "Lozenge"
```

FIGURE 5.19: *Coded Pixels:* Various smocking patterns and their Python smocking script code (Source: author).

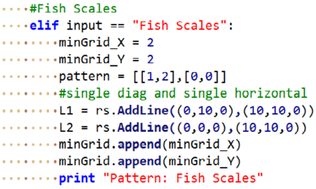


Fish Scales

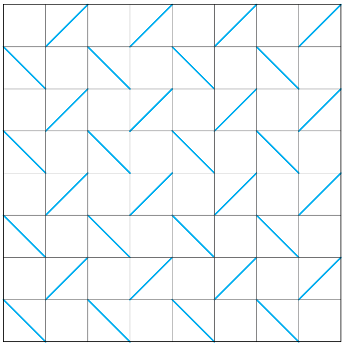


0	0
1	2

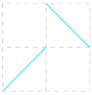
Pattern: Fish Scales
Minimum Grid Size: 2 x 2



```
    #Fish Scales
    elif input == "Fish Scales":
        minGrid_X = 2
        minGrid_Y = 2
        pattern = [[1,2],[0,0]]
        #single diag and single horizontal
        L1 = rs.AddLine((0,10,0),(10,10,0))
        L2 = rs.AddLine((0,0,0),(10,10,0))
        minGrid.append(minGrid_X)
        minGrid.append(minGrid_Y)
        print "Pattern: Fish Scales"
```

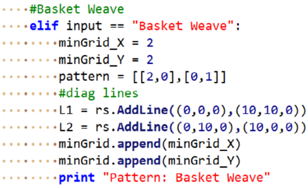


Basket Weave

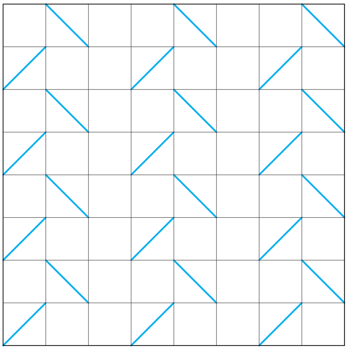


0	1
2	0

Pattern: Basket Weave
Minimum Grid Size: 2 x 2



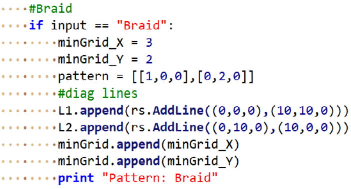
```
    #Basket Weave
    elif input == "Basket Weave":
        minGrid_X = 2
        minGrid_Y = 2
        pattern = [[2,0],[0,1]]
        #diag lines
        L1 = rs.AddLine((0,0,0),(10,10,0))
        L2 = rs.AddLine((0,10,0),(10,0,0))
        minGrid.append(minGrid_X)
        minGrid.append(minGrid_Y)
        print "Pattern: Basket Weave"
```



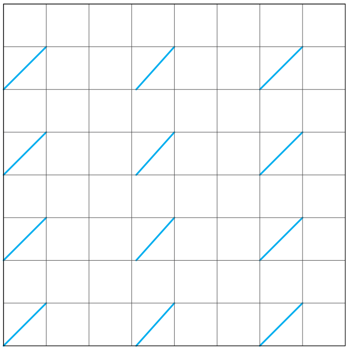
Braid

0	2	0
1	0	0

Pattern: Braid
Minimum Grid Size: 3 x 2



```
    #Braid
    if input == "Braid":
        minGrid_X = 3
        minGrid_Y = 2
        pattern = [[1,0,0],[0,2,0]]
        #diag lines
        L1.append(rs.AddLine((0,0,0),(10,10,0)))
        L2.append(rs.AddLine((0,10,0),(10,0,0)))
        minGrid.append(minGrid_X)
        minGrid.append(minGrid_Y)
        print "Pattern: Braid"
```

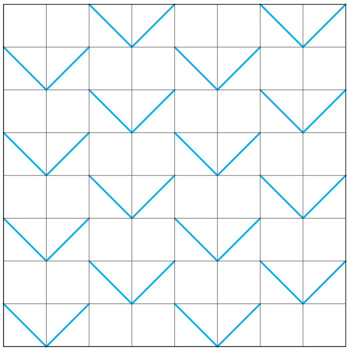


Waves

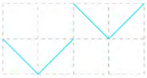
Pattern: Waves
Minimum Grid Size: 3 x 2

0	0	0
1	0	0

```
    #Waves
    elif input == "Waves":
        minGrid_X = 3
        minGrid_Y = 2
        pattern = [[1,0,0],[0,0,0]]
        #single diag
        L1 = rs.AddLine((0,0,0),(10,10,0))
        minGrid.append(minGrid_X)
        minGrid.append(minGrid_Y)
        print "Pattern: Waves"
```



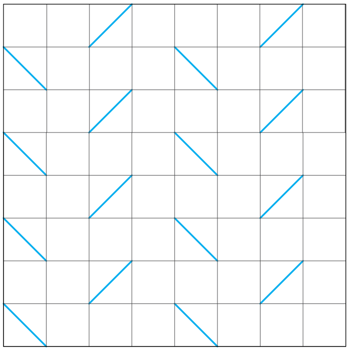
Arrow



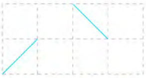
Pattern: Arrow
Minimum Grid Size: 4 x 2

0	0	2	1
2	1	0	0

```
    #Arrow
    elif input == "Arrow":
        minGrid_X = 4
        minGrid_Y = 2
        pattern = [[2,1,0,0],[0,0,2,1]]
        #diag lines
        L1 = rs.AddLine((0,10,0),(10,0,0))
        L2 = rs.AddLine((0,0,0),(10,10,0))
        minGrid.append(minGrid_X)
        minGrid.append(minGrid_Y)
        print "Pattern: Arrow"
```



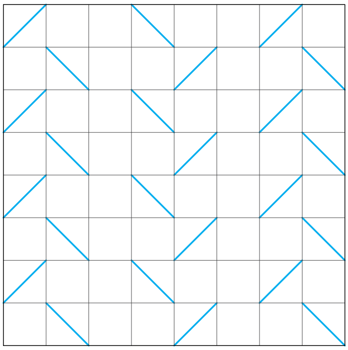
Criss Cross Bones



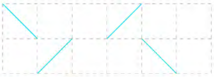
Pattern: Criss Cross Bones
Minimum Grid Size: 4 x 2

0	0	1	0
2	0	0	0

```
    #Criss Cross Bones
    elif input == "Criss Cross Bones":
        minGrid_X = 4
        minGrid_Y = 2
        pattern = [[2,0,0,0],[0,0,1,0]]
        #diag lines
        L1 = rs.AddLine((0,0,0),(10,10,0))
        L2 = rs.AddLine((0,10,0),(10,0,0))
        minGrid.append(minGrid_X)
        minGrid.append(minGrid_Y)
        print "Pattern: Criss Cross Bones"
```



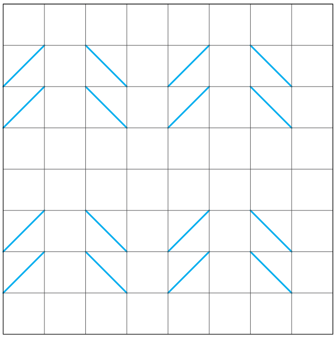
Leaf



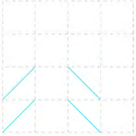
Pattern: Leaf
Minimum Grid Size: 6 x 2

1	0	0	2	0	0
0	2	0	0	1	0

```
    #Leaf
    elif input == "Leaf":
        minGrid_X = 6
        minGrid_Y = 2
        pattern = [[0,2,0,0,1,0],[1,0,0,2,0,0]]
        #diag lines
        L1 = rs.AddLine((0,0,0),(10,10,0))
        L2 = rs.AddLine((0,10,0),(10,0,0))
        minGrid.append(minGrid_X)
        minGrid.append(minGrid_Y)
        print "Leaf"
```



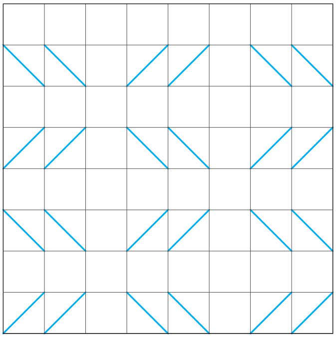
Double Arrows



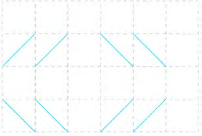
Pattern: Double Arrows
Minimum Grid Size: 4 x 4

0	0	0	0
0	0	0	0
2	0	1	0
2	0	1	0

```
    #Double Arrows
    elif input == "Double Arrows":
        minGrid_X = 4
        minGrid_Y = 4
        pattern = [[2,0,1,0],[2,0,1,0],
        [0,0,0,0],[0,0,0,0]]
        #diag lines
        L1 = rs.AddLine((0,0,0),(10,10,0))
        L2 = rs.AddLine((0,10,0),(10,0,0))
        minGrid.append(minGrid_X)
        minGrid.append(minGrid_Y)
        print "Pattern: Double Arrows"
```



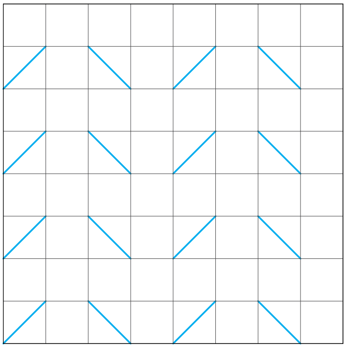
4-Point Star



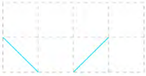
Pattern: 4 Point Star
Minimum Grid Size: 6 x 4

0	0	0	0	0	0
2	2	0	1	1	0
0	0	0	0	0	0
1	1	0	2	2	0

```
    #4 Pt Star
    elif input == "4 Point Star":
        minGrid_X = 6
        minGrid_Y = 4
        pattern = [[1,1,0,2,2,0],[0,0,0,0,0,0],
        [2,2,0,1,1,0],[0,0,0,0,0,0]]
        #diag lines
        L1.append(rs.AddLine((0,0,0),(10,10,0)))
        L2.append(rs.AddLine((0,10,0),(10,0,0)))
        minGrid.append(minGrid_X)
        minGrid.append(minGrid_Y)
        print "Pattern: 4 Point Star"
```



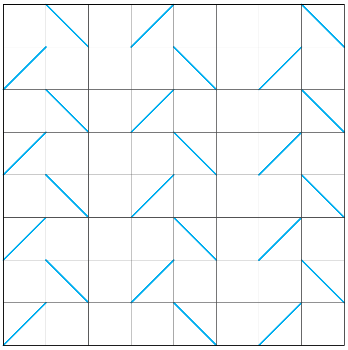
Zig Zag



Pattern: Zig Zag
Minimum Grid Size: 4 x 2

0	0	0	0
1	0	2	0

```
    #Zig Zag
    elif input == "Zig Zag":
        minGrid_X = 4
        minGrid_Y = 2
        pattern = [[1,0,2,0],[0,0,0,0]]
        #diag lines
        L1 = rs.AddLine((0,0,0),(10,10,0))
        L2 = rs.AddLine((0,10,0),(10,0,0))
        minGrid.append(minGrid_X)
        minGrid.append(minGrid_Y)
        print "Pattern: Zig Zag"
```

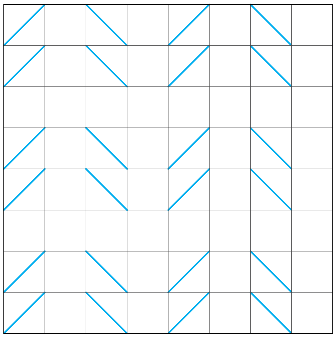


Shell

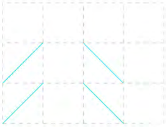
Pattern: Shell
Minimum Grid Size: 3 x 2

0	2	0
1	0	0

```
    #Shell
    elif input == "Shell":
        minGrid_X = 3
        minGrid_Y = 2
        pattern = [[1,0,0],[0,2,0]]
        #diag lines
        L1 = rs.AddLine((0,0,0),(10,10,0))
        L2 = rs.AddLine((0,10,0),(10,0,0))
        minGrid.append(minGrid_X)
        minGrid.append(minGrid_Y)
        print "Pattern: Shell"
```



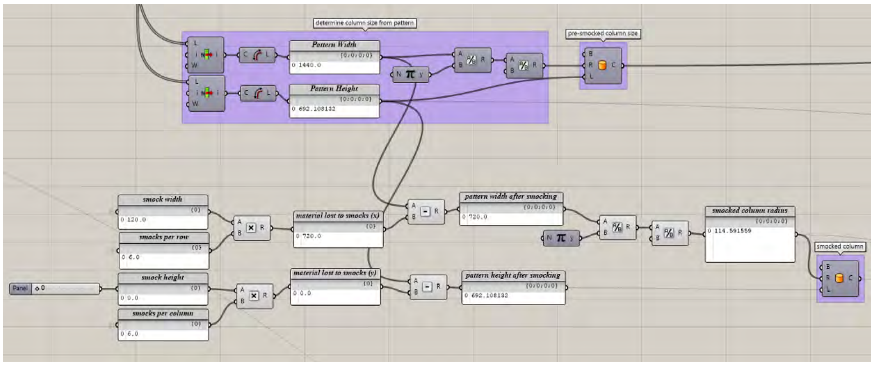
Hearts



Pattern: Hearts
Minimum Grid Size: 4 x 3

0	0	0	0
2	0	1	0
2	0	1	0

```
    #Hearts
    elif input == "Hearts":
        minGrid_X = 4
        minGrid_Y = 3
        pattern = [[2,0,1,0],[2,0,1,0],
        [0,0,0,0]]
        #diag lines
        L1 = rs.AddLine((0,0,0),(10,10,0))
        L2 = rs.AddLine((0,10,0),(10,0,0))
        minGrid.append(minGrid_X)
        minGrid.append(minGrid_Y)
        print "Pattern: Double Arrows"
```



Pattern Width {0;0;0;0} 0 1440.0

Pattern Height {0;0;0;0} 0 692.108132

smock width {0} 0 120.0

smocks per row {0} 0 6.0

smock height {0} 0 0.0

smocks per column {0} 0 6.0

material lost to smocks (x) {0} 0 720.0

material lost to smocks (y) {0} 0 0.0

pattern width after smocking {0;0;0;0} 0 720.0

pattern height after smocking {0;0;0;0} 0 692.108132

smocked column radius {0;0;0;0} 0 114.591559

FIGURE 5.20: Mathematical calculation to approximate pre- and post-smocking fabric sizes (in Grasshopper) (Source: author).

grid. In the event that the user-set grid size is not a multiple of the minimum grid size described earlier, the script compensates and reverts to the lowest divisible number of tiling. For example, if the user inputs a desired grid size of 11 x 13 and selects the ‘Criss-Cross Bones’ pattern (minimum grid size 4 x 2), the tool generates an 8 x 6 grid so that no grouping of repeated smock modules in the pattern is split. **FIGURE 5.19** shows the breakdown of each pattern in the *Coded Pixels* probe, the smallest repeating module (minimum grid size), the corresponding abstracted condition logic (0, 1, 2) and the Python script for each pattern. These are arranged in ascending order of the pattern's smallest repeating module size.

With the *First Fifteen Hand-Smocked Probes*, a general approximation of material loss was mathematically calculated; this was possible due to the repeating pattern and orientation of the smocking geometry (**FIGURE 5.20**). The final fabric size and shape were merely aggregations of the spaces between the smocking curves. The developed tool calculated this spacing and shape for every module. Although an un-skewed and -scaled grid is ideal for hand-marking the pattern and quickly calculating the final size of the fabric, more complex and varying smocking patterns are laborious if not impossible to calculate by hand.

5.2.2 Breaking the Grid

The *Coded Pixels* probe (introduced above) allowed for the efficient generation of many permutations based on any quadrilateral grid extent and shape. This logic can be applied to any number of regular or warped grids (**FIGURE 5.21-FIGURE**

5.22) and informed the *Skewed Grids* patterns (**FIGURE 5.9-FIGURE 5.10**) and the development of the *OriNuno* tool. These probes successfully demonstrated adequate control over two-dimensional pattern generation and parametrization.

The *Coded Pixels* probe was only the first stage of digitizing such techniques. While these developments were useful in understanding the underlying logic and tiling of smocking patterns, the tool was limited to parameterizing two-dimensional patterns without the context of the resulting shape. Without extensive familiarity with smocking patterns and their logic, it is difficult for the average user to look at a two-dimensional pattern (parameterized or not) and understand the implications of the three-dimensional form. The research aims were thus refocused towards developing an accessible digital tool that would generate smocking patterns from a user-input three-dimensional shape.

5.2.3 3D to 2D: Synthesizing Pattern-Generation Findings

As a result of the 'wandering' methodology of *Concrete Form[ing]work*, the experiments continually informed the research questions and process. Thus, a supplementary research question was formulated midway through the research process:

> *How does one construct a two-dimensional pattern from a three-dimensional input surface which accurately approximates the given form when sewn?*

As a result of an incomplete understanding of how to construct two-dimensional patterns for three-dimensional input shapes, the author adopted Krogh et al.'s *expansive* methodology for the experiments that followed. This 'wandering' approach supported exploration without a clear end goal in mind, and intuition regarding the answer to this research question led to an exploration of adjacent fields: mesh segmentation, surface unrolling, origami, kirigami, Resch patterns, auxetic materials and conformal mapping (introduced in **SECTION 4.2.3**).

As is discussed in the aforementioned section, generating flat patterns from three-dimensional input shapes is quite complex, and some researchers have dedicated their careers to researching this topic. Rigorous testing of Origamizer, Pepakura Designer, Ivy and BFF softwares was conducted to understand the limitations of these software packages. The *expansive* process of exhausting and trying to reverse-engineer these tools revealed unforeseen geometrical

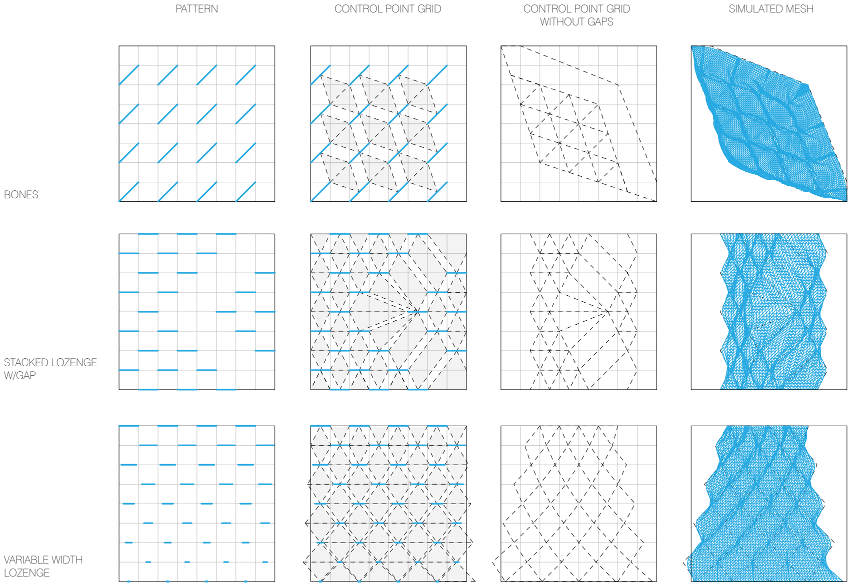


FIGURE 5.21: Development of *Skewed Grids* patterns (Source: author)

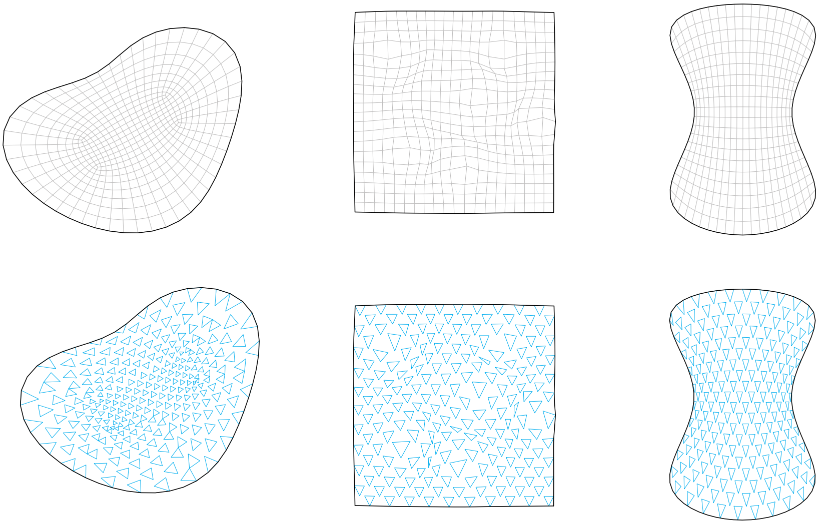


FIGURE 5.22: Skewing 'regular' grids to generate a corresponding 'Arrow' smocking pattern (Source: author)

connections between each of these surface-unrolling techniques used in the software packages. The discovery of these links and limitations of these software packages are discussed in the following sections; these served as the foundation of the digital tool, *OriNuno*, developed during the research presented in this thesis.

5.2.4 *Cone* and *Torus 1.0*: Origamizer and Strip Unrolling

While the previously conducted probe experiments in which two-dimensional patterns were parameterized provided a basic understanding, the process of constructing smocking patterns from three-dimensional input shapes remained too complex to formalize. A general goal of constructing geometries such as a cone and a torus was set to test this intuition.[20] These shapes were selected for simplicity; a cone has one-dimensional curvature, and a torus has two-dimensional curvature. Both were deemed to have enough variation for initial, intuitive exploration, and their subsequent pattern deconstruction provided further insight into making both single- and double-curved shapes.

Origamizer served as a springboard for investigating mesh unrolling to design smocking patterns from a three-dimensional input shape. This software was tested in the hope of adapting the tool for generating smocking patterns. Origamizer takes a polyhedral input manifold and generates a 'watertight' folding pattern that can be assembled into complex forms (Demaine & Tachi, 2017). After initial testing, a similarity between Origamizer's generated patterns and smocking patterns was identified. The software generates folding patterns to tuck excess paper between unfolded mesh faces. These tucks could be reinterpreted through the lens of smocking patterns, gathering excess material between mesh faces with a smock line rather than a fold. **FIGURE 5.23** shows Origamizer's output patterns for a cone and torus and the reinterpretation of these geometries into smocking patterns.

Origamizer-generated patterns could be sewn, although most of the patterns consisted of even-numbered smocks (similar to the 'Quilted Diamonds' pattern; **FIGURE 5.2**). The process of creating the patterns for the *First Fifteen Hand-Smocked Probes* showed that utilizing even-numbered smocking patterns is

---

[20] 'Intuition' is used in this instance to note that these probes were guided by a general 'feeling' of how to go about constructing these geometries, without fully comprehending the mathematical technicalities.

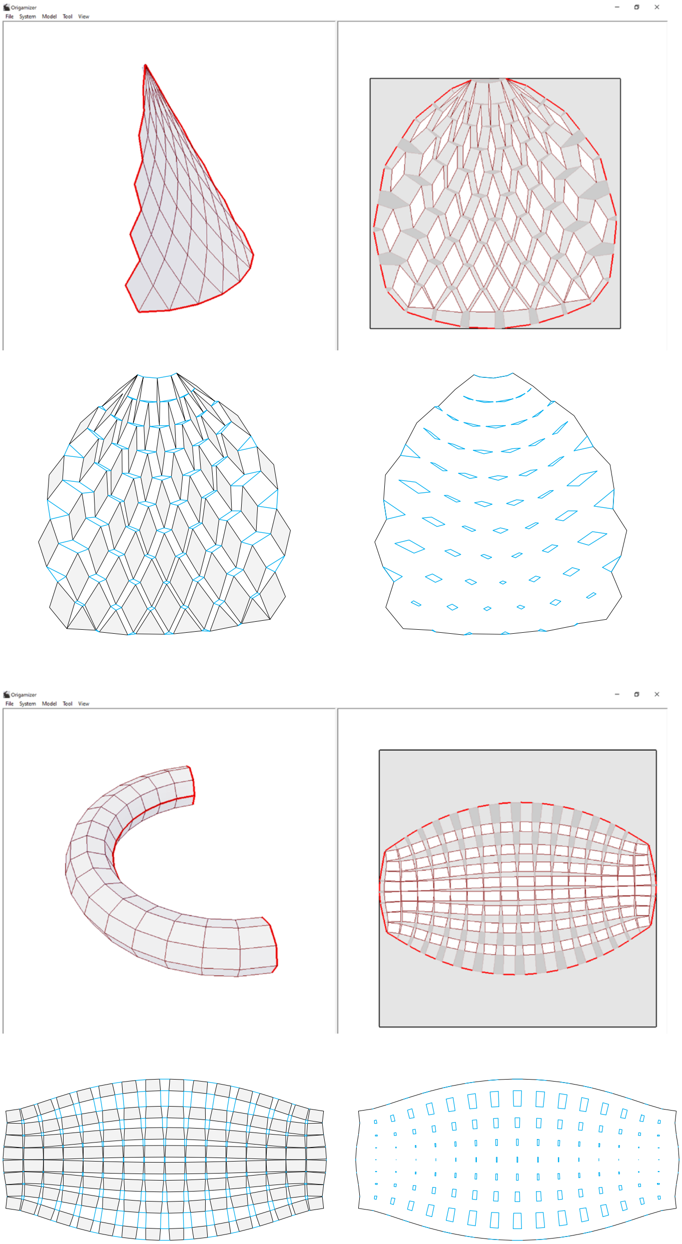


FIGURE 5.23: Smocking pattern generation of a cone and torus by using Origamizer (Source: author)

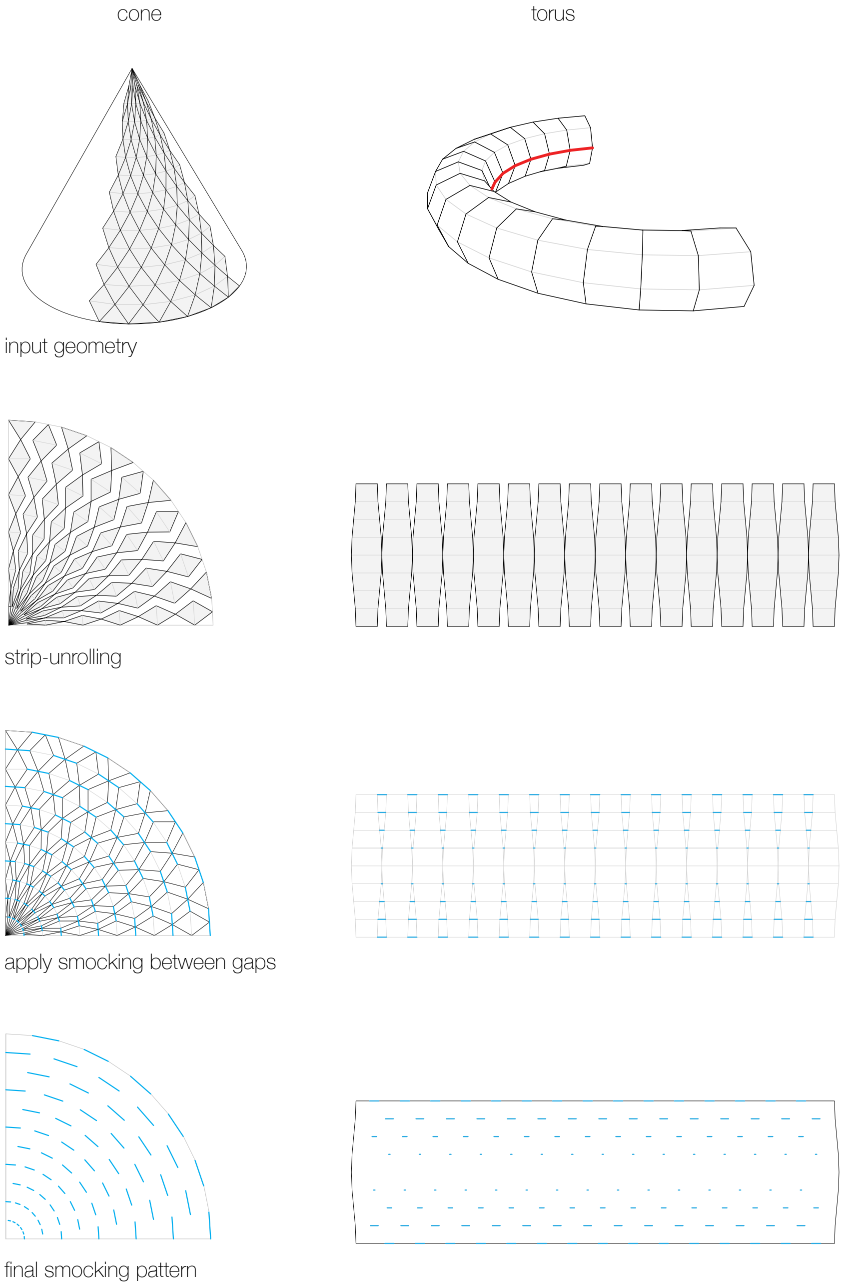


FIGURE 5.24: Pattern generation of *Cone* and *Torus 1.0* generated from strip unrolling technique (Source: author).

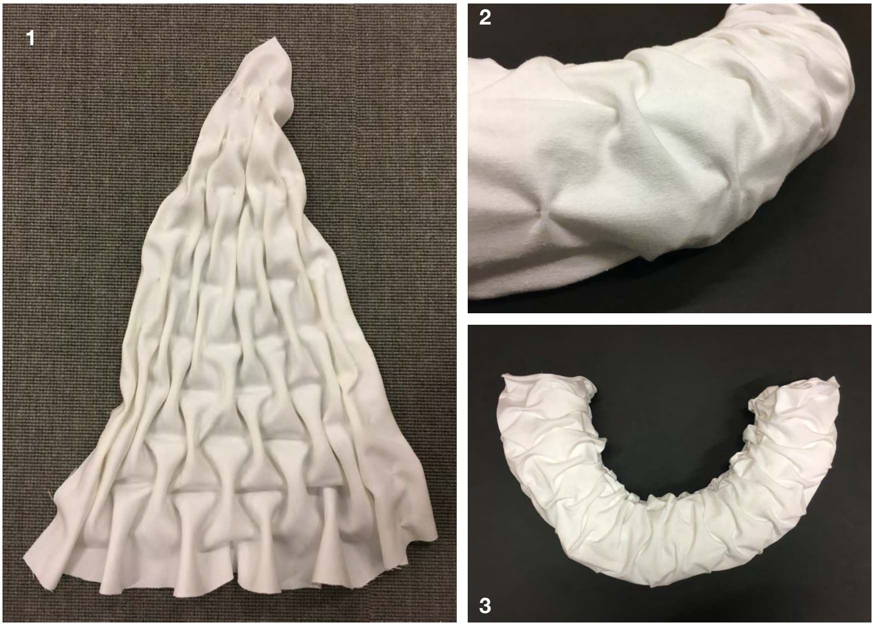


FIGURE 5.25: Smocked (1) *Cone* and (2, 3) *Torus 1.0* using 'Lozenge' pattern and strip unrolling technique (Source: author).

not ideal when constructing formwork for casting concrete, as these types of pattern block the flow of concrete through the smock. The 'black box' nature of the Origamizer software unfortunately means that it does not offer enough customization to generate odd-numbered smocking patterns.

While Origamizer served as an excellent springboard for understanding the deconstruction of complex three-dimensional shapes, it became clear that a greater degree of control and customization was required when unrolling a three-dimensional input mesh. In order to quickly generate viable smocking patterns from input three-dimensional shapes, it was clear that a custom tool needed to be developed. Thus, a step back was taken, and Mitani and Suzuki's strip-unrolling method (2004) was revisited to reduce the number of unknown variables (see **SECTION 4.2.3**).

FIGURE 5.24 shows the construction of the *Cone* and *Torus 1.0* smocking patterns using the strip-unrolling method. First, the strips were arrayed (polar and linear, respectively) and unrolled onto a base plane. The spaces between the unrolled mesh faces were filled with smocking pattern lines to gather the excess fabric material. The generated smocking patterns were then sewn to confirm the validity of the method, as shown in **FIGURE 5.25**. However, while these probes demonstrated that it was possible to generate a 'Lozenge' smocking pattern for both a cone and a torus, these findings were overly simplistic; the method was limited to generating patterns for input shapes with one-dimensional or double-curved shapes suitable for strip unrolling.

5.2.5 *Dome* Probe Using Generalized Ron Resch Patterns

Based on the nature of the 'Lozenge' pattern (a single line with two connection points), the pattern 'removed' or 'gathered' material in only one direction at each mesh vertex. In order to facilitate the generation of a more comprehensive array of three-dimensional shapes, further probes with an 'Arrow' pattern (a three-pointed smock that can manipulate curvature in three dimensions) were

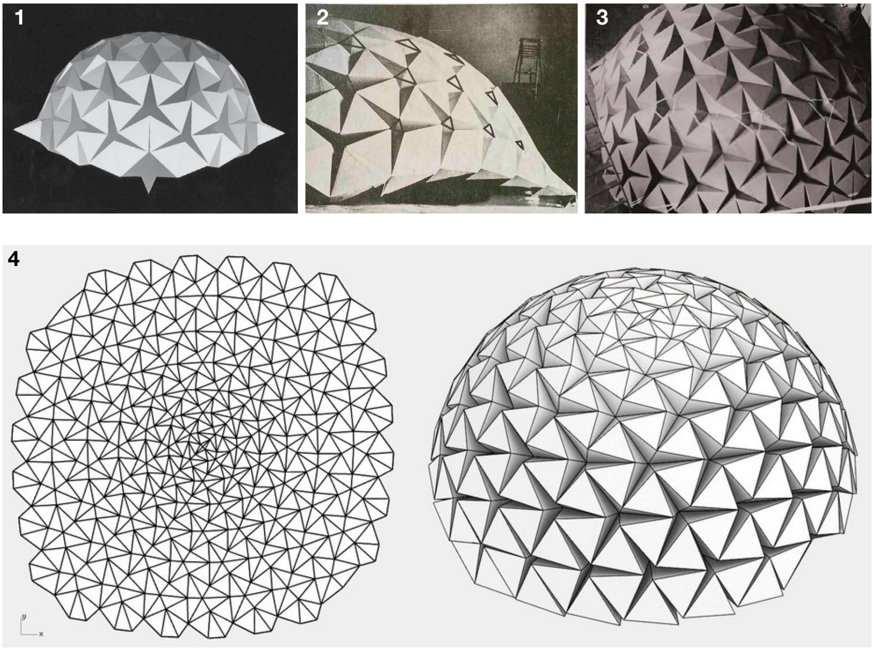


FIGURE 5.26: Resch's (1) pattern simulation, (2) vertex gap diagram and (3) constructed paper model (Resch & Christiansen, 1970).
Piker's (4) origami dome using a generalization of Resch's folding patterns (Piker, n.d.).

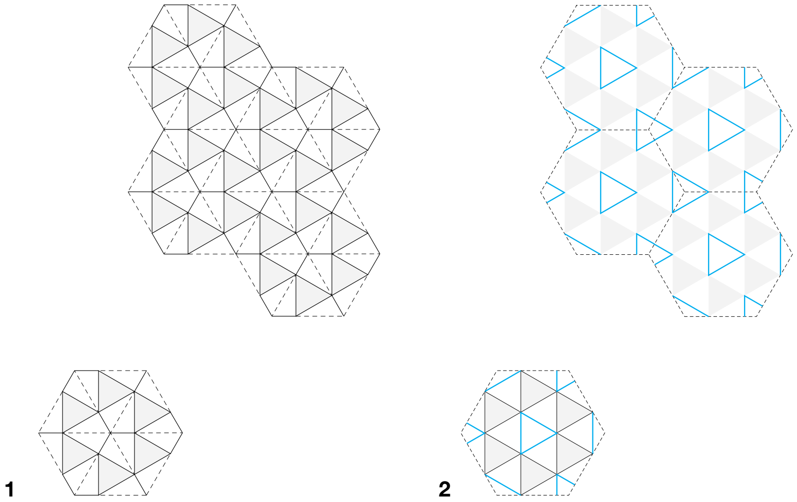


FIGURE 5.27: (1) Resch pattern vs. (2) 'Arrow' smock pattern (Source: author).

required. While it is technically possible to use a 'Lozenge' smocking pattern to achieve double-curved forms, this would require the curvature at each mesh vertex to be locally restricted to one dimension. With this logic, utilizing patterns such as the three-pointed 'Arrow' smock allowed multiple degrees of freedom, and this was determined to be the logical smocking pattern to test further.

Piker's origami dome study (**FIGURE 5.26 (4)**) built on Tachi's *Freeform Origami Tessellations by Generalizing Resch's Patterns* (Tachi, 2013), using his Kangaroo solver plugin for Grasshopper (Piker, 2014). Piker's mesh-flattening technique and patterning configuration hinted at a promising solution to generating three-point smocking patterns. The Ron Resch pattern (previously described in **SECTION 4.2.3**) is a geometrical system that can have open, half-folded and closed configurations upon assembly. It is characterized by six equilateral triangles arranged in a periodic hexagonal tiling. Similarly, the mountain and valley folds (represented with solid and dashed lines, respectively) can be programmed to 'hide' the extra paper between triangles. Piker first approximated a general solution for a Ron Resch origami pattern, then applied Kangaroo's 'Developablize' component to ensure a successful folding pattern using plugins for Rhino 3D. The simulated paper approximates a dome when 'folded.'

A similar result can be achieved through smocking. The equilateral triangle

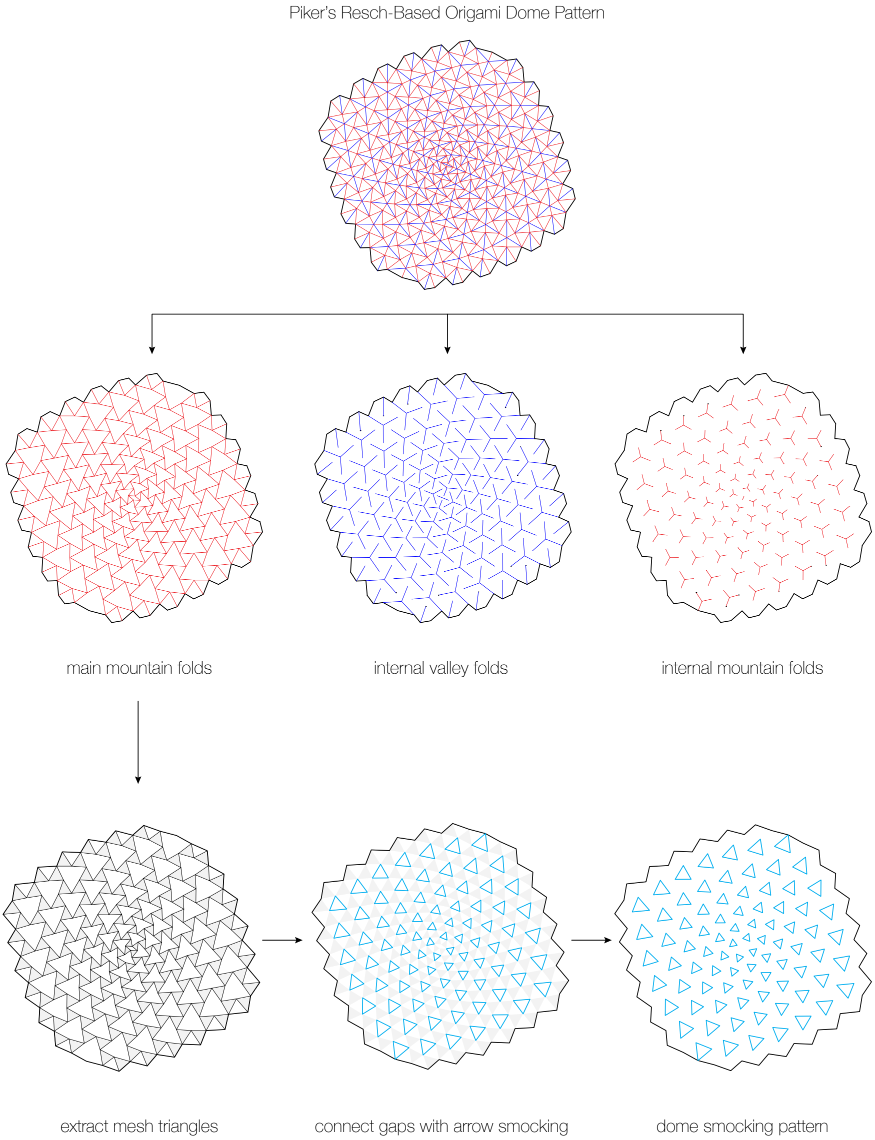


FIGURE 5.28: *Dome* smocking pattern from Ron Resch origami pattern (Source: author).

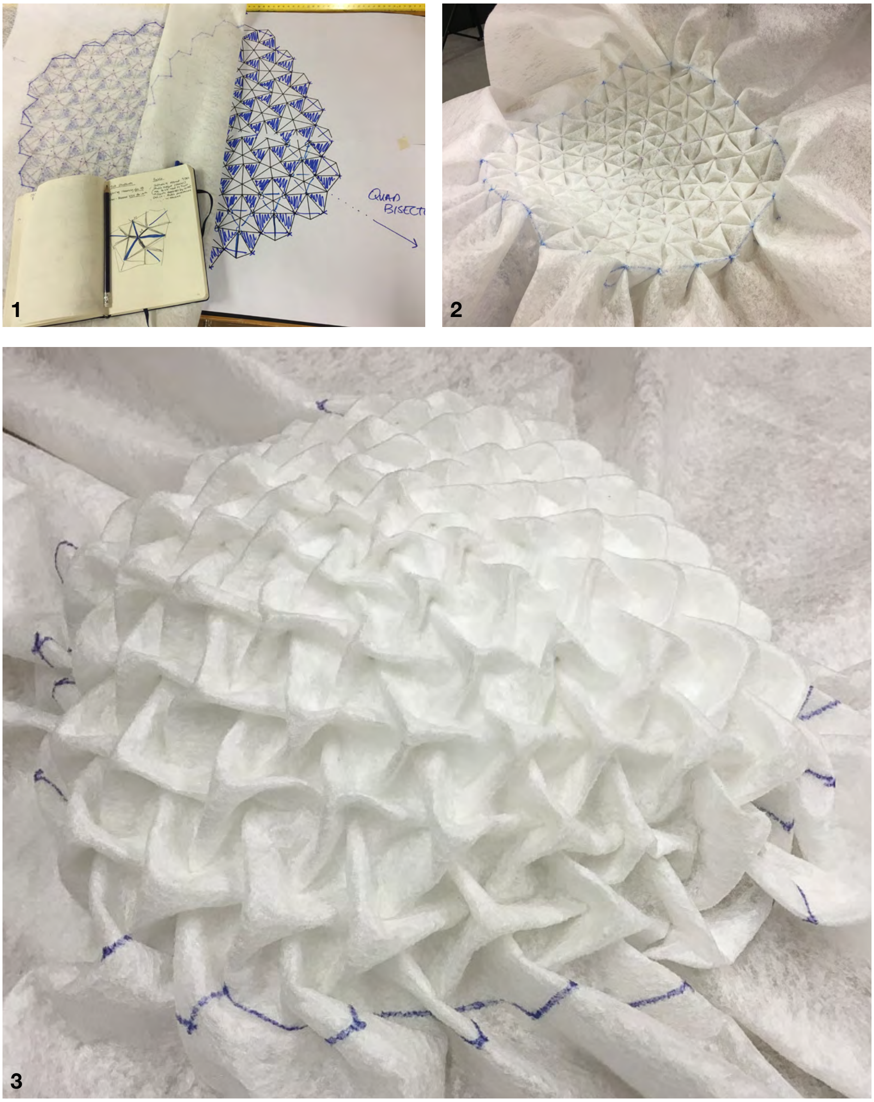


FIGURE 5.29: *Dome* probe: (1) smocking pattern marking, (2) ‘back’ side and (3) ‘front’ side (Source: author).

corners can be connected in such a way with an 'Arrow' smock to achieve the same final form, but with a pleat of fabric instead of a fold of paper (see **FIGURE 5.27**). This logic was applied to Piker's origami pattern (**FIGURE 5.28**), which functioned as a base substructure to generate a viable smocking pattern. The vertex folds were replaced with 'Arrow' smocks, and a sewn *Dome* probe was fabricated as a proof of concept (**FIGURE 5.29**). **FIGURE 5.30** highlights the difference between unrolling a tessellated dome mesh with Origamizer and Piker's Resch-inspired dome pattern; the main difference between them is that Origamizer works with even-numbered smocks while the Resch-based pattern works with three-point smocks.

The smocked *Dome* probe successfully demonstrated that it is possible to create double-curved surfaces from a single sheet of fabric using 'Arrow' smocks. It should be noted, however, that Piker's pattern is intended to be semi-folded in some areas,[21] while the smocked dome form (although it is double-curved) does not approximate a spherical dome but rather a flatter, yet still synclastic, form. In order to generate a sewn prototype identical to the input shape, the smocks would have to be only partially connected, leaving gaps (**FIGURE 5.26 (2)**).

While this probe did not produce a perfect, spherical dome, it was considered a success. The *Dome* probe not only combined the geometrical insights that had been produced thus far, but revealed that using the 'Arrow' smock was the key to producing patterns that would approximate double-curved surfaces. Compared to the previously discussed limitations of constructing viable smocking patterns with Origamizer, a custom user-generated tool using Resch tilings as a base was deemed to have far greater potential for generating viable smocking patterns. At this point in the research, the following had been accomplished:

- Construction of basic 'Lozenge' patterns using the strip-unrolling method.
- Understanding of the importance of the 'Arrow' smocking pattern to create double-curved surfaces using a single sheet of fabric.
- Three-dimensional simulation of parametrically produced two-dimensional patterns.

---

[21] Similar to Resch's studies, the origami domes in Piker's study was formed by partially folding the paper tucks. This folding approach differs from that of the Origamizer software, wherein patterns are constructed to be fully closed or 'watertight' (Demaine & Tachi, 2017; Tachi, 2013).

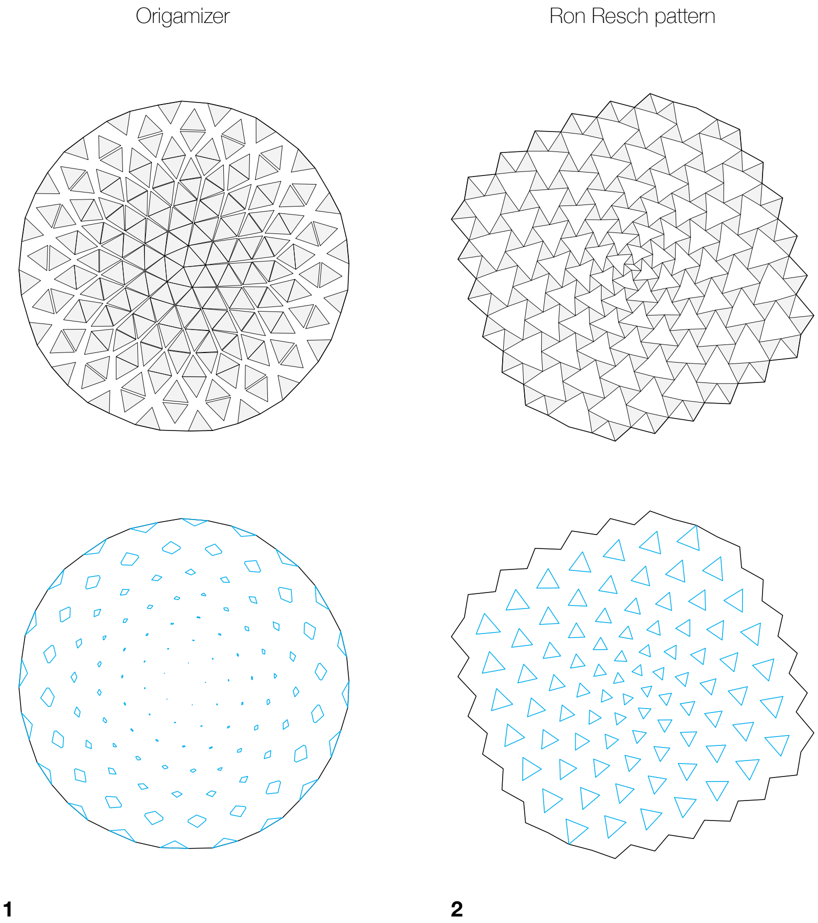
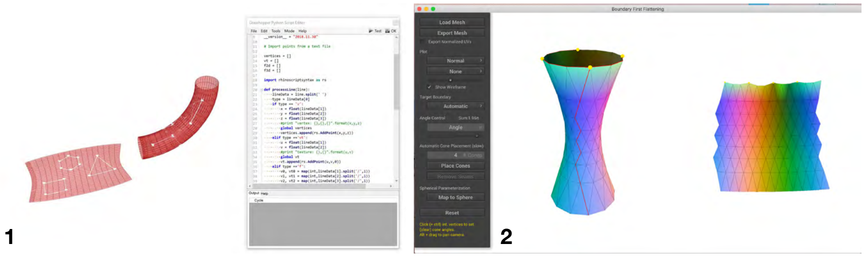


FIGURE 5.30: Comparison of (1) Origamizer and (2) Resch folding patterns respectively translated to smocking patterns (Source: author).



