MATERIAL STRATEGIES IN DIGITAL FABRICATION

2ND EDITION

Christopher Beorkrem

MATERIAL STRATEGIES IN DIGITAL FABRICATION

In this second edition of *Material Strategies in Digital Fabrication* are new case studies, improved wayfinding, the inclusion of composites and plastics, and references to similar strategies between different projects. In 400 step-by-step diagrams dissecting 39 case studies in 10 countries on 3 continents, the book shows you how material performance drives the digital fabrication process and determines technique. The book identifies the important characteristics of each material, including connection types, relative costs, deformation, color, texture, finish, dimensional properties, durability, and weathering and waterproofing to link design outcomes to form. The book is divided into five main chapters by material; wood, metal, concrete/masonry, composites/plastics, and recycled/pre-cycled, to help you reference construction techniques for the fabrication machines you have on-hand.

Includes projects by SHoP Architects, Gramazio Kohler Research, Schindlersalmeron, The Institute for Computational Design (Achim Menges, Patkau Architects,Sebastien Wierinck, Blue Dot Furniture, Marble Fairbanks, Studio Gang Architects, Macdowell.Tomova, Thomas Heatherwick Studio, Heather Roberge, MX3D, Matsys, Asbjorn Sondergaard, Block Research Group (Phillipe Block), Ball Nogues Studio, Matter Design, WORK Architecture Company, and SoftLab.

Christopher Beorkrem is associate professor of architecture at the University of North Carolina, Charlotte.

MATERIAL STRATEGIES IN DIGITAL FABRICATION

Second Edition

Christopher Beorkrem

Routledge
Taylor & Francis Group
NEW YORK AND LONDON

Second edition published 2017
by Routledge
711 Third Avenue, New York, NY 10017

and by Routledge
2 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

Routledge is an imprint of the Taylor & Francis Group, an informa business

First edition published by Routledge 2013
Second edition published by Routledge 2017

Library of Congress Cataloging in Publication Data
Names: Beorkrem, Christopher, author.Title: Material strategies in digital fabrication / Christopher Beorkrem.Description: Second edition. | New York : Routledge, 2017. | Includes bibliographical references and index.Identifiers: LCCN 2016055266| ISBN 9781138654181 (hb : alk. paper) | ISBN 9781138654204 (pb : alk. paper) | ISBN 9781315623368 (ebook)Subjects: LCSH: Building materials. | Architecture--Technological innovations. | Manufacturing processes--Data processing. | Manufacturing processes--Automation. | Computer integrated manufacturing systems.Classification: LCC NA4100 .B46 2017 | DDC 721/.040285--dc23LC record available at https://lccn.loc.gov/2016055266

ISBN: 978-1-138-65418-1 (hbk)
ISBN: 978-1-138-65420-4 (pbk)
ISBN: 978-1-315-62336-8 (ebk)

Publisher's Note
This book has been prepared from camera-ready copy provided by the author.

Book Design: Mikale Kwiatkowski
Cover Design: Jenny Beorkrem

ACKNOWLEDGEMENTS

I would like to thank first the talented designers, architects, artists, and photographers who supported this book through their work and contributions of drawings, diagrams and images.

I am grateful to my friends, colleagues and students at the College of Arts and Architecture at the University of North Carolina at Charlotte, for the generosity of their time and thoughtful feedback throughout this process. In particular, the support of Eric Sauda, Greg Snyder, Matt Parker, Bryan and Jen Shields, Jeff Balmer, Nick Senske, and Jefferson Ellinger was invaluable. I could not have done it without them. UNC Charlotte has provided financial support for this project, thanks to Ken Lambla and Jay Dominick.

My bright, patient, and diligent student collaborators included: Ryan Barkes, Andrew Beres, Samantha Buell, Wynn Buzzell, Dan Corte, Ashley Damiano, Patrick Gaither, Mikale Kwiatkowski, Rafael Lopez, Daniel McBride, Marlena McCall, Mitch McGregor, Taylor Milner, Noushin Radnia, James Rodgers, Carson Russell, Jeff Scott, Christian Sjoberg, Brian Smith, and Paul Stockhoff. (All student collaborators who worked on this project were compensated financially for their time.)

To my parents for their continuous love and support.

I would like to thank my sister, Jenny, for her impassioned design sensibilities, and constant willingness to collaborate, in work and in life.

And to Kelly, for her enduring love, encouragement, guidance, and patience throughout *both* editions of this project.

CONTENTS

FOREWORD TO THE SECOND EDITION

KIEL MOE

According to the terms developed by Gilbert Simondon (and later Gilles Deleuze and Felix Guattari), the traditional model of design in architecture is hylomorphic. In the hylomorphic schema, ideas are imposed on seemingly inert matter. As such, forms are determined independent and a priori to material. This schema is therefore transcendent and teleological, in that it assumes that the world is but the substrate of human agendas and action. The prevailing Anglo-American discourse on "form", as developed from the late sixties through today in architecture, has been overwhelmingly hylomorphic in its orientation. The epistemological limitations of this schema are great and continue to constrain the evolution of architecture. It now repays to ask: How else might something come to appear in architecture?

Other models of causality for form (and more importantly, formation) are possible and were in fact common in the history of techne prior to the development of professional education in the 19th century. In the more immanent modality of this line of thought, form is not determined by matter but it is dependent on it. As Deleuze and Guattari note, "one addresses less a form capable of imposing properties upon matter than material traits of expression constituting affects."[1] From this, formation is characterized more by its capacity to affect and be affected than the imposition of form through the mechanics of geometry and narration.

To illustrate this modality, Deleuze and Guattari use wood and metallurgy as examples. "It is a question of surrendering to the wood," they observe, "then following where it leads by connecting operations to a materiality, instead of imposing form upon a matter. ...this matter-flow can only be followed." In metallurgical terms, they state that "it is not a question of imposing a form upon matter but of elaborating an increasingly rich and consistent material, the better to tap increasingly intense forces."[2] This points to an entirely distinct epistemology for what we assume a form(ation) to be and how it comes to appear in the world.

Formation is foremost an expression of the intensive, rather than merely extensive, properties of architecture. Extensive properties depend on the amount of matter present and are proportional to the amount of material in the system, such as mass, volume, weight, and length. These are the traditional variables of hylomorphic design methodologies. But even in the most sophisticated transformation of extensive properties, the resulting physical state of the system remains extensively the same. This lack of state change is one of the primary epistemological limitations of hylomorphic models of design: it occludes the possibility of other states. Intensive properties—such as temperature, pressure, density, specific heat capacity, and conductivity—are not proportional to the amount of material in the system and thus introduce degrees of freedom and transformation into questions of formation. A fully immanent expression of architecture's intensive possibilities in its formation remains largely dormant in design discourse today.

But it would be a mistake to assume that design ought to be determined by the intensive properties and propensities of architecture's constitutive matter and energy. Rather, how designers both seek order from matter and energy, as well as direct the transformation of matter and energy. Indeed, to "follow" matter and its traits of intensive expression does not preclude novelty in the physical development of design, but it does temper it and direct in ways that our overt hylomorphic design training never could.

