Hybrid Intelligence in Architectural Robotic Materialization (HI-ARM)

Computational, Fabrication and Material Intelligence for Multi-Mode Robotic Production of Multi-Scale and Multi-Material Systems

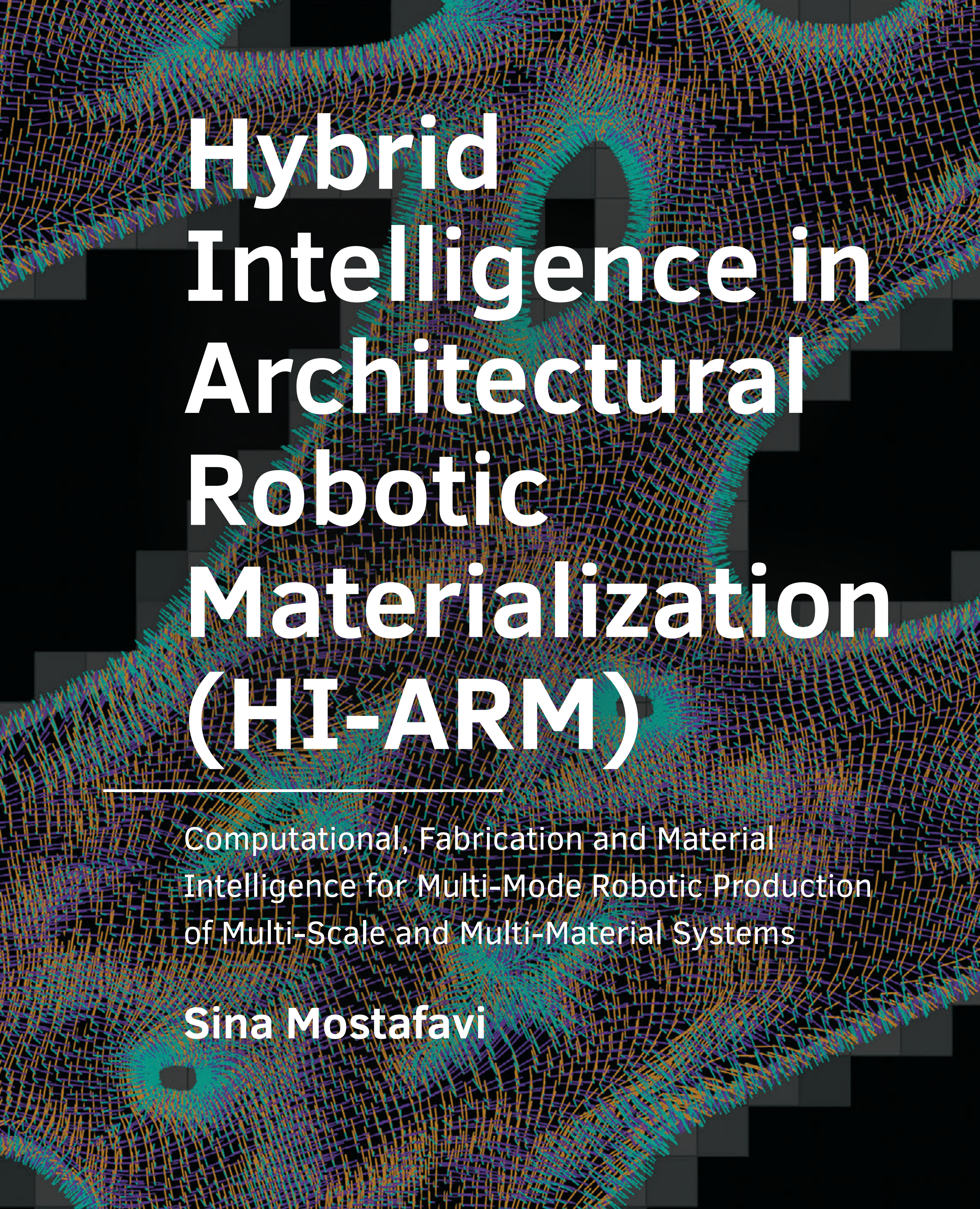
Mostafavi, Sina

DOI
10.7480/abe.2021.12

Publication date
2021

Document Version
Final published version

Citation (APA)
Mostafavi, S. (2021). *Hybrid Intelligence in Architectural Robotic Materialization (HI-ARM): Computational, Fabrication and Material Intelligence for Multi-Mode Robotic Production of Multi-Scale and Multi-Material Systems*. [Dissertation (TU Delft), Delft University of Technology]. A+BE | Architecture and the Built Environment. https://doi.org/10.7480/abe.2021.12



Hybrid Intelligence in Architectural Robotic Materialization (HI-ARM)

Computational, Fabrication and Material Intelligence for Multi-Mode Robotic Production of Multi-Scale and Multi-Material Systems

Sina Mostafavi

Hybrid Intelligence in Architectural Robotic Materialization (HI-ARM)

Computational, Fabrication and Material Intelligence for Multi-Mode Robotic Production of Multi-Scale and Multi-Material Systems

Sina Mostafavi

TOC

A+BE | Architecture and the Built Environment | TU Delft BK

21#12

Design | Sirene Ontwerpers, Véro Crickx

Cover Image | Vectors & Voxels: 3D Model from the Hybrid Concrete discussed in Chapter 4, Generative image designed by Sina Mostafavi and Adib Khaeez.

ISBN 978-94-6366-430-1
ISSN 2212-3202

This dissertation is open access at https://doi.org/10.7480/abe.2021.12

Unless otherwise specified, all the photographs in this thesis were taken by the author. For the use of illustrations effort has been made to ask permission for the legal owners as far as possible. We apologize for those cases in which we did not succeed. These legal owners are kindly requested to contact the author.

TOC

Hybrid Intelligence in Architectural Robotic Materialization (HI-ARM)

Computational, Fabrication and Material Intelligence for Multi-Mode Robotic Production of Multi-Scale and Multi-Material Systems

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus, Prof.dr.ir. T.H.J.J. van der Hagen
chair of the Board for Doctorates
to be defended publicly on
Monday, 7 June 2021 at 12:30 o'clock

by

Seyed Sina MOSTAFAVI
Master of Architecture
University of Tehran, Iran
born in Tehran, Iran

TOC

This dissertation has been approved by the promotors.

Composition of the doctoral committee:

Rector Magnificus,	chairperson
Prof.ir. K. Oosterhuis,	Delft University of Technology, promotor
Dr.-ing. H.H. Bier,	Delft University of Technology, copromotor
Dr. N.M. Biloria,	Delft University of Technology & University of Technology Sydney, copromotor

Independent members:

Prof.dr.-ing. M.U. Hensel,	Vienna University of Technology, Austria
Prof.dr. J. Burry,	Swinburne University of Technology, Australia
Prof.dr.-ing. P. Teuffel,	Eindhoven University of Technology
Prof.dr.ir A. van Timmeren,	Delft University of Technology
Prof.dr. P.W. Chan,	Delft University of Technology, Reserve member

TOC

To
Sarah, Fahimeh and Farid

TOC

TOC

Contents (concise)

TOC

Foreword

Framing, advancing, and finalizing this dissertation book has not been a linear experience for me. In parallel to this research, I have been involved in numerous research initiatives, teaching activities, and design and building projects. When I look back, I see most of them, if not all, as parts of the results and structure of this work.

In the early stages of this work, with an idea titled Design Information Modeling, I was interested in bridging the gaps between design conception stages to materialization and building processes. That interest is still the backbone of the theoretical and methodological frameworks and case studies, emphasizing systems thinking in design-to-production processes. Following this, I had the chance to prosper my passion for learning by creating and making through continuous efforts in developing and advancing robotic fabrication technologies. The experience of setting up and coordinating the robotic labs at Hyperbody Research Group of TU Delft as well as initiating and directing DARS [Design and Architectural Robotic Systems] studios at Dessau Institute of Architecture at Bauhaus Campus with passionate students and dedicated colleagues is strongly part of this research's development, implementation, and success.

Moreover, next to actively being involved in architectural design research on education, I have been practicing architecture and have led my design firm SETUP architecture studio. Even though the design and construction projects were not directly related to this research's core pilot objectives, several theoretical, methodical, and technological overlaps challenge and complement the work presented in this dissertation book. I believe this anchor to the world outside of academia has been instrumental in my research and teaching design studios, which have become laboratories for hands-on experiments and explorations. Thus, I see the feedback from practice as a way for us to constantly rethink the new models of practicing architecture and eventually influencing the building industry by creative integration of emerging and disruptive technologies in design and construction.

Lastly, I would like to close this foreword and open the book with a story about me, architecture, and somehow the position of this work in the larger context. I remember when I was a kid, my mother told me the story of renovating her office room, which she has also called it House of Objects. She was telling me how she asked the mason to carve out a medium-size niche inside a larger niche on the wall,

TOC

and inside that medium-size niche, again, carve out a small niche to store or exhibit an object. In my memory, that small niche was almost hidden, and when I think about the model of a niche in a niche, it is similar to when we conduct research on emerging and interdisciplinary fields. It is like we are relentlessly carving out small and hidden niches to discover new dimensions. We may argue that such an attitude, or let's call it continuous curiosity, is required in cutting-edge and innovative research in general and doctoral research in particular. However, I think in this context, there are two facts to consider. Firstly, it is crucial to stay conscious about the big picture and secondly acknowledge that, as time passes, that very small niche might become as large as a space surrounding us, most likely together with many others who have happened to explore and discover the same dimensions. In this research, I hope that I have managed to stay aware of the why and the big picture while continuously carving out new niches. Eventually, beyond the technological research deliverable, I believe the step-by-step process of how we experience such continuous excavation and progression is precious and important to document and share.