```
__version__ = "2018.11.30"

# Import points from a text file

vertices = []
vt = []
f2d = []
f3d = []

import rhinoscriptsyntax as rs

def processLine(line):
    lineData = line.split(' ')
    type = lineData[0]
    if type == 'v':
        x = float(lineData[1])
        y = float(lineData[2])
        z = float(lineData[3])
        #print "vertex: {},{},{}".format(x,y,z)
        global vertices
        vertices.append(rs.AddPoint(x,y,z))
    elif type =='vt':
        u = float(lineData[1])
        v = float(lineData[2])
        #print "texture: {},{}".format(u,v)
        global vt
        vt.append(rs.AddPoint(u,v,0))
    elif type =='f':
        v0, vt0 = map(int,lineData[1].split('/',1))
        v1, vt1 = map(int,lineData[2].split('/',1))
        v2, vt2 = map(int,lineData[3].split('/',1))
```

FIGURE 5.31: (1) conformal mapping in Python and (2) Boundary First Flattening (BFF) (Source: author).

These findings provided a base from which to construct *OriNuno*, which allowed for complete control over input shapes, unrolling and the relationship between the faces of the tessellated input geometries.

5.2.6 Synthesizing Ron Resch Patterns, Kirigami, BFF and Smocking

Following the completion of the *Dome* probe, the relationship between the patterning techniques that had been previously investigated (discussed in **SECTION 4.2.3**) became increasingly apparent. **FIGURE 5.31** shows a early study with Python and BFF, conducted to understand how conformal mapping and the geometrical principles of translating a three-dimensional input mesh to the C-plane could be applied to various input shapes. While mesh segmentation, Resch patterns, Origamizer, kirigami, auxetic materials and conformal mapping have various applications, they all have a unifying, underlying principle that allows the programming of surfaces which exhibit non-zero Gaussian curvature.[22] This geometrical principle can be simplified to programming the angular relationship between unrolled surface faces. **FIGURE 5.32** shows that, by changing the relation between the sum of the interior (θv, shown in red) and exterior (θe, shown in blue) angles, it is possible to program zero, positive and negative Gaussian curvature in a folded material (Scherer, 2019b, p. 764). Once the angular relationship has been specified on the C-plane, the excess material can be folded (Origamizer/Resch patterns) or removed (kirigami/auxetic materials).

---

[22] Examples of negative, zero and positive Gaussian curvature include a hyperboloid, cylinder and sphere, respectively. Non-zero Gaussian curvature in this instance refers to double-curved surfaces.

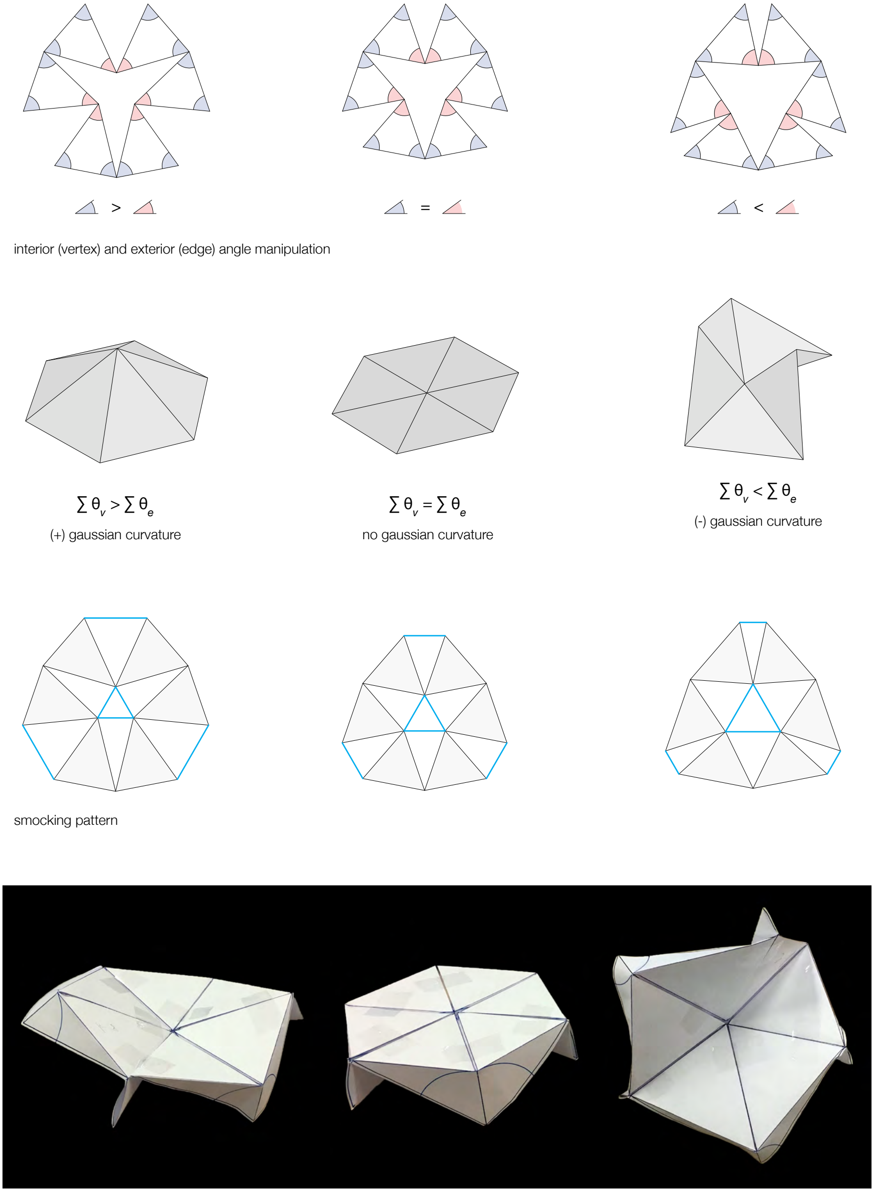


FIGURE 5.32: Generating single vertex smocking patterns of (+), (0), & (-) Gaussian curvature and corresponding folded paper models. (Source: author).

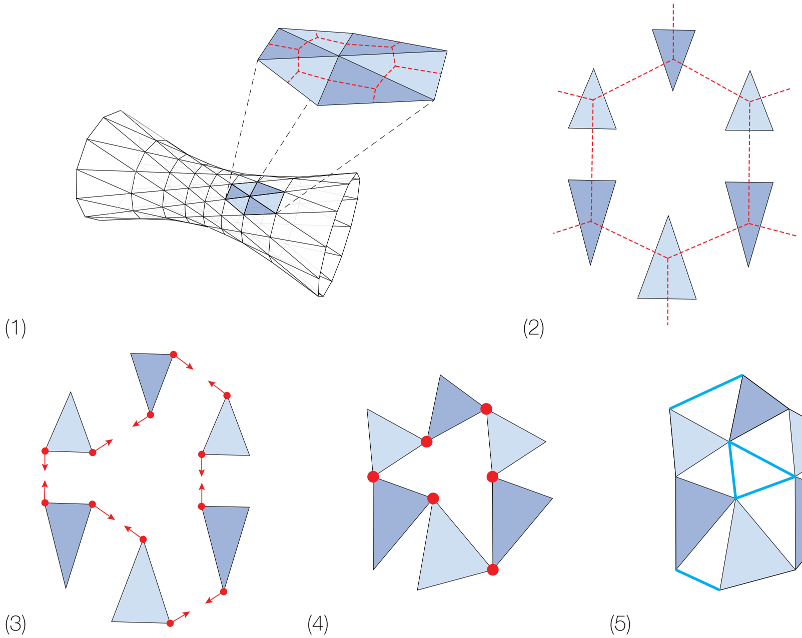


FIGURE 5.33: Steps for deconstructing an input surface into a smocking pattern, based on Ron Resch's origami patterns (Source: author).

Regardless of technique, the flat patterned material can be assembled into non-zero Gaussian surfaces. When combined with computation, this simple technique opens up vast, new possibilities for geometrical configurations in the realm of developable design.

The *OriNuno* tool developed for this thesis applies the same angular programming to computational smocking as Origamizer, kirigami and auxetic materials do. By varying the two-dimensional size, shape and angles of smock triangles (origami tucks in this case), it is possible to achieve a variable curvature. The corresponding origami models demonstrate positive, zero and negative Gaussian curvature. These diagrammatic studies were simplified to create six mesh face triangles to demonstrate the concept (**FIGURE 5.32**).

Theis process of programming three-dimensional curvature by manipulating two-dimensional patterns was reverse-engineered in *OriNuno*; **FIGURE 5.33** diagrams this process with the deconstruction of six mesh faces of a three-dimensional shape. A non-zero Gaussian surface was tiled with triangulated faces (**FIGURE 5.33 (1)**). This mesh triangulation had a hexagonal mesh dual[23] so that each mesh vertex had a valence of six.[24] The mesh dual was used as a basic substructure to help maintain the information of each triangle's placement in relation to its neighbors when unrolled. In (**FIGURE 5.33 (2)**), the three-dimensional mesh dual was conformally mapped to the C-Plane,[25] creating an identically structured (albeit skewed) two-dimensional mesh (see also **FIGURE 5.40 (2)** in **SECTION 5.2.2**. The flat mesh dual curves were 'equalized' in Kangaroo 2, and the three-dimensional mesh triangles were oriented in relation to this flat mesh dual based on their relative positions.

Based on previous conclusions relating to odd-numbered smocking modules (**SECTION 5.1.1**), several additional steps were required to achieve a viable smocking pattern for use in concrete casting. In order to transform a six-pointed smocking pattern into a three-pointed 'Arrow' pattern, a series of Kangaroo 2 springs were drawn (**FIGURE 5.33 (3)**) and set to a target length of zero (**FIGURE 5.33 (4)**). After the completion of the simulation, the interior vertices of the resulting 'gaps' were connected, resulting in a programmed smocking pattern (**FIGURE 5.33 (5)**) that approximated the target, non-zero Gaussian curvature surface. Together, these steps demonstrate the basic principles of deconstructing a three-dimensional shape and constructing a smocking pattern that approximates the input surface.

5.2.7 *Column 3.1*

The basic deconstruction techniques described in the previous section were applied to a one-sheet hyperboloid (also known as a hyperbolic hyperboloid). This prototype aided in developing and demonstrating pattern generation control. Although classified as a ruled surface,[26] a one-sheet hyperboloid is not developable as it exhibits non-zero Gaussian curvature. After the *OriNuno* tool

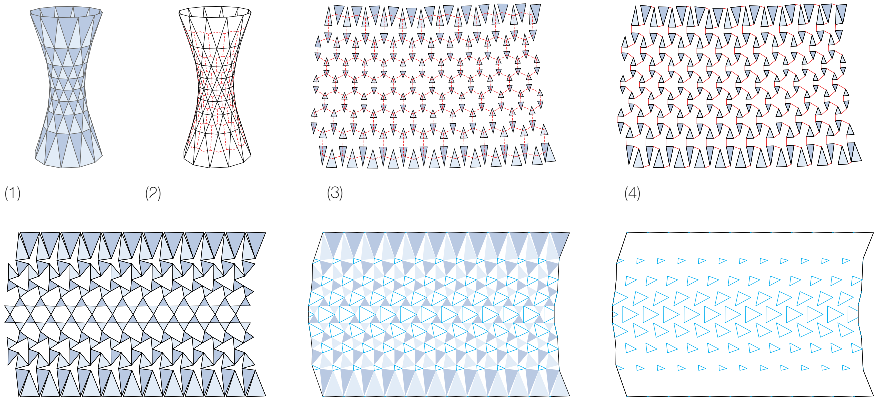
---

[23] A mesh dual is the connection of mesh triangle circumcenters (the point at which the angular bisectors of the triangles meet).

[24] This can also be written with the Schläfli symbol of {3,6}; i.e., six triangles around each vertex.

[25] While this was previously done using the BFF software (Sawhney & Crane, 2017), conformal mapping was later replaced with Kangaroo 2 components to minimize dependencies on external software.

[26] Meaning that it can be constructed by moving straight lines called 'generators' or 'rulings' (Pottman et al., 2007, p. 311).



(1) (2) (3) (4)

(7) (6) (5)

FIGURE 5.34: Smocking pattern generation from a tessellated one-sheet hyperboloid with negative Gaussian curvature (Source: author).

had been updated to account for more complex data flow, the process outlined in **FIGURE 5.33** was applied to a relatively complex mesh triangulation (**FIGURE 5.34**).

(1) A one-sheet hyperboloid with triangle mesh tessellation was tiled;
(2) A circumcenter mesh dual was found to retain tiling structure during unrolling;
(3) The mesh dual was scaled and the corresponding mesh triangles were laced on the XY plane;
(4) Alternating triangle vertices were connected and made to snap together;
(5) The Kangaroo 2 simulation was run, retaining mesh edge lengths while snapping appropriate triangle vertices together;
(6) The resulting ‘gaps’ were connected to smocking pattern lines;
(7) The fabrication pattern was produced.

As is shown in **FIGURE 5.35 (1)**, the pattern was hand-transferred to a large sheet of geotextile and smocked. **FIGURE 5.35 (2)** shows the completed fabric prototype; however, as the smocks were too detailed and had overlapping folds, concrete casting was not possible using this prototype. *Column 3.1* was

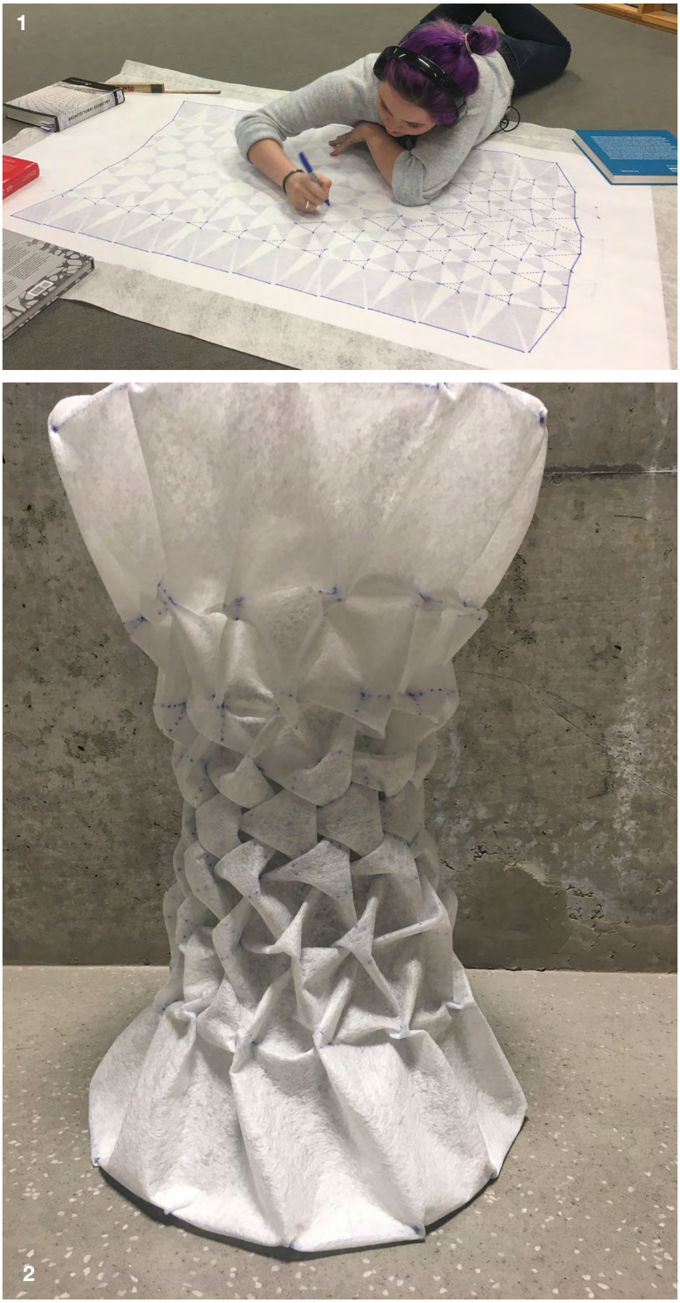


FIGURE 5.35: *Column 3.1*: (1) fabrication process and (2) final smocked prototype of (Source: author).

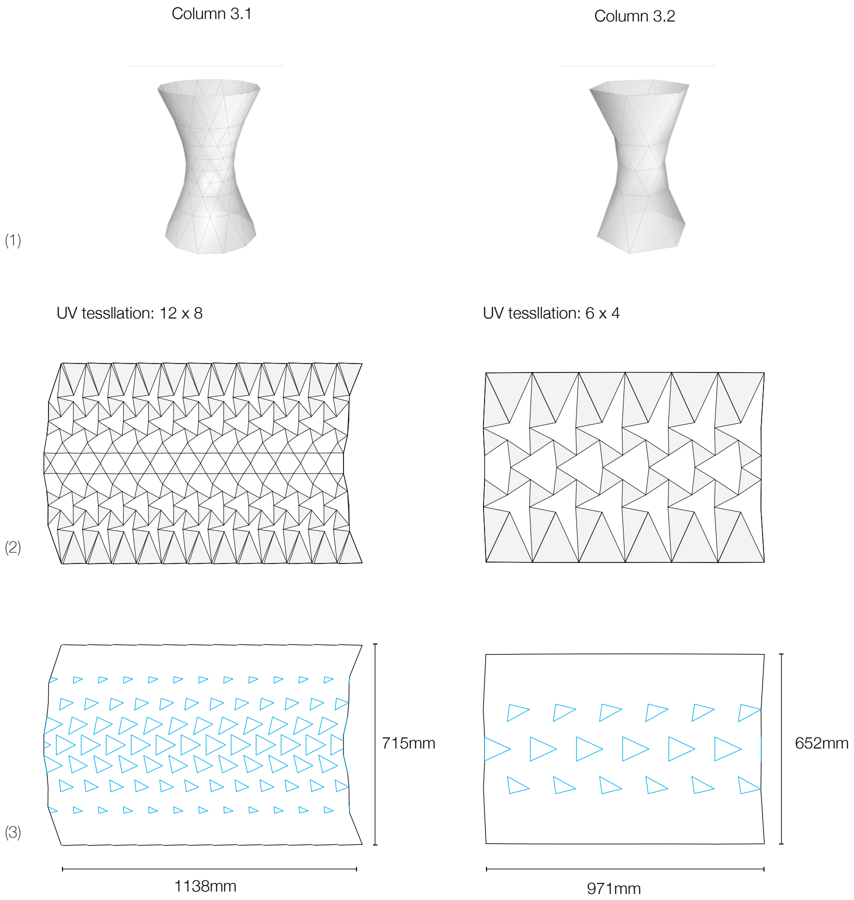
a successful proof of concept, demonstrating that it is possible to generate a smocking pattern for a three-dimensional, non-zero Gaussian input surface. For further information regarding this experiment, see **'APPENDED PAPER B'.**

Two challenges with this process should be noted: Firstly, the unrolled mesh faces along the pattern's border did not have enough Kangaroo 2 'goals' and flapped unpredictably during the simulation's spring-relaxation. While internal triangles had been fitted with a series of cross springs for stability, these edge conditions tended to rotate more freely due to a lack of constraints. Secondly, ensuring that the seam lines (left and right sides) matched proved to be more difficult than previously anticipated due to the over-rotation of the edge mesh triangles. These challenges were handled with an ad-hoc addition of several springs to ensure the uniformity of smock size and shape in the first prototype and the matter was later resolved entirely during the development of *OriNuno*.

5.2.1 *Column 3.2*

Column 3.1 successfully showcased the milestone of patterning development in deconstructing a three-dimensional input form to a two-dimensional 'Arrow' smocking pattern. In order to take this probe a step further while keeping with the methodology of this research, the *Column 3.2* pattern utilized a lower-resolution mesh tessellation to accommodate fabrication constraints such as smock size and spacing. The high resolution of *Column 3.1*'s tessellation meant that there were no constraints with regard to minimum smock dimension and ultimately proved to be too detailed and featured too many overlaps to be used in producing a viable concrete cast. These practical parameters, such as smock size constraints and tessellation variation, were integrated into the Kangaroo 2 tool. *Column 3.2* had an identical input shape to *Column 3.1*, but a lower resolution (12 x 8 as compared to 6 x 4). This change resulted in a decrease in the number of vertices in the mesh (and, in turn, the number of smocks); from 108 smocks for *Column 3.1* to a mere 18 smocks for *Column 3.2* (see **FIGURE 5.36**). The mesh tessellation resolution was inversely correlated with the size of each smock; by changing the tessellation parameters, it was possible to vary the pattern between numerous, smaller smocks and fewer, larger ones. Based on earlier casting probes using fabric formwork, the smock size bounds for *Column 3.2* were set to 200–280 mm, compared to 91–232 mm for *Column 3.1*.

The *Column 3.2* pattern successfully met the requirements for concrete casting.



Num smocks:	108
Starting fabric size:	1138 x 715 mm
Minimum smock size:	91 mm
Maximum smock size:	232 mm
Average smock size:	158 mm

Num smocks:	18
Starting fabric size:	971 x 652 mm
Minimum smock size:	216 mm
Maximum smock size:	280 mm
Average smock size:	239 mm

FIGURE 5.36: Comparison of *Column 3.1* and *3.2*: (1) mesh tessellation, (2) unrolled mesh faces and (3) smock pattern and fabrication data (Source: author).

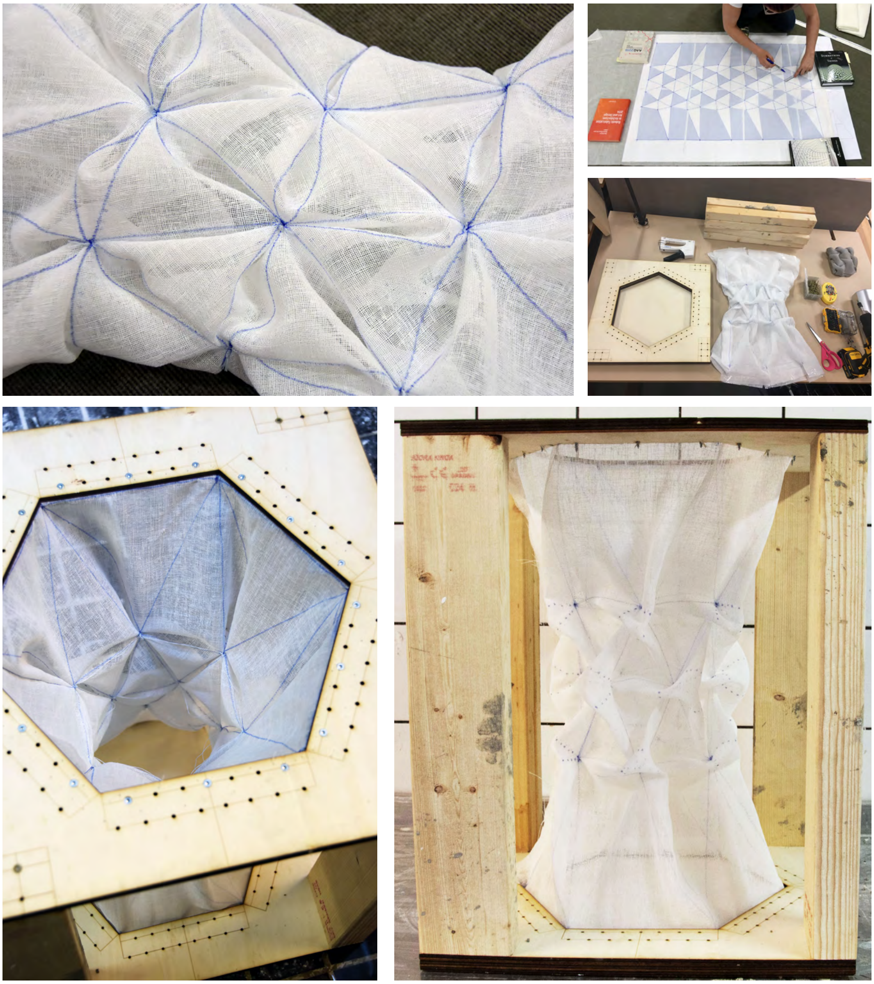


FIGURE 5.37: *Column 3.2* formwork fabrication (Source: author).

FIGURE 5.38: *Column 3.2* cast prototype (Source: author).

The formwork was produced using woven linen, and the smocking pattern was hand-transferred and smocked using the same method as previous probes in the *Column* series. The fabric was pliable yet non-elastic, allowing ease of workability without the risk of hydrostatic pressures compromising the global form. Tape was placed along the edge of the textile to limit fraying. The laser-cut top and bottom of the wooden part of the formwork ensured that the boundary conditions were fixed and ensured greater ease of correlation (see **SECTION 5.3**). Internally, a tension ring of industrial sewing thread was used to anchor the smocks relative to one another and maintain the specified target radius using tension. Despite a mixer malfunction during the casting of the upper section (which resulted in some superficial separation in the mix), *Column 3.2* was successful; the smock size and arrangement allowed the concrete to flow easily within the smock folds.

This prototype concluded the *Column series*, achieving a variety of milestones. The series demonstrated:

- Successful deconstruction of a three-dimensional shape into a smocking pattern.
- High precision and control over smock size and arrangement.
- Continuing inclusion of real-world fabrication constraints within the development workflow and design.
- Successful correlation to simulation (see **SECTION 5.3.6**) with -26.2 to 22.5 mm deviation.

5.2.2 *Torus 2.0*

When conducting research, it is valuable to relate experiments to practical applications and thus encourage adoption of novel techniques outside the realm of academia. ArroDesign's Lawton highlighted the difficulties involved in fabricating *Fabric Formed Stair* (**FIGURE 5.39**), a concrete wall that morphs into an arch situated underneath a long staircase (S. Lawton, personal communication, May 17, 2019). The project was cast in flexible formwork, although there was undesirable wrinkling of the fabric arch due to the approximating of a double-curved geometry using a fabric sheet. Projects such as these could benefit from smocked fabric formwork using programmed, parametric tucks and folds to avoid the incidence of undesirable wrinkles. This practical and relevant case study was an excellent test case to explore the potential of smocking with large-

FIGURE 5.39: ArroDesign's *Fabric Formed Stair* (Lawton, 2013).

scale architectural applications in mind.

While *Torus 1.0* (**FIGURE 5.25 (2, 3)**) was generated based on intuition and manual unrolling, the torus form was revisited with a more computationally-informed approach. Based on the evolution of and insights provided by the computational patterning probes (such as *Column 3.1*), the square tessellation was replaced with a triangular mesh; this enabled an appropriate substructure to generate an 'Arrow' smocking pattern using the same patterning steps outlined in previous sections. **FIGURE 5.40 (2)** shows the input torus mesh with numbered vertices as well as the conformally-mapped, flat mesh (with idential structure) before and after edge length equalization. The highlighted green mesh face in the three- and two-dimensional meshes served as confirmation that the flattened mesh was correctly oriented.

While some experiments used in the research presented in this thesis were designed to investigate a specific question or aim, this demonstrator was fabricated solely to showcase patterning control. *Torus 2.0* contrasts with *Cone*, *Dome* and *Torus 1.0*, highlighting the development and sophistication of the patterning technique achieved within the scope of this research. Constructing patterns based solely on intuition was replaced with deliberate, controlled and technical patterning techniques. A film showing the pattern generation process is linked in **'SELECTED VIDEO DOCUMENTATION'** (Scherer, 2019a).

5.2.3 The *Hyperbola Catalog*

As noted in **SECTION 4.1.1**, when experimenting with relatively novel techniques, rigorous testing with a wide variety of conditions is valuable to understand the

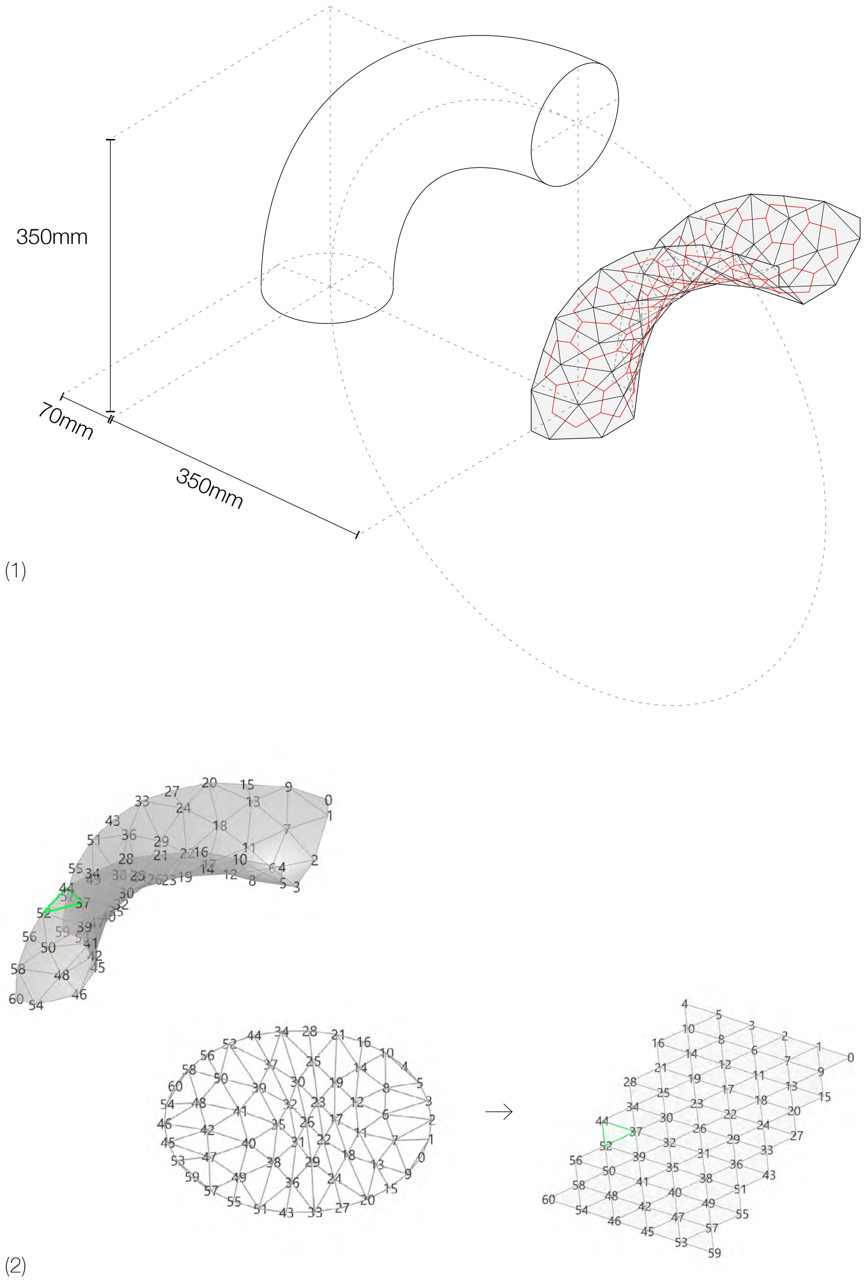
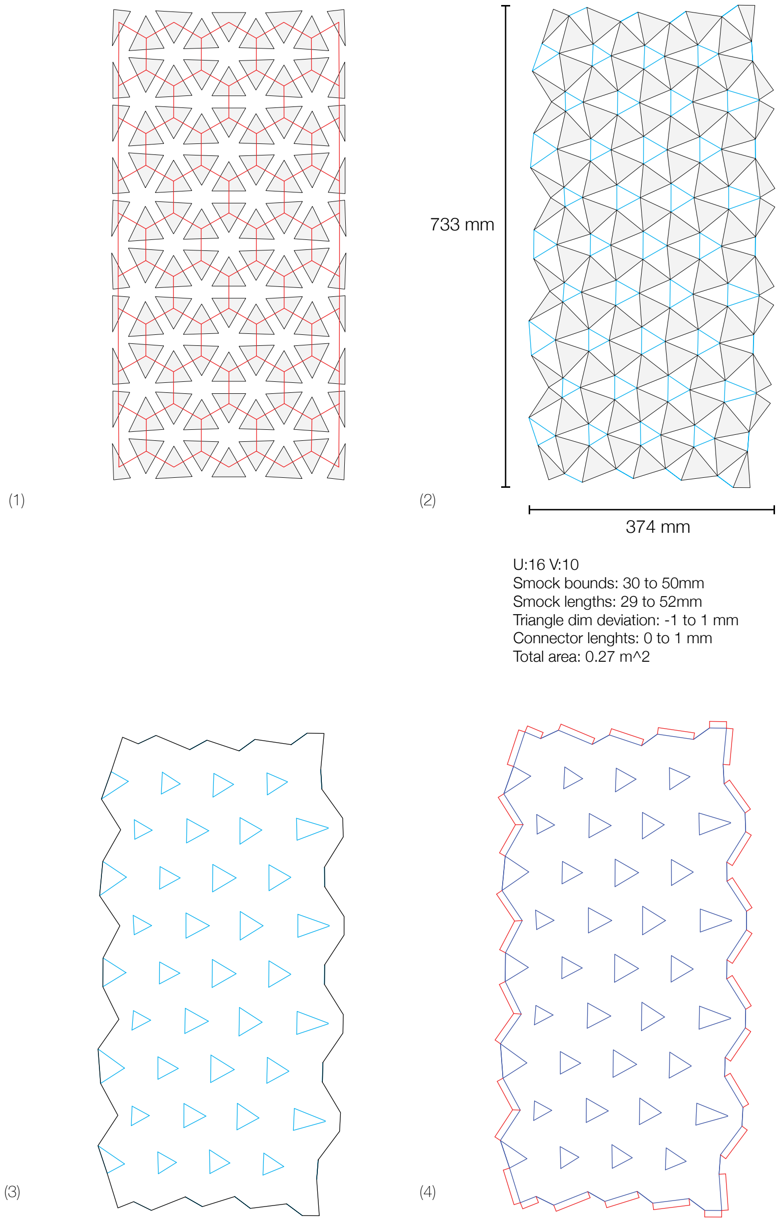


FIGURE 5.40: *Torus 2.0*: (1) hexagonal mesh dual substructure visualization and (2) conformal mapping with length equalization (Source: author).



U:16 V:10
Smock bounds: 30 to 50mm
Smock lengths: 29 to 52mm
Triangle dim deviation: -1 to 1 mm
Connector lenghts: 0 to 1 mm
Total area: 0.27 m^2

FIGURE 5.41: *Torus 2.0* pattern generation: (1) triangle mapping to flat mesh dual, (2) Kangaroo 2 relaxation with target lengths, (3) smock pattern and (4) laser cut file with tabs (Source: author).

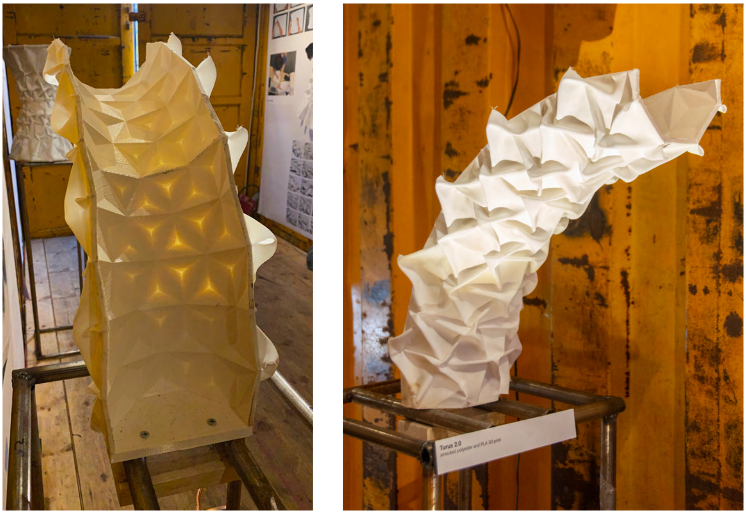


FIGURE 5.42: *Torus 2.0* fabricated model on exhibition at Galleri Frihamnstorget (Source: author).

strengths and limitations. The computational patterning experiments that have been presented thus far in the thesis did not focus on rapid prototyping and design variation. Hence, a series of hyperbola smocking patterns were rapidly prototyped to test the limits of *OriNuno* with various tessellations and smock constraints. This 'pringle' geometry was selected due to its well-known applications in architecture and engineering (see **FIGURE 3.2 (1)**) to create the *Hyperbola Catalog* demonstrator; this pushed the limits of the *OriNuno* tool, demonstrating control of smocking patterns and formalizing the knowledge obtained as a result of the research presented in this thesis into a clear catalog. The following patterning experiments are collected into a catalog as a demonstration of the range and flexibility of the *OriNuno* tool.

A hyperbolic surface measuring 200 x 200 x 150 mm served as the input form (**FIGURE 5.43**). It was selected because, as noted in *Architectural Geometry*,

> *Elliptic and hyperbolic vertices of a polyhedron are counterparts of elliptic and hyperbolic points of a smooth surface. Therefore, if a polyhedron is a good approximation of a smooth surface that contains hyperbolic regions (those with negative Gaussian curvature) there is no chance to obtain a connected unfolding without overlaps* (Pottman et al., 2007, pp. 562–563).