The central claim of this book—that material performance drives fabrication technique and processes—represents at least partial turn away from the hylomorphic habitus of architectural design. In the salient examples illustrated here, the flow of matter affects the formation in ways that enhance the performance of architecture (hopefully in all its spatial, material, energetic, and political dimensions). In other, more recidivist cases, designers impose form on matter through more familiar parametric, fabrication, and most overtly, geometric processes. In some examples, formation is over-determined by the technics of fabrication. But, all taken together, these projects provide a spectrum of consideration about non-hylomorphic possibilities in architecture. The texts and projects frame ways that fabrication processes can "follow" matter in novel ways. What is at stake in this book are some strategies for tapping into the intensive propensities of architecture's perennial materials through by now familiar fabrication processes. Beyond more limited discourses on ornament or surface, the ultimate agenda here is an epistemological turn towards other theories and practices of architecture formation.

Notes

1 Gilles Deleuze and Felix Guattari, *A Thousand Plateaus: Capitalism and Schizophrenia*, Minneapolis: University of Minnesota Press, 1987. P. 408.

2 Ibid, p. 411.

INTRODUCTION

Manuel DeLanda in his article “Philosophies of Design: The Case of Modeling Software” described the tendency for humans to value knowledge over know-how. With the advent of computational design technology, that tendency is reversing; machines are fully capable of storing the knowledge necessary to play chess, or to solve a math problem, while engineers struggle to design a "mechanical hand." DeLanda is pointing to humanity’s technological innovations as the actual source of the problems society had hoped they would solve. In design, this is most obvious when a material’s character (touch, density, and durability) is ignored in the production of architectural design.

> In other words the type of knowledge that we always thought was the most characteristic of human rationality, and hence, what made us different from animals is, in fact, the easier to mechanize. And the minor, less prestigious skills which we have always neglected to study, are the hardest to transmit to a machine, hence, the least mechanical.[1]

DeLanda goes on to describe how so often designers first select a ”surrendered” material, so that it can be used to create any shape desired. The projects in this text seek to find an alternative working method, one which relies on the material and its tooling first in the derivation of form.

Process-based design has quickly become an accepted method for the conceptual development of architectural form. At a multitude of scales, architects define systemic parameters or networked linkages that value relational dynamics over traditional, linear notions of design. From SHoP Architect’s materially constrained methodology,[1] defined through *Dunescape* designers are drawn away from the metaphor, back to logic-based (responsive) form-making processes. Designers empowered by new technology now consider form as it is defined by identifiable systems. This evidence-based, parametric methodology is a response to two decades of computationally derived projects, often produced simply for their novelty.

As far back as 1993 Juhani Pallasmaa was recognizing (and arguing for) a new “eco-functionalism” derived through linkages between technology, materiality, and form.

> Ecological architecture also implies a view of building more as a process than a product. And it suggests a new awareness in terms of recycling and responsibility exceeding the scope of life. It also seems that the architect’s role between the polarities of craft and art has been redefined. The priority of representation will be replaced by the priority of performance. After decades of affluence and abundance, architecture is likely to return to the aesthetics of necessity in which elements of metaphorical expression and practical craft fuse into each other again; utility and beauty again united.[3]

Material-constrained processes, as they have been used to date, are typically tied to unit-based logics or systems, often limited in scale and scope by relatively tight parameters. For instance, the precast brick veneer used on SHoP’s 290 Mulberry development is constrained to a $\frac{3}{32}$" (2.3mm) corbel or overlap, brick-to-brick. To minimize cost they were required to create a single precast mold, but inventively blocked out portions of the mold to create a variety of different building façade components, from that single mold. The project becomes a diagram of its own constraints, minimizing customization, while maximizing formal outcomes. It is a process with a sustainable ethic applied not as an overlay but embedded in its very inventions.

The material performance of a project such as *290 Mulberry* (p. 142) is defined primarily by the designer's need to create an identifiable façade, within the constraints of a city's zoning regulations and a developer's pro forma. The use of a certain lot size predefines a number of units, of a particular size, which will ensure profitability. However, there is also a desire to create an identifiable icon for the project on a prominent corner site. The material response, in this instance, helped create an iconographic brick façade, while minimizing the effect on the unit size and overall construction cost (see details on *290 Mulberry* p. 142).

The parametric links, which SHoP created between the city's zoning regulations, the developer's fiscal constraints, the manufacturer's construction specifications, and their own design intentions, exemplifies the type of parametric relationship this text seeks to celebrate.

THE MATERIALLY RESPONSIVE PARAMETER

In recent years, designers have developed processes for layering performance-based feedback into the early stages of design development.[4] This is often a response to the tendencies of a construction industry that values efficiency-resulting in excessive waste-over environmental steadfastness. However, a systematic design process, applied specifically to material constraints could frame awareness of the interconnectivity between the mediums of ecology, parametric modeling, and CNC fabrication. David Gissen outlines an architectural ideology based upon the definition of *Architectural Political Ecology*.[5] Gissen defines a variety of concepts to accomplish a "production of nature." He is attempting to look beyond the superficialities of so-called "green" design to a set of strategies that embrace substantive design rather than the relatively mundane aesthetics of environmental awareness as an applied layer to architectural design. This type of substantive design is defined by the tangible knowledge of material characteristics, such as: dimensional properties, durability, deformation, waterproofing and weathering (if applicable), connection types, relative costs, color, texture, and finish. These characteristics define some of the performance criteria, which can and should be layered into the early stages of each design process, linked to their formal expression through parametric design. Further, these performance-based characteristics can be identified as the primary device for delimiting form through parametric design, most often through geometric relationships.

"Form-finding" as defined by Andrew Kudless is "the self organization of material under force to discover stable forms." Using both analog methods of tension-only models hung in chain and fabric, and using advanced software tools such as *Thrust Network Analysis* (Philippe Block), there are many examples included in the following pages of work which attempt to respond to the form as it falls into stasis with gravity. These tests can result in forms hung in space as with *Feathered Edge* (p. 198), by Ball Nogues, or the fabric-formed beams of Mark West and C.A.S.T. (p. 128). These forms can also be inverted to create compression-only forms as with Philippe Block's Catalan Thin-Tile Vaulting (p. 154).

THE MATERIAL PARAMETER

Material selection can be based on a variety of choices. Often designers select materials for their shelf life, phenomenological qualities, or for the flexibility of their detailing or connection. However, the connection detail is most crucial to a system's flexibility and the aesthetic of complex architectural forms. From a simple nail to a custom-fabricated joint, the connection detail contains the information for delimiting the articulation and performance of a system.

Throughout this text the connection detail will be mapped as visibly as possible and discussed in language describing the specificity of its geometry (dimensions, angles, rotational capacity, and strength).

Materially relevant computational design was most visibly and memorably defined by one project; *Dunescape,* by SHoP Architects. *Dunescape* used a simple construction technique, uniquely grounded in its own efficiency. The simple wood lamination creates a repetitive spatial sequence of sections. The construction technique afforded the designers the ability to work through the material to articulate a new formal typology of construction and craft within computational design. *Dunescape*'s ultimate success rests fully on a keen understanding of the relationship between method, material(ity), construction, and assembly; all of which are critical elements of the knowledge necessary to produce a model of craftsmanship (see Chapter 1 for details on the material responsiveness of *Dunescape*).