TOC

Acknowledgments

This work, first and foremost, is dedicated to my family, my mother Fahimeh Mahfouz, my father Farid Mostafavi, and my beloved sister Sarah Mostafavi. It is only with them and their continuous support and encouragement that I started this journey and have had the courage to stand and continue.

I would like to express my gratitude and appreciation to my supervisors at TU Delft, Kas Oosterhuis as promotor with his insightful ideas and sharp comments, Henriette Bier and Nimish Biloria as co-promotors for their kind support and helpful advice.

I am sincerely thankful for the precious feedback and support of independent committee members Jane Burry, Michael Hensel, Patrick Teuffel, Arjan Van Timmeren, and Paul Chan, who have kindly agreed to read the dissertation and assess this research.

This work has been extensively benefited from the chance I had as a researcher, educator, and collaborator in the labs and studios of the Faculty of Architecture and the Built Environment at TU Delft and Dessau Institute of Architecture at the Bauhaus campus of Anhalt University of Applied Sciences. This work could not have been done without the generous and friendly support of colleagues and students in these two institutions.

In TU Delft's Hyperbody Research Group and Robotic Building studios, and DIA Bauhaus DARS studios, I had the chance to work with plenty of dedicated and intelligent students who then soon became more like colleagues and collaborators. Without them, this work would not have been possible: Ana Maria Anton, Serban Bodea, Marco Galli, Benjamin Kemper, Daniel Fischer, Arwin Hidding, Ralph Cloot, Chong Du in Delft, and Adib Khaeez, Valmir Kastrati, Iwan Mazlan in Dessau Institute of Architecture. Their contribution to this research is significant on many levels.

In AE+T, Architectural Engineering and Technology Department, at BK City TU Delft, I am thankful to many good friends with whom I had the chance to collaborate in research and education: Mauricio Beltran Morales, Jia Rey Chang, Yu Chou Chiang, and Vera László. In addition to the work, I am grateful for their tremendous kindness and encouragement towards me to finish this dissertation.

TOC

In Dessau, I would also like to thank my friend Manuel Kretzer with whom we had the chance to initiate collaborative projects between Architecture and Design Faculties. I strongly see the direction we took there as a successful continuation of our complementary interests and expertise.

I would like to thank all Master of Science students at BK City of TU Delft and Master of Architecture students at DIA at HS Anhalt, contributing to the design, research, and production. The list is so long, but still, I would like to try my best to name the ones whose contribution are directly or indirectly related to the body of the work presented in this dissertation: Mohammad Abdo, Shervin Azadi, Pouria Alighardashi, Oana Anghelache, Hossam Badr, Assaf Barnea, Mary Ann Berendson, Floris van Buren, Leong Chee Chung, Karim Daw, Dylan Deguzman, Olav van der Doorn, Jihong Duan, Maged Elbanna, Muhnnad Elmanaee, Siqi Fan, Radoslaw Fli, Yaseen Gabr, Amro Hamead, Hossam Hesham, Stef Hoeijmakers, Ruth Hoogenraad, Thijs IJperlaan, Hans de Jonge, Javid Jooshesh, Lim Tian Jing, Steph Kanters, Anneloes Kattemölle, Michal Korneck, Heeyoun Kim, Egor Kuzmin, Queena Le Mei Hui, Jingxiang Liu, Jeroen van Lit, Perry Low, Hidde Manders, Mohamed Mansour, Mahmoud Meligy, Florian Markus, Koen Marten, Mohammed Moharram, Rob Moors, Guus Mostart, Turkuaz Nacafi, Ginnevra Nazzarri, Neady Oduor, Blanka Omari, Jan Paclt, Sjoerd Poelman, Saurabh Prasadi, Berend Raaphorst, Niloufar Rahimi, Rutger Roodt, Tania Sabrina, Ahmed Saleh, Kasper Siderius, Apurva Singh, Karsimran Singh, Arthur Slob, Mathew Tanti, Lars Van Vianen, Arise Wan, Roel Westrik, Salam Yousef, Kamal Zaki, Eric Zanetti, Liwen Zhan, and many more. I would also like to thank Rossana Le Roy, who read the summary of this dissertation in Dutch and help me to be sharp with de tekst in het Netherlands.

Outside of BK City TU Delft and DIA Bauhaus, I had the opportunity to have friends and get to know great scholars, and collaborate with experts in academia and industry who have helped me in this research with their generous support and sharing experience and insight: Bart Al, Marta Male Alemany, Siebe Beker, Johannes Braumann, Sigrid Brell-Cokca, Biayna Bogosian, Marie-Ange Brayer, Mahesh Daas, Elif Erdine, Behnaz Farahi, Ali Farzaneh, David Gerber, Andrew John Wit, Neil Leach, Ilona Lénárd, Dagmar Reinhardt, Roland Schmehl, Thibault Schwartz, Ole Sigmund, Jeroen Snijker, Elnaz Tehrani, Soungmin Yu, and many more friends around the world in communities such as Rob|Arch, eCAADe, ACADIA, and DigitalFUTURS. .

I am also grateful for the support of Véro Crickx of Sirene Ontwerpers for her très professionnel work on the layout and graphic design of this book.

I would like to thank all members of Hyperbody Research, Robotic Building studios, 4TU. Bouw Center of Excellence for the Built Environment, Delft Robotic Institute,

100% Research, ABB and KUKA Benelux, AE+T Department at BK TU Delft, DARS units at Dessau Institute of Architecture, Bächer Bergmann GmbH (digital. productions), V2 Gallery Rotterdam, and colleagues in my firm SETUParchitecture studio who have supported projects presented in this dissertation in several phases and on different levels.

Moreover, I would like to thank colleagues of mine who have supported me institutionally or even with a small conversation about this work over coffee break: Thijs Asselbergs, Robert Babushka, Andy van Dobbelsteen, Alexander Liu Cheng, Han Feng, Jelle Feringa, Christain Fredrich, Alireza Hakak, Frank van Der Hoeven, Danielle Karakusa, Tomasz Jaskiewicz, Giancarlo Magnone, Achilleas Psyllidis, Francoise Puffelen, Ana Pereira Roders, Paul de Ruiter, Sevil Sariyildiz, Bo Song, Michela Turin, Barbara van Vliet, Martijn Wisse at TU Delft and Beeke Bartelt, Carl Buchmann, Jasper Cepl, Sandra Giegler, Alfred Jacoby, Ulrike Jost, Ralf Niebergall at DIA Bauhaus.

I also thank my beloved family members and my first mentors without whom it wouldn’t have been possible to finish this dissertation: Mahin Shariat, Farzaneh Mahfouz, Forouzandeh Mahfouz, Ahmadreza Mahfouz, Alireza Mahfouz, Zahra Mostafavi, Farokh Mostafavi, Zaki Mostafavi, Shahrouz Jahanshahi, Bamdad Nourian, Alireza Salami, Shiva Salami, Leila Salami, Pouya Mostafavi, Mohammad Chariat as my family and Kaveh Dadashzade, Sharman Taghavi, Touran Mirhadi, and Faramarz Ghordaninejad as my first mentors and role models.

I would also like to thank my friends in Iran, the Netherlands, and Germany with whom I had the chance to share the ups and downs of my work and every now and then celebrate the achievements: Samaneh Rezvani, Mazyar Abaee, Emil Madsen Brandt, Dena Kasraian, Rouzbehan Shahshahani, Rouzbeh Roudgari, Aftab Darvishi, Alejandra Tortosa, Bardia Mashhoudi, Siavash Maraghechi, Farshid Mirhosseini, Peyman Mohtashami, Ghazal Refalian, Hasty Goudarzi, Parinaz Mansouri, Rick Zwerner, Banafsheh Darvish, Hamid Khaki, Zahra Rezavani, Parisa Parvizi, Nika Jazaei, Matteo Baldassari, Shabnam Hosseini, Davide Ventura, Asma Mehan, Filippo Mortari, Piero Medici, Caterina Micucci, Manuela Triggianese, and Ashkan Rezvani Naraghi who left us too soon. Lastly, I would like to thank my brother Pirouz Nourian who has always been my closest friend and collaborator in every step I remember.

After all these years, the more I think about writing this acknowledgment, the more I understand how hard it is for me to close it. Again, I am thankful to all who have been with me on this journey, and I wish I could extend the list with more names and be able to be more specific about the contribution and support of my family members, students, colleagues, and friends.

TOC

Contents

TOC

TOC

List of Figures

Summary

With increasing advancements in information and manufacturing technologies, there is an ever-growing need for innovative integration and application of computational design and robotic fabrication in architecture. Hybrid Intelligence in Architectural Robotic Materialization (HI-ARM) provides methods and frameworks that target this need. HI-ARM introduces methodologies and technologies that incorporate computational, fabrication and material intelligence in integrated design-to-robotic-production workflows. The intelligence is explored at multiple architectural scales (Macro, Meso, Micro) through hybridization of building processes or multi-mode robotic production and multi-materiality.

Porosity, Hybridity, and Assembly are introduced as main constituents for materialization frameworks relying on computational design and robotic production. These are tested in a series of original experiments that are presented in this thesis together with four peer-reviewed published papers discussing the process of developing integrated design-to-production methodologies in detail. The contributions show how both architectural materialization processes and building products can be customized in different phases and scales. Moreover, the developed discourse and definitions address the impacts of this research through the lenses of computation and automation in research, education, and practice in the fields of Architecture, Engineering, and Construction. A summary of the six chapters of this dissertation is as follows:

Chapter 1 – **Introduction –** introduces the background and discusses the research methodology. The introduction begins with the background and the motivation that drives the project within the research context and related disciplines. The research problem, questions, and objectives are discussed and formulated and are followed by the focus, scopes, and target audience. Lastly, the research relevance and deliverables are explained and identified, and the dissertation structure and the outlines are presented.