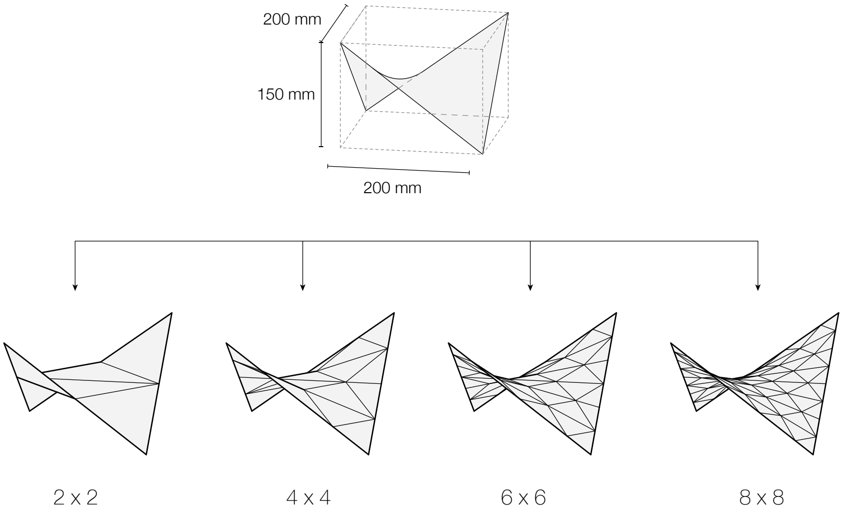


FIGURE 5.43: Variable hyperbola tessellation resolution as input for smocking pattern generation tool (Source: author).

Therefore, a hyperbolic shape was found to be an apt, fundamental shape for demonstrating the robustness of patterning flat sheet material into negatively curved surfaces.

A comparison between existing state-of-the-art unrolling techniques (Pepakura Designer, Ivy, Origamizer) and the smocking pattern generation tool developed during the research is shown in **FIGURE 5.44**. Pepakura Designer (a stand-alone software), while useful for hobby paper-craft projects, was quickly exhausted as the tool uses a strip-unroll approach that deconstructs input surfaces into many individual components. Ivy also generates multiple 'tabbed' parts from an input surface; however, given that it is more accessible (available as a Grasshopper plugin), various components such as 'mesh-dual' were later integrated into the *OriNuno* tool. These components enabled the mapping of three-dimensional mesh triangles to an identical, conformally-mapped, flat mesh (see **FIGURE 5.40 (2)**). As previously discussed, although Origamizer produces single-sheet folding patterns, due to the lack of customization options the *OriNuno* tool was developed.

A series of variable smocking patterns was generated and plotted on a graph

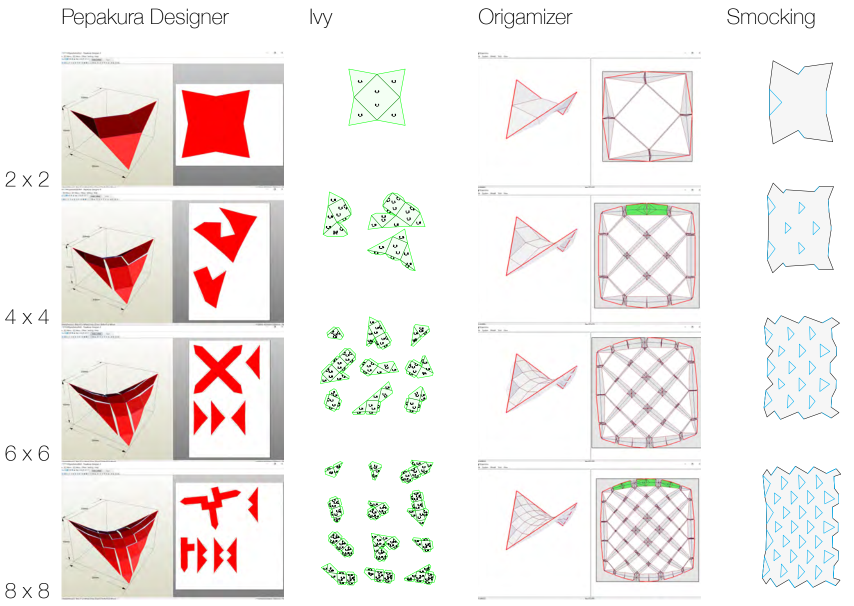


FIGURE 5.44: Various unfolding techniques of a hyperbola using Pepakura, Ivy, Origamizer, and smocking (Source: author).

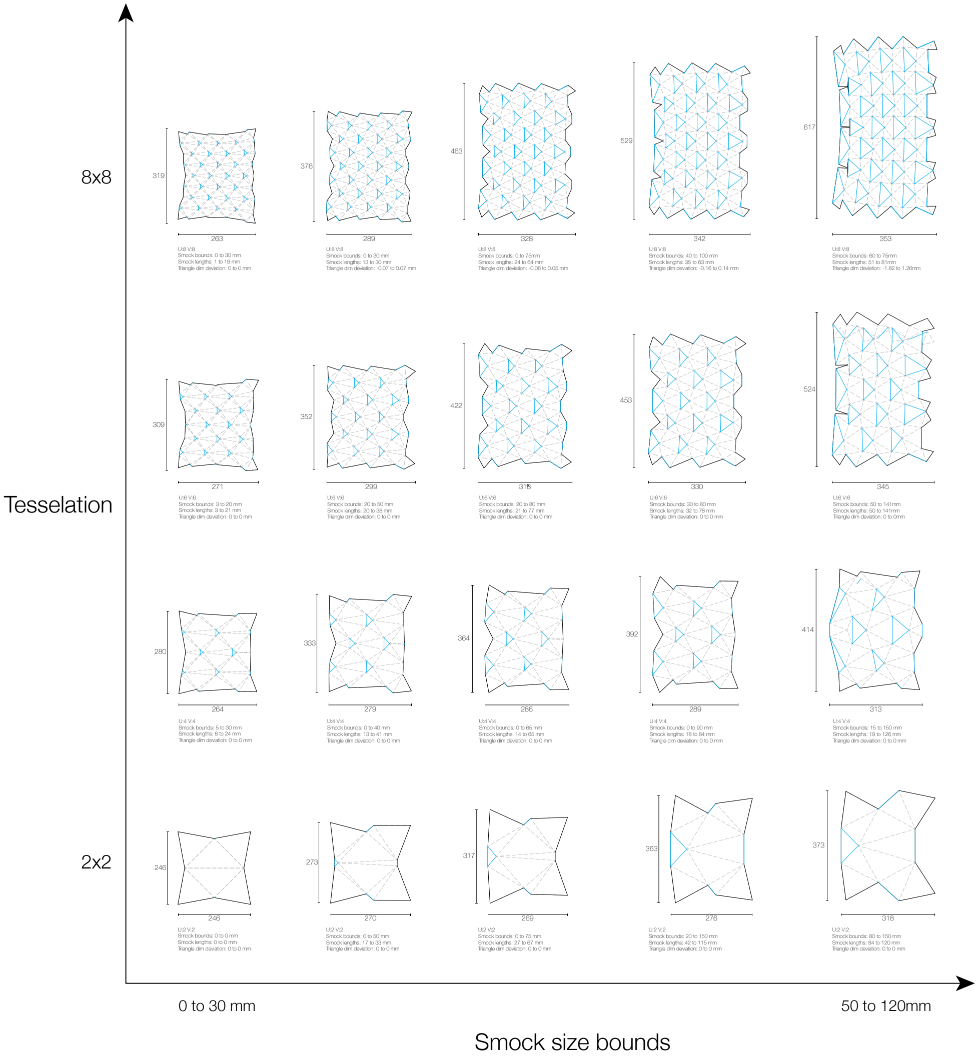


FIGURE 5.45: Generated smocking patterns of a hyperbolic input shape, showcasing control of smock dimension and resolution (Source: author).

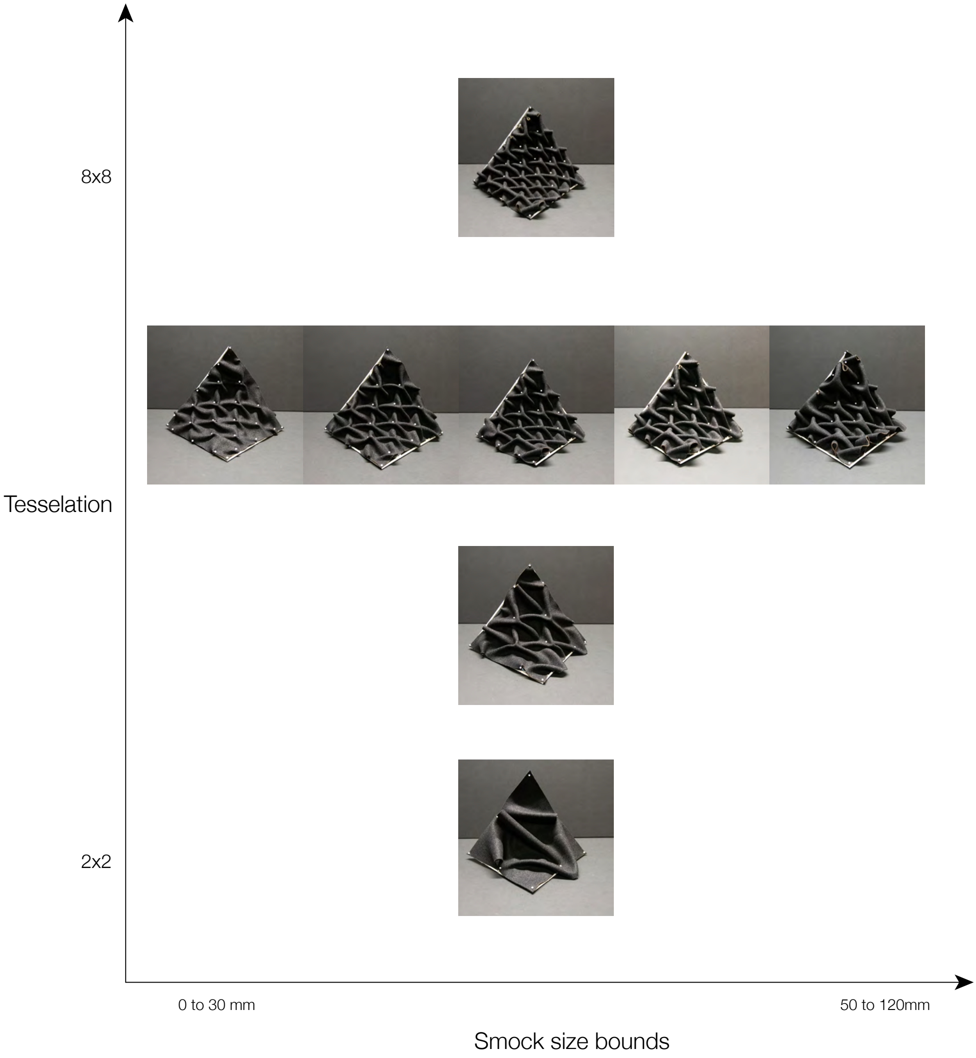
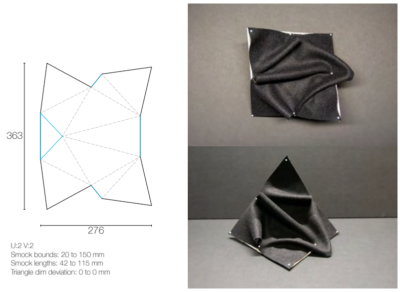
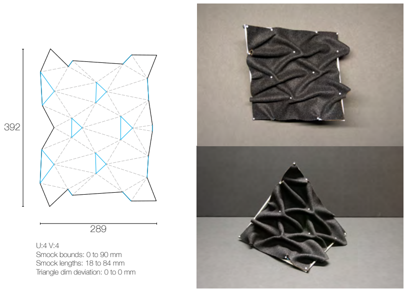


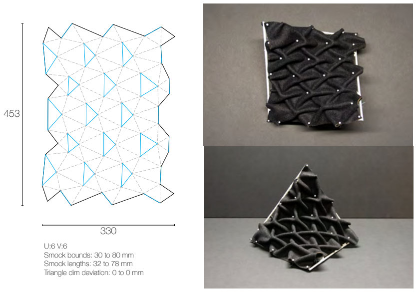
FIGURE 5.46: Hand-smocked hyperbola models plotted on a graph. Smock size is plotted on the X axis and smock resolution is plotted on the Y axis (Source: author).



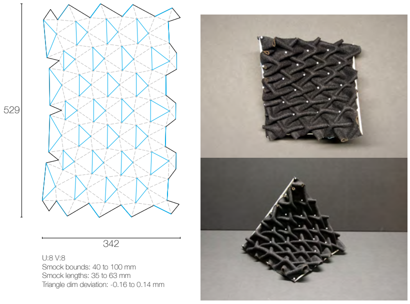
2 x 2



4 x 4

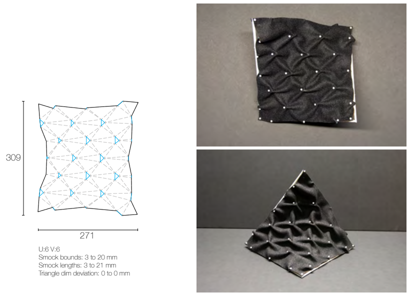


6 x 6

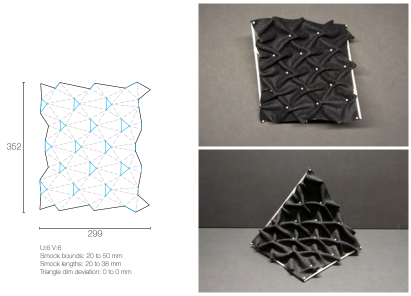


8 x 8

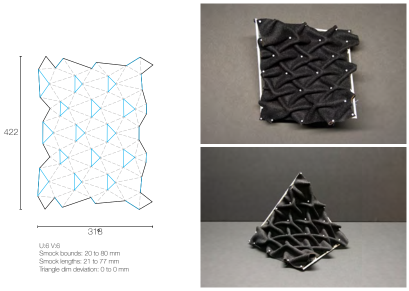
FIGURE 5.47: Variable smocking tessellation resolution of a hyperbola (Source: author).



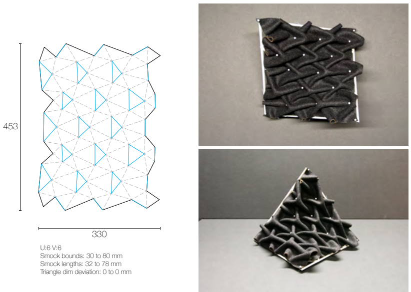
3-21 mm



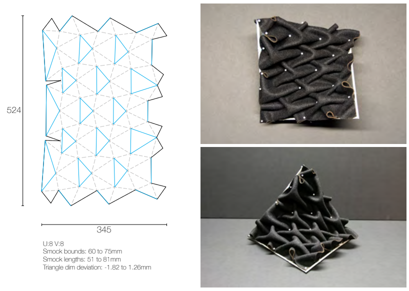
20-38 mm



21-77 mm



32-78 mm



51-81 mm

FIGURE 5.48: Variable smocking size (lengths) of within a 6 x 6 tessellated hyperbola (Source: author).

(**FIGURE 5.45**). The X axis increases the bounds of the smock sizes (with a bounds of 0 to 150mm). On the Y axis, the UV mesh tessellation increases from 2 x 2 up to 8 x 8. All 16 of these patterns were possible to smock, and nine were fabricated to showcase two subsets of themes (**FIGURE 5.46**). As shown **FIGURE 5.47**, the first subset exhibited a range of mesh tessellations approximate a shape with varying degrees of closeness. A trade-off existed between a higher tessellation (resulting in a greater number of smocks) with a higher shape fidelity and a lower tessellation (resulting in fewer smocks), the latter of which can result in faster fabrication and assembly.

The investigations of the second subset of hyperbolas (**FIGURE 5.48**) highlighted controllable variation in smock dimensions while approximating a shape with identical tessellation. From a practical fabrication perspective, having control over smock dimensions was essential. A low average smock size reduces the required fabric formwork area, resulting in lower material costs. However, should the smocks be too small, cast concrete may not flow into the folds, and the cast details may not be readable. Additionally, some flexible materials may be relatively stiff and a 'minimum smock size' parameter might be required (**SECTION 5.1.7**). The *Hyperbola Catalog* constituted a demonstrator that facilitated a high degree of control over the two core parameters of tessellation and smock size, both of which were possible to adjust for rapid pattern prototyping based on the material constraints of the intended form.

5.2.4 *Wall Three*

Having successfully obtained adequate control of smocking tessellation parameters with the *Hyperbola Catalog*, these findings were applied to an architectural context. The *Wall Three* demonstrator was formulated in response to the purely geometrical patterning demonstrators *Column 3.1* and the *Hyperbola Catalog* in order to apply full-scale smocking to a wall element. The following sections unpack the following 'groups' of the *OriNuno* tool: *design*, *pattern generation* and *fabrication constraints* (**FIGURE 5.17 (1-3)**) .

An investigation into the architectural applications of Concrete Canvas® (CC) and smocking was initiated to explore the geometrical possibilities of smocking without limiting the forms to 'castable,' solid geometries. CC is a layered composite consisting of PVC, concrete webbing and canvas (**FIGURE 5.49**) which is structural when hardened; this material facilitated the exploration of the parametrically tailoring of complex surfaces with regard to smocked architectural

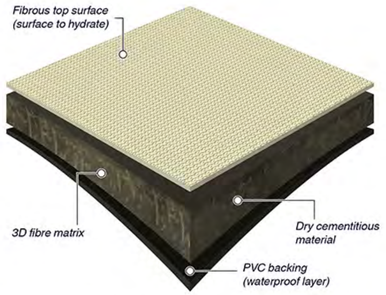


FIGURE 5.49: Concrete Canvas® (Concrete Canvas, n.d.).

geometries. This experiment served as a demonstrator, synthesizing the cumulative parametric patterning knowledge and integrating them with full-scale fabrication constraints.

CC material tests. Two sample pieces (measuring 20 x 28 cm) of CC were explored to understand how this material could be smocked (**FIGURE 5.50**). These probes used off-the-shelf grommets and zip-tie smock connections to investigate the thickness difference between CC with a thickness of 5 or 8 mm (referred to as 'CC5' and 'CC8,' respectively) when applied to full-scale smocking. Due to the increased thickness and consequently decreased bending radius of the material, CC8 required a larger minimum smock size (220 mm) as compared to CC5 (170 mm). Secondary experiments sought to answer more specific fabrication questions such as minimum (feasible) smock size (**FIGURE 5.51**) and panel connection hardware required (**FIGURE 5.52**). While the minimum smock size when working with CC was initially thought to be ≈200 mm (based on the material's bending radius), a 'Lozenge' probe with a 100 mm grid proved to be viable. No grommets were used in this test in order to determine the degree of their necessity; however, material tearing in the tests proved that grommet reinforcement is essential in large-scale applications. The smocks in **FIGURE 5.51** were joined together with an off-the-shelf cord lock rather than zip ties to retain adjustability and ensure ease of assembly. While this connection type functioned on a relatively small scale, further investigation was required for larger applications.

The process of investigating hardware connection and grommet types is shown

CC8 ‘Lozenge’ smock

CC5 ‘Arrow’ smock

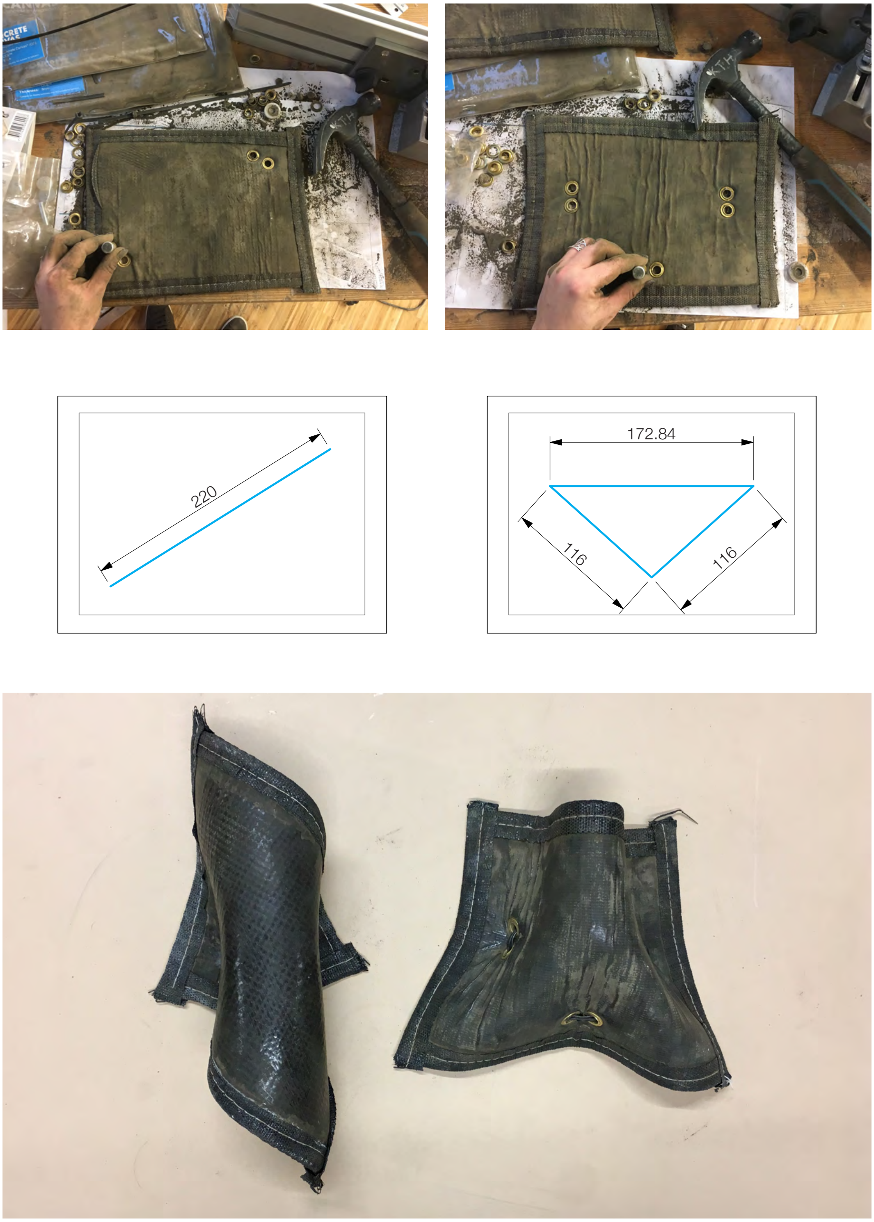


FIGURE 5.50: Material investigations of ‘Lozenge’ and ‘Arrow’ smocking on CC8 and CC5, respectively (Source: author).

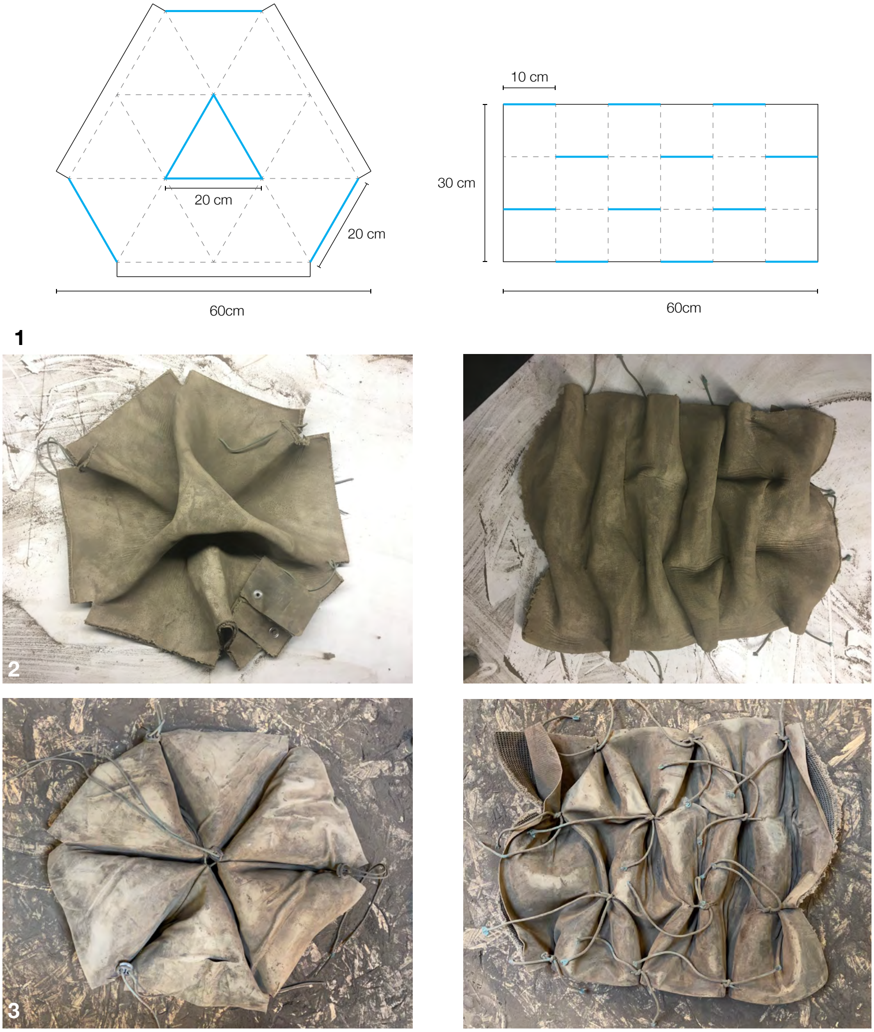


FIGURE 5.51: (1) 'Arrow' and 'Lozenge' patterns with (2) front and (3) back of corresponding CC5 material tests (Source: author).

FIGURE 5.52: Various connection hardware tests (Source: author).

in **FIGURE 5.52**. These tests explored the viability of button snaps and grommets of various neck lengths; a neck length of 9 mm was found to be optimal in conjunction with a material thickness of 5 mm. Potential seam connections such as heat welding and hardware ranging from bolts and rivets to molly bolts were also investigated. Heat welding was determined to be both the most secure and straightforward method and was undertaken using a heat gun and a roller; the PVC backing melted at 400°C and formed a watertight bond to the canvas layer of the next panel. While the hardware connections were also viable, they added unnecessary complexity to the construction process.[27]

Wall Three Design. With a continuous feedback loop between design, fabrication and simulation, the knowledge gleaned from these initial material tests was regularly integrated into the development of *OriNuno*. Three design proposals (**FIGURE 5.53**) were formulated using the *design* 'group' of *OriNuno* (**FIGURE 5.17 (1)**) for a full-scale wall installation:

- *Wall One*: A lofted surface consisting of mirrored sinusoidal waves (3 x 2 x 0.66 m).
- *Wall Two*: Lofted interpolated curves intended to demonstrate transitioning around a corner (2 x 2 x 2 m).
- *Wall Three*: A lofted surface between a sine wave curve and a straight line (4 x 2 x 1.73 m).

In order strengthen the cyclical flow of information between digital and physical realms, 1:10 scale models of *Wall One* and *Wall Three*'s patterns were laser-etched on the textile and sewn (see **FIGURE 5.54**). *Wall Three* was ultimately selected as the final design for this demonstrator, given its communication of design intention. The intention of this demonstrator was to showcase the ability to parametrically pattern a double-curved surface from a single, flat sheet of material; consequently, a simple surface that lofts between a straight line and a sinusoidal wave (exhibiting both positive and negative Gaussian curvature) was determined to be the strongest design candidate.

---

[27] While supplemental hardware was not utilized on the panel-seam connections of *Wall Three*, these methods could be utilized in situations where a heat-welded seam might require local material reinforcement.

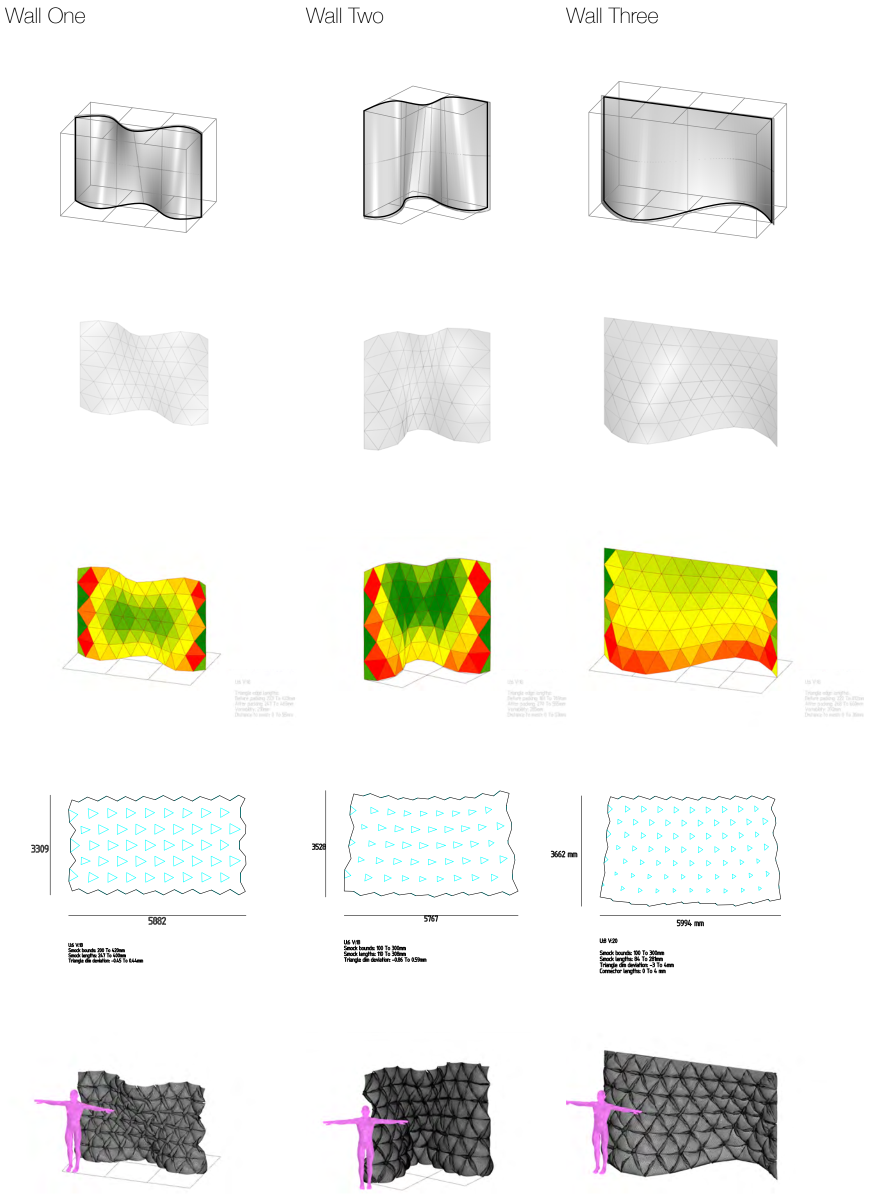
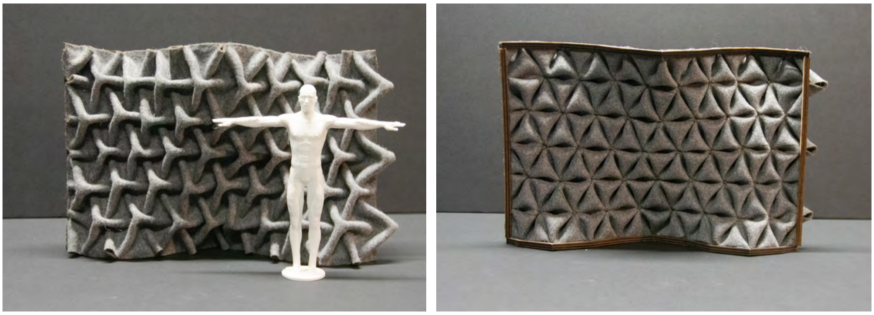


FIGURE 5.53: *Wall One*, *Two* and *Three* design exercise: (1) input surface, (2) surface tessellation, (3) circle packing and area equalization, (4) smocking pattern generation and (5) simulation (Source: author).

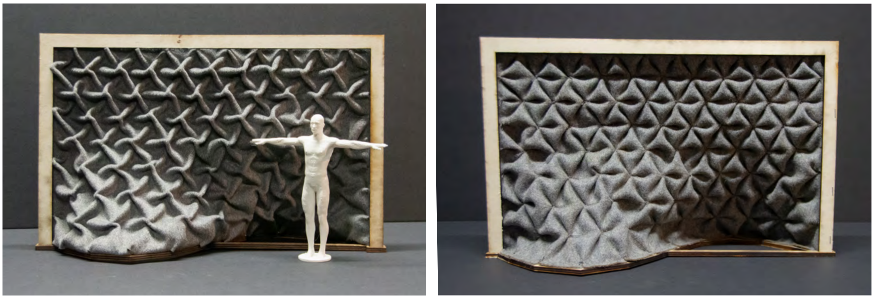


Wall One

Pattern:
U:V 6x18
Set smock bounds: 200 to 420mm
Actual smock lengths: 247 to 400mm

Unrolling Deviation:
Triangle edge lengths: -0.45 to .44mm
Connector lengths: 0mm

Fabrication:
Wall size: 2m x 3m x 0.66m
Fabric size: 5.88m x 3.31m



Wall Three

Pattern:
U:V 8x20
Set smock bounds: 100 to 300mm
Actual smock lengths: 84 to 281mm

Unrolling Deviation:
Triangle edge lengths: -3 to 4mm
Connector lengths: 0 to 4mm

Fabrication:
Wall size: 2.5m x 4m x 1.73m
Fabric size: 5.99m x 3.66m

FIGURE 5.54: *Wall One* & *Wall Three* 1:10 scale models with corresponding patterning and fabrication data (Source: author).

Wall Three Fabrication Constraints. After the *Wall Three*[28] design had been selected as the demonstrator, further investigation of detailing was conducted in relation to real-world fabrication implications (shown in **FIGURE 5.55**). This process utilized the patterning and simulation tool 'groups' of *OriNuno* (**FIGURE 5.17 (2-4)**) to compare and optimize the following parameters:

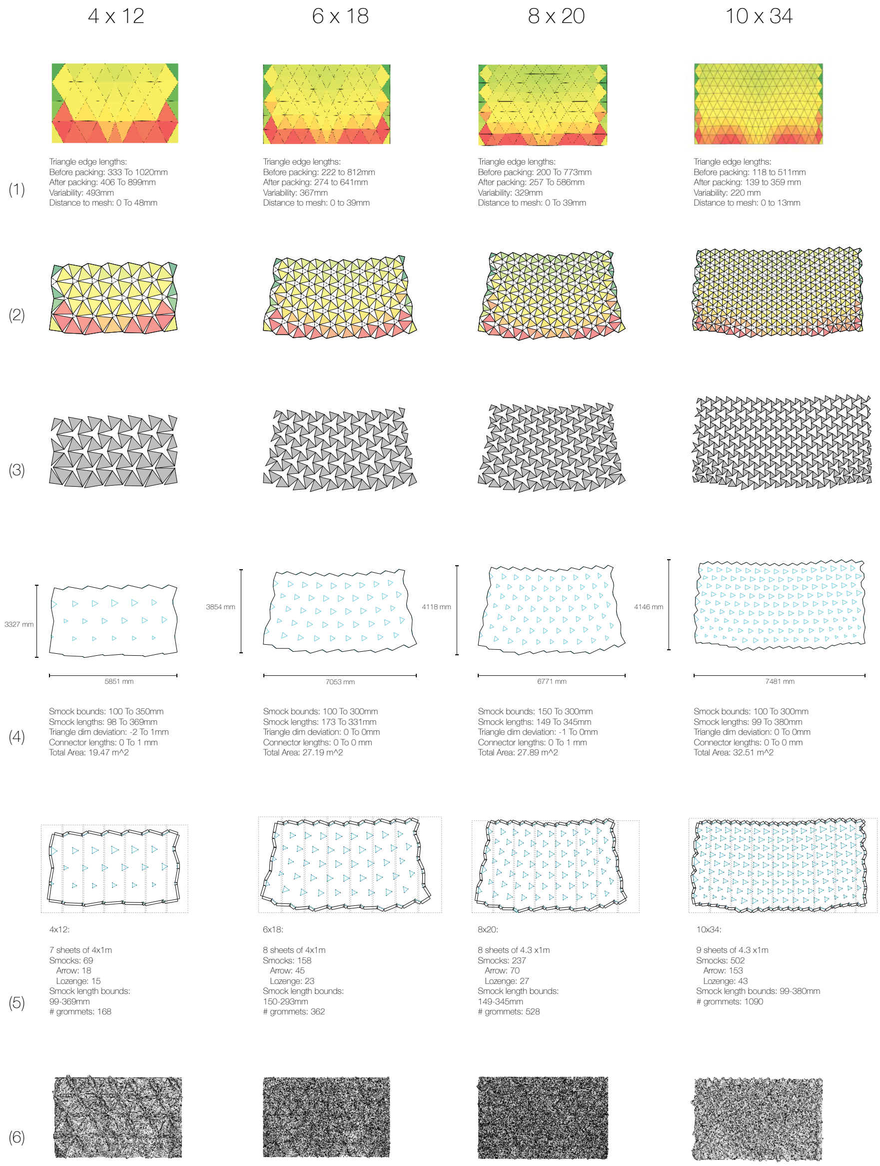
- Various mesh tessellation resolutions.
- Circle packing and deviation in relation to the original input surface.
- The deviation of the generated pattern from the original surface.
- Minimum and maximum smock sizes.
- The amount of required material in square meters, number of grommets and locations of seams.
- The visual depth of the simulated pattern.
- Minimal CC cutoff waste.

These parameters were interrelated; a higher mesh resolution more closely approximated the input surface, but there was a trade-off with regard to material use. For example, a 4 x 12 tessellation utilized 19 m^2 of fabric, while a 10 x 34 tessellation with the same smock size required 32 m^2 of fabric. It was possible to lower the smock length bounds to minimize material use, but only to a certain extent. Too small smocks could have negative implications with regard to fabrication aspects (minimum smock size) and surface differentiation. The 8 x 20 tessellation was found to have the optimum balance of these factors and was selected for the design. Based on the scaled model of *Wall Three* (smock length bounds of 81 to 281 mm), the final pattern had larger smock bounds (200 to 350 mm), providing more contrast between the hexagonally tessellated back side and flowing, smocked front side.

While this wall could be constructed from a single sheet, CC is typically sold in one-meter-wide rolls. With a pattern as large as *Wall Three*, it was important to investigate whether the grommet holes or smocks coinciding with a seam would be problematic. Investigation of this (**FIGURE 5.57**) ultimately concluded that,

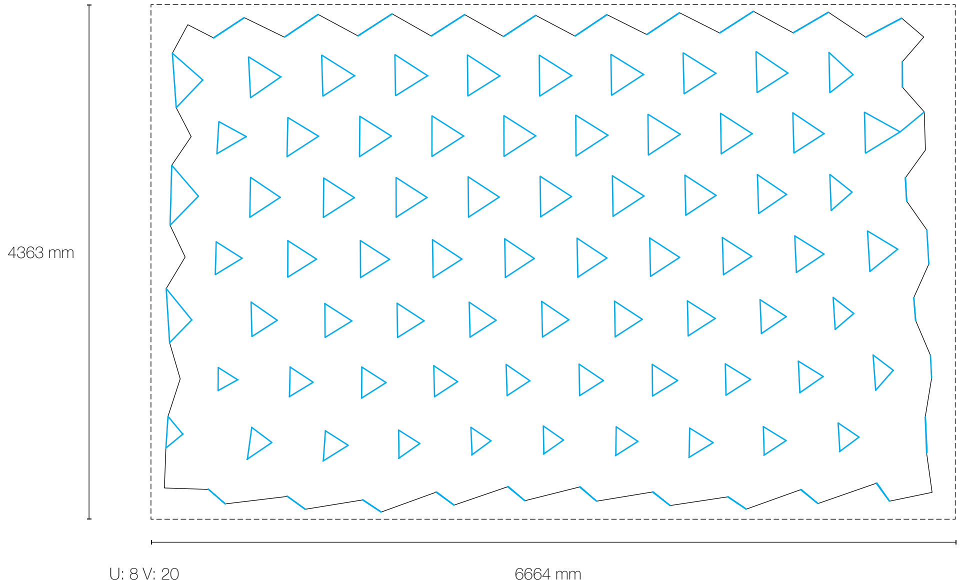
---

[28] While coincidentally the third design iteration, *Wall Three* is titled as such as a nod to the state-of-the-art, fabric formwork precedents *Wall One* and *Wall Two* (Chandler & Pedreschi, 2007, p. 58), which are discussed in **SECTION 3.3.2**.

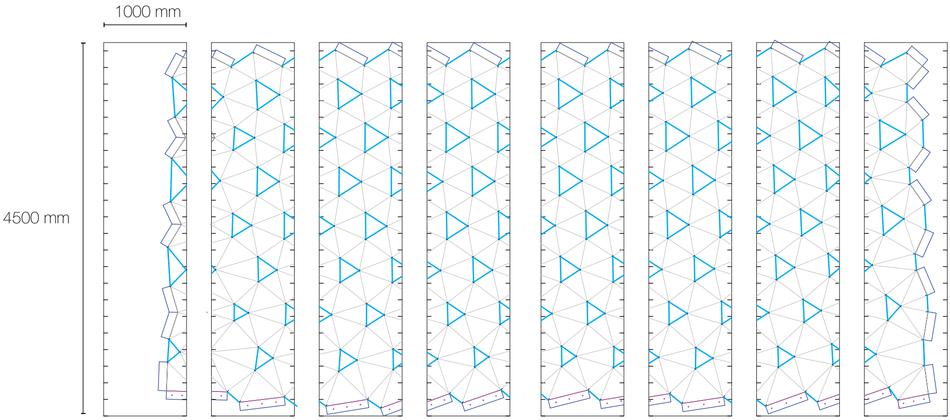


	4 x 12	6 x 18	8 x 20	10 x 34
(1)	Triangle edge lengths: Before packing: 333 To 1020mm After packing: 406 To 899mm Variability: 493mm Distance to mesh: 0 To 48mm	Triangle edge lengths: Before packing: 222 to 812mm After packing: 274 to 641mm Variability: 367mm Distance to mesh: 0 to 39mm	Triangle edge lengths: Before packing: 200 To 773mm After packing: 257 To 586mm Variability: 329mm Distance to mesh: 0 To 39mm	Triangle edge lengths: Before packing: 118 to 511mm After packing: 139 to 359 mm Variability: 220 mm Distance to mesh: 0 to 13mm
(4)	Smock bounds: 100 To 350mm Smock lengths: 98 To 369mm Triangle dim deviation: -2 To 1mm Connector lengths: 0 To 1 mm Total Area: 19.47 m^2	Smock bounds: 100 To 300mm Smock lengths: 173 To 331mm Triangle dim deviation: 0 To 0mm Connector lengths: 0 To 0 mm Total Area: 27.19 m^2	Smock bounds: 150 To 300mm Smock lengths: 149 To 345mm Triangle dim deviation: -1 To 0mm Connector lengths: 0 To 1 mm Total Area: 27.89 m^2	Smock bounds: 100 To 300mm Smock lengths: 99 To 380mm Triangle dim deviation: 0 To 0mm Connector lengths: 0 To 0 mm Total Area: 32.51 m^2
(5)	4x12: 7 sheets of 4x1m Smocks: 69 Arrow: 18 Lozenge: 15 Smock length bounds: 99-369mm # grommets: 168	6x18: 8 sheets of 4x1m Smocks: 158 Arrow: 45 Lozenge: 23 Smock length bounds: 150-293mm # grommets: 362	8x20: 8 sheets of 4.3 x1m Smocks: 237 Arrow: 70 Lozenge: 27 Smock length bounds: 149-345mm # grommets: 528	10x34: 9 sheets of 4.3 x1m Smocks: 502 Arrow: 153 Lozenge: 43 Smock length bounds: 99-380mm # grommets: 1090

FIGURE 5.55: *OriNuno* variations of *Wall Three* (1) tessellation resolution, (2) flat mesh triangle area deviation from input mesh, (3) unrolled mesh triangle faces, (4) smocking pattern, (5) fabrication data and (6) simulation (Source: author).



U: 8 V: 20
Smock bounds: 200 to 350mm
Smock lengths: 189 to 521
Triangle dim deviation: -6 to 6mm
Connector lengths: 0 to 8mm
Total Area: 28.97m
Grommets on seam: 0



Mesh triangles: 160
Total smocks (mesh vertices): 237
  Arrow: 70
  Lozenge: 27
Smock lengths: 194-521 mm
eyelets: 528

FIGURE 5.56: *Wall Three* digitally generated pattern and fabrication data (Source: author).

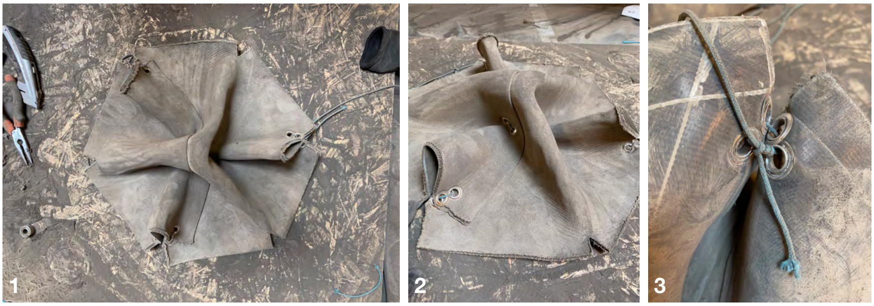


FIGURE 5.57: (1, 2) CC5 'Arrow' smock seam test and (3) tautline hitch detail (Source: author).

while it was physically possible to include grommets (smock vertices) within the seam, excluding grommets from the area avoided multiple neck lengths of grommets (a secondary, longer grommet neck length would have been required to reinforce the double layer of the thicker seam). Consequently, a pattern that supported grommet-less seams was prioritized. It is worth nothing that a seam through the *center* of the smock 'arrow' did not present any fabrication difficulties.

Wall Three Fabrication. *Wall Three* was constructed using ≈28 m^2 of CC, the entirety of which fit easily onto a pallet (**FIGURE 5.58**). The four rolls of CC were cut in half to make eight sheets (**FIGURE 5.58 (1, 2)**), onto which the pattern (which was printed on standard plotter sheets) was overlaid. The grommet holes were punched on each one-meter-wide CC panel using the printed pattern, and 9-mm grommets were inserted to span the 5-mm thickness of the fabric. Registration lines were marked on the panel edges every 20 cm to ensure fabrication accuracy during heat-welding (**FIGURE 5.59 (2)**).

The smocks were pre-laced with a 4-mm nylon rope and secured with a taut-line hitch knot (**FIGURE 5.59 (1)**). This adjustable knot is commonly used in outdoor activities such as camping and adjustable mooring, and increases in strength when tension is applied. While it was previously assumed that a secondary piece of hardware would be required to secure the smocking connection (and withstand the forces of self-weight), this was ultimately unnecessary due to the properties of the taut-line hitch. This specific knot facilitated not only the pre-lacing of the panels but also last-minute adjustments when a smock needed to be adjusted during assembly. After the pre-fabrication process, the panels were laid out and heat-welded together with a 5-mm connection overlap (**FIGURE 5.59 (3, 4)**). The pre-marked registration lines were imperative given that the multi-