The intent of this text is to map through materiality the simplest methods for making complex parametric forms, whether constructed by unskilled labor, or using complex systems of hybrid materials and assembly with 7-axis robots.

Contrary to the simplicity of a cedar 2" x 2", a renewed cultural attitude towards recycling has given designers the agency to consider salvaged products as plausible construction materials. However, the 21st century use of these materials must be predicated on the idea that they be employed in elegant and efficient construction processes. Parametric construction with recycled components can create iconic and aesthetically striking designs to impress the need for the industry and society to more readily accept and employ non-toxic, societal, or industrial by-products.

This text will provide clear narrative and diagrammatic, dissections of the computational and physical construction processes used in some of the more inventive solutions constructed since the advent of widespread parametric design. The text is divided into sections according to materiality. This has two purposes; most materials have relatively consistent performance criteria and connection types (connection details are often what ultimately defines the constraints of each system) and because most materials are processed using machines (both CNC and traditional) particular to their material composition.

THE MACHINE PARAMETER

The ubiquity and availability of CNC technology was driven by the mass production of servo and stepper motors, the most widespread method by which computers precisely control machine components. Originally developed in the 1950s and used to perform hard-coded repetitious tasks. The availability of complex pieces of software has broadened their applicability to nearly every possible field of manufacturing. However, buildings are constructed at a scale typically beyond that of conventional CNC machinery. For this reason, many of the projects constructed using CNC machines are relatively small. To increase the scale of their use, they are combined with off-the-shelf components or other conventional processes. The smart and ethical use of CNC technology is ultimately defined by the abilities and awareness of the user, and their ability to use the machine with a honed sense of craft.

More recently, the use of 7-axis industrial robots has enabled a much broader array of processes and materials to be computationally manufactured. The end-effectors, attached and controlled by these arms, are as diverse as the materials they can process. These have included all of the typical cutting systems (circular saw, router bits, water-jet, plasma and laser-cutting), as well as grippers, benders, hot-wire cutters, and others. Additionally, the robots' flexibility has allowed them to break the bounds of the factory floor, and operate on site. Gramazio Kohler Research have worked, most visibly, to establish methods for deploying these robotic arms on site, mounting them inside transport containers, on a set of tank treads, and outfitting them with scanners capable of providing real-time information about their surroundings back to the control machine. They have also worked to develop a system of quadcopters controlled by a computational script to assemble a foam-brick tower, completely freeing the construction process from the manufacturing facility and deploying it as a performance. This second edition of the book seeks to extoll the strengths of many of these new experiments as they expand into new materials and construction methods, well beyond convention.

This book celebrates projects which demonstrably strive to minimize CNC customization (as it often produces excessive amounts of waste) while maximizing formal expression. The ratio of customization to surface deviation will often be highlighted. This parameter is an ethical selection that can be paired with material selection to delimit the project's form, while maximizing the efficient use of CNC machinery.

The minimum knowledge for the use of CNC machines, is typically only a superficial understanding of the interface between machine and tool. However, as with any material, there are varying degrees of material intuition. While material knowledge gained through computational tools is different, it can be argued that this understanding is not less informed but fundamentally different, more directly linked to the interaction between tool and material. This perceived lack of tactile reciprocity is replaced instead by a more specific knowledge about the integration in all stages of the manufacturing process from concept, design, computation, and finally assembly.

This text will highlight not only material performance in each project, but also machine performance. This includes highlighting projects which maximize the exploration of a machine's capabilities to exude new characteristics from a material, giving the material properties unachievable without the machine.

THE APPLICATIONS (SOFTWARE) OF PARAMETRICS

Parametric software creates systems defined not by Cartesian coordinate systems, but by linkages and constraints between geometry. By their nature parametric systems do not have a specific solution but are capable of accommodating a range of possibilities.[6] The mapping of material constraints can be parameterized in two ways, through scripted or defined variables or through the definition of geometric relationships. As of publication, there are four primary pieces of software, which are typically employed for this type of user-defined parametric mapping: Gehry Technologies *Digital Project,* Robert McNeel and Associates' *Grasshopper*[7] scripting plug-in developed for *Rhinoceros*, and *Dynamo*, objected-oriented scripting for *Autodesk Revit* and *Generative Components* developed by Bentley Systems, Inc.

As an example, *Digital Project* uses geometric, organizational relationships to calculate components for complex surfaces for custom building systems and skins. This is most often done to apply a construction system to a predefined form. However, the modeler can also be used "backwards" to design complete, responsive systems and link them to flexible surfaces, allowing them to flow and redefine like they might if attached to a blanket.

The underlying geometric definitions of *Digital Project* allow designers to map limitations across a surface or across its edges. These limitations fail when an iteration of the surface is too dramatic for the constraints of the respective construction system. The topological nature of a form, when combined with the complexities of parametric systems, allow for variation through relationships, instead of individual parts. Additionally, other components of the software (Knowledgeware) can be used to map the maximum deviation of each piece of the system away from the original surface. When the deviation becomes too great compared to predefined standards (for aesthetic pairing or legibility of form) the system will identify the portions beyond those limits, so they may be adjusted.

The intent of this text is to communicate in software-neutral language the processes that designers have used to create materially linked parametric projects. These projects could be modeled using a variety of different computational and analog software and tools. The intent of the text is to break down each project using geometric relationships so that relatively any piece of software could be used to test similar processes with similar materials.

THE NECESSITY OF CRAFT (OR SOMETHING LIKE IT...)

Whether considering material, machine, or software usage, the understanding of one's craft is ultimately important. However, our understanding of craft in the 21st century has to be different, defined in the context of alternative methods of communication, learning, and apprenticeship.

Richard Sennett's text *The Craftsman*[8] defines craftsmanship as both an ancient and modern "basic human impulse, the desire to do a job well ... in any domain. Craftsmanship focuses on the objective standards, on the thing itself." Sennett goes on to describe how Western culture has long struggled to define and recognize craft as an ethic, to be sought after in any trade. By one measure, which Sennett uses, 10,000 hours are required to develop the skill of a craftsperson (Malcolm Gladwell, in his book *Outliers*, describes the "10,000 Hour Rule," as the amount of practice necessary for success in any field). The premise of automation stands in direct contradiction to this notion. As a society we search for ways to spend less of our life doing any type of repetitious activity. We must therefore search for methods to teach an apprentice without relying upon pure repetition and experience.

Today we struggle to imagine a scenario where an individual would use the same software or employ the same automated machine for 10,000 hours before one or the other is upgraded, or outsourced. Through Sennett's definitions we must question how we can teach our students to fully master a set of tools, working in a world where the pursuit of perpetual change and novelty are commonplace. In fact Sennett recognizes that the machine,[9] computer-aided design in this instance, was used in an attempt to increase efficiency, but in the end, resulted in increased repetition of detail and a relaxing of the user's ability to invent.