TOC

Chapter 2 – HI-ARM: Definitions and Frameworks – lays down the theoretical and methodological basis of this research. The chapter begins with a delineation of the title HI-ARM (Hybrid Intelligence in Architectural Robotic Materialization), and it positions the research within the broader context of the architecture discipline and the building industry. Definitions, in six clusters, establish interrelations between major concepts and terminologies, which are related to this research. Each cluster of definitions is discussed with references to the literature, as well as short descriptions on original experiments. The frameworks introduce conceptual and methodical workflows for Integrated Computational Design and Fabrication Intelligence for Multi-Mode Robotic Production of Multi-Scale and Multi-Material Systems. The conclusion in this chapter is an initial overview to the whole work and it also set the goals for the more extended case studies on Porosity, Hybridity, and Assembly in the following chapters.

Chapter 3 – Porosity: Computation and Production – focuses on the computation and production of porosity. Porosity within HI-ARM frameworks is introduced as a design materialization strategy for the intelligent distribution of matter and void in multiple scales. With an introduction to the objectives and applications of porosity, this chapter consists of two pilot case studies. The first case study mainly focuses on developing design systems as well as the integration of multiple disciplines such as architecture and structural design. This case study is an exemplar of developing integrated computational design systems by incorporating topology optimization methods within a bespoke computational design workflow. The second pilot project in this chapter focuses on the production of porosity, where an integrated design-to-production system is developed and tested for robotic 3D printing of ceramic structures. In this prototypical workflow, we discuss the methodologies of development of an Integrated Computational Design, which incorporates Material and Fabrication Intelligence.

Chapter 4 – Hybridity: Multi-Mode and Multi-Material – addresses hybridity from two main angles. Firstly, the hybridization of robotic fabrication methods or multi-mode robotic production addresses the challenges and potentialities of integrating multiple robotic production techniques. Secondly, hybridity refers to multi-materiality, where two or more materials are combined, modeled, computed, and produced using integrated computational design to multi-mode production systems. With a series of short case study descriptions and experiments on hybridity, the introduction discusses Computational Intelligence, Material Intelligence, and Fabrication Intelligence as bases of multi-mode materialization of multi-material systems. The chapter's main body, Materializing Hybridity in Architecture, presents three core case studies in more detail: Hybrid Cork, Hybrid Concrete, and Hybrid Silicone. The cases exemplify multi-mode robotic production methods such as

TOC

subtractive-subtractive using Robotic Hot Wire Cutting and Robotic Milling or Subtractive-Additive using Robotic Hot Wire Cutting and Robotic Milling combined with Robotic 3D printing.

Chapter 5 – Assembly: Component and Sequence – is centered on Assembly as the third subject explored and framed in this research next to Porosity and Hybridity. Assembly addresses the challenges of putting materials, building elements, and architectural components in various scales using integrated computational design to robotic production workflows. In the introduction, three major assembly concepts are discussed with a series of experiments and briefly presented projects: Connection, Component, and Sequence. The core case study of this chapter is focused on Design-to-Robotic-Production of Free-Form Reciprocal Frame Wooden Structures. The produced one-to-one prototype exemplifies a multi-directional approach to Assembly where the constraint and potentialities of production inform the design in terms of fabrication and assembly intelligence.

Chapter 6 – Conclusion – includes four parts: introduction, results and contributions, reflection and futures work, and final remarks. The introduction opens the conclusion by referring back to the main question and objective. Results and contributions recap the sub-questions corresponding to each of the four main chapters. The third part of this chapter provides sets of reflections and elaborates on the potential impact and future directions of this work and related fields in research, education, and practice. The final remarks close this dissertation by providing some concluding thoughts on the why, the how, and the what of the path that has been taken.

Sammenvatting

Door de toenemende ontwikkelingen in de informatie en productie technologie is er een constant groeiende behoefte naar een betere integratie en applicatie van Computational Design en Robotic Fabrication in de architectonische disciplines en de bouw industrie. Hybrid Intelligence in Architectural Robotic Materialization (HI-ARM) biedt methodes en ontwikkel kaders die in deze behoeftes voorzien.

Door de nadruk te leggen op research-by-design en prototyping, wil HI-ARM methodologieën en technologieën ontwikkelen die computationele, fabricage- en materiaalintelligentie integreren in geïntegreerde ontwerp-naar-robot productie workflows. De intelligentie wordt onderzocht en gearchiveerd in meerdere architecturale schalen (Macro, Meso, Micro) door middel van hybridisatie van bouwprocessen of multi-modaal robotproductie en multi-materialiteit.

De drie kernonderwerpen in dit werk: Porositeit, Hybriditeit en Assemblage, worden geïntroduceerd als oplossingen en vormen de basis van de materialisatiekaders met behulp van Computational Design en Robotic Fabrication. Aanvullend wordt een reeks originele experimenten in dit proefschrift behandeld en bespreken vier peer-reviewed gepubliceerde artikelen het ontwikkelingsproces naar een geïntegreerde Design-to- productie methodologieën in detail. Deze bijdragen tonen de wijze waarop zowel architectonische materialisatieprocessen als bouwproducten kunnen worden afgestemd op verschillende fasen en schaalniveaus. Daarnaast worden de impact van de ontwikkelde discours en haar definities behandeld vanuit het oogpunt van computationeel en geautomatiseerd onderzoek, onderwijs en de praktijk op het gebied van architectuur, engineering en constructie. Een samenvatting van de zes hoofdstukken van dit proefschrift is als volgt:

Hoofdstuk 1 – Inleiding – introduceert de achtergrond en bespreekt de onderzoeksmethodologie. De introductie begint met de onderbouwing en motivatie die de onderzoekskaders en aanverwante disciplines van het project bepalen. De probleemstelling, onderzoeksvragen en doelstellingen worden hier geformuleerd. Gevolgd door de focus, afbakening en doelgroep. Tot slot wordt de relevantie van het onderzoek besproken, de deliverables geïdentificeerd en worden de contouren van de dissertatiestructurr gepresenteerd.

TOC

Hoofdstuk 2 – HI-ARM: Definities and Frameworks – legt de theoretische en methodologische basis van dit onderzoek vast. Het hoofdstuk begint met een afbakening van de titel HI-ARM (Hybrid Intelligence in Architectural Robotic Materialization) en plaatst het onderzoek in de bredere context van de architectuurdiscipline en de bouwsector. Definities, in zes clusters, leggen onderlinge verbanden tussen primaire concepten en terminologieën die verband houden met dit onderzoek. Elk cluster van deze definities wordt behandeld middels verwijzing naar de literatuur, evenals korte een beschrijving van de originele experimenten. De frameworks introduceren conceptuele en methodische workflows voor Integrated Computational Design en Fabrication Intelligence voor Multi-Mode Robotic Production van Multi-Scale en Multi-Material Systems. De conclusie van dit hoofdstuk is een initieel overzicht van het hele werk en zet daarnaast de doelen voor meer uitgebreide casestudy's over porositeit, hybriditeit en assemblage in de volgende hoofdstukken.

Hoofdstuk 3 – Porositeit: computatie en productie – richt zich op computationele aspecten en productie van porositeit. Porositeit binnen HI-ARM kaders wordt geïntroduceerd als een ontwerp-materialisatie strategie voor een intelligente distributie van materie en leegte op meerdere schaalniveaus. Met een inleiding tot de doelstellingen en toepassingen van porositeit, bestaat dit hoofdstuk uit twee pilot casestudies. De eerste casestudie richt zich voornamelijk op het ontwikkelen van ontwerpsystemen, evenals de integratie van meerdere disciplines zoals architectuur en constructief ontwerp. Deze casestudie is een voorbeeld voor het ontwikkelen van geïntegreerde computationele ontwerpsystemen door topologie optimalisatiemethoden op te nemen in een op maat gemaakte computationele ontwerpworkflow. Het tweede pilot project in dit hoofdstuk richt zich op de productie van porositeit, waarbij een geïntegreerd ontwerp-tot-productie-systeem is ontwikkeld en getest op het robotisch 3D-printen van keramische structuren. In deze prototypische workflow bespreken we de methodologieën voor de ontwikkeling van een geïntegreerd computationeel ontwerp, dat materiaal- en fabricage-intelligentie omvat.