FIGURE 5.58: *Wall Three*: (1) panel fabrication, (2) printed pattern overlay and (3) total material volume (Source: author).

FIGURE 5.59: (1) Smock detail over a seam, (2) edge registration marks and (3,4) heat welding assembly (Source: author).

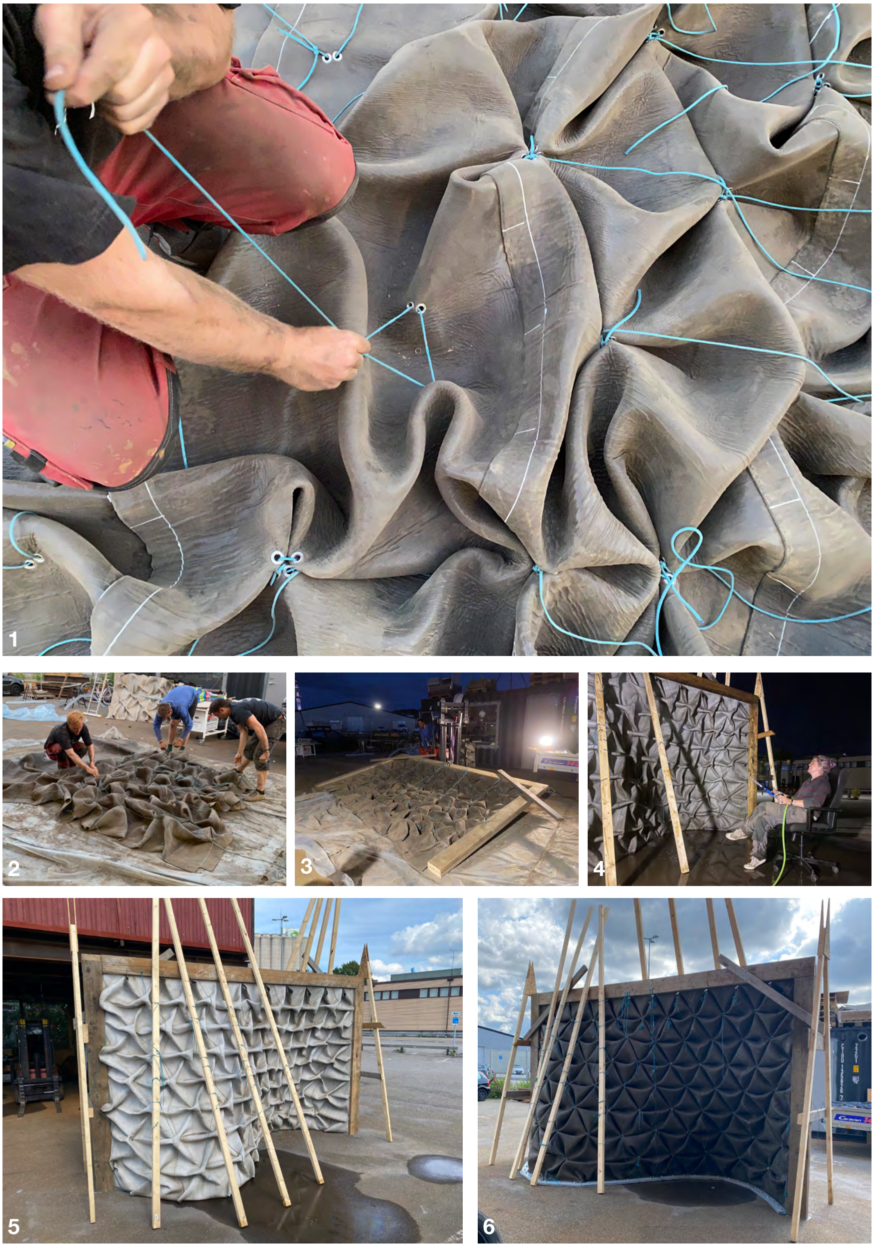


FIGURE 5.60: *Wall Three* (1,2) smocking process, (3) forklift tilt-up, (4) CC hydration, wall curing (5) front and (6) back (Source: author).

FIGURE 5.61: *Wall Three* (1) transport and placement, (2) frame removal, and (3) power washing (Source: author).

material concrete textile contracted asymmetrically when heat was applied.

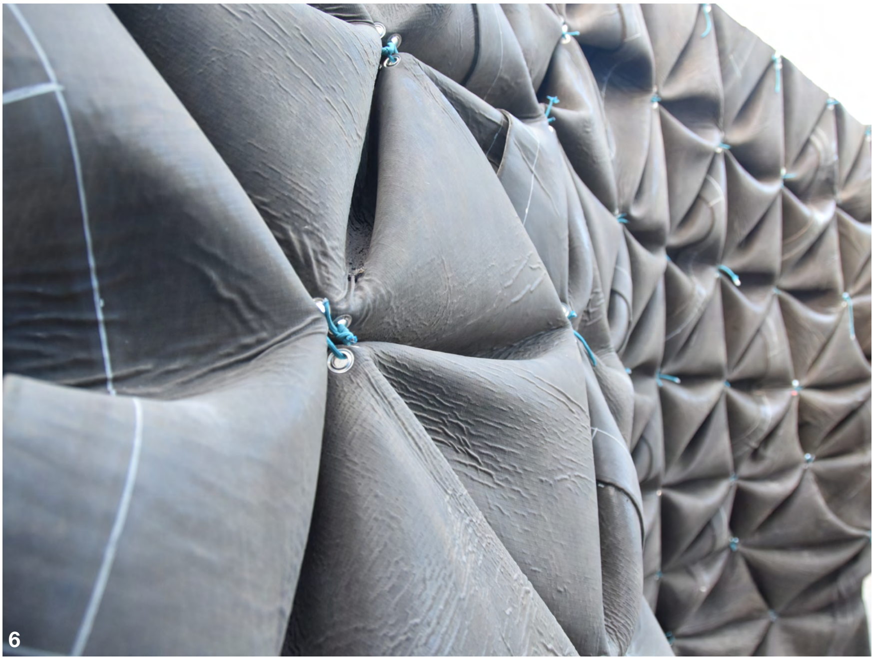
Once the panels were fully assembled, a team of four people began the task of hand-smocking the 28 m^2 of CC, which weighed approximately 200 kg (**FIGURE 5.60 (1, 2)**). Despite the scale and weight of the welded canvas sheet, careful planning, time management and a skilled team ensured a successful build. Upon completion of the smocking, the edge flaps of the wall were stapled onto a simple wooden A-frame and a forklift lifted the smocked CC into place. The bottom flaps were bolted onto a custom plasma-cut steel base. While it was unknown to what extent the fabric would sag under its own weight, the combination of the outside frame and base appropriately tensioned the textile in place, with only a few areas requiring additional tensioning (**FIGURE 5.60 (5, 6)**).

In total, the pre-fabrication of the panels took two people five days, and the installation itself was completed in a day by four team members. The canvas was hydrated (**FIGURE 5.60 (4)**), then allowed to cure for 24 hours before it was moved to its current location in Frihamnstorget (**FIGURE 5.61 (1)**). The frame and wall flaps were removed using an angle grinder (**FIGURE 5.61 (2)**), and the excess lengths of nylon smocking connection were trimmed. The wall was power-washed to remove excess concrete powder, which resulted in a bright-white finish (**FIGURE 5.61 (3)**). A film of the making of *Wall Three* is appended in **'SELECTED VIDEO DOCUMENTATION'** (Scherer, 2021).

Wall Three serves as a successful demonstrator, synthesizing a circuitous feedback loop between design methods of flexible formwork, computational patterning, simulation and correlation and applies this workflow to a full-scale architectural context. The total cost of the project was approximately 15,000 SEK, or €1,400. The fabrication of a self-supporting, four-meter, double-curved

FIGURE 5.62: Wall Three final photos (Source: F. Boukari (1–4), author (5,6)).

5



6

FIGURE 5.63: Permanent placement of *Wall Three* in Frihamnstorget square (Source: author).

architectural wall with such a low cost and efficient fabrication time opened up new possibilities for novel methods of fabricating bespoke concrete elements. Additionally, a relatively small volume of material was required both in terms of CC and supplemental bracing, minimizing resource usage. The relatively low requirements of the project, both in terms of cost and from a sustainability perspective, showed the feasibility of fabricating architectural elements of this type.

DIGITAL:

SIMULATION AND CORRELATION

5.3 Digital: Simulation and Correlation

As is discussed in **SECTION 4.1.1**, the research presented in this thesis made use of a circuitous feedback loop between fabrication tests, parametric patterning and simulation-tool development. The integration of simulation in the fabrication process of flexible formwork, which is normally guided by tacit material knowledge, laid the foundation for a cyclic methodology which evaluated the predictability and consistency of fabricated experiments. In turn, the simulation process, influenced by the physical prototypes, facilitated the generation of potential design solutions with high speed and quantity, which would not have been achievable through physical means. The final section of the chapter discusses the last 'group' of the developed *OriNuno* tool: *simulation and correlation* (**FIGURE 5.17(4)**).

5.3.1 Simulation 'Goal' Breakdown

When working with simple, repetitive patterns, as in the case of the *First Fifteen Hand-Smocked Probes*, the final cast form was relatively intuitive. As the research presented in this thesis progressed onto more irregular and complex patterns, the simulations produced by *OriNuno* were instrumental in visualizing patterns with final smocked forms that were less intuitively predictable. Using a combination of Grasshopper, Kangaroo 2 and Python scripting, *OriNuno* was continuously refined based on knowledge gained as a result of fabricating the initial physical probes.

The process of hand-marking the smocking pattern grid was translated into a more technical coordinate system of mesh lines and particle-based spring 'goals' within the Kangaroo 2 simulation environment. In the same manner that the endpoints of the smocking pattern curves were sewn together, the smocks directly translated into a spring system with a target length of zero (**FIGURE 5.64**). Kangaroo 2 'goals' included:

- A pressure component that simulated concrete inflation.
- Mesh edge lengths which translated to the elasticity of fabric.
- Edge anchor points which fixed the fabric edges to the formwork boundary.

FIGURE 5.65 shows a very early simulation probe with a simple 'Lozenge' pattern.

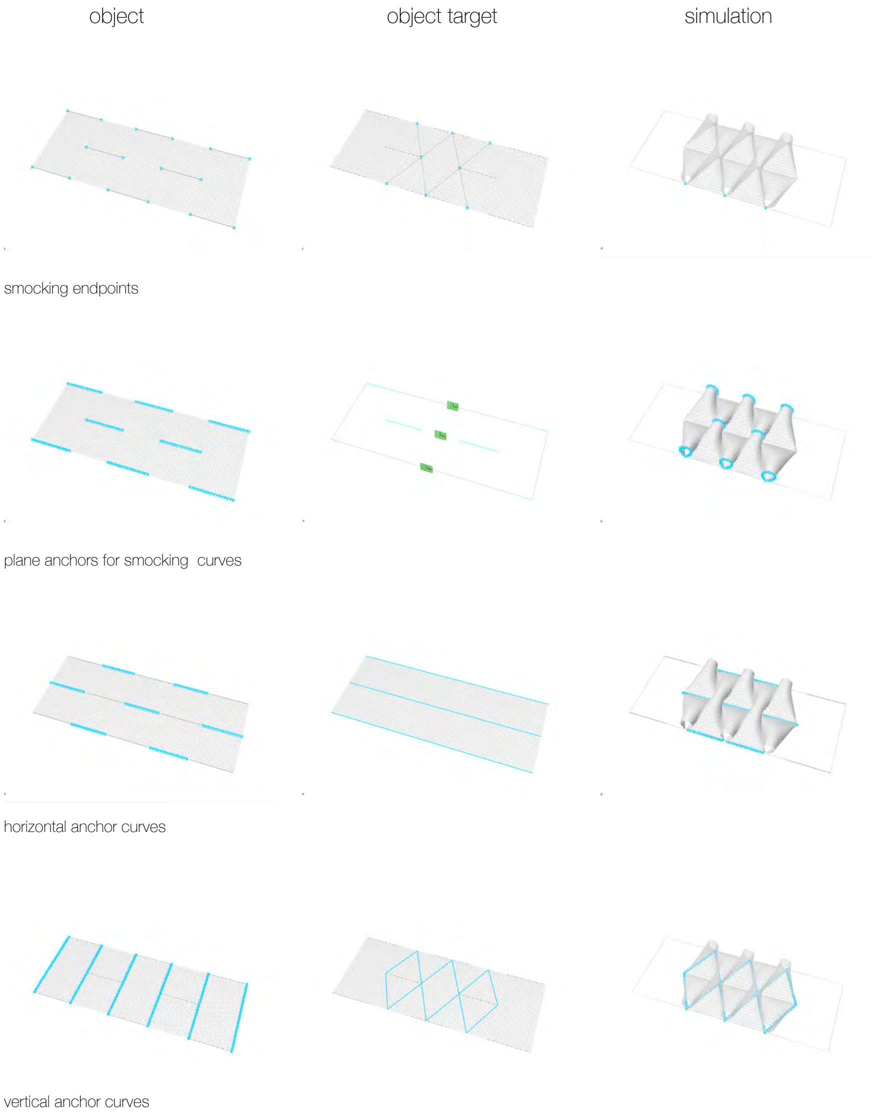


FIGURE 5.64: Summary of Kangaroo 2 ‘goals’ for a ‘Lozenge’ smock (Source: author).

5.3.2 Simulating Flat Smocking Patterns

This research investigated fabric materials with a wide range of elastic properties. This parameter was adjusted in the simulation by manipulating the relationship between the mesh line spring strength and pressure components such that a lower mesh line strength corresponded to a higher fabric elasticity. When the *First Fifteen Hand-Smocked Probes* were simulated, a low mesh strength was used to approximate the high elasticity of the jersey cotton fabric in response to the weight of the concrete.

FIGURE 5.66 shows visual approximations of the cast forms of six of the *First Fifteen Hand-Smocked Probes* developed during a preliminary simulation experiment, developed by visually approximating the cast form. Data points from scanned casts were not initially included in the development of *OriNuno*, as the tool was still in the early stages of development. While the intention of *Simulation 1.0* was to correlate the simulations with the cast probe scans, this was unfortunately not possible for two reasons: the first was due to the fact the

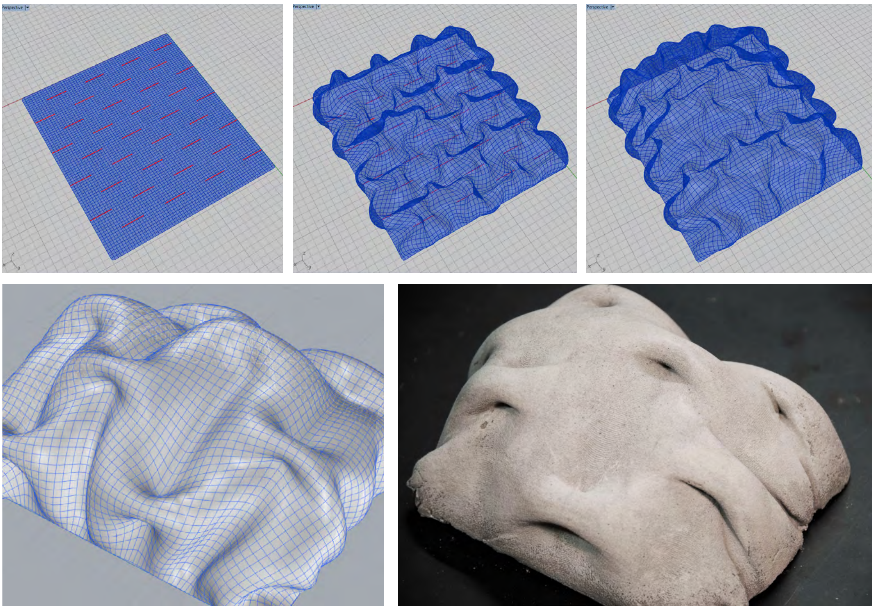


FIGURE 5.65: *Simulation 1.0* of “Lozenge” cast probe (Source: author).

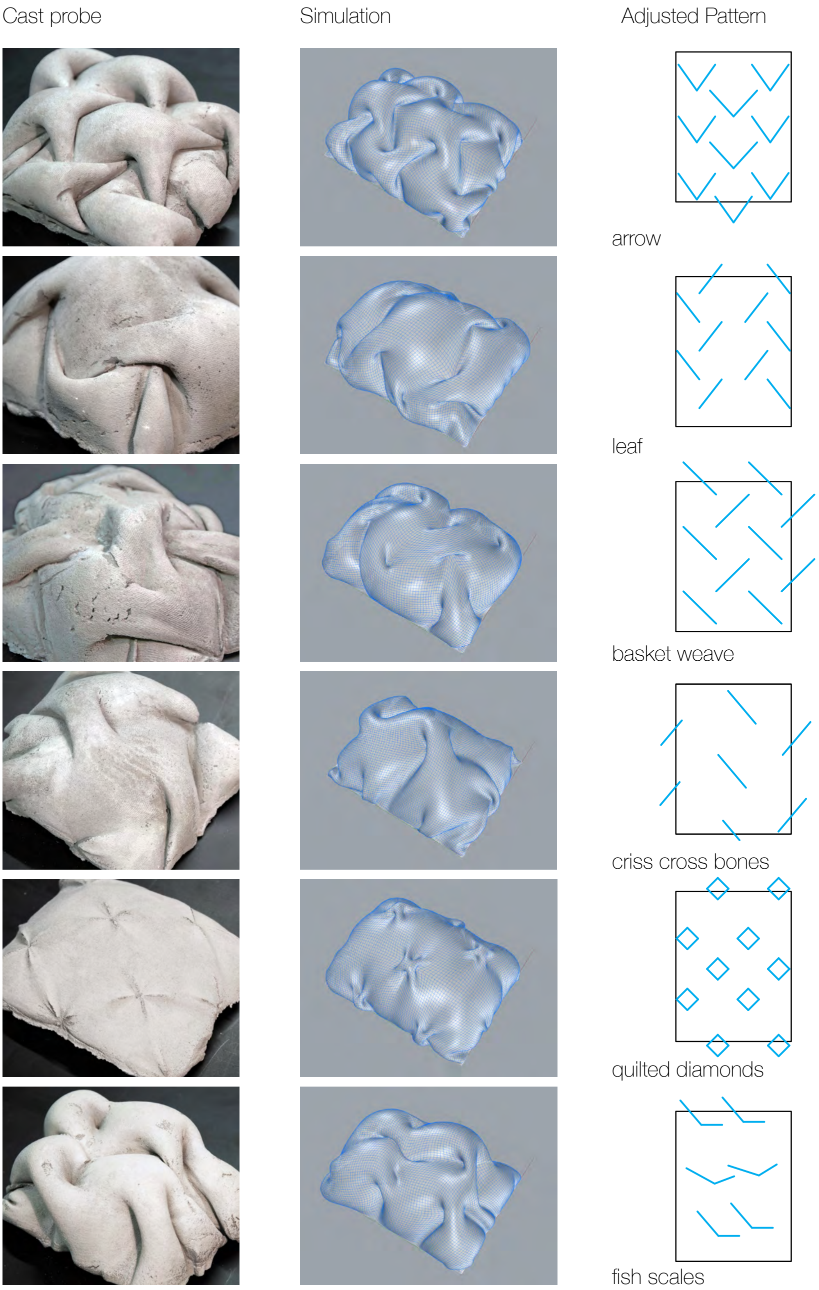


FIGURE 5.66: *Simulation 1.0* with corresponding cast probe and adjusted pattern (Source: author).

boundary outline was not marked on the fabric before smocking; consequently, the sewn formwork was imprecisely stapled to the wood frame. In order to simulate a visually similar form, manual adjustments had to be made to the two-dimensional pattern, as shown in **FIGURE 5.66**. The second reason, which only became apparent in hindsight, was the initially incorrect mesh size of these simulations. The starting size of the mesh was unintentionally (and undesirably) identical to the target boundary of the smocked and cast form (**FIGURE 5.65**). As diagrammed previously (**FIGURE 5.6**), un-smocked fabric is larger than, and in fact often double the size of, the final sewn form. Both the imprecise boundary conditions of the cast probes and the initial size of the digital mesh caused inconsistencies in the simulation, likely contributing to the need for ad hoc adjustments. The importance of these two details was not foreseen during the initial, exploratory phase of this research: the imprecise fabrication method resulted in it being impossible to correlate the cast probes to the simulation, and more exacting standards had to be implemented to correlate the fabricated probes.

The simulation tool was instrumental in visually understanding the underlying, geometrical logic of parametric smocking (**SECTION 5.2.2**). The *Skewed Grids* probes were simulated in conjunction with their pattern development; these were conducted not for the purpose of correlating them to a fabricated object, but to rapidly develop the author's understanding of skewed-grid smocking patterns and their three-dimensional formal implications. Using these tools made it possible to determine the local and global effects of varying a smocking grid (substructure) on fabric.

5.3.3 Rapid Prototyping of Smocked Columns

As the focus shifted to fabrication experiments that explored vertical casting, *OriNuno*'s capabilities were upgraded in parallel to accommodate a wider variety of forms. This evolution provided the opportunity to fine-tune *OriNuno* based on the analysis of the cast probes. The new conditions that arose as a result of the casting becoming vertical required additional Kangaroo 2 'goals'; these included components such as 'hydrostatic pressure' and additional 'anchor points' for the smocks. The carbon-fiber substructure of *Column 02* (**FIGURE 5.13 (1)**) and reinforcement bars of the *Lozenge Panels* (**FIGURE 5.14 (5)**), which were used to prevent global deformation during casting, inspired the introduction of digital smock anchor points in the simulation tool. By limiting global fabric stretching and allowing it to occur locally (only between smock points), the repeatability

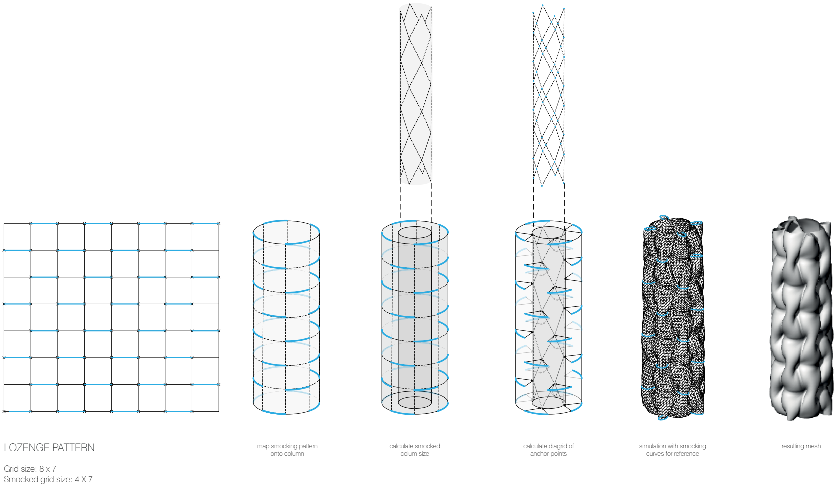


FIGURE 5.67: Smocking anchor point Kangaroo 2 goals for *Column 01* simulation (Source: author).

FIGURE 5.68: *Rapid Column Prototyping* 3D prints (Source: author).

and accuracy of the simulation tool was significantly improved. **FIGURE 5.67** diagrams the integration of these Kangaroo 2 'goals' into the simulation tool, and a video of the simulation is appended in **'SELECTED VIDEO DOCUMENTATION'** (Scherer, 2018).

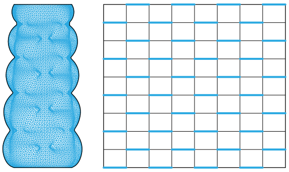
With these improvements to the simulation tool, it was possible to rapidly prototype numerous column variations digitally rather than physically. **FIGURE 5.69** details a selection of the simulated design possibilities. The simulation tool outputs information relevant to the designer, the simulator and the fabricator, including:

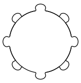
- Design:
    - Simulated cast form shape.
    - Section and plan drawings of simulated cast.
- Simulation tool parameters:
    - Mesh resolution.
    - Kangaroo 2 'goals.'
        - Mesh fabric elasticity.
        - Smocking connection springs.
        - Simulated pressure of concrete.
- Fabrication data:
    - Smocking pattern.
    - Smock dimensions.
    - Grid spacing.
    - Grid size.
    - Fabric size before and after smocking.
    - Column radius and height.

The tool includes a series of practicalities for accurate fabrication and simulation. The fabric smock size is based on the original fabric size and the material loss due to smocks in both the X and Y directions (diagrammed in **FIGURE 5.20**). The Kangaroo 2 simulation settings can be 'baked'[29] along with each simulated column for calibration (**FIGURE 5.70 (1)**). An estimate of the volume of

---

[29] A geometry constructed within a Grasshopper script is only a preview; 'baking' is the act of instantiating the desired Grasshopper output geometry into the Rhino 3D file.

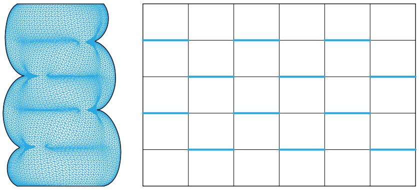


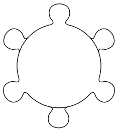


smock width (mm): 50.0
cols (x): 8
rows(y): 10
Y spacing (mm): 40.0
list multiplier: 0.0
Fabric pre-smocking: 400.0 X 360.0 mm
Fabric post-smocking: 200.0 X 360.0 mm
Grid size: 8 x 9

Column radius: 31.83 mm
Column height: 360.0 mm

mesh resolution: 80 X 72
mesh lines strength: 1.0
smocking pattern strength: 2.0
mesh inflate strength: 0.0055
hydrostatic k factor: 0.00001

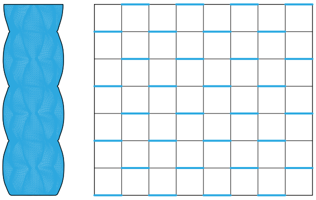


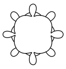


smock width (mm): 100.0
cols (x): 6
rows(y): 6
Y spacing (mm): 80.0
list multiplier: 0
Fabric pre-smocking: 600.0 X 400.0 mm
Fabric post-smocking: 300.0 X 400.0 mm
Grid size: 6 x 5

Column radius: 47.75 mm
Column height: 400.0 mm

mesh resolution: 60 X 40
mesh lines strength: 1.0
smocking pattern strength: 5.0
mesh inflate strength: 0.004
hydrostatic k factor: 6.0e-6

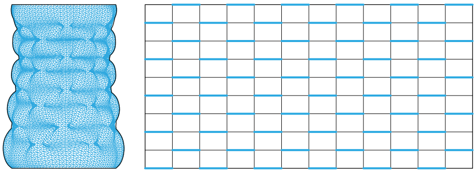


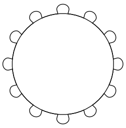


smock width (mm): 60.0
cols (x): 8
rows(y): 8
Y spacing (mm): 60.0
list multiplier: 0
Fabric pre-smocking: 480.0 X 420.0 mm
Fabric post-smocking: 240.0 X 420.0 mm
Grid size: 8 x 7

Column radius: 38.2 mm
Column height: 420.0 mm

mesh lines strength: 1.0
smocking pattern strength: 5.0
lines in plane strength: 5.0
mesh inflate strength: 0.004
hydrostatic k factor: 3.0e-6

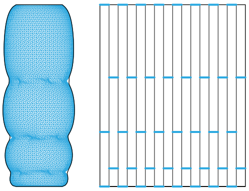


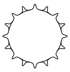


smock width (mm): 60.0
cols (x): 12
rows(y): 10
Y spacing (mm): 40.0
list multiplier: 0
Fabric pre-smocking: 720.0 X 360.0 mm
Fabric post-smocking: 360.0 X 360.0 mm
Grid size: 12 x 9

Column radius: 57.3 mm
Column height: 360.0 mm

mesh resolution: 120 X 60
mesh lines strength: 1.0
smocking pattern strength: 5.0
mesh inflate strength: 0.004
hydrostatic k factor: 6.0e-6

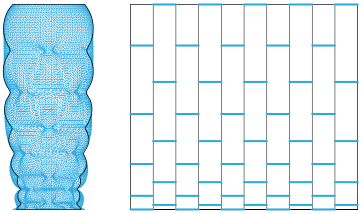


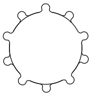


smock width (mm): 20.0
cols (x): 16
rows(y): 5
Y spacing (mm): 0.0
list multiplier: 40.0
list multiplier: 80.0
list multiplier: 120.0
list multiplier: 160.0
list multiplier: 200.0
Fabric pre-smocking: 320.0 X 400.0 mm
Fabric post-smocking: 160.0 X 400.0 mm
Grid size: 16 x 4

Column radius: 25.46 mm
Column height: 400.0 mm

mesh resolution: 160 X 200
mesh lines strength: 1.0
smocking pattern strength: 5.0
mesh inflate strength: 0.0045
hydrostatic k factor: 5.0e-6

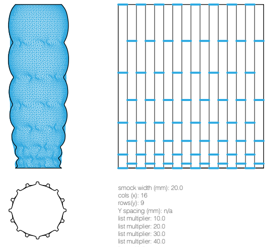




smock width (mm): 50.0
cols (x): 10
rows(y): 10
Y spacing (mm): 0.0
list multiplier: 10.0
list multiplier: 20.0
list multiplier: 30.0
list multiplier: 40.0
list multiplier: 50.0
list multiplier: 60.0
list multiplier: 70.0
list multiplier: 80.0
list multiplier: 90.0
list multiplier: 100.0
Fabric pre-smocking: 500.0 X 450.0 mm
Fabric post-smocking: 250.0 X 450.0 mm
Grid size: 10 x 9

Column radius: 39.79 mm
Column height: 450.0 mm

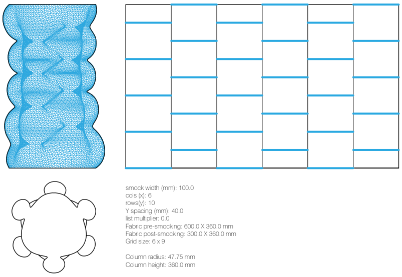
mesh resolution: 100 X 90
mesh lines strength: 1.0
smocking pattern strength: 5.0
mesh inflate strength: 0.004
hydrostatic k factor: 3.0e-6



smock width (mm): 20.0
cols (x): 16
rows(y): 9
Y spacing (mm): n/a
list multiplier: 10.0
list multiplier: 20.0
list multiplier: 30.0
list multiplier: 40.0
list multiplier: 50.0
list multiplier: 60.0
list multiplier: 70.0
list multiplier: 80.0
list multiplier: 90.0
Fabric pre-smocking: 320.0 X 360.0 mm
Fabric post-smocking: 160.0 X 360.0 mm
Grid size: 16 x 8

Column radius: 25.46 mm
Column height: 360.0 mm

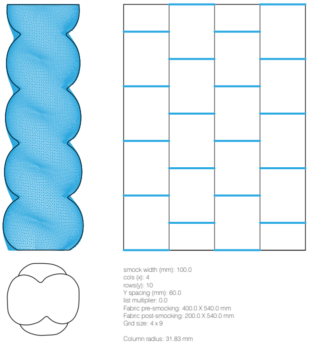
mesh resolution: 160 X 180
mesh lines strength: 1.0
smocking pattern strength: 5.0
mesh inflate strength: 0.0045
hydrostatic k factor: 5.0e-6



smock width (mm): 100.0
cols (x): 6
rows(y): 10
Y spacing (mm): 40.0
list multiplier: 0.0
Fabric pre-smocking: 600.0 X 360.0 mm
Fabric post-smocking: 300.0 X 360.0 mm
Grid size: 6 x 9

Column radius: 47.75 mm
Column height: 360.0 mm

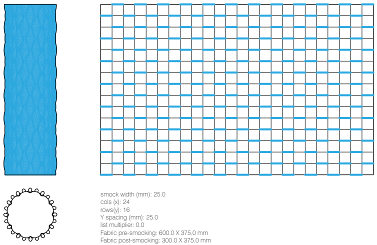
mesh resolution: 60 X 36
mesh lines strength: 1.0
smocking pattern strength: 2.0
mesh inflate strength: 0.0055
hydrostatic k factor: 5.0e-6



smock width (mm): 100.0
cols (x): 4
rows(y): 10
Y spacing (mm): 60.0
list multiplier: 0.0
Fabric pre-smocking: 400.0 X 540.0 mm
Fabric post-smocking: 200.0 X 540.0 mm
Grid size: 4 x 9

Column radius: 31.83 mm
Column height: 540.0 mm

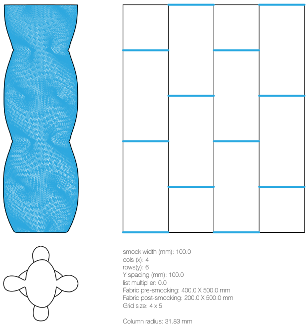
mesh resolution: 64 X 86
mesh lines strength: 1.0
smocking pattern strength: 5.0
lines in plane strength: 5.0
mesh inflate strength: 0.004
hydrostatic k factor: 5.0e-6



smock width (mm): 25.0
cols (x): 24
rows(y): 16
Y spacing (mm): 25.0
list multiplier: 0.0
Fabric pre-smocking: 600.0 X 375.0 mm
Fabric post-smocking: 300.0 X 375.0 mm
Grid size: 24 x 15

Column radius: 47.75 mm
Column height: 375.0 mm

mesh resolution: 144 X 90
mesh lines strength: 1.0
smocking pattern strength: 5.0
lines in plane strength: 5.0
mesh inflate strength: 0.004
hydrostatic k factor: 7.0e-6

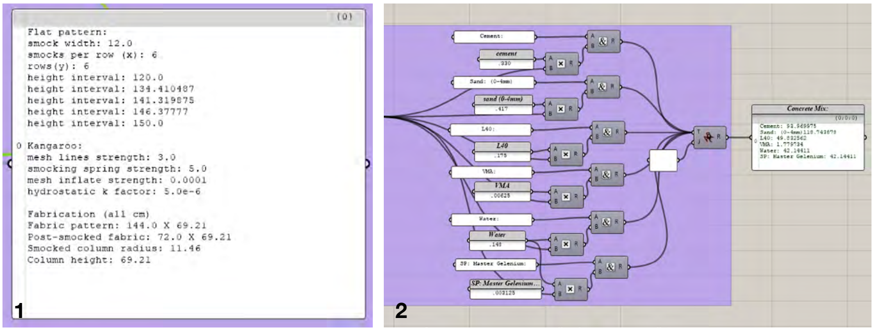


smock width (mm): 100.0
cols (x): 4
rows(y): 6
Y spacing (mm): 100.0
list multiplier: 0.0
Fabric pre-smocking: 400.0 X 500.0 mm
Fabric post-smocking: 200.0 X 500.0 mm
Grid size: 4 x 5

Column radius: 31.83 mm
Column height: 500.0 mm

mesh resolution: 80 X 100
mesh lines strength: 1.0
smocking pattern strength: 5.0
lines in plane strength: 5.0
mesh inflate strength: 0.004
hydrostatic k factor: 3.0e-6

FIGURE 5.69: Simulation tool development & design variations for the *Column* series (Source: author).