The goal for designers can no longer be to use entirely automated processes from beginning to end, as this removes any sense of character or craft from our creations, nor can we strive to become so familiar with the software or the machine as to assume that we may leave our own mark through the process of its use. We are left to determine a set of values, in a process defined through experience, to guide our sense of craft with the machine.

To extract new performance capabilities with both materiality and modern fabrication techniques, a dialog between material, machine, and designer must be the result of a refined craft defined in both modern and historic terms. More uniquely the apprenticeship, which has long determined the process for the development of a craft, has not gone away. The craftsman is no longer a single master but is a social structure of experience and knowledge, made available through 21st century processes of communication and interaction.

The infrastructure needed to create many of the projects included in this text requires both a developed sense of computational ability but also, and more importantly, an intimate knowledge of the systems and materials one is employing. Often this can be accomplished by inserting the skilled computational thinker/designer directly into the manufacturing facility (as SHoP and others have done) for an extended period, to observe each step of the manufacturing process, to learn from the experts, and to adapt their process to their observations, not force results based on other parameters. This allows the designer to subvert the otherwise frustrating amount of knowledge required to reinvent a construction system.

Notes

1 De Landa, Manuel. "Philosophies of Design: the Case of Modeling Software," *Verb: Architecture Boogazine*. Actar. January 1, 2002. Print.

2 The work of SHoP Architects often reflects a subversion of conventional design and construction processes. *Dunescape* (referenced later in this text) came very early and defined a new era of alternative thinking about process. See also *290 Mulberry* and *Porter House.*

3 Pallasmaa, Juhani, "From Metaphorical to Ecological," *The Architectural Review*, June 1993, pp. 74–79.

4 Seletsky calls this the "Computational Design Ecosystem," Kevin Klinger and Joshua Vermillion call it "Feedback Ecology," Achim Menges calls it "Computational Morphogenesis," Rivka and Robert Oxman call it "New Structuralism."

5 "...it forces us to consider what nature has been and may yet become; it enables us to establish linkages between buildings and nature that are more dialectical than mimetic; and it signals what nature can become when invested with new architectural concepts" (p 63). David Gissen, "APE," Lisa Tilder and Beth Blostein. (eds.) *Design Ecologies: Essays on the Nature of Design.* New York: Princeton Architectural Press, 2010.

6 Cynthia Ottchen's article "The Future of Information Modeling and the End of Theory: Less is Limited, More is Different" Architectural Design 79 (2) : 22 ~ 27 (2009) highlights the opportunities that information modeling and parametrics can harness when applied to the rigorous complexities of building design and production. She says that "soft" data is typically not considered quantifiable in information models. Ottchen argues that the combination, overlap, integration, and variability of qualitative information can be analyzed and used through not only parametric algorithms but also through the inclusion of underlying and sometimes more difficult to perceive information.

7 Grasshopper is still in beta development at time of publication. David Rutten is the developer of Grasshopper at McNeel Associates.

8 Sennett, Richard. *The Craftsman*, New Haven: Yale University Press.

9 "The enlightened way to use a machine is to judge its powers, fashion its uses, in light of our limits rather than the machine's potential. We should not compete against the machine. A machine, like any odel, ought to propose rather than command and humankind should certainly walk away from command to imitate perfection. Against the claim of perfection we can assert our own individuality, which gives distinct character to the work we do." Sennett, p. 105

CHAPTER 1: TIMBER/WOOD

Wood products are an intuitive choice for material-constrained design. Regularized components, easy and affordable machine processing, and a multitude of connection types define wood as one of the more varied yet visibly constrained materials architects can use. The examples included in this chapter will vary in scale from thin wood veneers to heavy timber and processing techniques ranging from a handsaw to a 7-axis robotic arm.

The projects illustrated here are representative of the processes employed by Charles and Ray Eames in their furniture studies. Drawn to new materials and processes, the Eames worked to develop a method for molding plywood in more than one direction, matching it to simple ergonomic forms. They worked ad hoc with their "*Kazam*" machine, which pressed electrically heated plaster molds against layers of glued veneers with pneumatic pressure supplied by a bicycle pump. These developments were first put into mass-production not for furniture but for the production of molded plywood leg splints, for the US Navy (they would manufacture more than 150,000 by the end of World War II).

This work would eventually lead to a relationship with the Herman Miller Furniture Company, who would market and distribute many of the Eames designs. Most importantly, the DCM chair design, which through the use of a doubly curved seat surface created a structurally rigid yet comfortable chair. This combination of structural expression and ergonomics is what provides a clear trajectory to many of the projects outlined in this chapter. In particular the *ICD/ITKE Pavilion* by Achim Menges, which uses CNC precision to lock plywood strips into elastic bending compression, creating undulating sets of structural units. Each plywood component has a purpose, either in tension or compression, balancing with one another, to create rigid strips of what is an otherwise elastic material, 3/8" (10mm) thick plywood.

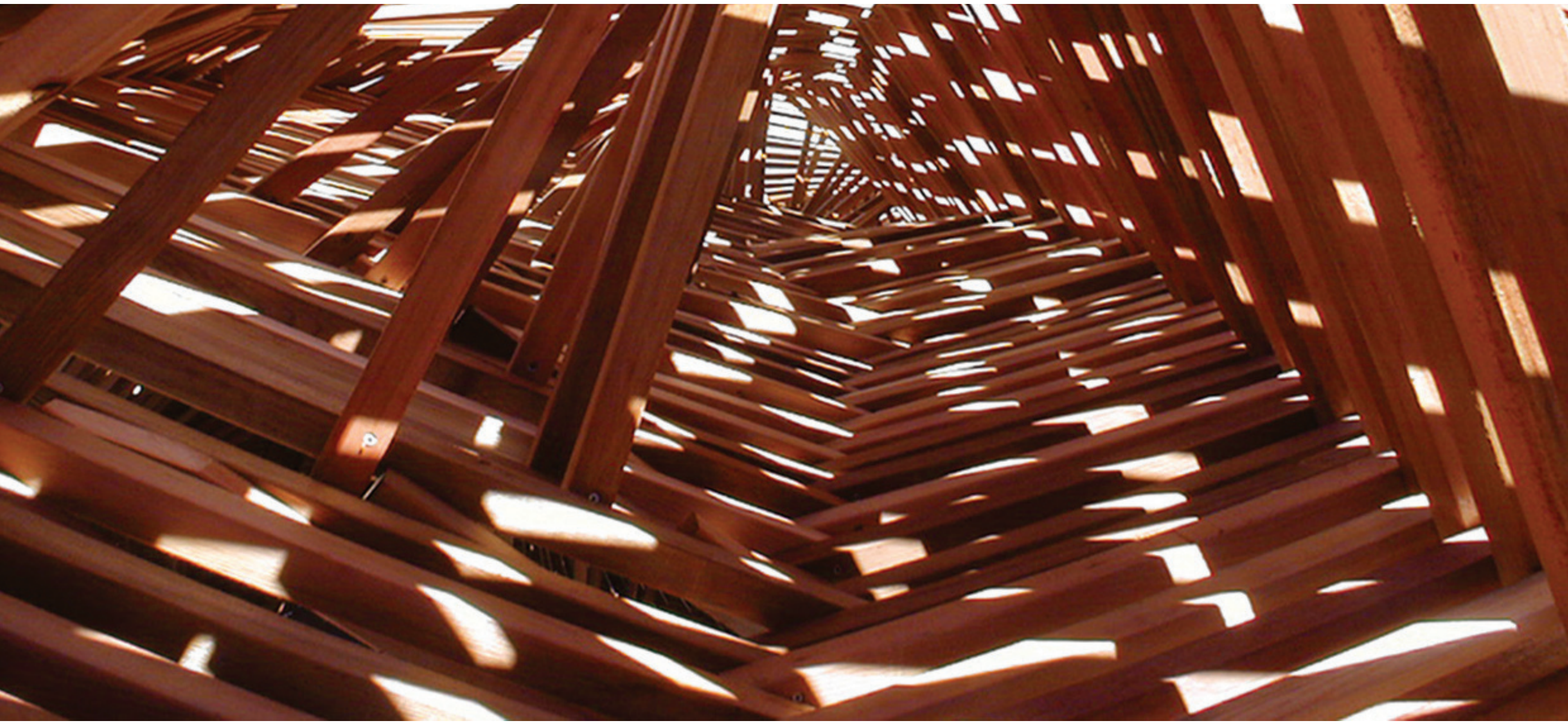
In computational manufacturing, wood products are an excellent material selection for testing parametric conditions. Off-the-shelf wood products come in manageable dimensions, capable of being easily and accurately cut. They can be repaired and worked with comparative ease. Additionally, wood products have a vast set of options meriting exploration of off-the-shelf connection types, affording many different geometric compositions. The thin profiles and smaller load capacities of wood products afford shorter span lengths, meaning that wood is typically used in smaller-scale designs. However, the projects represented in this chapter include both industrial design and architectural-scale detailing and assembly.