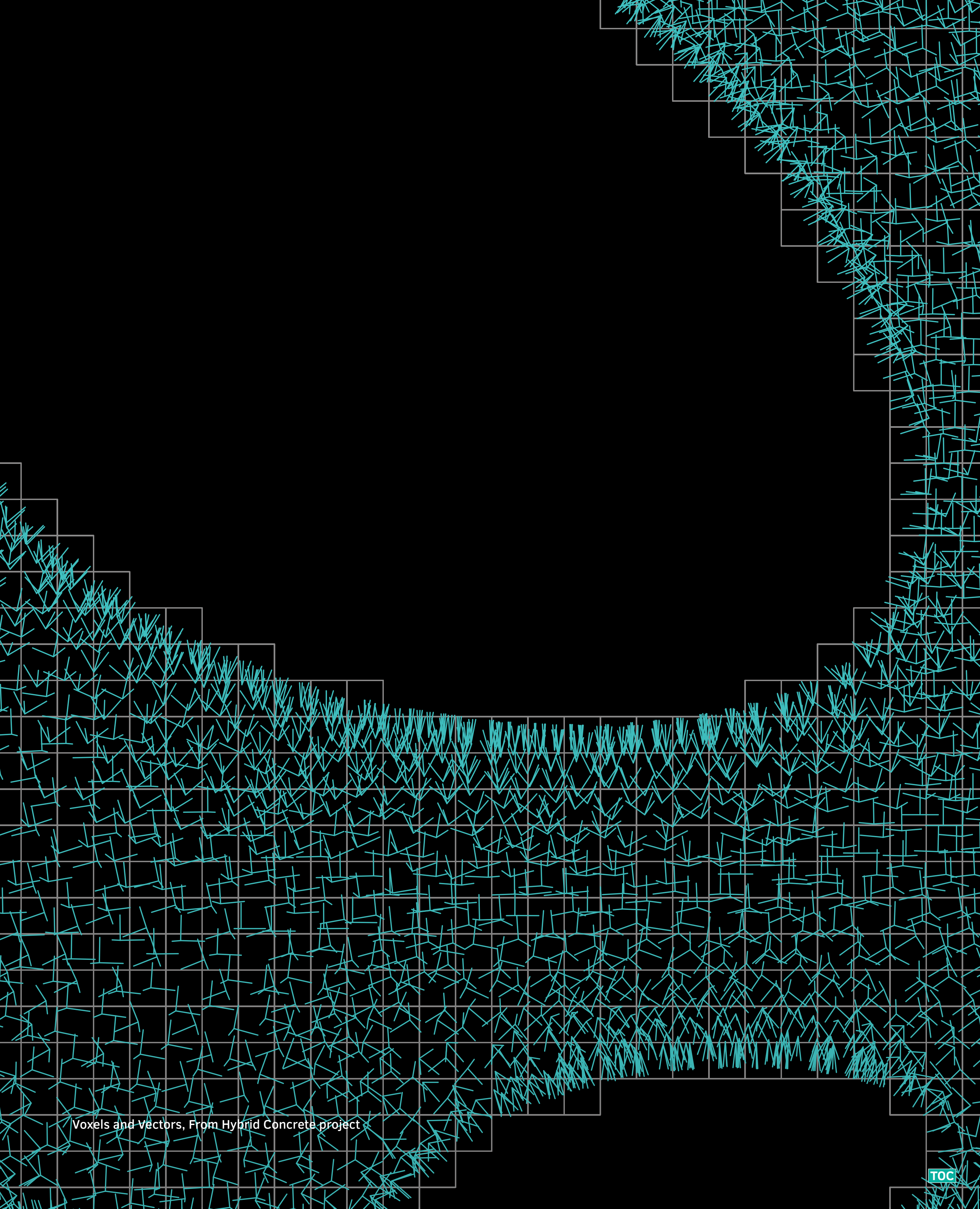
Hoofdstuk 4 – Hybriditeit: Multi-modaal en Multi-materiaal – behandelt hybriditeit vanuit twee invalshoeken. Ten eerste, adresseert de hybridisatie van robotische ontwikkelings methoden of multi-modaal robotische-productie de uitdagingen en mogelijkheden voor integratie van meerdere robotproductietechnieken. Ten tweede verwijst hybriditeit naar multi-materialiteit, waarbij twee of meer materialen worden gecombineerd, gemodelleerd, berekend en geproduceerd met behulp van een geïntegreerd computationeel ontwerp naar multi-mode productiesystemen. Op basis van een korte reeks casestudies, beschrijvingen en experimenten op het gebied van hybriditeit bespreekt de inleiding Computational Intelligence, Material Intelligence en

TOC

Fabrication Intelligence als basis voor multi-mode materialisatie van multi-materiële systemen. De hoofdtekst van het hoofdstuk, Materializing Hybridity in Architecture, presenteert drie kern casestudies meer in detail: Hybrid Cork, Hybrid Concrete en Hybrid Silicone. De cases zijn voorbeelden van multi-mode robotproductiemethoden zoals subtractief-subtractief met Robotic Hot Wire Cutting en Robotic Milling of subtractief-additief met Robotic Hot Wire Cutting en Robotic Milling gecombineerd met Robotic 3D printing.

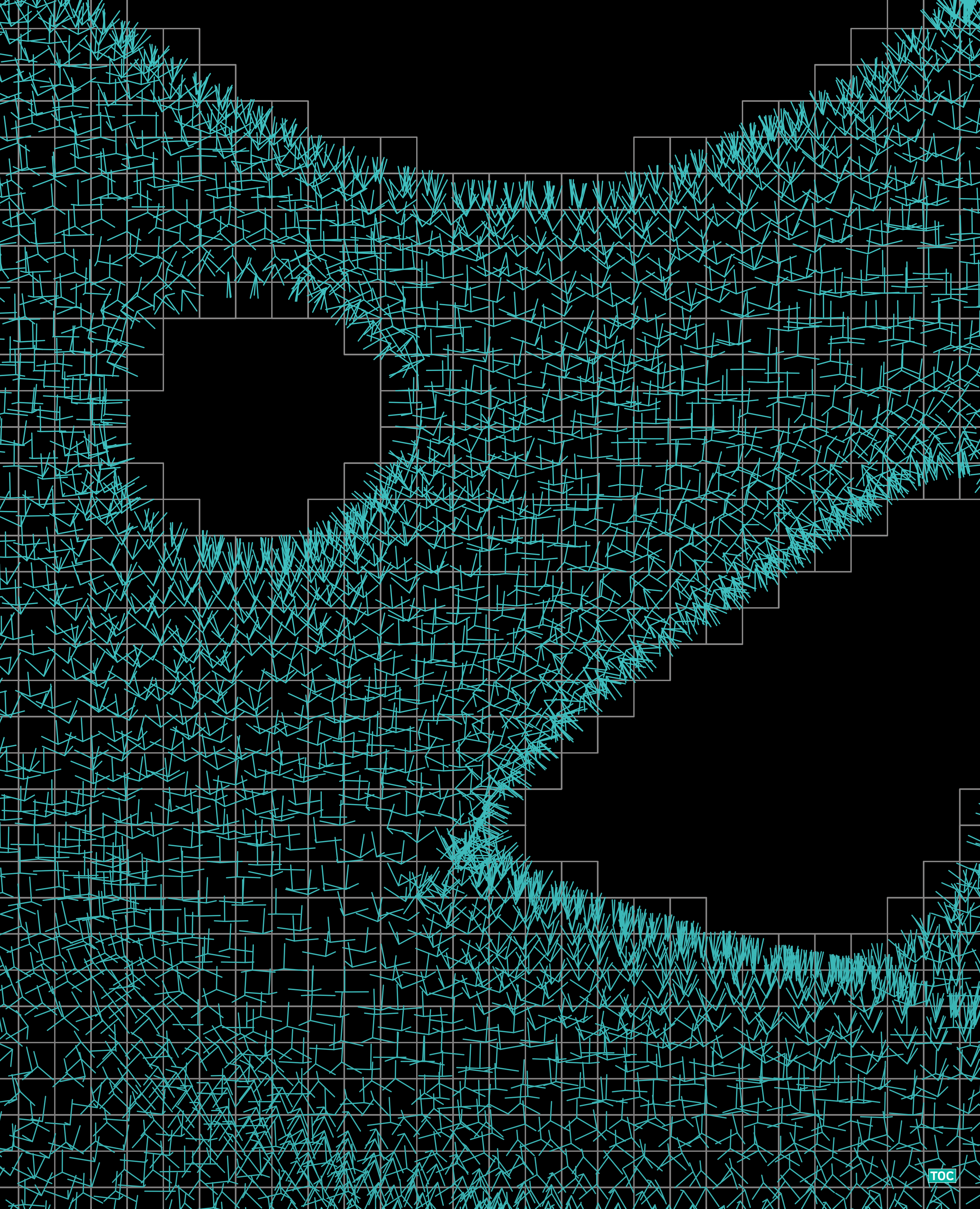
Hoofdstuk 5 – Assemblage: Component and Sequence – is gecentreerd rond het derde onderwerp, Assemblage dat in dit onderzoek wordt onderzocht en ingekaderd, naast Porositeit en Hybriditeit. Assemblage bespreekt de uitdagingen rond het plaatsen van materialen, bouwelementen en architectonische componenten op verschillende schaalniveaus met behulp van een geïntegreerd computationeel ontwerp voor robotproductie workflows. In de inleiding worden drie belangrijke assemblageconcepten besproken op basis van een reeks experimenten en beknopt gepresenteerde projecten: Verbinding, Component en Volgorde. De belangrijkste casestudie van dit hoofdstuk is gericht op design to robotic production van vrije vorm reciproke houten constructies. Het geproduceerde één-op-één prototype is een voorbeeld van een multi-directionele benadering van assemblage, waarbij de beperkingen en mogelijkheden van de productie het ontwerp informeren in termen van fabricage- en assemblage-intelligentie.

Hoofdstuk 6 – Conclusie – omvat vier delen: inleiding, resultaten en bijdragen, reflectie en toekomstig werk en slotopmerkingen. De inleiding opent de conclusie door te verwijzen naar de hoofdvraag en het hoofddoel. Resultaten en bijdragen geven een samenvatting van de deelvragen die overeenkomen met elk van de vier hoofdstukken. Het derde deel van dit hoofdstuk bevat een reeks reflecties en gaat dieper in op de mogelijke impact en vervolg van dit werk binnen aanverwante gebieden in onderzoek, onderwijs en praktijk. De slotopmerkingen sluiten dit proefschrift af met enkele laatste opmerkingen over het waarom, het hoe en wat van de ingeslagen weg van dit werk.



Voxels and Vectors, From Hybrid Concrete project

TOC



TOC

TOC

1 Introduction

ABSTRACT This chapter provides an overview of the work presented in this dissertation book. The introduction begins with the background and the motivation that drives the project within the research context and related disciplines. Further, the research problem, questions, and objectives are discussed and formulated. We then specify the focus, scopes, and the target audience. The chapter continues with the research methodology and introduces the research tools, methods, and approaches in the case studies and pilot projects. Consequently, research relevance and deliverables are explained and identified. The last section presents the dissertation structure, and it outlines each chapter with a brief.

1.1 Background

This project is a multidisciplinary research in the field of architectural design and building processes. Focusing on digital design workflows and emerging robotic production methods, the developed methodologies exemplify a set of prototypical and bespoke design to robotic materialization systems and projects. Therefore, in addition to generic subjects related to the discipline and practice of architecture, the background is manifold and constitutes the following primary domains: computation, automation, and material systems being implemented in Architecture, Engineering and Construction (AEC) sectors.