```
(0)
  Flat pattern:
  smock width: 12.0
  smocks per row (x): 6
  rows(y): 6
  height interval: 120.0
  height interval: 134.410487
  height interval: 141.319875
  height interval: 146.37777
  height interval: 150.0

0 Kangaroo:
  mesh lines strength: 3.0
  smocking spring strength: 5.0
  mesh inflate strength: 0.0001
  hydrostatic k factor: 5.0e-6

  Fabrication (all cm)
  Fabric pattern: 144.0 X 69.21
  Post-smocked fabric: 72.0 X 69.21
  Smocked column radius: 11.46
  Column height: 69.21
```

```
Cement:
cement .330
Sand: (0-4mm)
sand (0-4mm) .417
L40:
L40 .175
VMA:
VMA .00625
Water:
Water .148
SP: Master Gelenium:
SP: Master Gelenium... .003125
```

```
Concrete Mix:
                              {0;0;0}
0 Cement: 93.969975
  Sand: (0-4mm)118.743878
  L40: 49.832562
  VMA: 1.779734
  Water: 42.14411
  SP: Master Gelenium: 42.14411
```

FIGURE 5.70: Fabrication data for smock pattern (1) and cement mixture (2) (Source: author).

the simulated column and a detailed calculation of the ingredients used in the SCC mix helps to prepare for large-scale fabrications (**FIGURE 5.70 (2)**). The integration of this fabrication data can aid the designer should they need to repeat a simulation.

In narrowing the gap between designer and fabricator, the development of tools such as *OriNuno* enable those with little or no familiarity with flexible formwork and cast concrete to quickly and effectively generate a series of design solutions. This precise data output from the simulation tool enables a designer to integrate real-world fabrication constraints directly in the design process. The rapid prototyping process was concluded by 3D printing the simulated columns (**FIGURE 5.69**) to evaluate form and design of the column simulations depicted in **FIGURE 5.68**.

5.3.4 *Dome* Textile Simulation

While the primary development of the *Dome* probe focused on physically creating double-curved smocked forms (**SECTION 5.2.5**), a three-dimensional simulation tested the simulation aspect of *OriNuno*. As previously discussed, the *Dome* smocking pattern was based on Piker's Resch-inspired origami pattern (**FIGURE 5.26 (2)**), which approximates a half-sphere when folded halfway. This detail differs from how the smocked *Dome* probe was fabricated (**FIGURE 5.29**), as the sewing thread was fully tightened (equivalent to folding a closed version of Piker's pattern). At the time of simulation, this inconsistency went unnoticed. It was only when the simulated fabric smocks failed to anchor to their targets (three-dimensional sphere vertices) that this mistake became apparent.

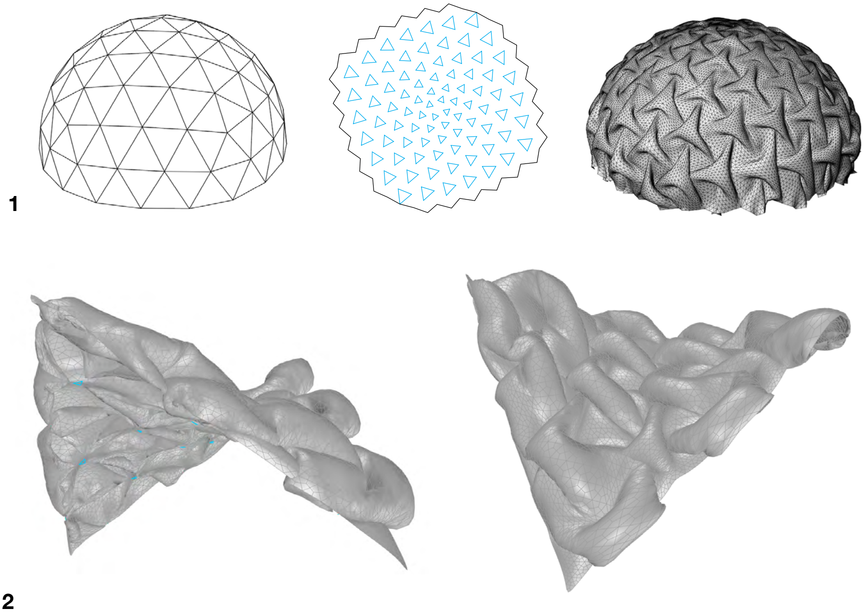


FIGURE 5.71: *Dome* probe: (1) base mesh, Resch/Piker-based smocking pattern and simulation (Source: author).
(2) Smocked hyperbola simulations (Source: author).

The simulation 'group' of *OriNuno* was, in this case, not used for predicting or correlating; instead, it served to create an understanding of geometrical constraints and rules more accurately than the smocked *Dome* probe, which ultimately proved to be misleading.

5.3.5 Externalizing Tacit Knowledge Through Simulation

The *Hyperbola Catalog* demonstrator focused on pattern development rather than further development of the simulation tool described in this thesis (**SECTION 5.2.3**). Although the hyperbola simulations themselves (**FIGURE 5.71 (2)**) did not result in novel findings, the surface geometries (and those of the other experiments) were used to rigorously test and debug the *OriNuno* tool in preparation for student workshops, yielding the following improvements:

- Structural improvements:
    - Support for various input surfaces.

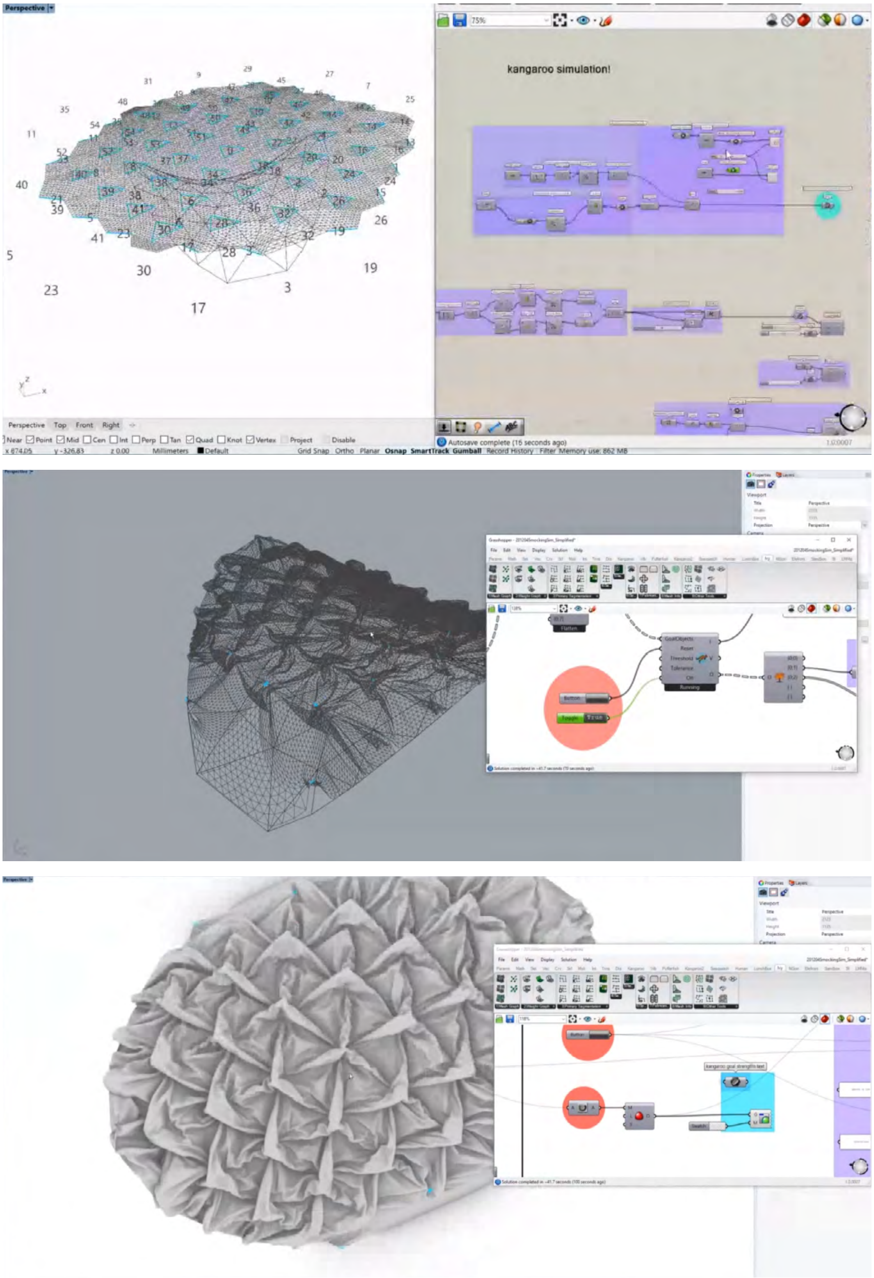


FIGURE 5.72: University of Málaga masters student workshop: testing patterning and simulation tool developed throughout *Concrete Form[ing]work* (Source: author).

    - Automatic generation of smock anchor points.
    - Visualization of smocks to check that they were fully closed.
- UI improvements:
    - Cleaned and commented script.
    - Clear demarcations of adjustable sliders and Kangaroo 2 solvers to run.
    - Color keys for smocks, springs, anchor points, etc.

The patterning and simulation 'groups' of *OriNuno* later formed the basis of a Kangaroo 2 workshop held online for Master's students at the University of Málaga[30] (see **'SELECTED WORKSHOPS & EXHIBITIONS'**). The workshop took place over two days, and included a general lecture regarding the research presented in this thesis, a day of deconstructing three-dimensional surfaces into two-dimensional smocking patterns and a day of testing the simulation tool. **FIGURE 5.72** shows simulations created by the students using the provided script.

The importance of holding workshops and lectures relates to this research's methodology of *externalizing* tacit material knowledge. The Kangaroo 2 workshop tested the author's ability to explicitly codify tacit learnings and clearly communicate patterning and simulation techniques to students and designers with no previous experience of such techniques. Although the third 'fabrication' day of the workshop was canceled due to COVID-19 restrictions, the workshop was valuable in addressing issues of dissemination, tacit knowledge externalization and engagement with an international audience.

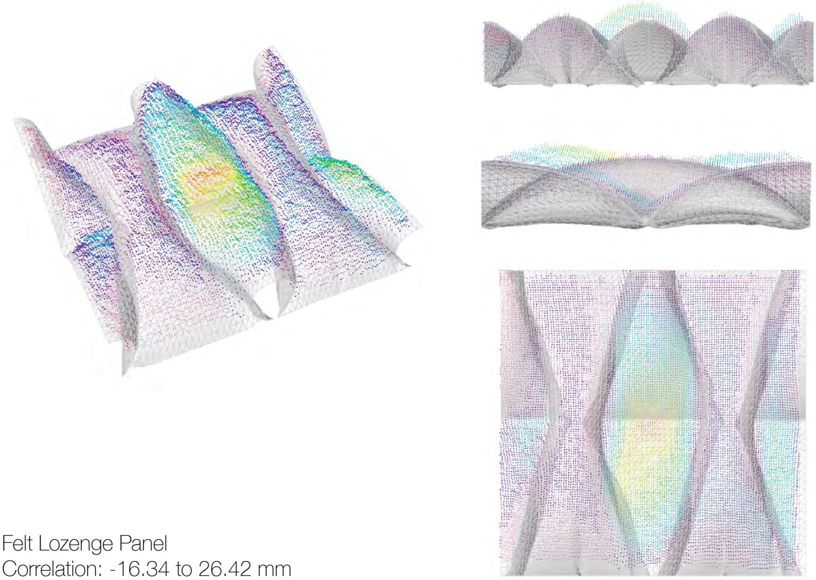
5.3.6 Accurate Correlation With Cast Probes

Column Series. The *OriNuno* was actively utilized and tested during the design and fabrication processes of the *Column* series. Unfortunately, due to the overwhelming hydrostatic pressures that caused formwork tearing of *Column 01*, it was not possible to accurately correlate the physical cast to the simulated model. The development of the *OriNuno* tool improved the precision of the fabrication process of *Columns 02* and *3.2*; registration lines placed where the fabric was to meet the plywood bracing. Furthermore, anchoring smock points

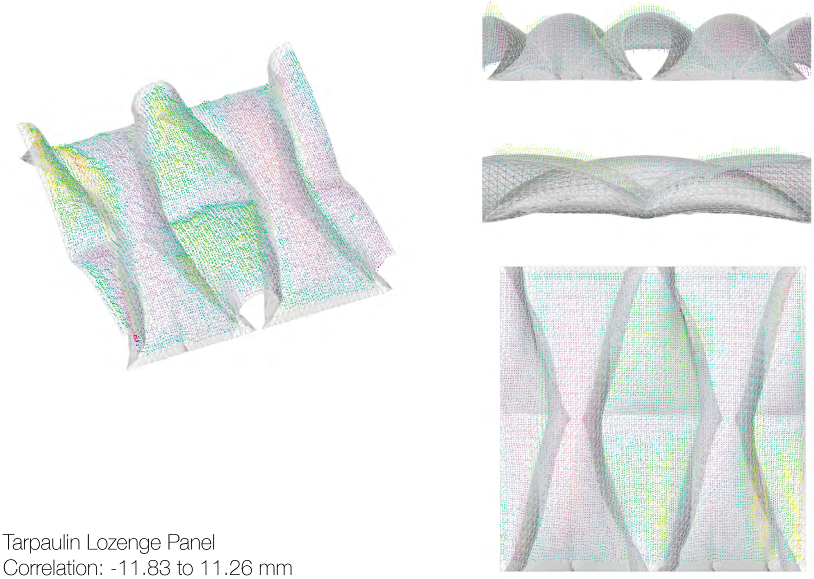
---

[30] These scripts are available online via the author's GitHub page (Scherer, 2020).

FIGURE 5.73: *Column 02* and *Column 3.2:* (1) simulation overlay with point cloud scan, colored for deviation and (2) cast prototype (Source: author).



Felt Lozenge Panel
Correlation: -16.34 to 26.42 mm



Tarpaulin Lozenge Panel
Correlation: -11.83 to 11.26 mm

FIGURE 5.74: *Lozenge Panels* simulations and physical scan correlations (Source: author).

to a substructure significantly increased the accuracy of subsequent simulation correlations with regard to the cast probes. The degree of precision of the simulation of *Column 02* was greater and the cast probe correlated within a few millimeters. The concrete mix was stable and the smocking pattern relatively simple, resulting in fewer variables to consider when simulating. The simulation and correlation of *Column 3.2* achieved similar results. Despite the concrete separation in the upper half of the column due to a mixer malfunction, *Column 3.2* retained high fidelity with the simulation model, with a -26 to 22 mm deviation. The principle deviation was prominent in the smock details where the concrete did not fully permeate the fabric smocks. Further refinement of the fluidity of the concrete mix (adjusting the superplasticizer ratio) may have alleviated this issue. The smock size used for *Column 3.2* approached the minimum required size for concrete to flow through, and can be seen as a benchmark for the maximum resolution achievable using smocked fabric formwork and cast concrete.

Lozenge Panels. The *Lozenge Panels* prototypes also had a high degree of correlation between casting and simulation. The deviation between the case and simulated forms of the felt panel and tarpaulin panels was -16 to 26 mm and -11 to 11 mm, respectively. The felt was slightly more elastic than the tarpaulin and the latter showed minimal material stretching in the middle. The thickness and rigidity of the tarpaulin, coupled with it being widely available, make it an obvious candidate for industrial-scale applications in which to construct reproducible flexible formwork for cast concrete.

Wall Three. As is discussed in **SECTION 5.2.4**, the simulation 'group' of *OriNuno* was instrumental in visualizing various wall design iterations (**FIGURE 5.53**). The simulated tessellation variations of *Wall Three* (**FIGURE 5.55**) were useful to quickly evaluate the visual and practical implications of tessellation resolution (i.e., the number of smocks) and visually ascertain appropriate smock bounds (sizes). Coupled with the fabrication data feedback (number of CC sheets, grommets, etc.), every aspect of the design and fabrication process was integrated within the *OriNuno* tool.

A finite element analysis (FEA) of an earlier, lower-tessellation wall iteration (**FIGURE 5.76**) evaluated the structural properties of CC and determined whether a smocked form using this material would be adequately self-supporting. Based on the industrial specifications, this surface estimation revealed (expected) bending forces where the textile folded, and the system was approved for physical fabrication. The red areas can be disregarded, as FEA does not take

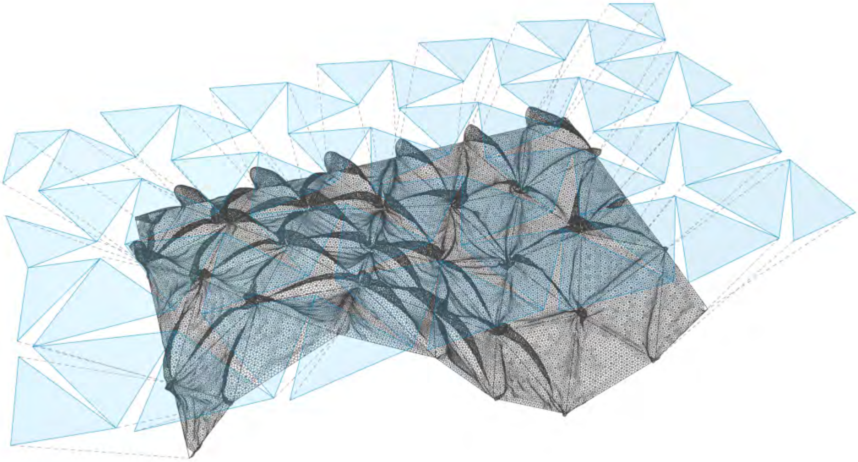


FIGURE 5.75: Early simulation of *Wall Three* with smock pattern overlay. The dashed lines represent the path of the two-dimensional smocking pattern vertices to their corresponding 'anchor' targets in Kangaroo 2 (Source: author).

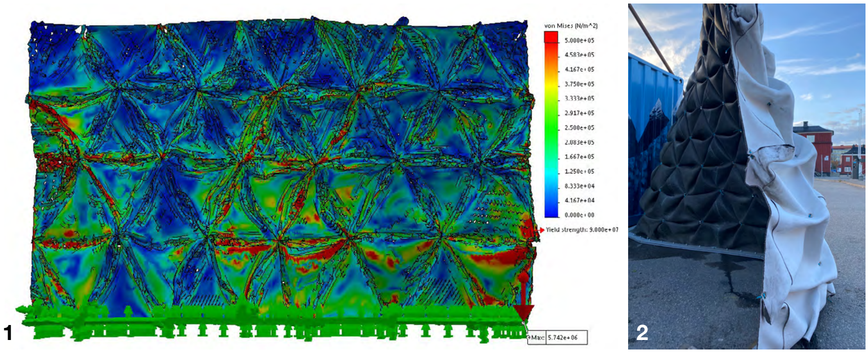
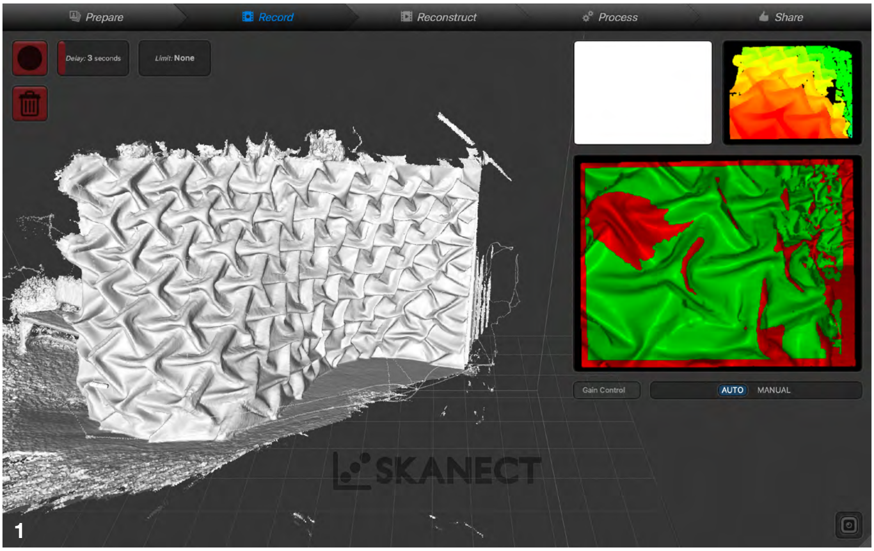


FIGURE 5.76: *Wall Three* (1) FEA and (2) structural failure from vandalism (Source: author).



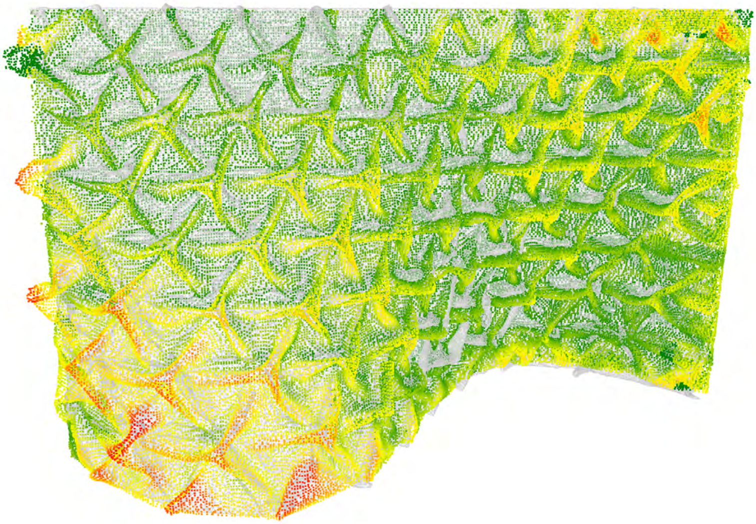


FIGURE 5.77: *Wall Three* scanning (1) Skanect software and (2) correlation of point cloud scan to simulated model (Source: author).

into account support between elements which are overlapping or touching.

FIGURE 5.77 shows the simulated textile overlaid with a point cloud scan of the fabricated wall; the correlation had an average deviation of 39 mm with a maximum of 213 mm. The areas with the most deviation are where additional tension points were added on-site to accommodate the 'sag' of the CC. While the wall was evaluated with FEA to be self-supporting under snow load, *Wall Three* was unfortunately vandalized a few months after its construction: a group of people chose to climb the wall (adding a 'live load') which caused minor cracking on the left side (**FIGURE 5.76 (2)**). Because the wall is in a public square and situations such as these cannot be prevented, a small, vertical steel beam on either side was added to prevent further damage.

The development of *OriNuno* addresses an identified gap in the field of flexible formwork simulation, providing an accurate and accessible simulation tool of flexible formwork. The simulation component of *OriNuno* integrated findings from the initial probes, evolved over the course of the research project and successfully produced simulations that are both useful in integrating design iterations and accurately predicting the rheological behavior of concrete. This integration allows designers who have never worked with flexible formwork (such as the participants of the Málaga workshop) to rapidly prototype smocked concrete forms, communicate fabrication data and create reliable approximations of said forms.

06. CONCLUSIONS & FURTHER RESEARCH

This thesis contributes to the development of computational patterning, simulation and correlation in the context of fabric formwork and concrete.

Situating the Research. An extensive survey of historical and current state-of-the-art fabric formwork systems identified a fracture between the design, simulation and fabrication of such systems. By developing a link to repair this fracture, industry's hesitance regarding the predictability and repeatability of fabric formwork systems were addressed without compromising notions of craft and materiality. The research presented in this thesis took note of the current architectural paradigm shift brought about by computation and mass customization and sought to utilize this momentum of change to reunite material and form. In doing so, this research was situated in reaction to current state-of-the-art research and contributes to bridging existing knowledge gaps that concern architectural applications of flexible formwork today.

Craft-Based Methodology. The research presented in this thesis investigated how research can be conducted with a craft-based methodology. Three characteristics of experimentation (*procedural workflows, evaluation criteria* and *externalization of tacit material knowledge*) were highlighted when formulating experiments and there was an emphasis on *how* design research is conducted, which can be considered to be a contribution in itself. The resulting experiments utilized the *Ways of Drifting* (*serial*, *expansive* and *probing*) methodology, producing results with varying levels of sophistication (*probe*, *prototype* and *demonstrator*). By investigating adjacent research fields (mesh segmentation, surface unrolling, origami, kirigami, auxetic materials and conformal mapping), the research presented in this thesis located geometrical commonalities within these fields and synthesized these findings for the design, fabrication, simulation and correlation of concrete structures using smocked textiles. The research questions were formulated with an embedded duality (rather than a 'true/false' scientific approach) in mind to allow for a more 'wandering' experimental process.

Cast Concrete in Flexible Formwork. A wide array of prototypes was produced during the research presented in this thesis, ranging in size, formwork type and casting direction. These probes, prototypes and demonstrators were thoroughly documented to highlight the importance of the *process*, in addition to that of the final fabricated form. The research explored and documented fabric types with varying degrees of elasticity in relation to concrete casting, and addressed full-scale fabrication details when tailoring smocked fabric.

The knowledge gained from numerous probes and prototypes added to the author's understanding and integration of tacit material knowledge within the digital feedback loop.

Parametric Patterning of Smocking. A thorough investigation of computational patterning techniques was conducted by integrating knowledge from the analogous disciplines of surface unrolling techniques, origami, kirigami, auxetic materials and conformal mapping. When applied to smocking, the findings were used to produce a wide array of parametrically manipulated two-dimensional patterns. Synthesizing the complexities of patterning, this research abstracted Resch-based folding patterns in order to deconstruct a series of three-dimensional shapes into their smocking patterns. Patterning of such forms included basic double-curved shapes such as a dome, torus and hyperbola. The fabrication of these patterns constituted a successful proof of concept. The research presented in this thesis involved the creation of a fully-developed patterning tool, *OriNuno* that enabled the deconstruction of complex three-dimensional hexagonal meshes into viable smocking patterns. Demonstrators such as the *Hyperbola Catalog* show that it is possible to achieve local and global surface articulation while retaining a high degree of control over patterning variables such as tessellation resolution and smock size.

Simulation and Correlation. The simulation 'group' of *OriNuno* contributes to bridging the disconnect between material and form, as well as designer and fabricator. This thesis addresses the current inability to reliably simulate flexible formwork in today's industry, which resulted in an impetus to create an accessible digital tool that facilitates digital simulation of and correlation to physical casts. *OriNuno* not only parametrically deconstructs input shapes into patterns but also simulates both the fabric smocking and casting processes, facilitating accurate correlation between simulations and casts. Developed in parallel with feedback from numerous physical experiments, *OriNuno* forms a circuitous feedback loop between design, fabrication and correlation between simulation and casting. Bridging the disconnect between these fields allows materiality to inform and, ultimately be exhibited in design.

Wall Three Demonstrator. The *Wall Three* demonstrator put into practice all of the learnings gained from previous experiments and investigated the implications of the large-scale fabrication of smocked concrete textiles. In this case, the designer (author) literally became the fabricator, as the visualization and simulation tools were tested first-hand during the construction of this demonstrator. From pattern generation and design to simulation, correlation, panel fabrication and wall assembly, the construction process of this demonstrator integrated the knowledge and experience gained through the experiments conducted during the research presented in this thesis.

Future Research. Future research topics that are not within the scope of this research project include applying smocking to additional architectural elements such as beams or hollow columns. In addition, double-sided smocked walls or hollow columns could address issues of sustainability and minimal material usage. The *Lozenge Panels* prototypes exemplified a need for further exploration of smocking anchoring/substructure systems. Future work might imagine complementary metal support frames, replacing reinforcement bars with topology-optimized metal substructures such as Baker's *Spin-Valence* space frame system (**SECTION 4.2.3**). Further collaboration with structural engineers would help to clarify the structural implications of smocking in buildings, e.g. to achieve comparable strength between large-scale hollow columns and uniform-section traditional ones.

Additionally, there is room for further development in terms of investigating a wider array of fabric materials. These could include but not be limited to fabrics such as nylon parachute materials, geotextiles and industrial sails (both Polypreg and carbon fiber). Another possibility is partnering with existing flexible formwork fabricators to optimize resources and learn from them by studying their full-scale casts so as to improve the flexibility, strength and surface texture of the experimental results presented in this thesis. Furthermore, additional studies of the smocking details of full-scale concrete casts would require a re-evaluation of smocking connections (presently nylon rope or zip ties) to prioritize ease of connection and disassembly.

Merging concrete materiality, textiles with accurate design and simulation tools, the research presented in this thesis contributes to current architectural design research; it does so by filling existing gaps in design research by combining a centuries-old sewing technique with digital fabrication and computational design. This expression of concrete materiality, when combined with the precision of modern simulation and fabrication tools, opens up a relatively unexplored avenue of flexible formwork research, and in doing so, reuniting the designer and fabricator once more.

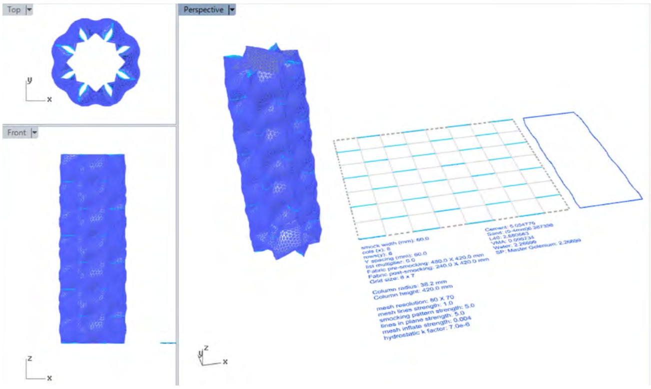
SELECTED VIDEO DOCUMENTATION

FILM 01

Column Casting Simulation with Lozenge Smocking Pattern Formwork

Presented at: Scherer, A.L. (2018) 50% Seminar. [Higher Seminar Series, KTH]

https://doi.org/10.5281/zenodo.5113233



smock width (mm): 60.0
cols (x): 8
rows(y): 8
Y spacing (mm): 60.0
list multiplier: 0.0
Fabric pre-smocking: 480.0 X 420.0 mm
Fabric post-smocking: 240.0 X 420.0 mm
Grid size: 8 x 7

Column radius: 38.2 mm
Column height: 420.0 mm

mesh resolution: 80 X 70
mesh lines strength: 1.0
smocking pattern strength: 5.0
lines in plane strength: 5.0
mesh inflate strength: 0.004
hydrostatic k factor: 7.0e-6

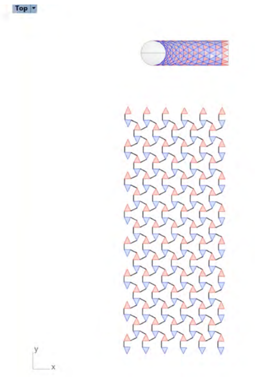
Cement: 5.054775
Sand: (0-4mm)6.387398
L40: 2.680563
VMA: 0.096734
Water: 2.26699
SP: Master Glenium: 2.26899

FILM 02

Torus 2.0 Tiling & Smocking Pattern Generation

Presented at eCAADe/SIGraDi 2019 in Porto, Portugal

https://doi.org/10.5281/zenodo.5113167



FILM 03

Wall Three: The Making of

Presented at: Scherer, A.L. (2020) *90% Seminar.* [Higher seminar series, KTH]

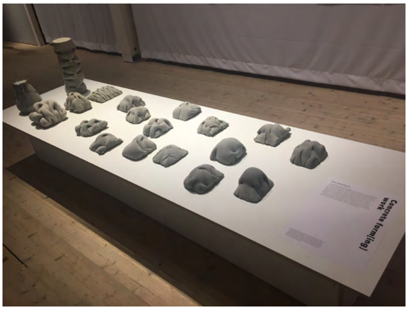
https://doi.org/10.5281/zenodo.5114112

SELECTED WORKSHOPS & EXHIBITIONS

EXHIBITION 1

Making Effect collective exhibition at ArkDes

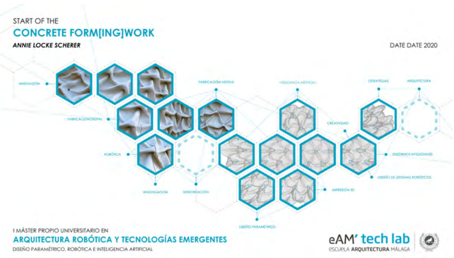
Stockholm | September 2017



WORKSHOP 1

Designing & Simulating Parametrically Patterned Fabric Forms

Universidad de Málaga | December 2020

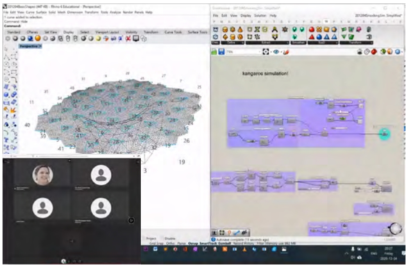


START OF THE
CONCRETE FORM[ING]WORK
ANNIE LOCKE SCHERER

DATE DATE 2020

I MÁSTER PROPIO UNIVERSITARIO EN
ARQUITECTURA ROBÓTICA Y TECNOLOGÍAS EMERGENTES
DISEÑO PARAMÉTRICO, ROBÓTICA E INTELIGENCIA ARTIFICIAL

eAM' tech lab
ESCUELA ARQUITECTURA MÁLAGA



EXHIBITION 2

Galleri Frihamnstorget: ‘Concrete Form[ing]work’

Stockholm | February 2021

SELECTED LECTURES

2020

MASTERS SEMINAR | *Pattern Generation & Simulation* | University of Málaga, Spain

HIGHER SEMINAR LECTURE SERIES | *Concrete Form[ing]work* [Project Presentation (90%)] | KTH, Sweden

2019

ECAADE/SIGRADI 2019 | *Concrete Form[ing]work* | University of Porto, Portugal

RETHINKING TECHNOLOGIES: ARCHITECTURAL PHILOSOPHIES | *Concrete Form[ing]work* | KTH, Sweden

2018

DIGITAL DESIGN UNIT | *Kangaroo 2* | Darmstadt, Germany

BIOMETRIC MASTERS STUDIO | *Concrete Form[ing]work* | University of Waterloo, Canada

ARUP GROUP | *Concrete Form[ing]work* | London, England

DIGITAL CONCRETE | *Concrete Form[ing]work* | ETH, Zurich, Switzerland

HIGHER SEMINAR LECTURE SERIES | *Concrete Form[ing]work* [Project Presentation (50%)] | KTH, Sweden

2017

SVERIGES ARKITEKTURGALAN | *Robots in Architecture* | Cirkus Arena, Stockholm, Sweden

DOME OF VISIONS | *Robotic Fabrication* | KTH, Sweden

HIGHER SEMINAR LECTURE SERIES | *Concrete Form[ing]work* [Project Presentation (25%)] | KTH, Sweden

2016

SWEDISH SCHOOL OF TEXTILES | *Concrete Form[ing]work* | Borås, Sweden

DIGITAL DESIGN UNIT | *Concrete Form[ing]work* | Darmstadt, Germany

SCHOOL FOR AUTONOMOUS SYSTEMS (CAS) | *Robotic Fabrication* | KTH, Sweden

SLUSH 2016 | *Robots in Architecture* | Helsinki, Finland

SWEDISH CEMENT AND CONCRETE RESEARCH INSTITUTE | *Concrete Form[ing]work* | KTH, Sweden

LIST OF FIGURES

01. INTRODUCTION

FIGURE 1.1: Traditional concrete formwork (Wikipedia Creative Commons).

02. THEORETICAL FRAMEWORK

FIGURE 2.1: "Drive wheel" model: constructing a hypothesis (Bang et al., 2012)

FIGURE 2.2: Krogh et. al's *Ways of Drifting* (Krogh et. al, 2015)

FIGURE 2.3: Spiral evolution of knowledge conversion and self-transcending process (Nonaka and Konno, 1998).

03. CONTEXT & STATE OF THE ART

FIGURE 3.1: (1) Gaudi's *hanging chain model* (Zexin & Mei, 2017).
(2) Otto's *soap bubble experiment* (Zexin & Mei, 2017).

FIGURE 3.2: (1) Candela's *L'Oceanogràfic* 2003 (Wikipedia Commons).
(2) Isler's *Klicherschale,* 1965 (Wikipedia Commons).
(3) Nervi's Orvieto Airport Hangar, 1935 (Leslie, 2018).
(4) Musmeci's *Viadotto dell'Industria,* Basento 1971–1976 (Marmo et al., 2019).

FIGURE 3.3: (1) Fisac's *Casa Pascual de Juan,* 1975 (Veenendaal, Coenders, et al., 2011).
(2) Fisac's *Hermanas Hospitalarias Social Center, Ciempozuelos* 1985–1986 ("Fundación Miguel Fisac").

FIGURE 3.4: (1) Unno's *URC House* (2003) (Veenendaal, West, et al., 2011).
(2) West's C.A.S.T. research, *Bone Beam* (West et al., 2016).
(3) ArroDesign's *Black Tree House* (2007) (Veenendaal, West, et al., 2011).

FIGURE 3.5: History of fabric formwork (Veenendaal, West, et al., 2011).

FIGURE 3.6: Chandler, Pedreschi and C.A.S.T. student workshop collaboration (1) *Wall One* (Chandler, 2004) and (2) *Wall Two* (Chandler & Pedreschi, 2007).

FIGURE 3.7: Chan et. al.'s UoE Disruptive Technologies Master's Thesis: *Single Cast Wall* (Milne et al., 2018).

FIGURE 3.8: Milne's MScR UofE thesis, *Tailored Fabric Formwork* (Milne, 2017).

FIGURE 3.9: (1) Manelius's *Ambiguous Chair,* 2009 (Manelius, 2009).
(2) Remy and Veenhuizen's *Concrete Chair,* 2010 (Etherington, 2010a).
(3) Van Maele's *Mass III Chair*, 2010 (Etherington, 2010b).
(4) Schmid's *Stitching Concrete*, 2011 (Schmid, 2011).
(5) Gustafsson's *Concrete Easy Chair*, 2011 (Gustavsson, 2013).

FIGURE 3.10: (1) Fab Form Fast-Tube™ (Fab-Form, n.d.).
(2) Concrete Canvas® *Disaster relief shelter* (Concrete Canvas, n.d.).

FIGURE 3.11: (1) Winsun's *Concrete 3D Printed Houses* (Blain, 2014).
(2) XtreeE's *Post* (Gaudillière et al., 2019).
(3) ETH's *Concrete Choreography* (Anton et al., 2020).
(4) Kapoor's *Cement Room* (Kapoor et al., 2009).

FIGURE 3.12: (1) Carlin et al.'s *Grompies*, student workshop, 2010 (Warmann, 2010a).
(2) Able et al.'s *[Fabric]ation* Master's thesis prototypes, 2012 (Able et al., 2012).

FIGURE 3.13: (1) Matsys' *P_Wall*, 2009 (Kudless, 2011).
(2) Nan et al.'s *Fabric Waisted Column & Twisted Column*, 2017 (Nan et al., 2017).

FIGURE 3.14: (1) Šinke Baranovskaya's *Knitflatable Architecture*, ITECH Master's thesis, 2015 (Baranovskaya, 2016).
(2) Ramsgaard Thomsen's *CAD CAM Knitting* (Tamke et al., 2012).

FIGURE 3.15: (1) Popescu's *KnitCandela* (M. A. Popescu, 2019).
(2) ETH Zurich's *Nest HiLo roof prototype* (Stoughton, 2018).

FIGURE 3.16: (1) Sturgeon, Holzwart & K. Raczkowski's *FattyShell* 2010 (Warmann, 2010).
(2) Sarafian & Culver's *MARS Pavilion* 2017 (Sarafian et al., 2017).

04. METHODS

FIGURE 4.1: Chronological workflow of research experiments (Source: author).

FIGURE 4.2: (1) *Lozenge* cast probe sheathing and (2) *Skewed Grids* cast probe (Source: author).

FIGURE 4.3: (1) *Farmer's smock* (Victoria and Albert Museum, 1796).
(2) *Liberty Dress* (Victoria and Albert Museum, 1893).

FIGURE 4.4: Vintage smocked dress patterns (McCall Printed Pattern 1350, 1947; Simplicity Printed Pattern 1863A, 1956).

FIGURE 4.5: Hand smocking a basic 'Lozenge' pattern (Source: author).

FIGURE 4.6: Kuma's *Spacer Fabric Architecture* Master's thesis (Kuma, 2014).

FIGURE 4.7: Mamou-Mani's *Magic Garden* (Mamou-Mani, 2013.).

FIGURE 4.8: Efrat's *Crafted Technology* Master's thesis (Efrat, 2016).

FIGURE 4.9: Millentrup's *Actuated Textile Hybrids* Master's thesis (Millentrup et al., 2019).
(1) Single curved surface unrolling (Source: author)
(2) Waldseemüller's 1507 globe segment map (Missinne, 2015).

FIGURE 4.11: (1) *Strip Unrolling Method* of the Stanford Bunny (Mitani & Suzuki, 2004).
(2) Pepakura Designer (Pepakura Designer, n.d.).

FIGURE 4.12: Resch's 1977 folding pattern patent (Resch, 1977) and paper studies (Resch, 1970).

FIGURE 4.13: T. Tachi *Origamizer* desired polyhedral model, crease pattern and first origami Stanford Bunny (Tachi, 2010).

FIGURE 4.14: (1) *Folding Honeycomb* kirigami fundamentals (Castle et al., 2014).
(2) *Programmable Folding* Master's Thesis (Source: author).

FIGURE 4.15: (1) *Programmable Auxetics* (Konaković-Luković et al., 2018).
(2) Conformal Mapping with *Boundary First Flattening* (Sawhney & Crane, 2017).

FIGURE 4.16: (1) Comparison of *Dermoid* FEA model with scan, CITA (Thomsen & Tamke, 2015).
(2) *Fatty Shell* comparison of digital model and fabricated form (D. Veenendaal & Block, 2012).

05. DESIGN RESEARCH DEVELOPMENT

FIGURE 5.1: *First Fifteen Hand-Smocked Probes* casting setup (Source: author).

FIGURE 5.2: Existing smocking patterns tested in *First Fifteen Hand-Smocked Probes* (Source: author).

FIGURE 5.3: *First Fifteen Hand-Smocked Probes* sewn textile (Source: author).

FIGURE 5.4: *First Fifteen Hand-Smocked Probes* casts (Source: author).

FIGURE 5.5: *First Fifteen Hand-Smocked Probes* (Source: author).

FIGURE 5.6: Diagram of pre- and post-smocked fabric size difference dependent on smocking orientation (Source: author).

FIGURE 5.7: Concrete mixture ratio and slump tests (Source: author).

FIGURE 5.8: *Skewed Grids* casting setup (Source: author).

FIGURE 5.9: *Skewed Grids*: smocking grid alternately shaded to visualize grid manipulation, resulting 'Lozenge' pattern and cast probes (Source: author).

FIGURE 5.10: *Skewed Grids*: smocking grid alternately shaded to visualize grid manipulation, resulting 'Arrow' pattern and cast probes (Source: author).

FIGURE 5.11: 'Lozenge' smock pattern applied to fabric of various elasticities and resulting casts (Source: author).

FIGURE 5.12: *Column 01* (1) pattern marking, (2) sewing, (3) formwork, (4) base detail, (5) cast column and (6) surface finish detail (Source: author).

FIGURE 5.13: *Column 02*: (1) carbon fiber substructure to anchor smocks, (2) smock pattern, (3) formwork, and (4) cast probe (Source: author).

FIGURE 5.14: *Lozenge Panels* (1) smocking process, (2) front, (3) back, (4) formwork and (5) smocking anchor reinforcement (Source: author).

FIGURE 5.15: Axonometric diagram of *Lozenge Panels* (1) fabric formwork, (2) wood frame and smocking anchor, (3) simulation anchor points and (4) flat pattern (Source: author).

FIGURE 5.16: Cast *Lozenge Panels*. Left and right are felt and tarpaulin, respectively (Source: author).

FIGURE 5.17: Diagrammatic representation of comprehensive scripting tool *OriNuno* with four 'groups': (1) design, (2) parametric pattern generation, (3) fabrication constraints, and (4) simulation and correlation (Source: author).

FIGURE 5.18: *Coded Pixels:* Human UI interface and sample smocking pattern generated with Python (Source: author).

FIGURE 5.19: *Coded Pixels:* Various smocking patterns and their Python smocking script code (Source: author).

FIGURE 5.20: Mathematical calculation to approximate pre- and post-smocking fabric sizes (in Grasshopper) (Source: author).

FIGURE 5.21: Development of *Skewed Grids* patterns (Source: author)

FIGURE 5.22: Skewing 'regular' grids to generate a corresponding 'Arrow' smocking pattern (Source: author)

FIGURE 5.23: Smocking pattern generation of a cone and torus by using Origamizer (Source: author)

FIGURE 5.24: Pattern generation of *Cone* and *Torus 1.0* generated from strip unrolling technique (Source: author).

FIGURE 5.25: Smocked (1) *Cone* and (2, 3) *Torus 1.0* using 'Lozenge' pattern and strip unrolling technique (Source: author).

FIGURE 5.26: Resch's (1) pattern simulation, (2) vertex gap diagram and (3) constructed paper model (Resch & Christiansen, 1970).
Piker's (4) origami dome using a generalization of Resch's folding patterns (Piker, n.d.).

FIGURE 5.27: (1) Resch pattern vs. (2) 'Arrow' smock pattern (Source: author).

FIGURE 5.28: *Dome* smocking pattern from Ron Resch origami pattern (Source: author).

FIGURE 5.29: *Dome* probe: (1) smocking pattern marking, (2) 'back' side and (3) 'front' side (Source: author).

FIGURE 5.30: Comparison of (1) Origamizer and (2) Resch folding patterns respectively translated to smocking patterns (Source: author).

FIGURE 5.31: (1) conformal mapping in Python and (2) Boundary First Flattening (BFF) (Source: author).

FIGURE 5.32: Generating single vertex smocking patterns of (+), (0), & (-) Gaussian curvature and corresponding folded paper models. (Source: author).

FIGURE 5.33: Steps for deconstructing an input surface into a smocking pattern, based on Ron Resch's origami patterns (Source: author).

FIGURE 5.34: Smocking pattern generation from a tessellated one-sheet hyperboloid with negative Gaussian curvature (Source: author).

FIGURE 5.35: *Column 3.1*: (1) fabrication process and (2) final smocked prototype of (Source: author).

FIGURE 5.36: Comparison of *Column 3.1* and *3.2*: (1) mesh tessellation, (2) unrolled mesh faces and (3) smock pattern and fabrication data (Source: author).

FIGURE 5.37: *Column 3.2* formwork fabrication (Source: author).

FIGURE 5.38: *Column 3.2* cast prototype (Source: author).

FIGURE 5.39: ArroDesign's *Fabric Formed Stair* (Lawton, 2013).

FIGURE 5.40: *Torus 2.0*: (1) hexagonal mesh dual substructure visualization and (2) conformal mapping with length equalization (Source: author).

FIGURE 5.41: *Torus 2.0* pattern generation: (1) triangle mapping to flat mesh dual, (2) Kangaroo 2 relaxation with target lengths, (3) smock pattern and (4) laser cut file with tabs (Source: author).

FIGURE 5.42: *Torus 2.0* fabricated model on exhibition at Galleri Frihamnstorget (Source: author).

FIGURE 5.43: Variable hyperbola tessellation resolution as input for smocking pattern generation tool (Source: author).

FIGURE 5.44: Various unfolding techniques of a hyperbola using Pepakura, Ivy, Origamizer, and smocking (Source: author).

FIGURE 5.45: Generated smocking patterns of a hyperbolic input shape, showcasing control of smock dimension and resolution (Source: author).

FIGURE 5.46: Hand-smocked hyperbola models plotted on a graph. Smock size is plotted on the X axis and smock resolution is plotted on the Y axis (Source: author).

FIGURE 5.47: Variable smocking tessellation resolution of a hyperbola (Source: author).

FIGURE 5.48: Variable smocking size (lengths) of within a 6 x 6 tessellated hyperbola (Source: author).

FIGURE 5.49: Concrete Canvas® (Concrete Canvas, n.d.).

FIGURE 5.50: Material investigations of 'Lozenge' and 'Arrow' smocking on CC8 and CC5, respectively (Source: author).