Each project in this chapter will provide evidence of constraints defined by wood's material performance and connection details. The details often employ off-the-shelf components (*Dunescape)* or minimally customized objects used in unconventional ways. Wood products, when paired with appropriate machinery, can be designed with built-in connection details. Alternatively, the formal logic of a design can be an expression of the performance of the manufacturing process, not just the material (*Stratifications, The Sequential Wall*).

Wood products have a unique phenomenological character. They are intended to be inhabited in more tactile and intimate ways than almost any other material conventionally employed in building design. The huge variety of color and texture in both manufactured wood products and natural grain woods can be used to mark their cultural significance and to note the craft of their assembly.

The structural capacity of wood products is varied and is most typically driven by their cross section. Wood products are typically supported in at least two directions (creating a diaphragm), as in plywood, by alternating granular layers, or by laterally bracing members on their perpendicular. Connection types for wood products are as varied as their use, and can be as simple as nails, glue, or screws or as complex as custom joinery created with multi-axis CNC machines.

Typically, the projects in this chapter have components cut with CNC mills and routers, or robotic armatures with a certain number of axes (typically 2.5–7) and a mechanical head, which spins a router bit upwards of 20,000 times per minute. The radius of each bit defines half the width of its cut, following a command along its centerline, creating a cut that can provide both constraints (no interior corners) and opportunities (beveled edges, and depth cuts). Small parts, with dimensions less than the width of a bit, are often destroyed or chipped during the milling process. Typical bits are incapable of tight interior corners, where they leave a radial or fillet at any corner. This makes it difficult to create accurate interior notching for connecting components perpendicular to each other as in a conventional two-directional, eggcrate section model. This is unique from other CNC tooling for metals and plastics, which often have a much thinner tooling head (lasers, plasma, or water-jets). Though lasers and water-jets can also be used to cut veneers and plywood.



DUNESCAPE

SHoP ARCHITECTS
NEW YORK – 2000

Dunescape was constructed in 2000 as the inaugural winner of the Young Architects Program, an award given to a design firm to construct a temporary installation for a "beach party" in the courtyard of the P.S. 1 Contemporary Art Center in Long Island City, NY. *Dunescape* established a process for design as a section-first exercise. SHoP mapped the human occupation of space through a series of sectional diagrams and organized those sections on the site to generate a form. Each section cut was developed to express typical activities found at the beach (cabana, beach chair, umbrella, boogie board, and surf). The forms were delimited by the material constraint of layers of 2" x 2" cedar wood members.

SHoP was first to articulate a process defined by the pairing of avant-garde modeling techniques with an awareness of how a simple system could function as a symbiotic, structural, formal, and material logic.[1] The intent was to create an installation with unskilled labor (paid architectural students) and without the use of any advanced machining processes. All of the processor-heavy work occurred through design development and was constrained to hours spent modeling in computer. This preemptive processing allowed for a relatively simple construction process.

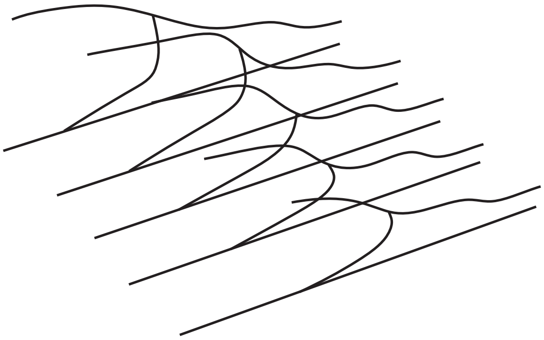
The initial form evolved from a series of simple diagrammatic sections within the courtyard. The form was defined as a surface generated by these sections, creating a clear linear logic. The essential character of the form and the functionality of each section is predicated on the pairing of both the programmatic and structural sections (1:1:1).

SOFTWARE:

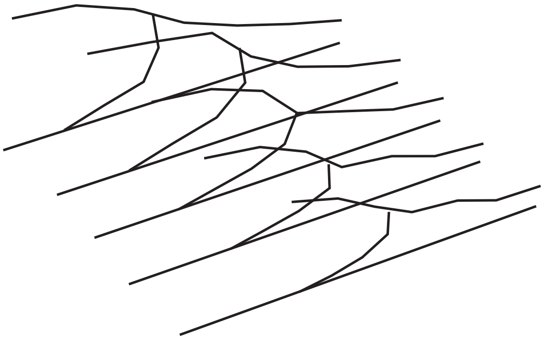
- Rhinoceros 3D
- Printed full-scale templates

MATERIAL CONSTRAINTS:

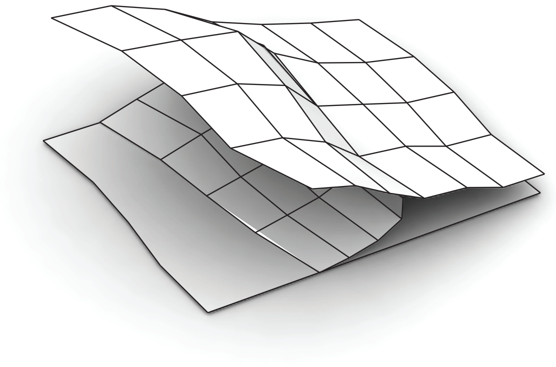
- Cedar is durable yet soft; the intent of the project was to create a platform for all of the activities of a typical beachgoer, and therefore needed to be both a surface to walk on but also one to sit and lounge on.
- Relative availability and affordability; the project had a budget of $10,000 and needed to withstand fairly intense use during parties thrown each weekend.
- Simple structural configurations; truss sections could be used to resist vertical loads while layering of the cross sections created a diaphragm for resisting horizontal forces.
- Color and texture; the consistent glowing brown coloration of the installation contrasts with the gravel floor and concrete walls of the courtyard.
- Simplicity of connection and construction; constructed with relatively unskilled labor using circular saws, framing screws and drawing templates.