Beyond today's cutting-edge architectural design and building technologies, the essence of this research may go back to a very fundamental challenge in the imagination and creation of human-made artifacts. How can the role of tools be defined and justified in a design and making process? How do we design-and-make differently with new tools? How do we perceive and create differently with new interfaces? How can we, as designers, be in charge of designing design-to-production systems? How do we change these tools, and how do we embrace the new mediums?

1.1.1 Context

From a theoretical standpoint, we may picture the role of emerging digital design and robotic technologies in architecture and building industry through the following phrase by John Culkin who is describing the work of media theoretician Marshal McLuhan: “we become what we behold, we shape our tools and then our tools shape us (Culkin 1967).” Expanding this line of thinking into the context of this research the following four main research background domains can be identified:

- **Process:** design and production systems, methods, technologies, and tools
- **Product:** physicality of built environments, efficiencies and building performance
- **Context:** societal, cultural, industrial and economic impacts
- **Cognition:** human-machine intelligence in design and making processes

From the early advent of Computer-Aided Design and Computer-Aided Manufacturing, the characteristics and functionalities of digital interfaces are advanced for application in different stages in the design process. While early attempts are made to develop and implement digital mediums as drafting tools for simple and later associative modeling of complex geometries (Inter al. Sutherland 1964; Gehry, Lloyd, and Shelden 2020), the recent works try to break the dichotomy of engineering and design. This mainly has happened through integrating geometry generation procedures with analysis, simulation, and evaluation. In parallel to the technological advancement in the 60s and 70s in CAD-CAM mainly pursued by engineers, a body of work on design methods, cybernetics, and systemic thinking in architectural design which is pursued by architects and designers is distinguishable (inter al. Alexander 1967; Pask 1969; Negroponte 1970; Price 1978; Frazer 1995). Borrowing concepts such as Generative Grammar from other disciplines such as computer science and linguistics, we are experiencing the proliferation of systemic and algorithmic thinking in digital design processes (Knight and Stiny 2015; Woodbury 2010).

The second background domain to this research, which is the materiality of architecture and building performance, can be tracked and categorized as performance-oriented architecture or data-driven design (inter al. Hensel 2013; Kolarevic and Malkawi 2005). In this domain, through a body of work both in academia and practice, the significance of interdisciplinary work in architecture and the building industry is framed and exemplified. In the context of this research, the integration of different disciplines and establishing feedback loops are among the core research objectives, which may potentially enhance building performances and introduce higher-resolution details in architecture. Therefore, the case studies explore and propose bespoke approaches for efficient materialization procedures that result in prototypical examples of robotic production advancing performative design methodologies.

Thirdly, the contemporary industrial revolutions empowered by cyber-physical systems, numerically controlled fabrication methods, and automation in construction have influenced and are influencing the design-to-production chains. With the shift from mass-production to mass-customization, the on-demand manufacturing of personalized and geometrically complex building products has become more affordable and accessible (Inter al. Kolarevic, 2004; Kolarevic and Klinger, 2008; Naboni and Paoletti 2015). In this context, architectural robotics as an emerging and evolving field enables the discipline of architecture to have an active role and creative impact on redefining certain fundamental aspects of the building industry, as well as the socio-cultural position of the changing discipline of architecture (Ratti and Claudel 2015; Picon 2010). With an analysis of the state-of-the-art of robotics in architecture, the projects presented in this dissertation exemplify how the flexibility and programmability of robots lead to product innovation and a new material culture for building applications.

Lastly, beyond the visible influences of emerging technologies, a further prominent impact includes how the thinking and working capacities of the architect or whoever is involved in the design and building processes are changing. In other words, how and to which extent we adapt our explicit knowledge about the physicality of the built environment as well as tacit design thinking capacities to cope with and be in charge to ride on the waves of emerging paradigm shifts. While the other three abovementioned domains are inherently more objective and measurable, investigating the so-called cognitive aspect may require longer-term observations in design pedagogy and practice. However, throughout the case studies and conclusions, this research relies on references in the field of design research (Inter al. Schon 1983; Cross 1999) to further elaborate and redefine the role and position of the architect in the age of computation and automation (Inter al. Sennett 2009; Bernstein 2018).

1.1.2 Motivation

This research started with an idea initially titled Design Information Modeling or DIM, with the goal to bridge the gap between early stages of the design process, materialization, and performance evaluations. Beyond mirroring the notion and questioning the field of BIM or Building Information Modeling, the initial motivation was to develop structurally and environmentally informed materialization processes.

Moreover, personal experiences in the implementation of digital fabrication in practice provoked several questions regarding the role and the impact of advanced and emerging production methods to achieve structurally, environmentally, and functionally efficient material systems. Further interests to do research by design, having a hands-on approach as well as the necessity to be interdisciplinary, the research focus is then directed towards the field of robotic fabrication in architecture. With these initial motivations and from an objective point of view, the goal is to make both design-to-building processes and products more efficient. Additionally, the novel methods of digital design and fabrication result in new materiality, which has unique and emerging aesthetic qualities that are explored and discussed throughout this research beyond the measurable performances. Last but not least, new design thinking models and approaches are required to purposefully and creatively exploit and apply new methods of design and production.

1.2 Problem Definition and Hypothesis

Defining a set of research problems and framing a hypothesis, this thesis values the meaning behind this quote by Cedric Price, stating that “Technology is the answer, but what was the question.” In other words, it is essential to specify domain-specific questions in order to advance existing methods and to further develop and deliver applicable methods and relevant bespoke technologies. However, before narrowing down the research questions, there are certain facts on a broader spectrum to address when it comes to the materialization approaches in the contemporary practice of architecture and state-of-the-art production technologies in the building industry. Therefore, to formulate a guiding research hypothesis, related challenges in the three realms of computation, automation, and materialization will be addressed in theoretical, methodological, and technological dimensions.

1.2.1 Problem Statement

1.2.1.1 Theoretical shifts, disruptive technologies and changing design paradigms

Research problems to this project are categorized and explained into multiple levels and realms- within the discipline of architecture, ranging from theory to technique and from design to production. From a theoretical standpoint, the relatively new and emerging field of architectural robotics requires comprehensive frameworks that could explicate the potentials as well as the shortcomings of such emerging fields at different scales and contexts. Beyond the developed methodological and technological aspects, the body of the work presented in this dissertation, as well as reflection on the literature plus conclusions, construct and propose design-to-production frameworks and theoretical discourses on various methods of robotic fabrication for architectural applications. In this context, the theoretical goal is not to provide a comprehensive theory of robotics in architecture with an extensive review of the literature. However, it addresses relevant theoretical shifts, which result from contemporary disruptive technologies in practice and pedagogy of architecture affecting the roles and positions of designers, builders, and users.

1.2.1.2 Methodological gaps, both in software and hardware domains

At the methodological level, pure digital design strategies for modeling of material behaviors and properties and simulation of production processes heavily rely on the abstraction of physicality. It is not that the abstraction is a threat to creative design thinking, but instead, usually in order to overcompensate the lack of materiality and building-related information in digital design interfaces, one may stick to the available material palette or blindly consider conventional methods of construction. Therefore, in common design practices, limited numbers of simplified approaches are implemented for material engineering, computation, and calculation, through which the designers explore and apply different materials, whereas each material or building approach may require its own specific hence customized design-to-production method.

TOC

Simultaneously, developing case-specific methods may not devalue the importance of automation in design and production. Therefore, understanding to which extend a certain materialization method needs to be generic yet not too general and needs to be specific yet not too ad-hoc requires systematic exploration, critical thinking, and prototypical case studies.

In this context, both in practice and academia, methods of interoperability or information exchange between synthetic and analytic or generative and evaluative routines is a subject for further exploration. Therefore, establishing consistent computational design systems for architectural applications that incorporate material and production logic demands innovative strategies for bridging between digital design interfaces and physical production setups. Hence, defining and employing feedback and feedforward loops in an integrated design-to-production system need experiments that facilitate this study.

Moreover, developing materially-informed and fabrication-aware design systems requires an interdisciplinary approach that is new to the practice and pedagogy of architecture. In the context of this research, multi-materiality and multi-mode robotic production methods in multiple scales are considered as two primary focuses for which prototypical projects are designed, tested, and discussed.

1.2.1.3 Technological lags, in production at multiple scales in building industry

The programmability and customizability of industrial robots have been exploited more extensively in mass-production-oriented industries such as automotive, electronics, and agriculture for repetitive assembly, advanced manufacturing, and hazardous operations (International Federation of Robotics 2016). The building industry may benefit from an immediate adaptation of such systems from other sectors; several challenges may question the one-to-one copying or reuse of the same technologies in architectural design and production. On this basis, the fact that each building or space needs to correspond to a specific societal and environmental context may explain the function and advantage of mass-customization in architecture. However, there are resistances to change both at conceptual design thinking and infrastructural building industry levels, which result in lags in integrating emerging technologies such as robotics in architectural production.

Consequently, there are deficiencies and discrepancies when it comes to the integration and implementation of robotic fabrication and advanced computational

TOC

design in the creative sector and industries such as architecture and construction. Additionally, the existing prevailing culture and the economy of design education and practice may not have the full capacity and adaptability that allows for this integration. In this context, this research is a methodological exploration through prototyping to provide new design-to-materialization frameworks that demonstrate and facilitate technology integration for creative and innovative architectural design to robotic production processes. Moreover, this thesis focuses on technology demonstration and prototyping of hybrid material systems using hybrid fabrication methods such as additive-subtractive processes.