FIGURE 5.51: (1) 'Arrow' and 'Lozenge' patterns with (2) front and (3) back of corresponding CC5 material tests (Source: author).

FIGURE 5.52: Various connection hardware tests (Source: author).

FIGURE 5.53: *Wall One*, *Two* and *Three* design exercise: (1) input surface, (2) surface tessellation, (3) circle packing and area equalization, (4) smocking pattern generation and (5) simulation (Source: author).

FIGURE 5.54: *Wall One* & *Wall Three* 1:10 scale models with corresponding patterning and fabrication data (Source: author).

FIGURE 5.55: *OriNuno* variations of *Wall Three* (1) tessellation resolution, (2) flat mesh triangle area deviation from input mesh, (3) unrolled mesh triangle faces, (4) smocking pattern, (5) fabrication data and (6) simulation (Source: author).

FIGURE 5.56: *Wall Three* digitally generated pattern and fabrication data (Source: author).

FIGURE 5.57: (1, 2) CC5 'Arrow' smock seam test and (3) tautline hitch detail (Source: author).

FIGURE 5.58: *Wall Three*: (1) panel fabrication, (2) printed pattern overlay and (3) total material volume (Source: author).

FIGURE 5.59: (1) Smock detail over a seam, (2) edge registration marks and (3,4) heat welding assembly (Source: author).

FIGURE 5.60: *Wall Three* (1,2) smocking

process, (3) forklift tilt-up, (4) CC hydration, wall curing (5) front and (6) back (Source: author).

FIGURE 5.61: *Wall Three* (1) transport and placement, (2) frame removal, and (3) power washing (Source: author).

FIGURE 5.62: Wall Three final photos (Source: F. Boukari (1–4), author (5,6)).

FIGURE 5.63: Permanent placement of *Wall Three* in Frihamnstorget square (Source: author).

FIGURE 5.64: Summary of Kangaroo 2 'goals' for a 'Lozenge' smock (Source: author).

FIGURE 5.65: *Simulation 1.0* of "Lozenge" cast probe (Source: author).

FIGURE 5.66: *Simulation 1.0* with corresponding cast probe and adjusted pattern (Source: author).

FIGURE 5.67: Smocking anchor point Kangaroo 2 goals for *Column 01* simulation (Source: author).

FIGURE 5.68: *Rapid Column Prototyping* 3D prints (Source: author).

FIGURE 5.69: Simulation tool development & design variations for the *Column* series (Source: author).

FIGURE 5.70: Fabrication data for smock pattern (1) and cement mixture (2) (Source: author).

FIGURE 5.71: *Dome* probe: (1) base mesh, Resch/Piker-based smocking pattern and simulation (Source: author).
(2) Smocked hyperbola simulations (Source: author).

FIGURE 5.72: University of Málaga masters student workshop: testing patterning and simulation tool developed throughout *Concrete Form[ing]work* (Source: author).

FIGURE 5.73: *Column 02* and *Column 3.2:* (1) simulation overlay with point cloud scan, colored for deviation and (2) cast prototype (Source: author).

FIGURE 5.74: *Lozenge Panels* simulations and physical scan correlations (Source: author).

FIGURE 5.75: Early simulation of *Wall Three* with smock pattern overlay.
The dashed lines represent the path of the two-dimensional smocking pattern vertices to their corresponding 'anchor' targets in Kangaroo 2 (Source: author).

FIGURE 5.76: *Wall Three* (1) FEA and (2) structural failure from vandalism (Source: author).

FIGURE 5.77: *Wall Three* scanning (1) Skanect software and (2) correlation of point cloud scan to simulated model (Source: author).

FOOTNOTES

pg. 18

[1] Karl Popper notably demarcated science from non-science with ‘the Falsification Principle’, arguing that theories must be falsifiable to be scientific (Popper, 1959, p. 6).

pg. 23

[2] This research methodology was also carried throughout the instruction of the Master’s-level program *Studio 09*, taught by the author and Pablo Miranda Carranza (for more details see (Scherer & Miranda-Carranza, 2019).

pg. 24

[3] Research *for* design focuses more on understanding pertinent architectural precedents. Research *into* or *about* design sets a specific goal of what design ‘should be’ and seeks to improve upon it (for further discussion, see (Downton, 2003).

pg. 24

[4] The research conducted within this thesis recognizes the other, more common conception of the term *externalization* which is chiefly psychological. The use of this term throughout this thesis follows Nonaka et al.'s understanding throughout.

pg. 29

[5] Kwinter distinguishes between “poor formalisms” (or “unextended formalisms”) as “a sloppy conflation of the notion of ‘form’ with that of ‘object’” while defining “true formalism” as systems which relate form, object, material and expression (Kwinter, 2003, p. 96).

pg. 29

[6] De Landa takes note of this paradigm shift by contrasting two philosophies of design (of particular relevance is his idea of "genesis of form"; (De Landa, 2001, p. 132): one being conceptual and assuming material homogeneity while the other portrays materials as active, heterogeneous, and integral to the design process.

pg. 30

[7] In mathematics, a minimal surface is one in which the surface area is minimized and has vanishing or zero mean curvature (Pottman et al., 2007, p. 647).

pg. 30

[8] Kangaroo, a plugin for Grasshopper 3D, is a spring-based Live Physics engine which uses Dynamic Relaxation (DR). The Kangaroo/Kangaroo 2 plugin provides a catalog of ‘goals,’ which are predefined functions which act on defined points, lines and meshes. These goals can include geometry constraint, curve bending or elasticity or applying loads and other forces. The goals are aggregated in the ‘solver,’ which dynamically applies the specified goals based on user-input ‘strengths.’

pg. 31

[9] These include the rubber membrane method, hanging textile method, foam flow method and shaking method (Baghdadi et al., 2019, p. 493).

pg. 40

[10] Milne et al. note that designers “often develop their own approach to particular solutions differentiated from conventional or traditional processes.” They refer to this tacit material knowledge as “sticky” given that it is “difficult to transfer to those

not experienced in the relevant techniques" (Milne et al., 2018, p. 2).

pg. 60

[11] Technology readiness levels (TRLs) are a NASA-developed method of uniformly evaluating various types of technology from multiple fields based on their 'maturity' and development (Héder, 2017).

pg. 61

[12] For further discussion regarding this methodology, see Scherer (2017).

pg. 67

[13] The two major traditions in smocking are the classic English and the later-developed North American. The former is a two-step procedure in which the fabric is first folded into regular pleats. After the smocking is complete, the threads holding the pleats in place are removed. Elasticity is a characteristic of this type of stitching (Wolff, 1996, p. 129). The latter, on the other hand, is based on a grid that is drawn on the fabric, does not involve pre-pleating and works entirely on the reverse side of the fabric (1996, p. 141). The research presented in this thesis focuses on the North-American technique; it has the most potential for grid abstraction and single-sided stitching, which is more suitable when combined with cast concrete.

pg. 70

[14] This technique is an heirloom craft, primarily popular with older generations; perhaps this partly explains why there has been little interest in manipulating these patterns digitally.

pg. 100

[15] These two smock types are the simplest components of smocking patterns. 'Lozenge' and 'Arrow' smocks are made by gathering two or three points of fabric, respectively. As discovered during the creation of the *First Fifteen Hand-Smocked Probes*, other existing pattern bases are more complex in terms of either varying or combining these two base elements.

pg. 107

[16] This is roughly the minimum smocking size possible with this specific fabric and concrete mix combination (without causing cracking upon formwork removal), as determined through testing.

pg. 119

[17] In computer science, pseudocode is the informal 'translation' of an algorithm or programming language to plain language or diagrams; they are intended to be read by humans, rather than machines ("Pseudocode," 2021).

pg. 119

[18] Note that the 'Shell' and 'Leaf' patterns were later found to be identical, aside from a 180-degree difference in orientation and were thus consolidated.

pg. 119

[19] Human UI is a plugin for Grasshopper that facilitates the generation of custom user interfaces, developed by the Design Computation Leadership Team of the American architecture, planning and design firm NBBJ.

pg. 129

[20] 'Intuition' is used in this instance to note that these probes were guided by a general 'feeling' of how to go about constructing these geometries, without fully comprehending the mathematical technicalities.

pg. 137 [21] Similar to Resch's studies, the origami domes in Piker's study was formed by partially folding the paper tucks. This folding approach differs from that of the Origamizer software, wherein patterns are constructed to be fully closed or 'watertight' (Demaine & Tachi, 2017; Tachi, 2013).

pg. 139 [22] Examples of negative, zero and positive Gaussian curvature include a hyperboloid, cylinder and sphere, respectively. Non-zero Gaussian curvature in this instance refers to double-curved surfaces.

pg. 142 [23] A mesh dual is the connection of mesh triangle circumcenters (the point at which the angular bisectors of the triangles meet).

pg. 142 [24] This can also be written with the Schläfli symbol of {3,6}; i.e., six triangles around each vertex.

pg. 142 [25] While this was previously done using the BFF software (Sawhney & Crane, 2017), conformal mapping was later replaced with Kangaroo 2 components to minimize dependencies on external software.

pg. 142 [26] Meaning that it can be constructed by moving straight lines called 'generators' or 'rulings' (Pottman et al., 2007, p. 311).

pg. 165 [27] While supplemental hardware was not utilized on the panel-seam connections of *Wall Three*, these methods could be utilized in situations where a heat-welded seam might require local material reinforcement.

pg. 168 [28] While coincidentally the third design iteration, *Wall Three* is titled as such as a nod to the state-of-the-art, fabric formwork precedents *Wall One* and *Wall Two* (Chandler & Pedreschi, 2007, p. 58), which are discussed in **SECTION 3.3.2**.

pg. 189 [29] A geometry constructed within a Grasshopper script is only a preview; 'baking' is the act of instantiating the desired Grasshopper output geometry into the Rhino 3D file.

pg. 195 [30] These scripts are available online via the author's GitHub page (Scherer, 2020).

APPENDED PAPERS

PAPER A

Concrete Form[ing]work:
Integrating Patterns in Flexible Formwork for Cast Concrete

Annie Locke Scherer

Published In:

ArchiDOCT 5–1, no. 9 (2017): 27–39.

archi DOCT

The e-journal for the dissemination of doctoral research in architecture.

Supported by the ENHSA Network | *Fueled by the* ENHSA Observatory

9
July2017
www.enhsa.net/archidoct
ISSN 2309-0103

PROTOTYPING STRUCTURES IN ARCHITECTURE

Lifelong Learning Programme

european network enhsa of heads of schools of architecture

European Observatory of Doctoral Research in Architecture

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 5 (1) / July 2017

Concrete Form[ing]work: Integrating patterns in flexible formwork for cast concrete

Annie Locke Scherer // KTH Royal Institute of Technology

Abstract

This paper outlines the design methods in the research project Concrete Form[ing]work, and seeks to contextualize these methods within design research. First, it examines current design methodology in practice and situates this research within existing work. The second section provides an overview of ongoing and planned probes, while the third reflects on future uses and practice-based design applications. Concrete Form[ing]work explores the integration of smocking and cast concrete to investigate novel techniques for creating architectural elements (Figure 1). While traditional formwork for custom or sinuous concrete structures is often costly or impossible to fabricate, this research looks at numerous techniques to custom-tailor fabric for casting. These include traditional hand smocking as well as more recent research into custom knit structures that can react and transform in response to heat, water, or electrical currents. The integration of such methods advances new possibilities of design research and fabrication techniques with regard to what can be achieved with state-of-the-art fabric formwork. It also speculates on additional research that could introduce robotics and sensors to further explore issues of repeatability, scale, and economy.

Keywords

Flexible formwork, Concrete, Parametric patterning, Materiality, Digital craft.

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 5 (1) / July 2017

Introduction

Concrete construction has always defaulted to the economy and simplicity of rational, planar elements. Because of the ability to rationalize and evaluate planar formwork, and standardized assembly processes in the construction industry, efficiency in building has been valued over experimentation. Designers have chosen to default to what is "known" instead of re-imagining novel methods of using existing materials. With the technological revolution in the second half of the 19th century came a shift away from the fabrication of forms that were logical slabs, beams, and columns. Instead, construction methods developed expressive personalities of their own based on a material's characteristics. Designers began to recognize that such simplified elements did not use the material in the most rational means, but did not trust cost evaluations for these novel construction methods. Eladio Dieste, one of the pioneers of vaulting and thin shell concrete construction, expressed his concern of designers settling for fabricating planar elements because of the simplicity in testing and evaluation. While he recognizes that it is critical to have an analytical evaluation of construction methods and economy, he argues that simplification of construction is "unjustified," and that it is not enough of a reason to default to simple, economical structures in practice-based design research (Dieste, 2004).

Dieste argues that while architecture is a construction, it is also an art. An engineer himself, he looked to architecture and design to solve problems that were inherently structural. "For architecture to be truly constructed, the materials should not be used without a deep respect for their essence and consequently for their possibilities" (Dieste, 2004). There must be a relationship between rationality and expressiveness in order to achieve progress. By re-envisioning material possibilities and resisting the temptation to only build simple, economical structures, designers choose innovation over certainty. Over the next few decades, Dieste dedicated his life to the investigating the essence of materials and their mysteries and applied these economically. Keeping an artistic inquiry inherent in design, research raises new problems and research questions that would emerge otherwise.

Reflecting on the difficulties of testing and disseminating novel construction methods, designers and architects must continually develop evaluation methods for their research, particularly as new methods of fabrication evolve. Mette Ramsgard Thomsen and Martin Tamke note that inherent differences between architecture and engineering, as well as the varying levels of inquiry, require designers to develop more cyclical methods of evaluation. The recent advancement of digital machines and fabrication has shifted the means in which we conduct design research; we must create new methods in evaluating material evidence in relation to architectural practice. Thomsen and Tamke present three types of material evidence as means of evaluating research within our field: the design probe, the material prototype and the demonstrator (Ramsgard Thomsen and Tamke, 2009).

Because architecture is always embodied by the material, these three modes of material evidence allow architects to apply a dimensionality to a given design question and solution. While the design probe is more speculative investigation of design criteria, the material prototype explores the material behavior and extrapolates upon the criteria set up by the probe (Ramsgard Thomsen and Tamke, 2009). The demonstrator then builds upon this further, taking the wandering and sometimes fragmented prototyping process and applying real-world constraints to construct a more conclusive investigation. By arguing that utilizing the integrated approach of research by design and emphasizing the implementation of physical demonstrators, architects can aptly position their research to create a more cyclical and reflective connection between design, analysis, specification and fabrication

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 5 (1) / July 2017

Figure 1.
Cast concrete probes

(Ramsgard Thomsen and Tamke, 2015).

Coupling the understanding of materials with complex rather than static behaviors, we can work with the fears of innovation as observed by Dieste, and use demonstrators and full-scale architectural installations to realize new material practices. This reflection must also be used when evaluating the complex relationship between digital and the physical prototype. Material testing and probes must be developed simultaneously with digital models. Data from physical testing is used to inform the digital tools and in turn, the digital models help develop an understanding of material behaviors and structures not achievable by prototypes. What is critical is that we must verify our computational models by simultaneously developing both physical and digital tools in order to evaluate the appropriateness and precision

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 5 (1) / July 2017

of our experiments. Figure 2 shows a comparison between the digital model of CITA's Dermoid and final scan of the demonstrator. Even after fabrication is complete, reflection on the validity and precision of the digital model is vital.

Embracing Materiality

After examining the design methodology as outlined by Dieste and Thomsen, it is possible to more critically question traditional concrete formwork. Design research by architects and engineers such as Mark West, Remo Pedreschi, and Alan Chandler look to merge the process of, making as a craft, with the importance of delivering a precise form in industry. As noted above, contractors are reluctant to embrace techniques outside conventional rigid formwork because of a lack of precision and predictability. Projects such as West's beams, Chandler's Wall One, and Pedreschi's Kate Moss column (Figure 3) utilize flexible formwork to incorporate both an expression of materiality of concrete while simultaneously adhering to an acceptable manner of repeatability and reliability (West, 2017; Chandler and Pedreschi, 2007). Their experimental applications of flexible formwork to construct traditional architectural elements such as beams, walls, and columns investigate what aspects of these elements need to be precise for industrial applications, and those that have the possibility of being be more unpredictable and dynamic. This delicate balance is achieved through simultaneous physical experimentation and informed intuition of material behavior.

These projects utilize fluid-responsive formwork as casting techniques to allow the engagement of materiality and rheology within the construction process, and re-envisions the workers' role to be much more active in the design. Upon embracing the inherent rheological qualities of concrete rather than constraining them to rigid formwork, the material and fabricator are allowed to take an active role in the more dynamic casting process.

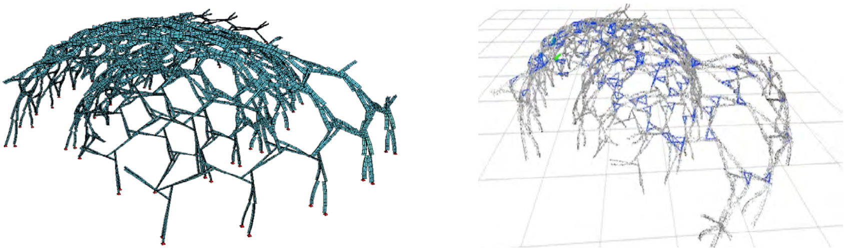


Figure 2.

Comparison of Dermoid digital model and scan, CITA

Figure 3.
Traditional concrete elements constructed from fabric formwork by A. Chandler, and R. Pedreschi
Image: Dirk Lellau (left), Remo Pedreschi (right)

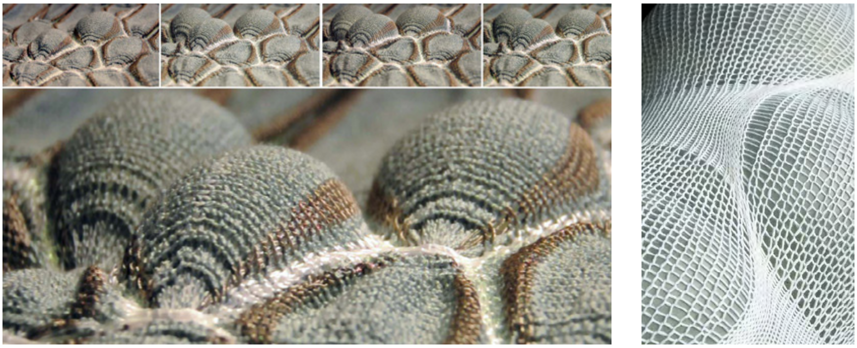


Figure 4.
Mette Ramsgard Thomsen's *Listener* and Yuliya Baranovskaya *Knitflatable Architecture*
Image: Mette Ramsgard Thomsen (left), Yuliya Baranovskaya (right)

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 5 (1) / July 2017

In addition to a more interactive fabrication process and expressive final form, fabric formwork evokes drastically different possibilities for construction, inherently sustainable in both material usage and formwork cost. Mark West's points out the material waste in standard, cross-section beams, and demonstrates that fabric formwork can be used as an easily-deployable, low-cost solution to manufacturing variable sectioned elements. Material density, strength, and durability of the cast object increases as a result of excess water allowed to wick through the pores of the fabric. Furthermore, portability becomes an option. Materials can be fit into duffel bags that can be easily transported for efficient, on-site deployment and later re-used for future projects (West, 2017).

Projects such as Mette Ramsgard Thomsen's *Listener* and Yuliya Baranovskaya's *Knitflatable Architecture* (Figure 4) take textile research one step further, examining the implications of programming material with inherent, varied elasticities and material properties. Envisioning these coupled with cast concrete, fabric textures and seams could leave their own trace on the form and articulate structural mass and depth with sinuous bumps and bulges. When pressure is applied to this differentiated material, either hydrostatic or pneumatic, the once-flat pattern is transformed into a complex, differentiated volume. By differentiating areas of varying elasticity, these techniques can be coupled with flexible formwork for concrete, allowing the hydrostatic pressure of the material to act as both a form finder and form giver.

Smocking

In an effort to integrate current fabric formwork research with more specified material differentiation as seen in *Listener* and *Knitflatable Architecture*, *Concrete Form[ing]work* investigates patterning techniques to formally manipulate flat sheets of fabric. This project examines smocking (Figure 5), a embroidery technique of gathering fabric to increase elasticity, and questions how this technique can be applied to differentiation of fabric formwork. Used in the absence of elastic, smocking refers to the gathering and stitching together of fabric in a wide variety of patterns, commonly used in clothing applications for cuffs, necklines, and waistlines. It reduces the size of the fabric to roughly one third of its original size, and these techniques can be applied to flexible formwork to specify varying areas of elasticity as well as differentiate global geometry.

Research Development

In order to better understand this process and potential architectural applications, a series of smocking patterns were produced by hand. The jersey cotton fabric was laid out on a grid and points of connection were marked with a felt pen. These areas were hand-stitched with a cotton thread to create a variety of different textures and forms, a few of which are exhibited in Figure 6. Some patterns proved to have too complex of folds or overlapping to allow the cast concrete to easily flow and were discarded. In partnering with the The Swedish Cement and Concrete Research Institute, a SCC (semi self-consolidating concrete) mix was developed with a 600-650mm spread. This mix comprised of a ratio of 1:1.2:.5:.4 (cement: fine aggregate: L 40 Lime: Water) with an additional 0.1% VMA and 0.1% superplasticizer. Limestone counteracts the tendency of particles to separate with the addition of the Superplasticizer (Master Gelenium 51), which increases fluidity without adding more water to the mixture. The VMA (viscosity modifying agent) is used as a starch to produce a homogenous composition and maintain cohesion. All of these modifications to the mix allow for fluidity and strength, while also producing a more durable and economically sustainable cast. This mixture will continue to be developed, based on the rheological needs of each particular smocking pattern and construction.

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 5 (1) / July 2017

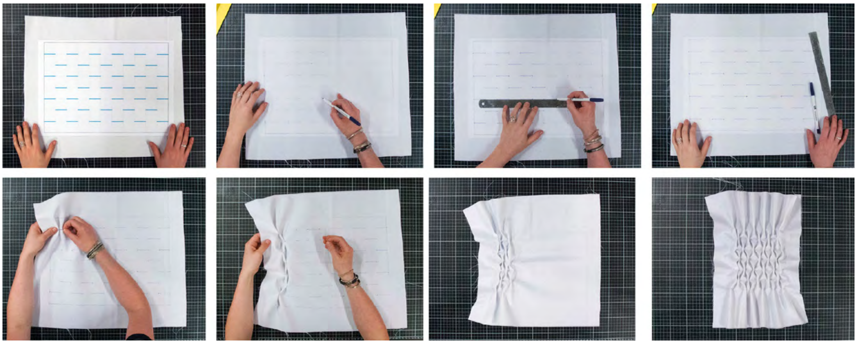


Figure 5.
Smocking technique

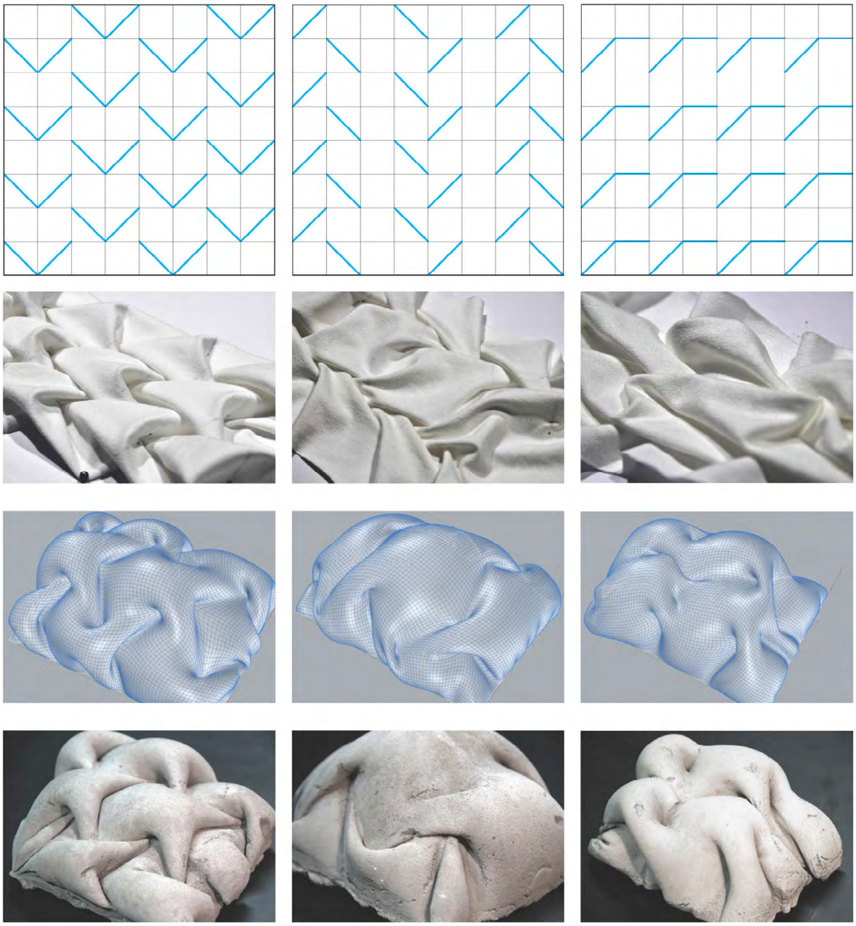


Figure 6.
Smocking patterns of "arrow," "leaf," and " fish scales," respectively in addition to sewn fabric, digital simulation, and final cast

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 5 (1) / July 2017

This research is currently in the process of creating a catalogue of potential smocking techniques that could be used in this manner. After rigorous testing of the application of smocking to two-dimensional surfaces, the next steps will apply these patterns to architectural tectonics, as investigated by West, Pedreschi, and Chandler. Looking at the application of smocking in the form of beams, columns, and walls brings a greater understanding as to how these techniques could be applied to architectural elements. This learning through fabrication technique will undoubtedly produce a series of unforeseen results, which will inform the design decisions that must be made, when scaling up and adding multi-dimensionality to global forms. Such parameters could include:

- concrete slump under larger weight and hydrostatic pressures
- fabric selection to avoid connection breakage
- improvement and specification of rheology of the concrete mixture
- evel of detail that can be achieved without cracking of concrete
- parameterization of patterns
- application of smocking for both ornamentation and topology

METHODS OF EXPERIMENTATION

During this experimentation, a series of research questions were developed:

> *How can fabric formwork be re-envisioned through smocking to create novel casting techniques?*
>
> *How can smocking be parameterized and differentiated to articulate new methods of fabricating architectural elements?*
>
> *What are the opportunities for applying smocking at multiple scales, and how can this be transferred to an industrial context?*

In developing these questions, it is critical to specify and reflect on how current methods of experimentation are carried out and evaluate their relation to the research questions at hand. Peter Krogh's "Ways of Drifting" describes an applicable series of research methodologies that can be used to evaluate experiments carried out to test a hypothesis. He describes a few methods of "drifting" for designers to evaluate learning from findings: accumulative, comparative, serial, expansive, and probing (Krogh, Markussen and Bang, 2015). When looking at *Concrete Form[ing]work's* methodology, the most logical means of experimentation lie somewhere between comparative and serial (Figure 7).

The *comparative* typology, as developed by Fogtmann and Ross, explores a number of cases to evaluate results in an overarching comparison. It involves testing central design cases in both identical and wide ranges of design context. The application of such typology results in exposing the complexity of an experiment by applying the design scenario in a multitude of situations (Krogh, Markussen and Bang, 2015). The application of smocking to a variety of architectural typologies will take this comparative approach.

Serial experimentation compliments the comparative method, where this "denotes how design experiments are being carried out in a certain order or logic of locality determined by how neighboring experiments in a sequence influence one another" (Krogh, Markussen and Bang, 2015) This chronological approach continually builds upon the previous experiments and "systematizing local knowledge." While a portion of *Concrete Form[ing]work* will be comparative, this serial typology is

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 5 (1) / July 2017

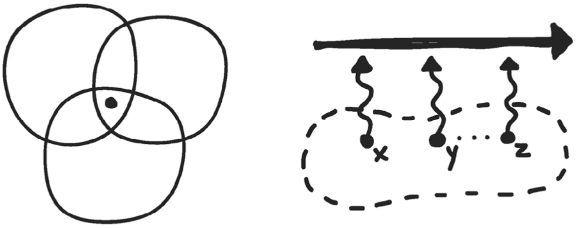


Figure 7.
Comparative and serial typologies as outlined by Krogh

also useful in evaluating the value of each experiment. New constraints and unknown discoveries will come about as more fabrication experience is amassed, and this will aid in determining the feasibility and fabrication of complex smocking patterns on multiple scales. Over the course of this research, fabrication intuition will be improved and tuned, and further experimentation of smocking's relation to concrete rheology and materiality build upon previous results.

These methods of "drifting" are not the only means of assessing the value of experimentation. It is important to view a research hypothesis as provisional and changing. The critical aspect is how the hypothesis evolves; being certain to learn from careful and methodical, rather than unsystematic, experimentation. Whether experimentation is conducted with one of Krogh's typologies or is simply an isolated probe with a novel approach, evaluation changes over time and often includes post-rationalization. What is most important is the rigorous process in which a designer must compare experimentation and research questions, and consistently check to make sure the two correlate.

CNC Knitted and Smart Textiles

While fabric formwork with concrete has evolved in the last half century, there has been very little experimentation with differentiation of materials. The past few decades have shown a huge increase in the fabrication of smart-textiles that are "augmented with the power of change and have the ability to perform or respond" (Verbüken, 2003). With the aid of computing technology and CNC knitting machines, it is possible to integrate "smart" materials with textiles (Figure 8, 9). This can, in turn, question the current research into fabric-cast architectural elements.

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 5 (1) / July 2017

In a partnership with KTH, The Swedish School of Textiles in Borås has been investigating novel methods of developing interactive textiles, with an emphasis on various interactive expressions such as water, heat, electrical and touch reaction. With the use of industrial weaving and knitting machines, there is the possibility of fabricating more complex, reactive formwork that could open a new realm of possibilities when working with cast concrete. Such exploration could include a blend of a base material and reactive materials such as:

- PVA: a fabric that dissolves when in contact with water
- Pemotex: a material that hardens when heat is applied
- Polyester or nylon blends that shrink when heat is applied
- Nitinol or Flexinol integration that actuates or shrinks when heat or electrical current is applied (Satomi, 2014)

These shape-changing materials could change traditional design to fabrication methods to one, which is interactive and iterative throughout the casting process. Formwork could be pre-programmed to harden or shrink, when it comes into contact with the moisture of the cast concrete. After a form is cast, heat or electrical current could be applied to continually sculpt the formwork even after the concrete has been poured. The exploration of textiles that have pattern differentiation with structure-changing properties, whether it be shrinking, stiffening, dissolving or actuating, could have significant architectural and industrial applications. These untapped possibilities will be explored in the coming year with KTH's partnership with the Swedish School of Textiles.

Robotics and Industrial Applications

The added complexity of integrating smart textiles brings up the question of industrialization and mass-production. Currently, these material probes are sewn by hand, in order to develop an understanding of smocking patterns and their fabrication. While analog experiments are vital to a significant understanding of material behavior, it is important to critically question the industrial applications when working with these techniques on a larger scale. More rigorous testing of hand-fabricated elements will uncover the limitations of what is possible to fabricate with smocked formwork.

Arcane knowledge of fabrication with industrial robot arms previously belonged to specialized engineers. This recent transfer of this knowledge and accessible interfaces has allowed architects, designers, researchers, educators, and artists to take up their own robotic projects within the creative industry. Robotic arms signify a new type of tool and a possible shift away from a conventional linear workflow. Previous conventional workflow was linear - design to fabrication - in which robotics were simply used in the fabrication of a predetermined design. With industrial robot arms, we can see the emergence of bi-directional workflows that supports the possibility of designer-robot-interaction. Figure 10 catalogues some recent uses for industrial robot arms and demonstrates the huge breath possibilities for their use in architecture.

While there are a huge range of existing applications for robotics, it is important to view a robot as a tool with limitations. That being said, it can be used in conjunction with *Concrete Form[ing]work* to develop processes that might not be possible by hand. Robotics could be

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 5 (1) / July 2017