1:1:1 Section diagrams define the logic of the form.

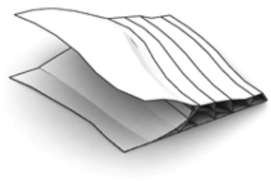


1:1:2 Curves are converted into polylines or curves made of straight components.



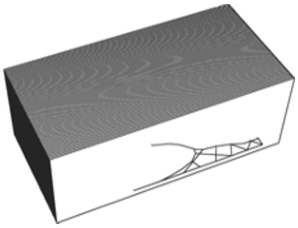
1:1:3 A set of surfaces created from sectional diagrams.

Along this linear set of surfaces are multiple iterations of each section, each of which is indicative of a variation of programmatic space along the length of the surface. The initial structural moves were made by offsetting or thickening the cantilevered or bridging layers of the surface. Using the isocurves or long grain curves of each surface, the surfaces were divided into appropriately sized lengths. In this case the members were approximately 1'–4' in length. The intent of this evaluative mapping technique is to minimize the number of components while maximizing the legibility of form.



1:1:4 Truss-like profiles were created using triangulation defined by new surfaces between offsets.

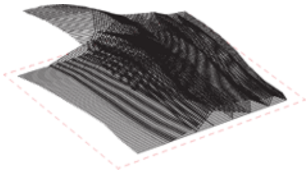
To create the triangulated sections, surfaces were defined by mapping diagonal linkages (1:1:4) between edges of every other surface (this creates what looks like a sandwich of diagonal bracing). These triangulated members convert each series of 2" (50mm) x 2" members into what operates much like a truss. The entire system transfers lateral and horizontal loads as with conventional decking or a bidirectional structural system.



1:1:5 Section cuts are sliced using planes on 1.5" (nominal 2") intervals.

The smooth surfaces mapped onto each of the sectional diagrams are converted into a linear series of components. This can be done in a variety of ways, by refining the surface with fewer degrees of curvature or by using the edges of the surface to loft straight versions of each. This conversion is also where the overlap between each 2" (50mm) x 2" can be defined. Offsetting the edges between surfaces will allow the depth of adjacent members to overlap.

Alternating surfaces need to be grouped separately to indicate which surfaces define even or odd sections. A set of reference points or a bounding box around the entire set of surfaces will help to snap the two systems back together (1:1:6). Contour or cut serial sets of sections through each surface separately (1:1:5). The first set of surfaces should be sectioned on 3" (75mm) intervals (nominal 1.5" (38mm) member + 1.5" spacer). The second set of surfaces should be made of a similar set of section cuts, but the initial starting point should be offset 1.5" from the start point of the first set of surfaces (this allows for alternating members to interlock like the fingers of two hands).



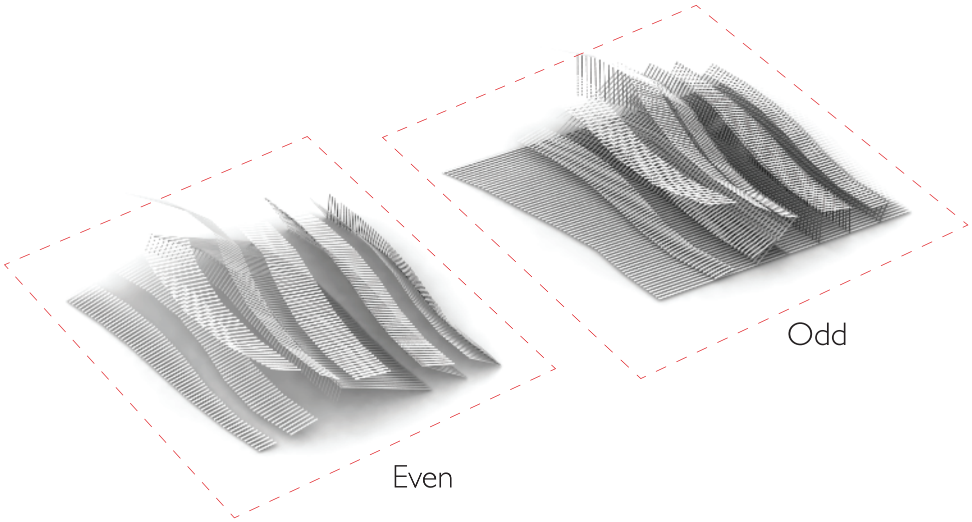
1:1:6 Contour or sets of section cuts (note reference bounding box which will be used to realign sets of members).

These contours can function as the geometric map of the overall surface. To map the actual 2" (50mm) x 2" members, extrude them 1.5" perpendicular to the direction of the section cuts. Offset the extruded surfaces to create 1.5" (38mm) x 1.5" nominal dimension wood members (1:1:7).

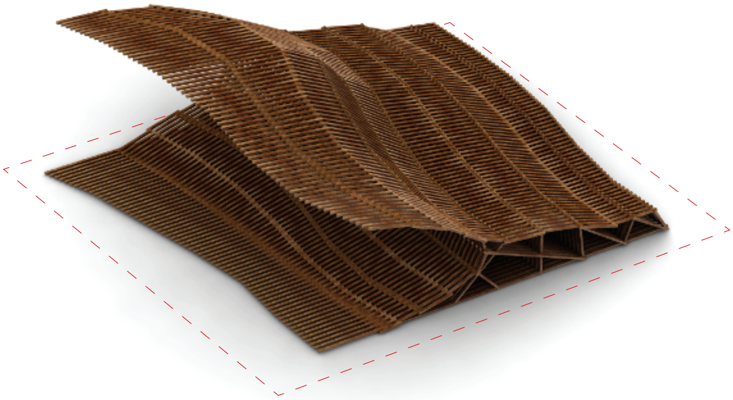
The entirety of the surface was broken into sets of approximately 12 section shapes. To construct each section SHoP plotted the section shapes using color-coded (1:1:9) designations so that an entire set could be plotted on one drawing. The cedar 2" (50mm) x 2"s were marked using the plotted drawings and cut using circular saws on site. Sets of section assemblies were constructed directly on top of each plot. Each section was screwed to the one below using 3" screws at each joint. Entire sets were placed aside and screwed together in place to create the final installation (1:1:10).