1.2.2 Research Hypothesis and Propositions

This research is mainly constructed upon a series of interrelated explorations and design-driven experiments. Design in this context refers to the process of designing and developing systems that may include the methodology of modeling and making of a space or a building component, or it may involve the design and advancement of a particular building manufacturing technology. Therefore, due to the more objective-oriented nature of this research, narrowing it down to one comprehensive research hypothesis or single proposition is not enough, if not simplistic, but yet it is necessary. Thus, the research hypothesis is formulated as follows:

On multiple levels, hybrid intelligence in design and materialization processes will improve and advance the state of the art and future of design and building processes that demand integrated computational design to multi-mode robotic production methodologies and technologies, consequently resulting in multi-performative, multi-material, and multi-scale resolutions.

The research hypothesis statement does not aim to prove or disprove an existing theory of architecture or be more specific to provide a thorough theory of architectural materialization. Rather, it is a proposition considering the guiding research direction and framework. In this framework, materialization is the goal, while computation and automation are the means. Hybrid intelligence refers to hybridization on multiple levels, such as the hybrid of human-robot and human-computer intelligence, hybridization in materiality, and hybridization of production techniques. Multi-mode refers to different production and material processing methods, such as additive, subtractive, formative, and modificative. The measurements for efficiency or performance criteria such as functional, environmental, and structural, as well as for the scale may vary from case to case.

With the above-mentioned research hypothesis, the proposition is to explore and incorporate design and production intelligence for porosity, hybridity, and assembly. In this context, studying and materializing complex topologies and geometries is not the goal, but rather it is the mean and the strategy for explorations and developments of the novel and innovative methods.

1.3 Research Questions and Objectives

The major outcomes of this research include theoretical frameworks, methodological workflows, technological integrations, and domain and case-specific methods and techniques. Therefore, most of the research questions are formulated in the how-question formats, and some of which are more related to specific methodical and technical aspects of case studies are expressed as what-questions.

1.3.1 Research Questions

The background question of this research is: How emerging technologies are transforming the experience and the practice of architecture and the building industry? In this context, the main research question, in short, is: How can we incorporate integrated design-to-production intelligence in architectural design and building processes? The further extended main research question is as follows:

- **How can we develop and deploy integrated computational design to robotic production systems for efficient architectural materialization and effective building?**

Considering the previously stated research hypothesis, the immediate answer to the main question is: By achieving multi-performative, multi-scale, and multi-material solutions through hybrid intelligence in architectural robotic materialization. Based on this main question, the research sub-questions are:

- What are the main scopes of an interdisciplinary and integrated computational design to a robotic production system? (Chapter 2)
- What are the key definitions in a theoretical, methodological and technological frameworks for innovative architectural robotic materialization? (Mainly Chapter 2, plus Chapters 3-4-5)
- How can we incorporate multiple performance criteria such as structural, environmental and functional, in an integrated design to the Multi-mode robotic production process in multiple scales (Mainly Chapter 2, plus Chapters 3-4-5)
- How can designers establish feedback and feedforward loops between robotic production processes and various stages of design? (Mainly Chapters 2 and 6)
- How digital design interfaces and modeling approaches can become more material and fabrication aware? (Mainly Chapter 2, plus Chapters 3-4-5)
- How can we develop and implement hybrid intelligence for robotically producible porosity? And how can we develop an integrated computational design to robotic production processes for efficient porous building systems? (Chapter 3)
- What are the main challenges of computation and robotic production of porosity? (Chapter 3)
- How can we develop and implement hybrid intelligence for robotically producible hybridity? And how can we develop integrated computational design to robotic production processes for efficient multi-materiality? (Chapter 4)
- How can we develop and implement multi-mode subtractive-additive design to robotic production processes for architectural applications? (Chapter 4)
- What are the main challenges of computation and robotic production of multi-materiality? (Chapter 4)
- How can we develop and implement hybrid intelligence for assembly in integrated computational design to robotic production processes? (Chapter 5)
- What are the main challenges of computing and integrating assembly rationale in design to robotic production processes? (Chapter 5)
- How can the customizability, programmability, and scalability of integrated design to robotic production systems influence the present and future of the practice and the industry? (Chapter 6)
- What are the future directions of computation, automation and advanced materialization in the research, pedagogy and practice of architecture and the building industry? (Chapter 6)

1.3.2 Research Objectives and deliverables

Bridging the gaps between design and construction, the main research objective of this research is:

- **Achieve integrated design to production intelligence by developing and deploying design to production systems which include frameworks, workflows, methods and techniques of bespoke computational design and customized multi-mode robotic production processes for the materialization of performance-driven multi-materiality at multiple scales;**

The corresponding sub-objectives and deliverables of each chapter are as follows:

- **Chapter 2:** Hybrid Intelligence in Architectural Robotic Materialization (HI-ARM) Frameworks ; HI-ARM Theoretical Outline and Methodological Workflows; Framework for the Integration of Design Space, Material Space, Production Space with integrated Feedforward ad Feedback loops; Multi-Mode Multi-Scale Multi-Material Multi-Performative Frameworks; HI-ARM Porosity, Hybridity, Assembly Framework;

- **Chapter 3:** Workflows and Methods of Material Computation and Robotic Production of Porosity; Performance Driven and Design Information Exchange Models for Structurally Informed Material Distribution; Design to Robotic 3D Printing (R3DP) of Porous Material Systems; Ceramic Robotic 3D Printing Setup;

- **Chapter 4:** Workflows and Methods of Computation of Multi-Materiality and Multi-Mode Robotic Production of Hybridity; Subtractive-Subtractive (Robotic Hot Wire Cutting (RHWC)– Robotic 3D Milling (R3DM) and Subtractive-Additive (RHWC-R3DM-R3DP) Multi-Mode Design to Robotic Production Systems; Prototypical Design To Robotic Production of Hybrid Material Systems (Hybrid Cork, Hybrid Concrete and Hybrid Silicone);

- **Chapter 5:** Workflows and Methods of Modeling and Computation of Sequence of Assembly and Component-Based Design; Workflows of Robotic Stacking of Non-Uniform Elements; Integrated Design to Robotic Production of Reciprocal Wooden Structures for Multi-Directional Assembly;

- **Chapter 6:** Conclusion and guidelines for the Constructive and Creative application of HI-ARM and Integrated Computational Design to Robotic Production systems in Architectural Practices, Interdisciplinary Research and Pedagogy and the Building Industry;

1.4 Research Focus and Reach

The core subjects and the case studies of this interdisciplinary research are within the field Architecture and the Built Environments (ABE), crossing the boundaries between Architecture, Engineering and Construction (AEC) by establishing correlations and feedback between Computation Automation and Materialization.

1.4.1 Scope

Directly related scopes, domains and disciplines to this research are:

- Architectural Design Building Industry
- Architectural Robotics
- Computation, Digitization and Digitalization plus Automation and Robotization
- Computational Design, Computer-Aided Design
- Computational Geometry, Computer Graphics, Computer Simulations
- Advanced Manufacturing, Industrial Robotics, Computer-Aided Manufacturing
- Additive Manufacturing, Subtractive Manufacturing, 3D Printing
- Materialization, Material Computation, Material Properties and Behaviors
- Structural Design and Engineering, Environmental Design and Engineering
- Form-Finding, Design Optimization Material Optimization
- Architectural Theory, Design Research and Pedagogy

Indirectly related scopes, domains and disciplines to this research are:

- Robotics and Artificial Intelligence
- Creative Industries
- Sustainability and Circularity
- Building Information Modeling
- Emerging modes of architectural practices
- Entrepreneurial innovation in design and construction
- Smart Materials and Adaptive Systems
- Computer Science and Information Technology
- Systemic Thinking and Cybernetics
- User Interface Design and Design Decision Support Systems
- Industrial Design and Material Science
- History and Philosophy of Science, Disruptive Innovations and Industrial Revolutions

TOC

1.4.2 Audience

Corresponding to the aforementioned scopes, the audiences of this research are:

- Architects, designers, scientist, makers and builders in ABE fields and AEC sectors
- Researchers in the field of architectural robotics and computational design
- Educators and students in the disciplines of architecture, design, creative industries, as well as related engineering and manufacturing fields

1.5 Research Methodology

This research implements a combination of different research methodologies and strategies which are complementary. As the main body of the research is based on objective-oriented case studies, then heuristic explorations and experimental methods, instantiation, and research by design and prototyping are the backbones of the implemented research approaches. Moreover, since we have guiding initial propositions and presumptions, therefore, hypothesis-driven research approaches such as observation, deduction, and generalization are also applicable. Consequently, the developed posteriori knowledge, which is based on experimentation, is the main driving force alongside the fundamental priori knowledge and reasoning methods that are applicable in the AEC sectors and creative design industries.

1.5.1 Methods and Tools

The theoretical and methodological frameworks are evolved and constructed based on analyzing and observing the results of the case studies as well as state of the art. Further research tools for the case studies are modeling, simulation, prototyping, measuring, testing, integrating, comparing, and validating. Moreover, through participatory and action research approaches in architectural design and production studios, the methodologies and technologies are iteratively explored, developed evaluated. Further research strategies are mixed qualitative and quantitative methods (Creswell and Creswell 2018), experimental and quasi-experimental research strategies (Groat and Wang 2013).

1.5.2 Literature Review

The literature review in this dissertation is spread throughout the whole book in three levels. Firstly, background theoretical and historical references are briefly provided as needed as a part of the problem statement formulation in chapter one, as well as the introduction to the HI-ARM in chapter two. The second level of the literature review is the study of examples in the fields of methodologies and technologies in art, design, and building industry. These examples are introduced and analyzed and compared together with certain aspects of the conducted small experiments or more extensive pilot case studies. Thirdly, the domain-specific literature review is provided for each case study in chapters three, four, and five.