Figure 8.
Pemotex hardening with heat, M. Bobeck, shrinking textiles at the Swedish School of Textiles in Borås, and integration of heat-shrinking thread in custom-knit textiles, D. Dumitrescu and A. Persson
Image: Malin Bobeck (left), Delia Dumitrescu (right)

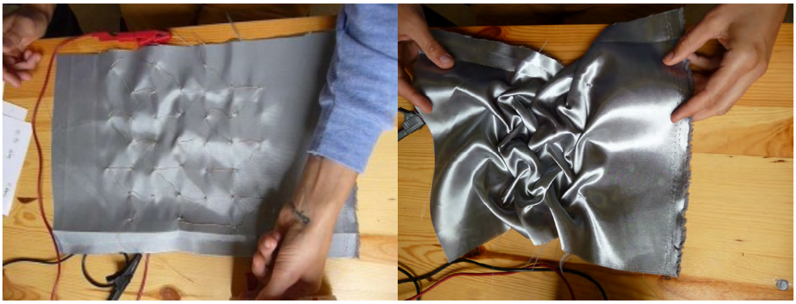


Figure 9.
Reversible Nitinol actuation with textiles (E-textile summer camp)

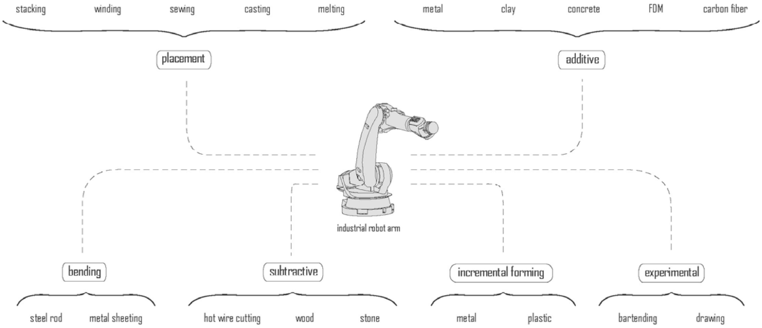


Figure 10.
Robots in architecture applications

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 5 (1) / July 2017

integrated in a way to take advantage of its precision, whether it is creating an industrial smocking technique, or using the robot to sense and accurately apply heat or other inputs to manipulate both local and global geometry to a cast form.

Conclusions

Through these design explorations and considerations, *Concrete Form[ing]work* seeks to evaluate existing casting techniques and re-envision these in the context of smocking, smart textiles and robotics. While current flexible formwork mainly focuses on simplicity of form, the introduction of CNC knitted textiles can bring about a similar ease of fabrication, as well as introducing local and global articulation. Varying scales of smocking applications, and the exploration of parametric patterns will produce a new vocabulary of spatial structures possible with flexible formwork.

With the possibility of integrating heat, touch, or electrical responsiveness, this research challenges conventional workflows of design to fabrication by employing a more iterative and interactive production process. A new method of making enables the fabricator to take an interactive role in the design of the form, rather than producing a product according to exact, pre-determined specifications. This participatory fabrication process allows the capacity to maintain craft while applying flexible formwork to industrial contexts. Furthermore, the correlation between probes and digital simulation augment this transition to industry, enabling fabricators to have confidence in the validity of their models and a reasonable amount of predictability.

The ability of flexible formwork to both express gravity and materiality of concrete, coupled with the increased predictability for industrial applications, is largely unexplored in architectural research. *Concrete Form[ing]work* fills a niche of articulated surface differentiation, while simultaneously addressing issues of repeatability, scale, and economy. Coupling reactive formwork and expressive materiality of concrete exposes a myriad of new possibilities of fabric cast forms and seeks to blur the line between where design ends and fabricator begins.

Acknowledgement

Concrete Form[ing] work is part of the research project: "Concrete Performance: Towards Digitally Informed Cement-Bound Material Systems" funded by Formas, the Swedish Research Council and headed by Prof. Dr. Oliver Tessmann.

ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 5 (1) / July 2017

References

Chandler, A. and Pedreschi, R., 2007. *Fabric Formwork.* London: Riba Publishing.

Culver, R., Koerner, J. and Sarafian, J., 2016. *Fabric Forms: The Robotic Positioning of Fabric Formwork.* RobArch 2016. Sydney, Australia.

Dieste, E., 2004. *Architecture in Construction.* reprinted in A. Stanford, ed. Eladio Dieste Innovation in Structural Art. New York: Princeton Architectural Press. Originally published July 1980.

Dumitrescu, D. and Persson, A., 2011. *Exploring Heat as Interactive Expressions for Knitted Structures.* The Swedish School of Textiles: University of Borås. Nordic Design Research Conference.

Krogh, P.G., Markussen, T. and Bang, A.L., 2015. *Ways of Drifting: 5 Methods of experimentation in research through design.* Proceedings of ICoRD Research into Design Across Boundaries, volume 1: Theory, Research Methodology, Aesthetics, Human Factors and Education.

Manelius, A.M., 2012. *Fabric Formwork: Investigations into Formwork Tectonics and Stereogeneity in Architectural Constructions.* Danish Royal Academy. CINARK.

Meibodi, M., 2015. *Manifested In Form: Tensions Between Utility and Form in the Digital Design of Architecture.* Lulea University of Technology. Stockholm, Sweden.

Norell, D., 2016. *Taming the Erratic: Representation and materialization in post-digital architectural design.* Licentiate Thesis: Stockholm, Sweden.

Ramsgard Thomsen, M. and Tamke, M., 2009. *Narratives of Making: Thinking Practice Led Research in Architecture.*

Ramsgard Thomsen, M. and Tamke, M., 2015. Prototyping Practice: Merging Digital and Physical Inquiries. *Rethink! Prototyping: Trans-disciplinary Concepts of Prototyping.* Springer, pp. 49-62.

Satomi, M., 2014. *E-Textile Summer Camp: SMA Meets Smocking.* < http://etextile-summercamp.org/2014/sma-meets-smocking/ >.

Verbüken, M., 2003. *Towards a new sensoriality. The New Everyday - Views on Ambient Intelligence.* Rotterdam: 010 Publishers, pp. 54-59.

West, M., 2017. *The Fabric Formwork Book.* London: Routledge.

PAPER B

Concrete Form[ing]work:
Designing and Simulating Parametrically-Patterned Fabric Formwork for Cast Concrete

Annie Locke Scherer

Published In:

Architecture in the Age of the 4th Industrial Revolution, 2:759–68. University of Porto, Porto, Portugal, 2019.

Concrete Form[ing]work:

Designing and Simulating Parametrically-Patterned Fabric Formwork for Cast Concrete

Annie Locke Scherer[1]
[1]KTH Royal Institute of Technology
[1]schere@kth.se

Concrete is one of the most widely used construction materials globally, yet its industrial fabrication techniques continue to default to planar formwork and uniform cross sections for the sake of simplicity and predictability. /Concrete Form[ing]work/ evaluates state-of-the-art fabric formwork research and explores the industry's reticence to integrate these novel design approaches. This research has identified two challenges that have significantly hindered the adoption of fabric formwork in architectural design: complex tailoring of parametrically designed forms and the lack of accurate simulation tools for flexible formwork. /Concrete Form[ing]work/ develops methods to address both of these issues, providing an alternative approach to more simply tailor fabric forms and accurately simulate these patterns' response to casting. In doing so, this research has the potential to fundamentally change and streamline how the field of flexible formwork is approached and integrated within architectural design. This paper will present the process of parametrically tailoring non-developable surfaces from single sheets and document the advancement of these simulation tools.

Keywords: *flexible formwork, concrete, simulation, parametric patterning, smocking*

1 CONTEXT

In the 1960's, designers and engineers such as Miguel Fisac ("Fundación Miguel Fisac" n.d.) began to explore the architectural implications of textile use with cast concrete as an alternative to the costly standard of rigid formwork. This simple, technical re-imagining of formwork material brought about research such as Mark West's materially efficient beams (West et al., 2016) and Kenzo Unno's in situ, low-waste houses (Veenendaal et al. 2011). This past research is well documented yet does not address newer technological methods of production.

The advent of digital design and parametric fabrication in recent years has resulted in an era of mass-customization, often directly clashing with fabricability. Consequently, despite considerable advances in the field of fabric formwork, industrial applications of flexible formwork and cast concrete are extremely limited (Concrete Canvas, n.d.; "FASTFOOT Fabric Formed Footings," n.d.). *Concrete Form[ing]work* has

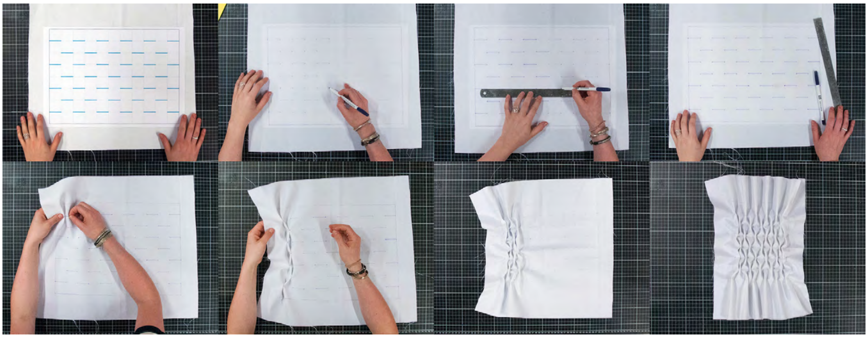


Figure 1
Smocking process of a basic lozenge pattern

surveyed recent architectural research in the field of flexible formwork to understand potential limitations of industrial applications. Projects such as Fatty Shell (Holzwart et al., n.d.) and MARS Pavilion (Sarafian et al., 2017) are prime examples of the vast amount of tailoring that is required to create complex forms from flat sheet material. The large number of components and high degree of fabrication accuracy required in both projects identifies an area that requires further development in order to make flexible formwork more readily accessible to designers.

The second limitation of current flexible formwork methods is the lack of simulation utilized by current design methods. Varying fabric elasticity, hydrostatic pressures, and tacit material knowledge of concrete are all reasons cited for the difficulty in simulating cast forms. Mark West's research team at C.A.S.T. (West et al., 2016) and Remo Pedreschi's Disruptive Technologies studio (Bush, 2012), both leading researchers in the field of flexible formwork, refrain from using digital modeling, preferring to rely on tacit material knowledge. Fabric patterns are hand-drawn with chalk onto sandwiched sheets of fabric, ultimately designed from material intuition derived from previous experiments. While this is an excellent hands-on approach to research and learning, this technique can hinder the ability of those who have no previous casting experience to accurately design, predict or model flexible formwork for cast concrete. Some projects such as Fatty Shell utilize limited 3D modeling, but do so by over-simplifying the formwork as an abstracted, minimal surface mesh. Consequently, this adaptation leads to unanticipated hydrostatic pressure and required ad hoc solutions to keep the formwork in position (Veenendaal and Block, 2012). The crucial link between concrete, parametric tailoring of fabric, and precise simulation is missing, and is a core basis of why flexible formwork has not been more commonly integrated into architectural design and industry. *Concrete Form[ing]work* aims to combine the tacit knowledge of materiality and parametric patterning of formwork within a digital and physical workflow.

2 METHODS

2.1 Smocking

In the context of the current state-of-the art flexible formwork, *Concrete Form[ing]work* investigates alternatives to tailor flexible formwork without the need of several hundred unique components sewn together. The research re-imagines the use of traditional smocking, an embroidery technique used since the middle ages to tailor a laborer's clothing (Cave and Hodges, 1984). The term comes from "*smock*", a farmer's work shirt, and the technique was popularized in the eighteenth and nineteenth cen-

Figure 2
A selection of conventional smocking patterns, sewn fabric and resulting cast counterparts

Figure 3
Column 1 lozenge smocking pattern, fabric formwork, and cast probe

turies as it was possible to more easily tailor flat panels of fabric to the shape of the human body without labor-intensive cutting and sewing of numerous pattern pieces. Hand smocking typically involves marking a regular grid onto the sheet of material to tailor, and connecting the end points of pattern lines where excess material needs to be gathered. The steps of constructing a basic ”lozenge” smocking pattern are exhibited in Figure 1.

The potentials of locally detailing flexible formwork with smocking provide new possibilities when combined with cast concrete. During the initial stages of research a series of fifteen hand-sewn smocking patterns were cast to examine the feasibility of casting concrete in smocking, a selection of which are shown in Figure 2. In context of these experiments, a more in-depth investigation was carried out to understand the implications of applying smocking to a fundamental architectural element: the column. The aim of the first column probe was to explore vertical casting in a smocked fabric column formwork and to understand how the pattern would react to hydrostatic pressures and gravity. A simple lozenge pattern was selected and consisted of an alternating series of pattern lines on a 5 cm grid (seen in cyan in Figure 3). The starting fabric width was doubled to accommodate the decrease in size due to gathered detailing. The end points of these lines were connected by hand with industrial-grade thread.

A self-compacting concrete recipe, developed in collaboration with the Swedish Cement and Concrete Research Institute (CBI) at KTH was selected. This mix is characterized by a high fluidity to strength ratio without the addition of excess water, and meets the demand of being self-consolidating (compacting) under its own weight, without vibration. Because vibration is not necessary, this recipe affords ease in fabrication of the prototype, and the fluidity achieved by the super plasticizer (Master Gelenium) allows the concrete to easily permeate the smocking details. While this initial prototype failed in the lower sections due to fabric tearing, the smocking details were easily readable and informed future selection of fabric and smocking patterns in subsequent prototypes. The base detail was unfortunately not clearly distinguished due to the combination of the very elastic material and high hydrostatic pressures at the base of the column, but will be further explored in later mockups.

Figure 4
Column 02 basic arrow smocking pattern, formwork, carbon fiber reinforcement grid and cast probe

Column 2 was developed to test multi-directional smocking patterns as well as local anchoring points between the fabric and reinforcement. In response to the learnings from the previous probe, a thicker jersey cotton fabric was used and smocking connections were reinforced to prevent the fabric from tearing. The base was simplified to a circle profile in order to limit the number of new variables introduced. Previous tests determined that the lower limit dimension of a smock detail with this particular fabric and concrete mix is ˜35mm. In order to construct an arrow patterned column with a similar size and radius as column 1, the pre-smocked fabric had to be doubled in both width and height, to correspond to the material loss due to the multi-directional pattern. (Note this scale of prototyping was retained as it results in a cast that can be reasonably transported by one person). A carbon fiber grid was placed inside to achieve two goals: first, it serves as general reinforcement for the cast column. Second, it provides a substructure to anchor the smocking connections, minimizing the global "ballooning" deformation of the column and isolating it to only occur locally between smocks.

2.2 Digital Prototyping & Casting Simulation of Flexible Formwork

Simulation in the field of flexible formwork is relatively unexplored, due to the complexities of modeling the stretch of the fabric and hydrostatic pressures. Researchers prefer to rely on hand-drawn patterns and material intuition, or simple minimal surface abstractions. The lack of predictability and ease of replication are the main hindrances that deters industry's enthusiastic adoption of flexible formwork. This

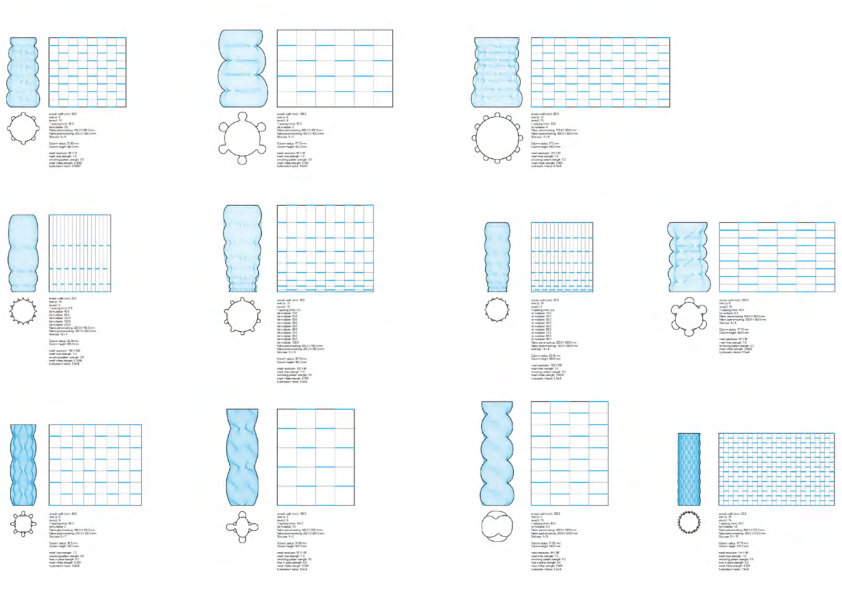


Figure 5
Simulation tool development & design variations

research seeks to understand the accuracy possible with accessible tools to architects, such as Grasshopper, Python, and Kangaroo 2. *Concrete Form[ing]work* uses these tools to develop a parametric workflow for pattern generation, as well as simulating the smocking process and resultant cast geometries of the patterned formwork. With complex parametric patterning, it becomes critical to negotiate a digital workflow of simulation, fabrication, and calibration to anticipate flexible formwork's response to hydrostatic pressure. The first parametric design studies of varying patterns of columns are seen in Figure 5 and Figure 6. Their correlation will be discussed in a later section.

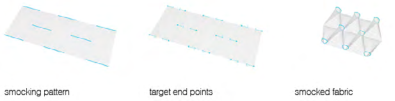


Figure 6
Basic smocking kangaroo simulation

3 DESIGN RESEARCH DEVELOPMENT

3.1 Parametric Patterning of Non-Developable Surfaces with Smocking

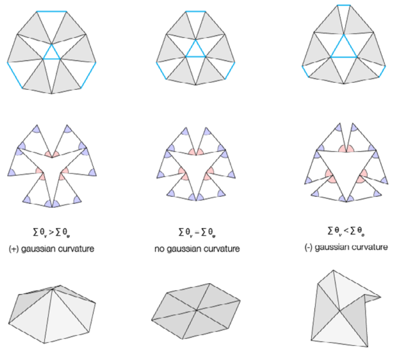


Figure 7
Programming patterns with Gaussian curvature

Until this step in the research, only manipulation of 2D patterns was possible and relied heavily on intuition gained from working with smocking. The next series of probes investigated the deconstruction of non-developable, tessellated meshes into flat smocking patterns. In order to re-imagine the complex tailoring of parametrically patterned fabric formwork, *Concrete Form[ing]work* synthesizes a variety of research fields that address the task of programming curvature within flat sheet material. It builds upon geometric principles of Ron Resch patterns ("The Works of Ron Resch," n.d.), Tomohiro Tachi's Origamizer (Tachi, 2010), auxetic materials (Konaković-Luković et al., 2018) and kirigami (Castle et al., 2016), (Scherer, 2015) and applies these geometric findings to smocking. The underlying principles of these research topics include tessellation and programmed curvature. Similar to kirigami (a variation of origami with cuts), or programmed auxetic materials, a smocking pattern can be abstracted as a mesh. The "cuts" or "holes" of these precedents can be re-imagined as smocks or "tucks." A computationally-designed smock, in a similar manner as a Ron Resch pattern, gathers excess material at specified vertices, to follow the changing relative angles and mesh curvature. This principle is illustrated in Figure 7. By changing the relation between the sum of the interior angles (θv) shown in red and the exterior angles (θe) shown in blue, it is possible to program zero, positive, or negative Gaussian curvature in a folded material or fabric.

Deconstructing a 3D mesh to a smock pattern. Figure 8 details the principles behind generating a smocking pattern from a 3D mesh. (1) The desired 3D shape is tessellated with mesh triangles and the circumcenters (point where three perpendicular bisectors of the triangle meet) are calculated and connected (dual graph). In (2), the triangles (with same edge lengths and relative positioning as their 3D counterparts) are laid out on a flat hexagonal grid, which is a scaled and flattened version of the 3D mesh dual. In order to achieve an arrow smocking pattern, alternating inside and outside vertices of the triangles are identified to anchor together in Kangaroo (3). The simulation is run (4) and the specified vertices snap together, all the while retaining the same mesh edge lengths as the 3D configuration. Finally, the vertices of the "gaps" are connected (5, seen in cyan), and are the smocking pattern connection points.

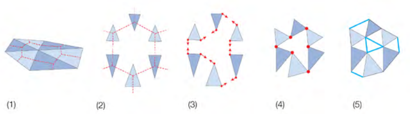


Figure 8
Deconstructing a double-curved surface into a smocking pattern, based on Ron Resch's origami pattern

Column 3.1 Demonstrator. This deconstruction process was applied to a one-sheet hyperboloid with negative Gaussian curvature to create a non-developable surface from a single sheet of material. Figure 9 shows the (1) triangle mesh tessellation, (2) circumcenter mesh dual found to retain tiling structure when unrolling (3) scaling of the mesh dual and placement of corresponding mesh triangles in the XY plane (4) connecting alternating triangle vertices to

Figure 9
Smocking pattern generation from a tessellated one-sheet hyperboloid with negative Gaussian curvature

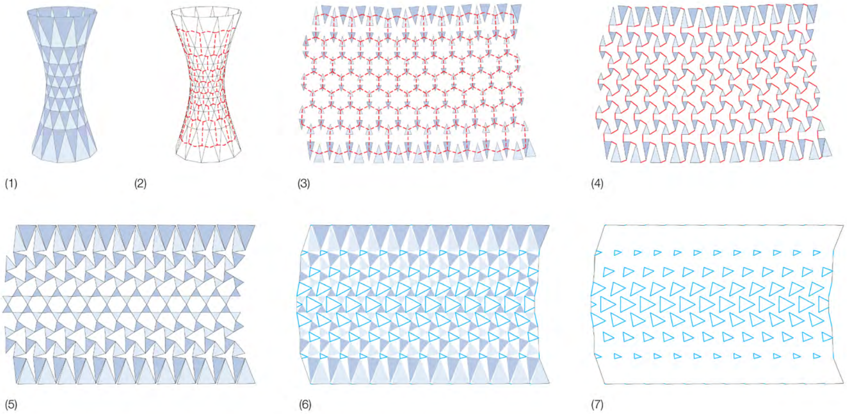


Figure 10
Column 3.1 demonstrator of a one-sheet hyperboloid fabricated from a single sheet of material

snap together (5) running the Kangaroo simulation, retaining mesh edge lengths while snapping appropriate triangle vertices together (6) connecting resulting "gaps" with smocking pattern lines and finally (7) producing the fabrication pattern. The size of the smocks in column 3.1 do not meet the minimum requirements for concrete to correctly flow into the details, and the demonstrator was fabricated solely as a geometrical proof of concept (Figure 10). A lower resolution version of this pattern was cast (column 3.2) and is detailed in Figure 12.

Concrete Forming[work] has successfully developed a tool in which a desired shape can be input by the user and outputs a Ron Resch-based smocking pattern to apply to the fabric in order to achieve the desired curvature. This research investigates the parameterization of smocked patterns and showcases its possibilities for programming both local and global articulation in a single piece of fabric, eliminating the need to sew hundreds of individual components together.

3.2 Correlation with Cast Probes

The concrete industry today is hesitant to integrate non-planar fabrication methods, citing a lack of accurate simulation tools and repeatability with flexible formwork. In addition to constructing parametric patterns to tailor formwork into non-developable surfaces, this research also acknowledges the vital development of digital models in parallel with material testing. Results from physical probes must inform simulation tools, and in turn, computational models must be verified by correlation to realized prototypes. This feedback loop is relatively undeveloped in flexible formwork research today, and is critical to establish to successfully integrate flexible formwork at an industrial level.

Column 2 Simulation & Correlation. *Concrete Form[ing]work* has developed a Kangaroo simulation in parallel with fabrication of physical probes. This tool provides valuable fabrication information to the user such as starting fabric size, smocking pattern, simulated fabric tensile stresses and a detailed calculation of the concrete mixture. Column 2 was scanned and correlated and the point cloud was colorized based on deviation from the simulation (Figure 11). The maximum deviation of the simulation from the point cloud was between -21 to 12.8 mm. The main source of this error was that the column twisted slightly during fabrication, due to the elasticity of the fabric.

Figure 11
Column 2 cast probe and simulation correlation

Column 3.2 Simulation & Correlation. In order to test the applications of the parametric patterning findings in the previous section, a lower-resolution version of column 3.1 was produced. These smocks meet the minimum requirements to be appropriately filled with concrete without overlapping, thus allowing the fabric to be more easily removed after casting. The same patterning methods as Figure 9 were used, but based on a more simplified mesh triangulation. The linen fabric was laid out and marked, and an additional string tension ring was added to maintain column section dimensions. The fabrication steps, including the smocking pattern, formwork sewing, casting and correlation can be seen in Figure 12. While a mixer malfunction during the last phase of casting unfortunately caused some separation in the upper section of the column, the cast probe still correlated to the simulation model with a -26.2 to 22.5 mm deviation. This appears to be caused by some smocking details being less filled by the concrete mix than others, and a closer look into mixture ratios and minimum smocking size will be included in future probes.

CONCLUSION

In conclusion, this series of prototypes details Concrete Forming[work]'s ability to parametrically pattern non-developable formwork for cast concrete and fabricate demonstrators that accurately correlate with their corresponding simulations. Learnings from these tests such as fabric selection, minimum smocking size, and base detailing will be further developed in future probes. The next step is a series of larger investigations, as it is critical to address smocking connections and fabric type at at full-scale.

Concrete Form[ing]work synthesizes hand-craft construction technologies with computational design and simulation to address gaps in current state-of-the-art flexible formwork research. This project achieves parametric patterning of doubly curved surfaces with smocking, eliminating the need for complex tailoring of individual elements and provides development of interactive, accurate, and accessible

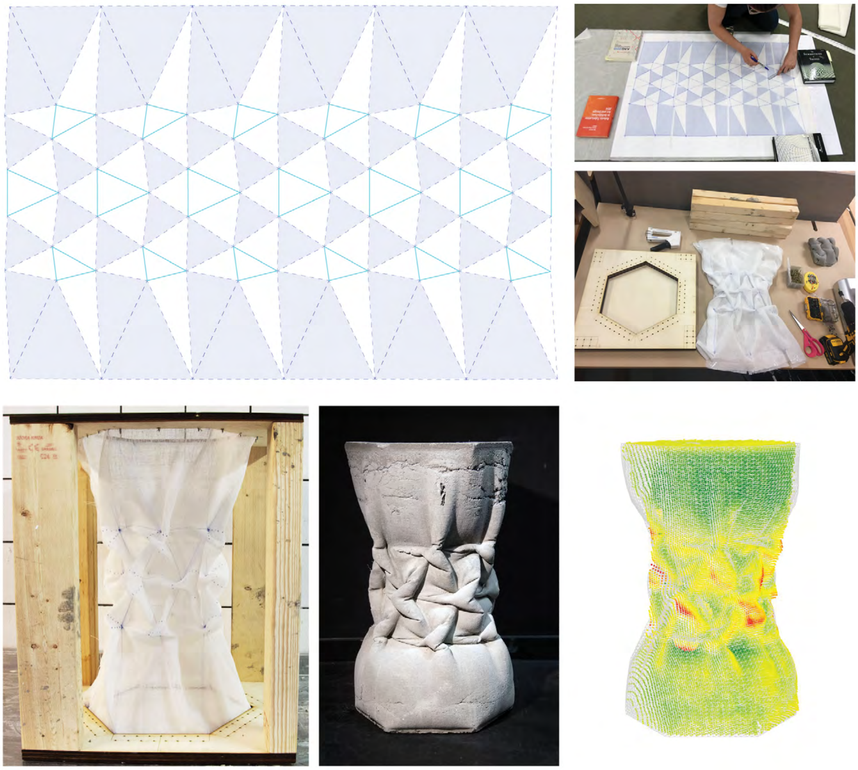


Figure 12
Column 3.2 pattern, fabrication, cast probe and simulation correlation

design and simulation tools. Because it is possible to accurately simulate flexible formwork under the hydrostatic pressures of cast concrete, this tool opens the possibility for designers with no previous flexible formwork or casting experience to utilize these techniques, without having to first acquire tacit material knowledge. It is situated within current architectural design and expands upon the field by combining a centuries-old sewing technique with computational design. The integration of such techniques is a relatively unexplored topic in current fabric formwork research, and the tools developed within this project aim to increase the accessibility and reliability of flexible formwork, narrowing the existing gap in fabrication processes today.

REFERENCES

Castle, T, Sussman, D, Tanis, M and Kamien, R 2016, 'Additive Lattice Kirigami', *Science Advances*, 2, p. 11

Cave, E and Hodges, J 1984, *Smocking: Traditional & Modern Approaches*, B.T. Batsford LTD, London

Konaković-Luković, M, Panetta, J, Crane, K and Pauly, M 2018, 'Rapid Deployment of Curved Surfaces via Programmable Auxetics', *ACM Transactions on Graphics*, 37(106), pp. 1-13

Sarafian, J and Culver, R 2017 'Robotic Formwork in the MARS Pavilion: Form Found Design Towards The Creation Of Programmable Matter', *Proceedings of ACADIA 2017*, Cambridge, MA, pp. 522-533

Scherer, AL 2015, *Programmable Folding: Computational Design with an Embedded Assembly Logic*, Master's Thesis, Universität Stuttgart ITECH

Tachi, T 2010, 'Origamizing Polyhedral Surfaces', *IEEE Transactions on Visualization and Computer Graphics*, 16(2), pp. 298-311

Tachi, T 2013 'Freeform Origami Tessellations by Generalizing Resch's Patterns', *Proceedings of the ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Portland, Oregon, USA, pp. 1-10

Veenendaal, D and Block, P 2012 'Computational form-finding of fabric formworks : an overview and discussion', *Proceedings of the 2nd international conference on flexible formwork*, Bath, UK, pp. 368-378

Veenendaal, D, West, M and Block, P 2011, 'History and Overview of Fabric Formwork: Using Fabrics for Concrete Casting', *Structural Concrete - Journal of the fib*, 12(3), pp. 164-177

West, M, Allen, E, Ochsendorf, J, Veenendaal, D and Araya-Caceres, R 2016, *The Fabric Formwork Book: Methods for Building New Architectural and Structural Forms in Concrete*, Routledge, London

[1] http://cargocollective.com/fabroboticsnet/Fatty-Shell-Flexible-Formwork
[2] https://richardbush.wordpress.com
[3] http://www.fundacionfisac.com
[4] https://www.concretecanvas.com
[5] http://www.fastfoot.com
[6] http://www.ronresch.org

BIBLIOGRAPHY

Abdelgader, H., West, M., & Górski, J. (2018). Fabric Formwork—An Alternative to Traditional Formwork. *Betonwerk Und Fertigteil-Technik/Concrete Precasting Plant and Technology*, *84*, 48–57.

Able, C., Arias, A., & Montgomery, E. (2012). *[Fabric]ation* [Master's Thesis, Columbia GSAPP]. https://issuu.com/charlieable/docs/gsapp-portfolio-2009-2012

Adil, S. E., Vasudev, A., Kumar, P., & Reddy, A. (2017). Study on C_{O2} Absorbing Concrete. *International Journal of Civil Engineering and Technology*, 8, 1778–1784.

AFGC. (2000). Bétons Auto-Plaçants: Recommandations provisoires. Association Française de Génie Civil.

Aish, R., & Bredella, N. (2017). The Evolution of Architectural Computing: From Building Modelling to Design Computation. *Architectural Research Quarterly*, 21, 65–73. https://doi.org/10.1017/S1359135517000185

Aitchison, J. (2011). Craft Thinking & Digital Making: The Role of the Architect in the Digital Era. http://www.frrarchitects.co.uk/wp-content/uploads/2011/07/craft-thinking-digital-making_Joanne-Aitchison.pdf

Allen, S., & Agrest, D. (2000). Practice: Architecture, Technique and Representation. Routledge: Taylor & Francis Group.

American Concrete Institute. (2007). ACI 237R-07: Self-Consolidating Concrete. https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/18605

Ananthasuresh, G. (2015). Buckminster Fuller and his Fabulous Designs. Resonance, *20*, 98–122. https://doi.org/10.1007/s12045-015-0159-6

Andrasek, A. (2016, May 18). *Theory of Computation* [Innochain Lecture].

Anton, A., Bedarf, P., Yoo, A., Reiter, L., Wangler, T., Flatt, R., & Dillenburger, B. (2020). *Concrete Choreography: Prefabrication of 3D-Printed Columns* (pp. 286–293). https://doi.org/10.2307/j.ctv13xpsvw.41

Baghdadi, A., Heristchian, M., & Kloft, H. (2019). Structural Assessment of Remodelled Shells of Heinz Isler. *International Journal of Advanced Structural Engineering*, *11*(4), 491–502. https://doi.org/10.1007/s40091-019-00248-4

Baker, E. (2014). Search for a Rooted Aesthetic: Study in Spin-Valence. In F. Gramazio, M. Kohler, & S. Langenberg (Eds.), *Fabricate 2014* (pp. 128–135). UCL Press. https://doi.org/10.2307/j.ctt1tp3c5w.20

Bang, A. L., Krogh, P. G., Ludvigsen, M., & Markussen, T. (2012). The Role of Hypothesis in

Constructive Design Research. *Making, Reflecting and Understanding - Aalto University School of Arts, Design and Architecture, Helsinki, Finland*, 1–11. https://adk.elsevierpure.com/ws/portalfiles/portal/39583287/The_Role_of_Hypothesis_in_Constructive_Design_Research_Final_Version.pdf

Baranovskaya, Y. (2016). Knitflatable Architecture—Pneumatically Activated Pre-Programmed Knitted Textiles. In H. Aulikki, T. Österlund, & P. Markkanen (Eds.), Complexity & Simplicity—Proceedings of the 34th eCAADe Conference (Vol. 1, pp. 571–580). CumInCAD. http://papers.cumincad.org/cgi-bin/works/paper/ecaade2016_055

Barcelo, L., Kline, J., Walenta, G., & Gartner, E. (2014). Cement and Carbon Emissions. *Materials and Structures*, 47(6), 1055–1065. https://doi.org/10.1617/s11527-013-0114-5

Barnes, M. (1994). Form and Stress Engineering of Tension Structures. Structural Engineering Review, *6*(3). https://researchportal.bath.ac.uk/en/publications/form-and-stress-engineering-of-tension-structures

Benjamin, A. (2003). *Jesse Reiser and Nanako Umemoto*. BOMB Magazine. https://bombmagazine.org/articles/jesse-reiser-and-nanako-umemoto/

Billberg, P. (1999). *Self-Compacting Concrete for Civil Engineering Structures: The Swedish experience*. Cement och Betong Institutet. http://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-2812

Blain, L. (2014, April 23). *Chinese Company Uses 3D Printing to Build 10 Houses in a Day*. New Atlas. https://newatlas.com/china-winsun-3d-printed-house/31757/

Blees, M. K., Barnard, A. W., Rose, P. A., Roberts, S. P., McGill, K. L., Huang, P. Y., Ruyack, A. R., Kevek, J. W., Kobrin, B., Muller, D. A., & McEuen, P. L. (2015). Graphene Kirigami. *Nature*, *524*(7564), 204–207. https://doi.org/10.1038/nature14588

Boller, G., & Schwartz, J. (2020). Modelling the form. Heinz Isler, Frei Otto and their approaches to form-finding. *Iron, Steel and Buildings: Studies in the History of Construction. The Proceedings of the Seventh Annual Conference of the Construction History Society*, 565–576. https://www.research-collection.ethz.ch/handle/20.500.11850/457240

Brandt, E., & Binder, T. (2007). *Experimental Design Research: Genealogy—Intervention—Argument*. International Association of Societies of Design Research, Hong Kong. https://adk.elsevierpure.com/en/publications/experimental-design-research-genealogy-intervention-argument

Burry, J., & Burry, M. (2016). *Prototyping for Architects: Real Building for the Next Generation of* Digital Designers. Thames & Hudson.

Burry, J., Felicetti, P., Tang, J., Burry, M., & Xie, M. (2005). Dynamical Structural Modeling: A Collaborative Design Exploration. *International Journal of Architectural Computing,* 3(1), 27–42. https://doi.org/10.1260/1478077053739595

Bush, R. (2010, October 12). Bubble Wrapped Concrete! More Fun Than Popping It? *Concrete Fabrication*. https://richardbush.wordpress.com/2010/10/12/bubble-wrapped-concrete-more-fun-than-popping-it/

Bush, R. (2012). *Concrete Fabrication* | *Disruptive Technologies: Material – Immaterial*. https://richardbush.wordpress.com/

Carpo, M. (2011). *The Alphabet and the Algorithm*. MIT Press.

Carpo, M. (2012). Digital Darwinism: Mass Collaboration, Form-Finding and the Dissolution of Authorship. *Log, 26*.

Castle, T., Cho, Y., Gong, X., Jung, E., Sussman, D. M., Yang, S., & Kamien, R. D. (2014). Making the Cut: Lattice Kirigami Rules. *Physical Review Letters, 113*(24), 245502. https://doi.org/10.1103/PhysRevLett.113.245502

Castle, T., Sussman, D. M., Tanis, M., & Kamien, R. D. (2016). Additive Lattice Kirigami. *Science Advances, 2*(9), 11. https://doi.org/10.1126/sciadv.1601258

Chan, T., Bush, R., & Powell, A. (2011). *Single Cast Wall* [M.Arch Thesis]. Dept. Arch, University of Edinburgh.

Chandler, A. (2004). Building Walls – a Philosophy of Engagement. *Architectural Research Quarterly*, *8*(3–4), 204–214. https://doi.org/10.1017/S1359135504000259

Chandler, A. (2015). Fabric Formwork – Prototype to Typology. *The Journal of Architecture, 20*(3), 420–429. https://doi.org/10.1080/13602365.2015.1042904

Chandler, A., & Pedreschi, R. (2007). *Fabric Formwork*. Riba Publishing.

Chiang, Y.-C. (2019). *Programming Flat-to-Synclastic Reconfiguration. ArchiDOCT, 6*(2), 17.