Note

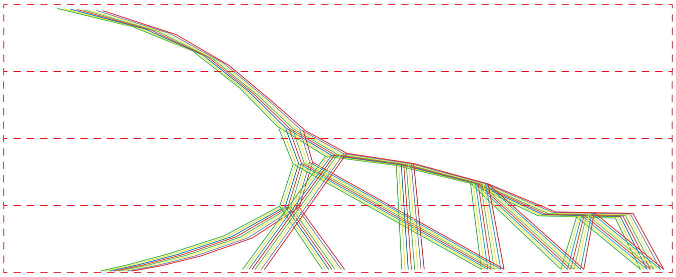
1 "Surface structure and program collapsed into a single entity." Sharples Holden Pasquarelli, "Introduction," in: Sharples Holden Pasquarelli, (ed.) *Architectural Design: Versioning: Evolutionary Techniques in Architecture*. London: Wiley, 2002. p. 91.



1:1:7 Splitting of the surface components into two arrays.



1:1:8 Merging of two component arrays to create complete model; this realignment is done using the reference bounding box.



1:1:9 Each cross section is indicated in varying colors to create cross-section layers by assembling 8–10 layers to match a plotted set of drawings. Red dashed lines represent plot width.

1:1:10 Final assembly of one set of components, which are screwed to subsequent sections.

THE SEQUENTIAL WALL

GRAMAZIO KOHLER RESEARCH
ETH ZURICH
ZURICH – 2008

Gramazio Kohler Research has forged new frontiers in digital fabrication by employing the use of a 7-axis robotic armature. The robot is capable of swapping "hands," called end-effectors. These end-effectors give the robot the ability to create custom components by gripping, bending, spraying, or using conventional cutting tools (milling, laser-cutting).

This project is similar to other work by Gramazio Kohler Research (*West Fest Pavilion, Procedural Landscapes*) and others (*Dunescape*). However, the intent for this project was to create a wall cavity found in a typical exterior building shell. This constraint matched with the limitations that each batten on the surface be the same length.

The surface used to create each portion of the wall should be a multiple of the width of a single wood batten. A single surface type longer than the complete wall can be shifted along and used again at other heights on the wall. For this system there are two unique surfaces,[1] repeated up the height of the wall. One surface falls on even-numbered variations of the batten and the other the odd. In each instance the length of the batten is uniform (1:2:1).

To determine the location of each batten along these initial surfaces, array a single line the length of a batten along the face of each surface. The spacing of each line should be twice the width of a batten (nominal 3") to accommodate the width of the alternating battens (1:2:2). A line should be used, as no matter how the line rotates along the surface it does not shift its relationship to the ground (a three-dimensional object will twist relative to the ground plane).

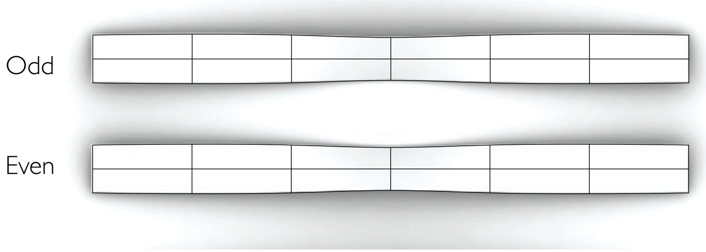
Once each of the curves are positioned they can be extruded (1:2:3) parallel to the ground plane. This once again is crucial to ensuring that battens are parallel to one another, but are pivoting along the face of the surface. Add the third dimension of each component by offsetting (1:2:4) each of the extrusions the height of the batten. These sets of battens can be offset in the x-axis against one another in increments equivalent to a multiple of the width of a single batten (1:2:5).

SOFTWARE:

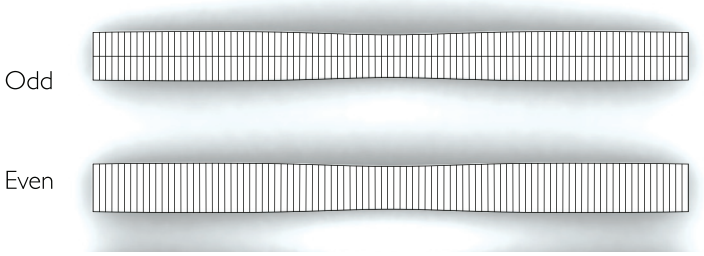
- Rhinoceros 3D
- Grasshopper 3D
- KUKA PRC

MATERIAL CONSTRAINTS:

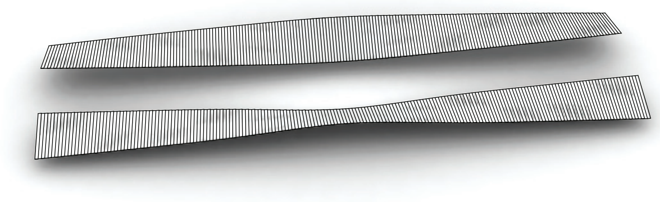
- Wall cavity; the creation of a wall cavity for its insulative properties was a primary criteria for the creation of this project. The cantilevered members of the wall needed to nest into that cavity while still creating an air pocket of separation.
- Water shedding; the wall was intended to be created with a geometry capable of wicking water away from the façade along the length of the members and down to the ground. The wood members would require regular sealants to perform in this way, though the geometry is capable of responding to this criteria.
- Ease of assembly and conventional construction; this project would require little more than simple saws and hammers to assemble with the assistance of a template. Each section would be assembled individually and added together aggregating into the entire assembly.



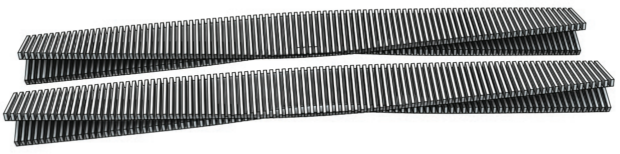
1:2:1 Two versions of each surface are offset from one another by multiples of the board width.



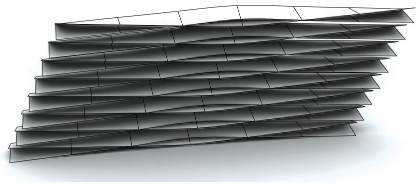
1:2:2 Array straight curves along each surface with spacing twice the width of each member to accommodate for the alternating members.



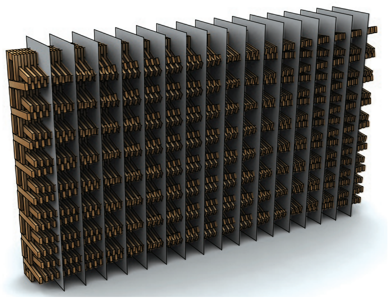
1:2:3 Extrude the curves the width of each member and then offset surfaces the height of each member to create the rectilinear geometry of the board.



1:2:4 Offset or array each set of members the distance equal to a multiple of the width of a board.



1:2:5 Array the sets of members to create variation across the entire installation.

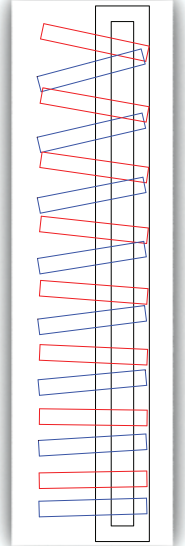


1:2:6 Trim the surfaces to create straight sections of wall, and split the entire assembly into construction sets.