1.5.3 Research by Design

The term and concept of Research by Design is widely addressed and defined as a research approach in fields of industrial design and architecture (Inter al. Cross 1999; Laurel 2003; Horváth 2007; Horváth 2008; Koskinen et al. 2011; Hensel 2012; Rodgers and Yee 2018). In research by design, the architectural design process forms a pathway through which new insights, knowledge, practices, or products come into being. In the context of this research, Research by Design refers to the systematic design and development of project-driven case studies in which computational design and robotic production technologies and methodologies are explored and delivered. The case studies include short and small experiments as well as more extensive and comprehensive architectural design to prototyping projects. Within these projects, both explanatory sequences (explain, follow up, understand, set systems) and exploratory sequences (develop, design, build) are implemented. Therefore, research by design and prototyping are key aspects of the research methodology through which the main and the sub-questions and objectives are addressed and tackled.

1.6 Relevance

The significance and the applicability of this research are identified in multiple fronts such as the domain-specific or interdisciplinary-oriented scientific contributions, the potential societal and environmental impacts, as well as the methodological, technological, and case-specific deliverables.

1.6.1 Scientific Relevance

This research extends the knowledge in the fields of Architecture and the Built Environment by exploring and developing a series of integrated design to production systems in forms of computational design methodologies and robotic production technologies. On the methodological front, the contribution is through the theoretical and the know-how knowledge for better comprehension, application, analysis, evaluation, and synthesis of architectural design and building systems and solutions.

Within the context of the contemporary industrial revolution, the research framework and the prototypical case studies provide examples of interdisciplinary approaches required to integrate digitalization and automation in the disciplines of design, the practice of architecture, and the building industry. Consequently, this research bridges the gap between design and construction by establishing feedforward and feedback loops to the realms of computation, robotization, and emerging materials and innovative technologies.

Moreover, the design and fabrication of complex and highly-detailed architectural components and high-performance building materials and systems require advanced computation and production methods. Therefore, this research develops integrated design to robotic production processes and solutions by considering the growing demands for efficient construction of such complex forms and building systems that potentially can fulfill higher efficiencies by integrating knowledge from multiple domains such as structural design and mechanics, material science, advanced manufacturing, computer graphics, computer science, and computational design and robotics.

1.6.2 Societal Relevance

The potential societal impact and the significance of this research is multifaceted. Firstly, at a larger scale of the users' society of the built environment, this research, directly and indirectly, facilitates means for on-demand production and mass-customization. Therefore, a higher level of personification, eventually with no extra cost, if not less, may result in improved designs and building products, delivering a better quality of life. Secondly, from a socio-cultural perspective, the creative implementation of advanced manufacturing methods, such as robotic fabrication and 3D printing, enables the exploration and realization of new material cultures and aesthetics. These emerging visual qualities beyond their potential cultural values may redefine the role of ornaments and details in design and architecture. This research may not directly discuss intersubjective dimensions, but eventually, it does not devalue or ignore their importance. The third view is entrepreneurial, which applies to the societies of architects, designers, researchers, educators, builders, and creative makers. In this context, this research provides opportunities for setting interdisciplinary spin-offs, start-ups, businesses, and institutions, which eventually result in design practices and building industries that are more responsive to the growing digitalization and automation processes.

1.6.3 Environmental Relevance

The building industry is a carbon-intensive industry [1]. This research facilitates the designing and making of building systems and components that have less embodied energy and are more resource-efficient. This is achievable by designing and producing robotically constructible components that are more porous, less heavy with more efficient structural and environmental performances.

Further, robotization of building processes may result in circular and sustainable solutions through localization and decentralization of production and manufacturing infrastructures, which eventually can reduce the need for transportation of raw, processed, or even remotely prefabricated building elements.

TOC

1.7 Outline

This dissertation book is based on several peer-reviewed papers. While the conclusion chapter is a reflection and response to the introduction chapter, the second chapter is an overview of the HI-ARM framework. The three core chapters of Porosity, Hybridity, and Assembly explain the pilot projects to introduce the developed design methodologies and production technologies in further detail. The reader may receive these three chapters as publication-based parts of this dissertation with introductions and conclusions added to this dissertation. The exact citations to the original peer-reviewed publications by the author are provided in these chapters, as well as the end of this dissertation book as a list of related publications. In the paper-based chapters, minor changes and edits are made to outline the entirety of this book as an independent and coherent work. In each of these three thematic chapters, major sub-topics are discussed: Computation and Production in Porosity chapter, Multi-mode and Multi-material in Hybridity chapter, and Sequence and Component in the Assembly chapter. This outline does not mean that these sub-topics are researched and developed separately, but instead, this structure is set as such in order to address the research questions and objectives more in-depth through the case studies with more detail.

1.7.1 Structure

The textual and visual information in this dissertation is structured in three complementary layers. The Introduction and the conclusion chapters together define and address the What and the Why. Chapter two sets the scope of the research by giving reference to the literature and state-of-the-art, as well as certain aspects of different conducted experiments. In this chapter, the definitions are discussed in six clusters, while the How is only is explained briefly to present the four frameworks of the integrated design to production methodologies. The third layer is the body of the dissertation, which consists of three thematic chapters with several case studies that provide more extensive information and descriptions about the How. An overview of the structure is illustrated in FIG 1.1.

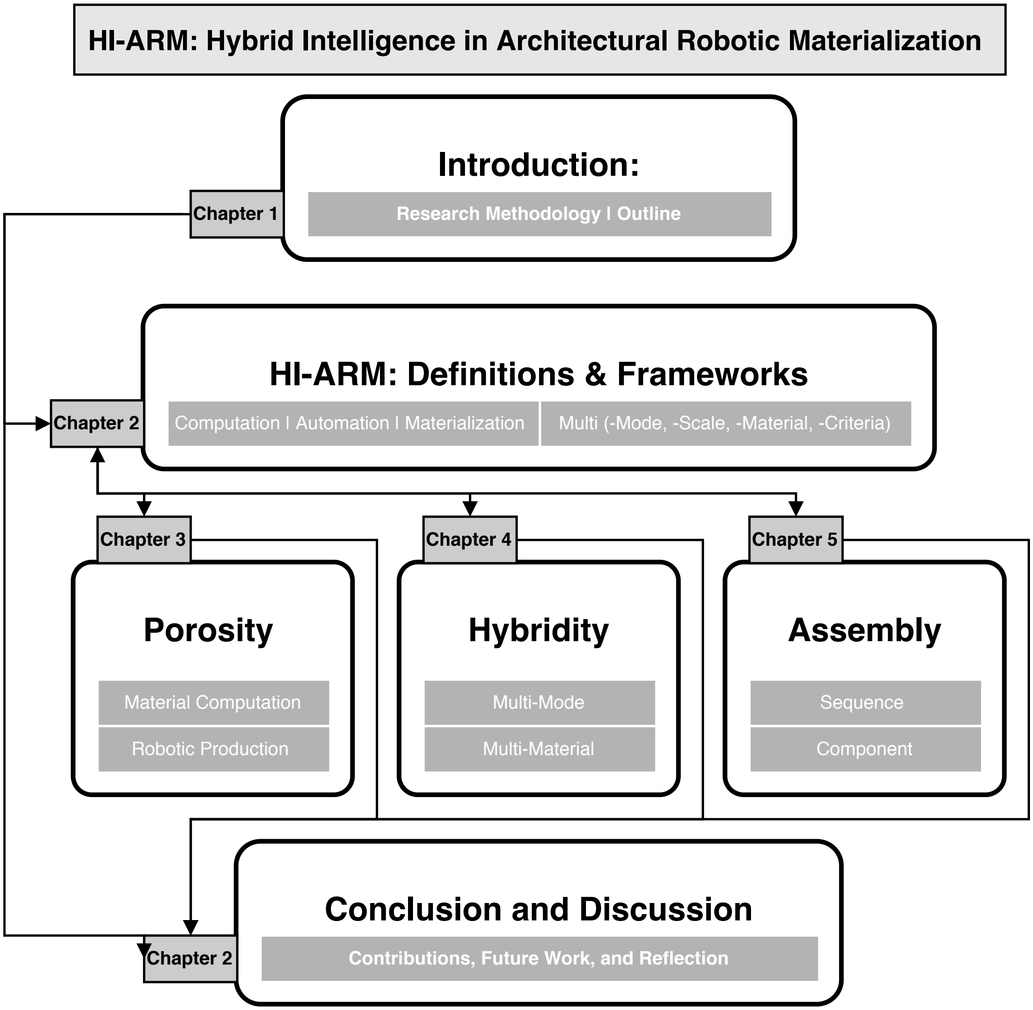


FIG. 1.1 HI-ARM research outline and structure.

1.7.2 Chapters Briefs

1.7.2.1 Chapter 1 Introduction

Besides introducing the research background, problems, objectives, scopes, methodology, few references to the literature are provided and discussed throughout this chapter. The deliverables and the research relevance are explained, and the outline introduces different ways of reading and using the book.

1.7.2.2 Chapter 2 HI-ARM: Definitions and Frameworks

The definitions in this chapter are presented by giving references to the literature and state-of-the-art, as well as providing short descriptions of different conducted experiments and case studies. These definitions are constructing a discourse that explains the key terminologies, concepts, and challenges of HI-ARM. The key topics are discussed in six clusters:

- Cluster 1: Design Systems, Computation and Automation
- Cluster 2: Topology and Geometry, Tectonic and Component
- Cluster 3: Digital-Physical Integration
- Cluster 4: Performance and Variation
- Cluster 5: Rationalization and Approximation versus Simplification
- Cluster 6: Interdisciplinarity and Industrial Revolutions

This chapter concludes with four HI-ARM Theoretical, Methodological, and Technological frameworks:

- Framework 1: Interdisciplinary Domains Interrelations Outlook
- Framework 2: Design-Material-Production Space
- Framework 3: Multi-Scale/Mode/Material/Criteria
- Framework 4: Porosity-Hybridity-Assembly Materialization Model

1.7.2.3 Chapter 3 Porosity: Computation and Production

Chapter three focuses on design computation and robotic production of porosity. Porosity in this work is concerned with the distribution of the matter and the ratio between mass and void in multiple architectural scales ranging from material to space. Two pilot projects are discussed in detail. The first case is on developing materially-informed and performance-driven design systems as well as design information exchange and topology optimization for efficient material distribution. Building upon the developed methodologies in the first case, the second project is on Robotic 3D printing of porous structures. In this case study, the process of developing custom-made additive manufacturing robotic design to production setup is discussed in detail.