Concrete Canvas. (n.d.). *Home*. *Concrete Canvas: Erosion Control & Containment.* Retrieved March 24, 2018, from https://www.concretecanvas.com

Cross, N. (2006). *Designerly Ways of Knowing*. Springer-Verlag. https://doi.org/10.1007/1-84628-301-9

De Laet, L., Mollaert, M., Luchsinger, R. H., Temmerman, N. D., & Guldentops, L. (2010). Mechanisms for Deployable Tensairity Structures. *Evolution and Trends in Design, Analysis and Construction of Shell and Spatial Structures.* International Association for Shell and Spatial Structures (IASS) Symposium, Valencia. https://riunet.upv.es/handle/10251/7282

De Landa, M. (2001). Philosophies of Design, The Case of Modeling Software. *Verb - Architecture Boogazine*, 129–142.

de Soto, B. G., Agustí-Juan, I., Hunhevicz, J., Joss, S., Graser, K., Habert, G., & Adey, B. T. (2018). Productivity of Digital Fabrication in construction: Cost and Time Analysis of a Robotically-Built Wall. *Automation in Construction*, *92*, 297–311. https://doi.org/10.1016/j.autcon.2018.04.004

Demaine, E. D., & O'Rourke, J. (2007). *Geometric Folding Algorithms: Linkages, Origami, Polyhedra*. Cambridge University Press. https://doi.org/10.1017/CBO9780511735172

Demaine, E. D., & Tachi, T. (2017). Origamizer: A Practical Algorithm for Folding Any Polyhedron. *33rd International Symposium on Computational Geometry (SoCG 2017), 34*, 3–8. https://doi.org/10.4230/LIPIcs.SoCG.2017.34

DeMarly, D. (1987). *Working Dress: A History of Occupational Clothing.* Holmes & Meier Pub.

Deplazes, A. (2005). *Constructing Architecture: Materials, Processes, Structures, a Handbook*. Birkhäuser-Publishers for Architecture.

Desbrun, M., Meyer, M., & Alliez, P. (2002). Intrinsic Parameterizations of Surface Meshes. *Computer Graphics Forum, 21*(3), 209–218. https://doi.org/10.1111/1467-8659.00580

Dieste, Eladio. (2004). Architecture in Construction. In *Eladio Dieste Innovation in Structural Art*.

Downton, P. (2003). *Design Research*. RMIT Publishing.

Dillenburger, B., & Hansmeyer, M. (2013). The Resolution of Architecture in the Digital Age. In J. Zhang & C. Sun (Eds.), *Global Design and Local Materialization* (pp. 347–357). Springer. https://doi.org/10.1007/978-3-642-38974-0_33

Echenagucia, T. M., Pigram, D., Liew, A., Van Mele, T., & Block, P. (2019). A Cable-Net and Fabric Formwork System for the Construction of Concrete Shells: Design, Fabrication and Construction of a Full Scale Prototype. *Structures*, *18*, 72–82. https://doi.org/10.1016/j.istruc.2018.10.004

Edwin, A. (2020). *Anita Edwin Crafts*. https://www.youtube.com/channel/UCYS6MzpsDowauBLjOlpeo5g/videos

Efrat, T. A., Mizrahi, M., & Zoran, A. (2016). The Hybrid Bricolage: Bridging Parametric Design with Craft through Algorithmic Modularity. *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, 5984–5995. https://doi.org/10.1145/2858036.2858441

Etherington, R. (2010a, March 18). *Concrete Chair by Tejo Remy & René Veenhuizen*. Dezeen. https://www.dezeen.com/2010/03/18/concrete-chair-by-tejo-remy-renee-veenhuizen/

Etherington, R. (2010b, September 1). *Mass IIII by Janwillem Van Maele.* Dezeen. https://www.dezeen.com/2010/09/01/mass-iiii-by-janwillem-van-maele/

European Ready Mixed Concrete Organization. (2018). *Ready-Mixed Concrete Industry Statistics*. https://mediatheque.snpb.org/userfiles/file/Statistics%20Bound%20Volume%2030_08_2019%20-%20R4.pdf

Fab-Form. (n.d.). *Fab-Form: Sustainable Foundations*. Fast-Tube Overview. Retrieved September 3, 2020, from https://www.fab-form.com/fast-tube/fast-tubeOverview.php

FASTFOOT Fabric Formed Footings. (n.d.). FASTFOOT Fabric Formed Footings. Retrieved October 23, 2017, from http://www.fastfoot.com/

Felix, E. (2005, October 4). *Drawing Digitally*. Urban Design Seminar, MIT, Cambridge, Mass.

Fisac, M. (2010). *Carta a mis Sobrinos (Estudiantes de Arquitectura).* Fundación Miguel Fisac.

Forty, A. (2006). *Liquid Stone: New Architecture in Concrete* (J.-L. Cohen & G. M. Moeller, Eds.). Princeton Architectural Press.

Frayling, C. (1993). *Research in Art and Design* (Vol. 1). Royal College of Art.

Frearson, A. (2014, November 25). *Foster + Partners works on "Commercial Concrete-Printing Robot."* Dezeen. https://www.dezeen.com/2014/11/25/foster-partners-skanska-worlds-first-commercial-concrete-3d-printing-robot/

Fundación Miguel Fisac. (n.d.). Retrieved August 17, 2017, from http://www.fundacionfisac.com/

Garber, R. (2009). Alberti's Paradigm. *Architectural Design, 79*(2), 88–93. https://doi.org/10.1002/ad.859

Garber, R. (2017). Digital Workflows and the Expanded Territory of the Architect. *Architectural Design, 87*(3), 6–13. https://doi.org/10.1002/ad.2167

Garlock, M. E. M., & Billington, D. P. (2008). *Félix Candela: Engineer, Builder, Structural Artist*. Yale University Press.

Gaudillière, N., Duballet, R., Bouyssou, C., Mallet, A., Roux, P., Zakeri, M., & Dirrenberger, J. (2019). Building Applications Using Lost Formworks Obtained Through Large-Scale Additive Manufacturing of Ultra-High-Performance Concrete. In *3D Concrete Printing Technology* (pp. 37–58). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-12-815481-6.00003-8

Gavriletea, M. (2017). Environmental Impacts of Sand Exploitation. Analysis of Sand Market. *Sustainability, 9*, 1118. https://doi.org/10.3390/su9071118

Gehry, F. (1995). *Conversations with Frank O. Gehry* (A. Zaera, Interviewer) [Published in: El Croquis 74/75]. https://cdn.shopify.com/s/files/1/1380/4487/files/conversaciones_con_gehry.pdf?153

Gell, A., & Hirsch, E. (2020). The Technology of Enchantment and the Enchantment of Technology. In E. Hirsch (Ed.), *The Art of Anthropology* (1st ed., pp. 40–63). Routledge. https://doi.org/10.4324/9781003136545-6

Green, C. (2005). Was Babbage's Analytical Engine Intended to Be a Mechanical Model of the Mind? *History of Psychology, 8*, 35–45. https://doi.org/10.1037/1093-4510.8.1.35

Guseinov, R., Miguel, E., & Bickel, B. (2017). CurveUps: Shaping Objects from Flat Plates with Tension-Actuated Curvature. *ACM Trans. Graph. Article, 36*(64). https://doi.org/10.1145/3072959.3073709

Gustavsson, M. (2014, April 2). *Concrete Easy Chair*. Concrete Construction. https://www.concreteconstruction.net/products/concrete-construction-equipment-tools/concrete-easy-chair_o

Hacking, I. (1983). *Representing and Intervening: Introductory Topics in the Philosophy of Natural Science*. Cambridge University Press.

Hanna, A. S. (1999). *Concrete Formwork Systems*. Marcel Dekker.

Hawkins, W. J., Herrmann, M., Ibell, T. J., Kromoser, B., Michaelski, A., Orr, J. J., Pedreschi, R., Pronk, A., Schipper, H. R., Shepherd, P., Veenendaal, D., Wansdronk, R., & West, M. (2016). Flexible Formwork Technologies – A State of the Art Review. *Structural Concrete*, *17*(6), 911–935.

Héder, M. (2017). From NASA to EU: The Evolution of the TRL scale in Public Sector Innovation. *The Innovation Journal*, *22*(2). https://www.semanticscholar.org/paper/From-NASA-to-EU%3A-the-evolution-of-the-TRL-scale-in-H%C3%A9der/7d72b6a1dd7f1920934464d0075ea6aac8a848a3

Heinz Isler. (2020). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Heinz_Isler&oldid=994516134

Hensel, M., Sunguroglu, D., & Menges, A. (2008). Material Performance. *Architectural Design, 78*(2), 34–41.

Herbert, G. (1984). *Dream of the Factory-Made House: Walter Gropius and Konrad Wachsmann* (First Edition). The MIT Press.

Hoitinik, A., & Cabral, I. (2014). *SMA meets smocking*. http://etextile-summercamp.org/2014/sma-meets-smocking/

Huerta, S. (2006). Structural Design in the Work of Gaudí. *Architectural Science Review*, *49*, 324–339. https://doi.org/10.3763/asre.2006.4943

Ingold, T. (2002). Of String Bags and Birds' Nests: Skill and the Construction of Artefacts. In *The Perception of the Environment: Essays on Livelihood, Dwelling & Skill* (pp. 349–361).

Ingold, T. (2013). *Making: Anthropology, Archaeology, Art and Architecture*. Routledge.

Isler, H. (1959). New Shapes for Shells. *Journal of the International Association for Shell and Spatial Structures*, paper C-3.

Isler, H. (1994). Concrete Shells Derived from Experimental Shapes. *Structural Engineering International, 4*(3), 142–147. https://doi.org/10.2749/101686694780601935

Jindal, B. B. (2018). Concrete Cloth: An Innovative Versatile Construction Material. *Trends in Civil Engineering and Its Architecture*, *1*(1), 001–004. https://doi.org/10.32474/

TCEIA.2018.01.000123

Kapoor, A., Lowe, A., & Schaffer, S. (2009). *Unconformity and Entropy: Greyman Cries, Shaman Dies, Billowing Smoke, Beauty Evoked* (1st ed.). Turner

Kolarevic, B., & Klinger, K. R. (Eds.). (2008). *Manufacturing Material Effects: Rethinking Design and Making Architecture*. Routledge.

Konaković-Luković, M., Crane, K., Deng, B., Bouaziz, S., Piker, D., & Pauly, M. (2016). Beyond Developable: Computational Design and Fabrication with Auxetic Materials. *ACM Transactions on Graphics, 35*(4), 1–11. https://doi.org/10.1145/2897824.2925944

Konaković-Luković, M., Panetta, J., Crane, K., & Pauly, M. (2018). Rapid Deployment of Curved Surfaces via Programmable Auxetics. *ACM Transactions on Graphics, 37*(4), 1–13. https://doi.org/10.1145/3197517.3201373

Koskinen, I., Zimmerman, J., Binder, T., Redstrom, J., & Wensveen, S. (2011). *Design Research Through Practice: From the Lab, Field, and Showroom* (Vol. 56). Morgan Kaufmann. https://doi.org/10.1016/C2010-0-65896-2

Krogh, P. G. (2016, November 8). *Methodology and Experiment*.

Krogh, P. G., Markussen, T., & Bang, A. L. (2015). *Ways of Drifting—Five Methods of Experimentation in Research Through Design*. In A. Chakrabarti (Ed.), *ICoRD'15 – Research into Design Across Boundaries Volume 1* (pp. 39–50). Springer India. https://doi.org/10.1007/978-81-322-2232-3_4

Kudless, A. (2013). *P_Wall (2013)*. Matsys. https://www.matsys.design/p_wall-2013

Kudless, A. (2011). Bodies in Formation: The Material Evolution of Flexible Formworks. *31st Annual Conference of the Association for Computer Aided Design in Architecture, 98–105*. http://papers.cumincad.org/cgi-bin/works/paper/acadia11_98

Kuma, T. (2014). *ITECH M.Sc. 2014: Spacer Fabric Architecture*. https://www.icd.uni-stuttgart.de/teaching/master-theses/itech-m-sc-2014-spacer-fabric-architecture/

Kwinter, S. (2003). Who's Afraid of Formalism? In M. Kubo & A. Ferré (Eds.), *Phylogenesis: FOA's Ark/Foreign Office Architects* (pp. 96–99). Originally published in *Any Magazine* no. 7(8) (1994). https://actar.com/phylogenesis/

Lab, R. H. (2007, April). Think Formwork—Reduce Costs. *Structure Magazine*, 14–16.

Lang, R., & Foer, J. (2014). Paper Perfect: Robert Lang and the Science of Origami. *Virginia Quarterly Review, 90*, 12–19.

Lawton, S. (2013, December 30). Fabric Formed Stair – Vergennes, Vermont. *Arro Design*. http://www.arrodesign.org/projects/fabric-formed-stair-vergennes-vermont/

Lawton, S. (2019, May 17). *Skype Interview with Sandy Lawton* [Personal communication].

Leemann, A., & Winnefeld, F. (2007). The Effect of Viscosity Modifying Agents on Mortar and

Concrete. *Cement and Concrete Composites, 29*, 341–349. https://doi.org/10.1016/j.cemconcomp.2007.01.004

Leslie, T. (2018, July 17). *"Laborious and Difficult:" Pier Luigi Nervi's Hangars for the Italian Air Force, 1936-42*. 6th International Congress on Construction History, Brussels, Belgium. https://doi.org/10.13140/RG.2.2.31482.39367

Levy, B., Petitjean, S., Ray, N., & Maillot, J. (2002). Least Squares Conformal Maps for Automatic Texture Atlas Generation. *ACM Trans. Graph., 21*, 362–371. https://doi.org/10.1145/566654.566590

Lewis, W., & Lewis, T. S. (1996). Application of Formian and Dynamic Relaxation to the Form-Finding of Minimal Surfaces. *Undefined*. https://www.semanticscholar.org/paper/Application-of-formian-and-dynamic-relaxation-to-of-Lewis-Lewis/001920b9bc307db418c4e71ceb09a99977ce7f94

Lim, S., Buswell, R. A., Valentine, P. J., Piker, D., Austin, S. A., & De Kestelier, X. (2016). Modelling Curved-Layered Printing Paths for Fabricating Large-Scale Construction Components. *Additive Manufacturing, 12,* 216–230. https://doi.org/10.1016/j.addma.2016.06.004

Loh, P., Burry, J., & Wagenfeld, M. (2016). Reconsidering Pye's Theory of Making Through Digital Craft Practice: A theoretical framework towards continuous designing. *Craft Research, 7*, 187–206. https://doi.org/10.1386/crre.7.2.187_1

Mamou-Mani, A. (2013). *The Magic Garden—Karen Millen RIBA Regent Street Window Display 2013*. https://vimeo.com/78069864

Manelius, A.-M. (2010, March 5). Ambiguous Chairs - a Surprise Encounter with Concrete. *CONCRETELY*. http://concretely.blogspot.com/2010/03/ambiguous-chairs.html

Manelius, A.-M. (2012). *Fabric Formwork: Investigations into Formwork Tectonics and Stereogeneity in Architectural Constructions* [PhD Dissertation, The Royal Danish Academy of Fine Arts]. https://adk.elsevierpure.com/en/publications/tekstilforskalling-til-beton-unders%C3%B8gelser-af-forskallingstektoni

Manelius, A.-M. (2009). *Ambiguous Chairs Cast in Fabric Formed Concrete.*

Marmo, F., Demartino, C., Candela, G., Sulpizio, C., Briseghella, B., Spagnuolo, R., Xiao, Y., Vanzi, I., & Rosati, L. (2019). On the form of the Musmeci's bridge over the Basento river. *Engineering Structures, 191*, 658–673. https://doi.org/10.1016/j.engstruct.2019.04.069

Marshall, B. (1980). *Smocks and Smocking* (1st.ed. edition). Alphabooks.

Master Builders Solutions. (2015). *MasterGlenium 51: Superplasticerare*. https://assets.master-builders-solutions.com/sv-se/mbs-masterglenium-51-db.pdf

McCall Printed Pattern 1350. (1947, ca). Vintage Sewing Patterns. https://vintagepatterns.

fandom.com/wiki/McCall_1350

McCullough, M. (1996). *Abstracting Craft: The Practiced Digital Hand*. Massachusetts Institute of Technology. https://www.semanticscholar.org/paper/Abstracting-Craft%3A-The-Practiced-Digital-Hand-McCullough/ac076fae55181c0aa3e1f18023568ce557be63c3

Millentrup, V., Thomsen, M. R., & Nicholas, P. (2019). Actuated Textile Hybrids Textile Smocking for Designing Dynamic Force Equilibria in Membrane Structures. *Blucher Design Proceedings*, 521–530. https://doi.org/10.5151/proceedings-ecaadesigradi2019_521

Miller-Johnson, R. (2009). *Fabric Formwork—An Alternative Concrete Construction System*. 1–5. https://doi.org/10.1061/41031(341)273

Milne, K. (2017). *Tailored Fabric Formwork* [MScR thesis]. Dept. Arch, University of Edinburgh.

Milne, K., Pedreschi, R., & Richardson, L. (2015, August 16). *Tailoring Fabric Formwork*. International Society of Flexible Formwork (ISOFF) Symposium 2015, Amsterdam. https://sites.eca.ed.ac.uk/fabricformedconcrete/files/2015/08/Tailoring-fabric-formwork.pdf

Milne, K., Pedreschi, R., & Richardson, L. (2018). The Formworker. In C. Mueller & S. Adriaenssens (Eds.), *Creativity in Structural Design*. https://www.research.ed.ac.uk/en/publications/the-formworker

Missinne, S. (2015). America's Birth Certificate: The Oldest Globular World Map: c. 1507. *Advances in Historical Studies, 04*, 239–307. https://doi.org/10.4236/ahs.2015.43019

Mitani, J., & Suzuki, H. (2004). Making Papercraft Toys from Meshes using Strip-Based Approximate Unfolding. *ACM Trans. Graphics, 23*(3), 259–263.

Mohite, A. (2021). Speed-Based Additive Manufacturing Technique [Doctoral Thesis (in press)]. Aalto University: School of Arts, Design and Architecture.

Morrow, R. (2017). *Material Witchery: Tactility Factory as a Site of Emerging Ethical Practice*. In *Feminist Futures of Spatial Practice: Materialisms, Activisms, Dialogues, Pedagogies, Projections* (pp. 75–93). Spurbuchverlag: Art Architecture Design Research. https://pure.qub.ac.uk/en/publications/material-witchery-tactility-factory-as-a-site-of-emerging-ethical

Murray, S. F. (2013). Design Research: Translating Theory Into Practice. In *Design Research in Architecture: An Overview* (pp. 95–116). Ashgate Publishing Limited.

Nan, C., Patterson, C., & Pedreschi, R. (2017). *Emerging Territories of Digital Material Practice*. https://www.pure.ed.ac.uk/ws/portalfiles/portal/35208473/Nan_final_pdf.pdf

Nejur, A., & Steinfeld, K. (2017). *Ivy Progress in Developing Practical Applications for a Weighted-Mesh Representation for Use in Generative Architectural Design*. 37th Annual Conference of the Association for Computer Aided Design in Architecture, 446–455. http://papers.cumincad.org/cgi-bin/works/paper/acadia17_446

Nervi, P. L. (1944). Nuove Possibilità per le Costruzioni Navali in Cemento Armato (Patent No. 429.331).

Nervi, P. L. (1948). Procedimento Costruttivo per la Realizzazione di Strutture Cementizie Ondulate o Curve con o Senza Tensioni Preventive (Patent No. 445.781).

Nervi, P. L. (1950). *Procedimento Costruttivo per la Realizzazione di Superfici Resistenti Piane o Curve Costituite da Reticolati di Nervature in Cemento Armato, Completate o Meno da Solette di Collegamento tra le Nervature.* (Patent No. 465.636).

Nervi, P. L. (1956). *Structures* (G. Salvadori & M. Salvadori, Trans.). F.W. Dodge Corp.

Nicholas, P. (2016, November 9). *Methodology and Experiment: Stressed Skins* [Lecture].

Nonaka, I. (1994). A Dynamic Theory of Organizational Knowledge Creation. *Organization Science*, *5*(1), 14–37. https://doi.org/10.1287/orsc.5.1.14

Nonaka, I., & Konno, N. (1998). *The Concept of "Ba": Building a Foundation for Knowledge Creation*. https://doi.org/10.2307/41165942

Nonaka, I., & Takeuchi, H. (1995). *The Knowledge-Creating Company: How Japanese Companies Create the Dynamics of Innovation.* Oxford University Press.

Norell, D. (2016). *Taming the Erratic: Representation and Materialization in Post-Digital Architectural Design* [KTH Royal Institute of Technology]. http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-195099

Orr, J. J., Darby, A. P., Ibell, T. J., Evernden, M. C., & Otlet, M. (2011). Concrete Structures using Fabric Formwork. *The Structural Engineer*, *89*(8), 20–26. http://dx.doi.org/10.17863/CAM.17019

Ouchi, M. (1999). State-of-the-Art report on Self-Compactability Evaluation. *International Workshop on Self-Compacting Concrete*.

Ozawa, K., Maekawa, K., & Okamura, H. (1992). Development of High Performance Concrete. *Journal of the Faculty of Engineering, University of Tokyo, Series B; (Japan)*, *41:3.* https://www.osti.gov/etdeweb/biblio/6509280

Pedreschi, R. (2013). *CAST: Innovations in Concrete | Fabric Formed Concrete*. https://sites.eca.ed.ac.uk/fabricformedconcrete/exhibitions/cast-innovations-in-concrete/

Pedreschi, R. (2016, April 15). *Making Concrete More Sustainable: Fabric Formwork*. https://www.youtube.com/watch?v=z8a9kAwOCiY

Pedreschi, R., & Lee, D. S.-H. (2014). Structure, Form and Construction: Fabric Formwork for Concrete. *48th International Conference of the Architectural Science Association*. Across: Architectural Research through to Practice, Genoa. https://doi.org/10.13140/RG.2.1.4599.3683

Pepakura Designer. (n.d.). Retrieved May 8, 2018, from https://tamasoft.co.jp/pepakura-en/

Piker, D. (2014). *Developable Dome—Grasshopper*. https://www.grasshopper3d.com/photo/

developable-dome?overrideMobileRedirect=1

Polanyi, M. (1958). *Personal Knowledge: Towards a Post-Critical Philosophy*. University of Chicago Press.

Polanyi, M. (1966). *The Tacit Dimension*. Routledge & Kegan Paul.

Popescu, M. A. (2019). *KnitCrete: Stay-in-Place Knitted Formworks for Complex Concrete Structures* [Doctoral Thesis, ETH Zurich]. https://doi.org/10.3929/ethz-b-000408640

Popescu, M., Rippmann, M., Van Mele, T., & Block, P. (2020). KnitCandela—Challenging the Construction, Logistics, Waste and Economy of Concrete-Shell Formworks. *Fabricate 2020: Making Resilient Architecture*, 194–201. https://doi.org/10.3929/ethz-b-000440088

Popper, K. R. (1959). *The Logic of Scientific Discovery*. Psychology Press.

Pottman, H., Asperl, A., Hofer, M., & Kilian, A. (2007). *Architectural Geometry* (D. Bentley, Ed.). Bentley Institute Press.

Precast/Prestressed Concrete Institute. (2003). *TR-6-03 Interim Guidelines for the Use of Self-Consolidating Concrete in PCI Member Plants* (pp. 1–5). PCI.

Protevi, J. (2001). *Political Physics: Deleuze, Derrida, and the Body Politic. The* Athlone Press.

Pseudocode. (2021). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Pseudocode&oldid=1013834720

Pye, D. (1978). *The Nature and Art of Workmanship*. UnivPress.

Ramsgaard Thomsen, M., & Karmon, A. (2011). Listener: A Probe Into Information Based Material Specification. *Studies in Material Thinking, 07*(Where Art, Technology and Design Meet), 158–163.

Ramsgaard Thomsen, M., & Tamke, M. (2016). Prototyping Practice: Merging Digital and Physical Enquiries. In C. Gengnagel, E. Nagy, & R. Stark (Eds.), *Rethink! Prototyping: Transdisciplinary Concepts of Prototyping* (pp. 49–62). Springer International Publishing. https://doi.org/10.1007/978-3-319-24439-6_5

Ramsgaard Thomsen, M., & Tamke, M. (2009). *Narratives of Making: Thinking Practice Led Research in Architecture*. 1–8. https://adk.elsevierpure.com/en/publications/narratives-of-making-thinking-practice-led-research-in-architectu

Reiser, J. (2006). *Atlas of Novel Tectonics*. Princeton Architectural Press.

Relph-Knight, L. (2014). Modular Values. *Architectural Review*, *235*(1408), 122–127.

Resch, R. (1970). *The Works of Ron Resch—Ron Resch Official Website*. http://www.ronresch.org/ronresch/

Resch, R. (1977). *Self-Supporting Structural Unit Having a Three-Dimensional Surface* (Patent No. 4059932). http://www.freepatentsonline.com/4059932.html

Resch, R. (2000). *The Vegreville Pysanka—Ron Resch Official Website*. http://www.ronresch.org/ronresch/the-egg/

Resch, R. (1973). The Topological Design of Sculptural and Architectural Systems. *Proceedings of the June 4-8, 1973, National Computer Conference and Exposition on - AFIPS '73*, 643. https://doi.org/10.1145/1499586.1499744

Resch, R., & Christiansen, H. (1970, September). *The Design and Analysis of Kinematic Folded Plate Systems*. IASS Symposium on Folded Plates and Prismatic Structures, Vienna, Austria.

Rörig, T., Sechelmann, S., Kycia, A., & Fleischmann, M. (2015). Surface Panelization Using Periodic Conformal Maps. In P. Block, J. Knippers, N. J. Mitra, & W. Wang (Eds.), *Advances in Architectural Geometry 2014* (pp. 199–214). Springer International Publishing. https://doi.org/10.1007/978-3-319-11418-7_13

Sahuc, J. (2019). *Experimental and Analytical Investigation of the Spin-Valence Kirigami Space Frame* [Master of Engineering in Civil and Environmental Engineering, Massachusetts Institute of Technology]. https://dspace.mit.edu/handle/1721.1/123221

Sarafian, J. (2018, March 27). *Skype Interview with Joseph Sarafian* [Personal communication].

Sarafian, J., Culver, R., & Lewis, T. S. (2017). Robotic Formwork in the MARS Pavilion: Form Found Design Towards The Creation of Programmable Matter. *Disciplines & Disruption*, 522–533. http://papers.cumincad.org/cgi-bin/works/paper/acadia17_522

Sarafian, J., Will, P., & Culver, R. (2016). *Fabric-Formed Robotic Facades: The Robotic Positioning of Fabric Formwzork* (D. Noble, K. Kensek, & S. Das, Eds.; Vol. 1, pp. 25–36). Facade Tectonics Institute.

Savorra, M., & Fabbrocino, G. (2013). *Félix Candela between Philosophy and Engineering: The meaning of shape*. https://doi.org/10.1201/b15267-33

Sawhney, R., & Crane, K. (2017). *Boundary First Flattening. 37*(1). https://doi.org/10.1145/3132705

Scherer, A. **L.** (2015). *Programmable Folding: Computational Design with an Embedded Assembly Logic* [M.Sc ITECH Programme, Universität Stuttgart]. https://issuu.com/annielockescherer/docs/alscherer_programmablefolding

Scherer, A. L. (2017). Concrete Form[ing]work: Integrating Patterns in Flexible Formwork for Cast Concrete. *ArchiDOCT, 5*, 27–39.

Scherer, A. L. (2018, September 10). *Column Casting Simulation with Lozenge Smocking Pattern Formwork*. Zenodo. https://doi.org/10.5281/zenodo.5113233

Scherer, A. L. (2019a, September 12). *Torus 2.0 Tiling & Smocking Pattern Generation*. Zenodo.

https://doi.org/10.5281/zenodo.5113167

Scherer, A. L. (2020, December 2). *Concrete Form[ing]work: Smocking Pattern Generation and Simulation Files*. GitHub. https://github.com/AnnieLocke

Scherer, A. L. (2021, July 19). *Wall Three Fabrication Process*. Zenodo. https://doi.org/10.5281/zenodo.5114112

Scherer, A. L. (2019b). Concrete Form[ing]work: Designing and Simulating Parametrically-Patterned Fabric Formwork for Cast Concrete. *Architecture in the Age of the 4th Industrial Revolution, 2*, 759–768. https://doi.org/10.5151/proceedings-ecaadesigradi2019_193

Scherer, A. L., & Miranda Carranza, P. (2019). *Studio 9: Architectural Notations – KTH Royal Institute of Technology Architecture School*. https://www.studio9.arch.kth.se/

Schiftner, A., Höbinger, M., Wallner, J., & Pottmann, H. (2009). Packing Circles and Spheres on Surfaces. *ACM Transactions on Graphics (TOG), 28*(5), 1–8. https://doi.org/10.1145/1618452.1618485

Schmid, F. (2013). *Stitching Concrete—Bench & Chair*. http://www.florian-schmid.com/stitching_concrete_collection.html

Schmidt, M. & Fehling, E. (2005). Ultra-High-Performance Concrete: Research, Development and Application in Europe. *ACI Special Publication, 1 & 2*, 51–78. http://worldcat.org/isbn/0870311808

Schmitz, R. (2014, June 20). *Fabric-formed concrete: a Novel Method for Forming Concrete Structures*. 3rd International Conference on Civil Engineering and Urban Planning, Wuhan, China.

Schmitz, R. (2018, December 18). *Is There a Future for Fabric-Formed Concrete Structures?* 3rd International Conference on Structures and Architecture. ICSA 2016, Guimaraes, Portugal.

Scully, P. (2016, May 19). *Theory of Computation*.

Sennett, R. (2008). The Craftsman. Yale University Press.

Shah, A., Shah, A., & Shah, P. (2018). Performance Evaluation of Fabric Formwork. 683–690.

Shore, D. (2013). *Modern Smocking*. Vivebooks.

Simplicity Printed Pattern 1863A. (1956, ca). Vintage Sewing Patterns. https://vintagepatterns.fandom.com/wiki/Simplicity_1863_A

Sitnikov, V. (2020). *Ice Formwork: The Rationale and Potential of Ice-Based Moulding Systems for the Production of Complex-Geometry Precast Concrete* [Doctoral Thesis, KTH School of Architecture adn the Built Environment]. http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1485414&dswid=201

Stalder, L. (2013). No Limits to Growth: The Global and Interplanetary Urban Models of Fritz Haller. *AA Files, 66,* 145–152.

Stanford Bunny. (2020). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Stanford_bunny&oldid=967179662

Stoughton, J. (2018, March 2). *Ultra-Thin Concrete Roof to Cap a Net-Positive Energy Rooftop Apartment*. The Architect's Newspaper. https://www.archpaper.com/2018/03/ultra-thin-concrete-roof-cap-net-positive-energy-rooftop-apartment/

Sun, A. (2015, February 26). *3D-Printed Cities: Is This the Future?* The Guardian. http://www.theguardian.com/cities/2015/feb/26/3d-printed-cities-future-housing-architecture

Tachi, T. (2010). Origamizing Polyhedral Surfaces. *IEEE Transactions on Visualization and Computer Graphics, 16*(2), 298–311. https://doi.org/10.1109/TVCG.2009.67

Tachi, T. (2009). 3D Origami Design Based on Tucking Module. *Proceedings of Fourth International Conference Origami in Science, Math., and Education (Origami4)*, 259–272. https://doi.org/10.1016/j.leaqua.2011.04.011

Tachi, T. (2013). Freeform Origami Tessellations by Generalizing Resch's Patterns. *IDETC-CIE 2013*, 10. https://doi.org/10.1115/DETC2013-12326

Tamke, M., Hernández, E. L., Deleuran, A., Gengnagel, C., Burry, M., & Thomsen, M. R. (2012). *A New Material Practice*: Integrating Design and Material Behavior. *SimAUD 2012: Proceedings of the Symposium on Simulation for Architecture and Urban Design, Orlando, USA*, 5–12. https://adk.elsevierpure.com/en/publications/a-new-material-practice-integrating-design-and-material-behavior

Tamke, M., Nicholas, P., & Thomsen, M. (2017). *What Does It Mean To Make An Experiment? Arena Third Annual Conference*, 219–238. https://arch.kuleuven.be/english/research/conferences/impactbydesigning

Tessmann, O. (2008). *Collaborative Design Procedures for Architects and Engineers* [Doctoral Thesis, Universität Kassel]. http://kobra.bibliothek.uni-kassel.de/bitstream/urn:nbn:de:hebis:34-2008100124162/3/Tessmann_DocThesis.pdf

The Express Wire. (2021). *Global Self Compacting Concrete Market Size 2021: Industry Analysis by Top Manufacturers, Development Revenue and Regional Analysis with Growth Trends by 2027* (pp. 1–132). https://www.360researchreports.com/2021-2027-global-and-regional-self-compacting-concrete-industry-status-and-prospects-professional-market-18109024

The Sewing Directory. (2020). Canadian Smocking Tutorial | Tutorials. *Canadian Smocking Tutorial | Tutorials*. https://1001fashiontrends.blogspot.com/2010/05/canadian-smocking-tutorial-tutorials.html

Tomita, H., Higaki, T., Kobayashi, T., Fujii, T., & Fujimoto, K. (2015). Stenting for Curved Lesions Using a Novel Curved Balloon: Preliminary Experimental Study. *Journal of*

Cardiology, 66(2), 120–124. https://doi.org/10.1016/j.jjcc.2014.10.009

Tsubaki, K. (2012). Foldout Drawing: A Projective Drawing for Fabric Forming. *Journal of Architectural Education, 66*(1), 98–106. https://doi.org/10.1080/10464883.2012.719821

Tysmans, T., Adriaenssens, S., & Wastiels, J. (2011). Form Finding Methodology for Force-Modelled Anticlastic Shells in Glass Fibre Textile Reinforced Cement Composites. *Engineering Structures*, *33*(9), 2603–2611.

Van Mele, T., & Block, P. (2011). A novel form finding method for fabric formwork for concrete shells. *Journal of the International Association for Shell and Spatial Structures*, *52*.

Veenendaal, D. (2017). *Design and Form Finding of Flexibly Formed Concrete Shell Structures* [Doctoral Thesis, ETH Zurich]. https://doi.org/10.3929/ethz-a-010831669

Veenendaal, D., & Block, P. (2012). *Computational Form-Finding of Fabric Formworks: An Overview and Discussion* (J. Ohr, Ed.; pp. 368–378). https://www.block.arch.ethz.ch/brg/files/P35.pdf

Veenendaal, D., Coenders, J., Vambersky, J., & West, M. (2011). Design and optimization of fabric-formed beams and trusses: Evolutionary algorithms and form-finding. *Structural Concrete, 12*(4), 241–254. https://doi.org/10.1002/suco.201100020

Veenendaal, D., West, M., & Block, P. (2011). History and Overview of Fabric Formwork: Using Fabrics for Concrete Casting. *Structural Concrete*, *12*, 164–177. https://doi.org/10.1002/suco.201100014

Verhaegh, R. W. A. (2010). *Free Forms in Concrete: The Fabrication of Free-Form Concrete Segments Using Fabric Formwork* [Master Thesis]. Eindhoven University of Technology.

Victoria and Albert Museum. (1796). *Smock Frock | Unknown | V&A Explore The Collections*. Victoria and Albert Museum: Explore the Collections. https://artsandculture.google.com/asset/smock-frock-unknown/wQEoFTN8ZxvKOA

Victoria and Albert Museum. (1893). *Liberty Dress | V&A Explore The Collections*. Victoria and Albert Museum: Explore the Collections. https://collections.vam.ac.uk/item/O92186/smock-unknown/

Waldseemüller map. (2020). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Waldseem%C3%BCller_map&oldid=973343196

Wang, C., Li, J., & Zhang, D. (2021). Optimization Design Method for Kirigami-Inspired Space Deployable Structures with Cylindrical Surfaces. *Applied Mathematical Modelling*, *89*, 1575–1598. https://doi.org/10.1016/j.apm.2020.07.005

Warmann, C. (2010a, May 6). *Grompies*. Dezeen. https://www.dezeen.com/2010/05/06/grompies-by-berndon-carlin/

Warmann, C. (2010b, May 19). *FattyShell (v.01) by Kyle Sturgeon, Chris Holzwart and Kelly Raczkowski | Dezeen*. https://www.dezeen.com/2010/05/19/fattyshell-v-01-by-kyle-a-sturgeon-chris-holzwart-and-kelly-raczkowski/

West, M. (2004). Fabric-Formed Concrete Columns for Casa Dent in Culebra Puerto Rico. *Concrete International, 26*(6), 42–45.

West, M. (2011, June 30). *Heavy Light—Fabric-Formed Concrete Structures*. https://www.youtube.com/watch?v=36gOx3dguWs&ab_channel=dveenendaal

West, M., Allen, E., Ochsendorf, J., Veenendaal, D., & Caceres, R. (2016). *The Fabric Formwork Book: Methods for Building New Architectural and Structural Forms in Concrete*. Routledge.

Westerlind, H. (2021). *Choreographing Flow: A Study in Concrete Deposition* [Doctoral Thesis, KTH School of Architecture adn the Built Environment]. http://kth.diva-portal.org/smash/record.jsf?pid=diva2%3A1557397&dswid=816

Winsberg, E. (2010). *Science in the Age of Computer Simulation*. University of Chicago Press.

Winsberg, E. (2019). Computer Simulations in Science. In E. N. Zalta (Ed.), *The Stanford Encyclopedia of Philosophy* (Winter 2019). Metaphysics Research Lab, Stanford University. https://plato.stanford.edu/archives/win2019/entries/simulations-science/

Wolff, C. (1996). *The Art of Manipulating Fabric*. Krause Publications.

Zareiyan, B., & Khoshnevis, B. (2017). Effects of Interlocking on Interlayer Adhesion and Strength of Structures in 3D Printing of Concrete. *Automation in Construction*, *83,* 212–221. https://doi.org/10.1016/j.autcon.2017.08.019

Zexin, S., & Mei, H. (2017). Robotic Form-Finding and Construction Based on the Architectural Projection Logic. *IOP Conference Series: Materials Science and Engineering, 216*, 012058. https://doi.org/10.1088/1757-899X/216/1/012058

Zimmerman, J., & Forlizzi, J. (2008). The Role of Design Artifacts in Design Theory Construction. *Artifact, 2*(1), 41–45. https://doi.org/10.1080/17493460802276893