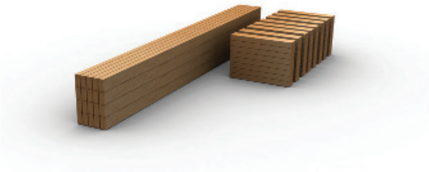
The vertical members require custom cutting and are all of unique lengths, though they do not require tight precision, as they serve primarily as spacers. Each of these spacers works both horizontally and vertically to distribute loads down through the surface. The lengths of each vertical can be found by drawing perpendicular lines between the endpoint of each pair of horizontal battens. The two layers of these vertical components create the wall cavity and the structural support for the system.

Though Gramazio Kohler Research programmed a 7-axis robot to cut and then assemble this wall system, it is reasonable to imagine a method for assembling the system without access to a tool of this nature. The following section will highlight this process. Similar to *Dunescape* a series of plotted drawings can be used (1:2:7) as templates for assembly. This requires a conversion of the three-dimensional information into a two-dimensional drawing. The start position and each angle can be measured against the datum of the straight width of the wall cavity.

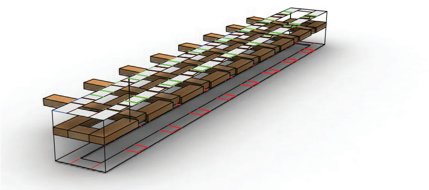
The sets of section shapes were translated into two-dimensional drawings. This drawing can provide the lengths of each of the spacers or vertical members. Each plot provides all the necessary information to assemble sets of sections on the ground (1:2:9-11). Once each section is assembled, subsets are attached to one another to create the final form.



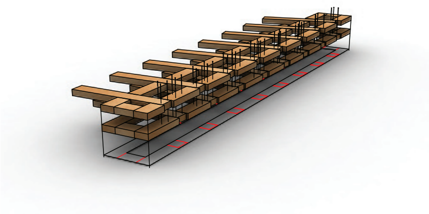
1:2:7 Plotted drawing which could be used for assembly of the subset of the system.



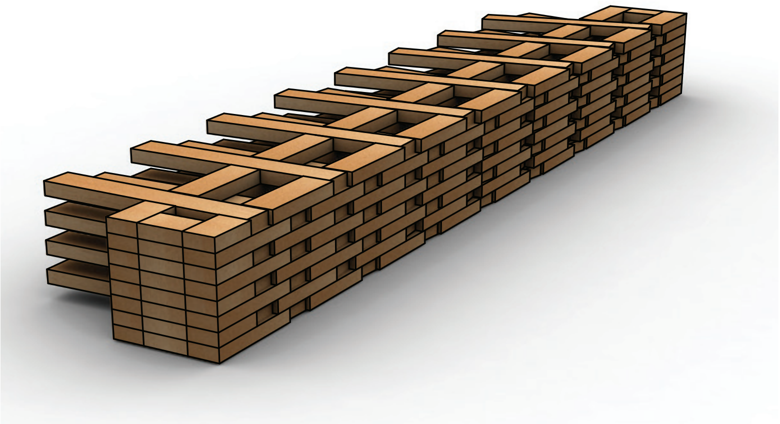
1:2:8 Equal-length members and planks to be trimmed for spacers, according to plotted dimensions.



1:2:9 Assemble each section from ground up on top of plotted drawing.



1:2:10 Continue to assemble sections of 8–12 sets on each plotted drawing.



1:2:11 Rendering of the subset of the section assembly.

Note

---

1 The intention was to provide surfaces, which would shield the surface of the wall from rain water, channeling it away from the wall along the surface of the downward shapes.

STRATIFICATIONS

GRAMAZIO KOHLER RESEARCH
ETH ZURICH
ZURICH – 2012

Building upon the early assembly tests such as *The Sequential Wall*, Gramazio Kohler Research developed this project to test a responsive construction process using a stationary 5-axis robotic arm. The project is assembled out of three different types of wood blocks. All have the same width and length, but have variable thicknesses. As the robot assembles the wall it pulls blocks from a dispenser. The planimetric location of each block in the dispenser is provided by an automated script; however, the Z-height position of each block is determined individually by a scanner fitted as an end-effector on the robot. This is one in a series of explorations, which are attempting to create more adaptable fabrication tools, initially, investigating how a 7-axis arm could be deployed on site using a shipping container (see *Structural Oscillations* p. 148). Here the beginnings of that research demonstrate how a robot is able to adjust its script based on information that it collects as it works.

Gramazio Kohler Research has also deployed other robots capable of moving on site as they work, including a robotic arm attached to a pair of tank treads, and their late 2011 installation at the FRAC Centre entitled *Flight Assembled Architecture* in cooperation with Raffaello D'Andrea. In this installation they deployed remote-controlled quadcopters as mechanisms for constructing a foam brick tower inside of a gallery, as an autonomous script.

As the robot is static for this installation, the perimeter of this project is constrained to the inner and outer radius of the robot arm. As the robot moves sequentially around each circumference it makes a scan to determine the height that each block needs to be laid. This ensures that it neither bumps into the block below nor drops the block from a height above where it ought to be placed. The shifting pattern of the assembly is simply a product of the number of each block size placed in a row.

SOFTWARE:

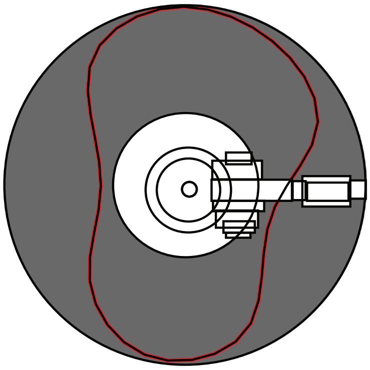
- Rhinoceros 3D
- Grasshopper 3D
- KUKA PRC

MATERIAL CONSTRAINTS:

- Variable yet limited components; the robot in this instance was pulling three different types of blocks from a Pez-dispenser-like receptacle. This delimitation allows formal expression while minimizing the number of custom components.
- Durable yet soft; the project is easily managed by the gripper of the robot and would be relatively soft to human touch.
- Relative availability and affordability; simple blocks of wood are readily available in various thicknesses and can simply be cut into uniform lengths.
- Color and light; the patterning of the wall would create a unique expression of light and color when lit from within.
- Sequential patterning; the robot is capable of scanning the layer which underlays the upcoming layer, creating an adaptive strategy for assembly, based on sequencing.

Each layer is differentiated by a shifting number of each size block as you work from one edge to the next (1:3:3). This causes the diagonal shifting visible in the elevation. The height of the blocks create a visible diagonal shift in the blocks, slightly from parallel with the ground plane to accommodate the changing heights (1:3:5). In this instance, the sequence of blocks, requires responsive machine capable of adjusting to various heights and even human intervention, without the need to adjust the program or script.

The ABB robot used in this installation has both a minimal and maximum radius when used in a fixed situation such as this (1:3:1). These radii constrain the form of this wall assembly. The curve used to create this composition falls between these two radii. The robot is programmed to follow this same curve for each row, though each row is staggered to create an overlapping brick composition. Therefore there are two repeating patterns, one for each "type" of row, even and odd (1:3:3).



1:3:1 Minimum and maximum radii of the robot constrains the form options for the wall.

1:3:2 Every other layer has the same form. Array block shapes along a curve.