1.7.2.4 Chapter 4 Hybridity: Multi-Mode and Multi-Material

Chapter four expand the definition of hybridity in integrated design-to-production systems. The main definition of hybridity in this work is set out as the topological, geometric, and physical compositions of multiple materials together. Moreover, in this dissertation, from the production and material processing point of view, hybridity refers to a combination of multiple methods of robotic production. Therefore, Multi-Mode robotic production systems plus computation and production of Multi-Materiality are discussed as two major topics related to the notion of hybridity. Multi-Mode case studies address the integration of different subtractive robotic manufacturing methods as well as compound subtractive-additive methods.

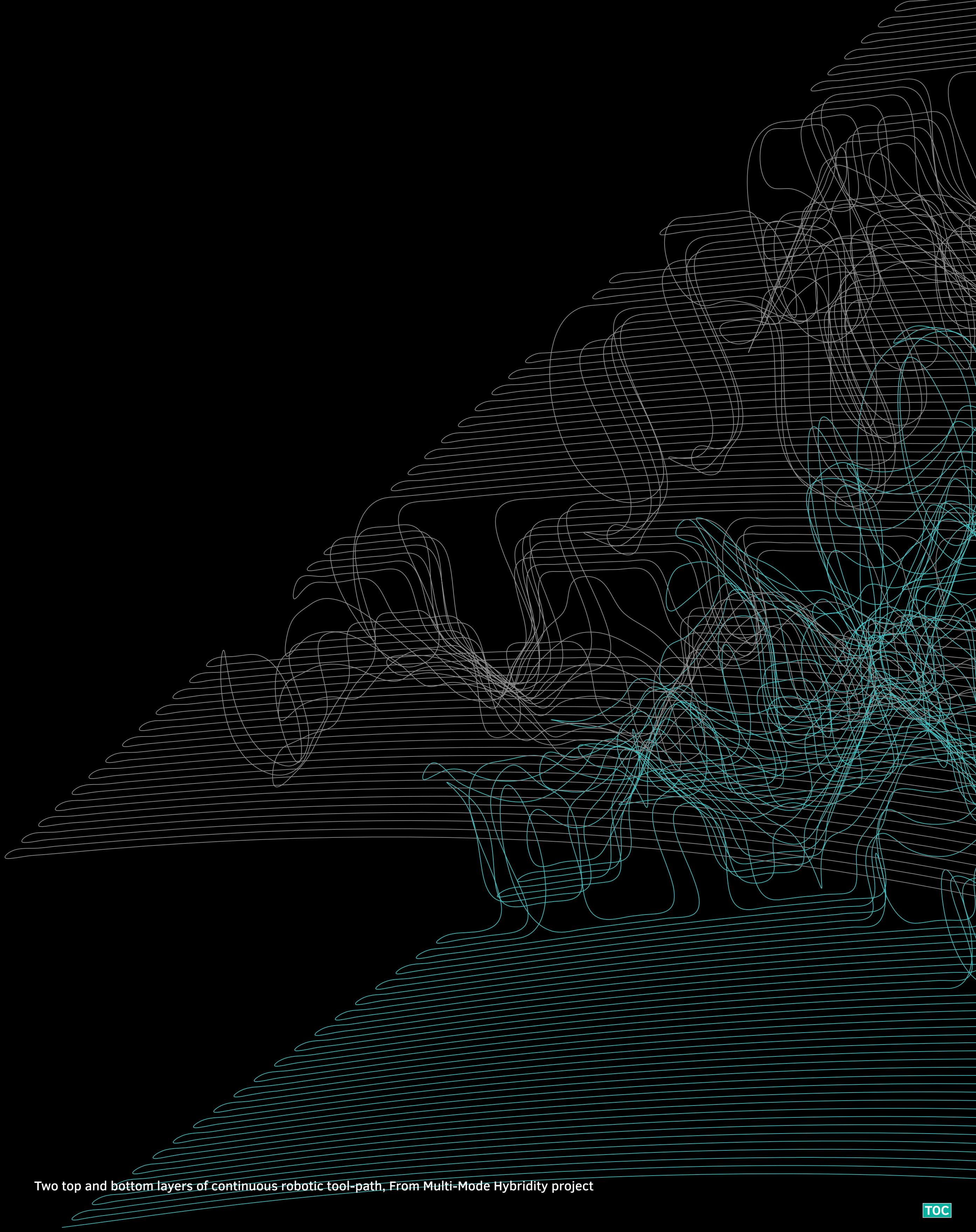
1.7.2.5 Chapter 5 Assembly: Component and Sequence

Chapter five is focused on assembly, and it is about going larger than the reachable dimensions of robotic production setups. Moreover, the factor of time in assembly processes is explored and discussed. Therefore, mapping and computing the sequence of assembly is addressed in the pilot projects in this chapter. Additionally, the robotic production of connections and component-based design is discussed and prototyped.

TOC

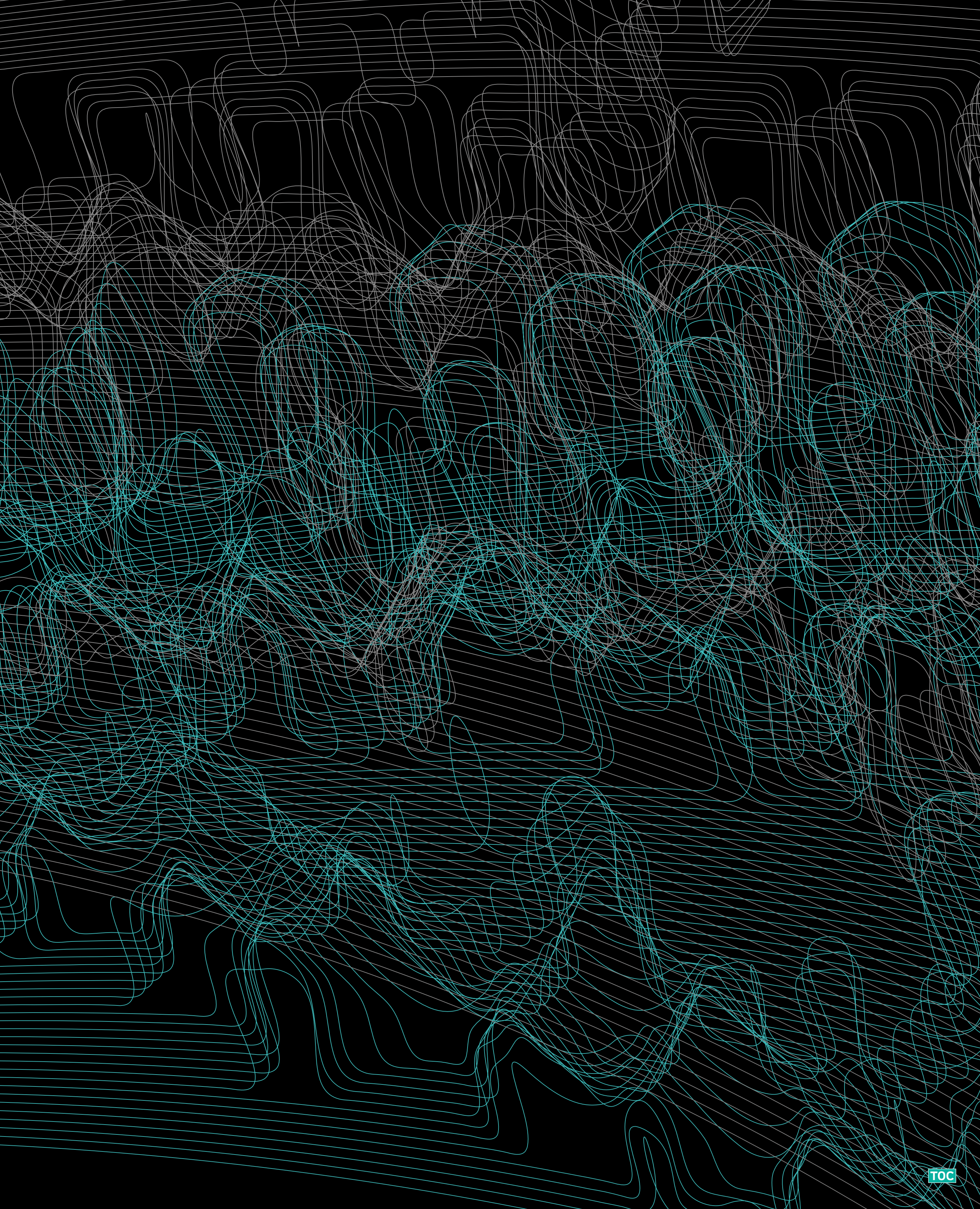
1.7.2.6 Chapter 6 Conclusion

Chapter six, as the concluding chapter, is structured in three parts. Firstly, a general conclusion is written where answers and reflections are addressing the research questions and objectives. The second part defines the contribution of the HI-ARM as a whole as well as case-specific contributions through the case studies of Porosity, Hybridity, and Assembly. In this part, guidelines and conclusions are discussed as computational design and robotic production intelligence for each of the three thematic topics. The last part of this chapter discusses the possible and potential future directions for multidisciplinary works in research, pedagogy, and practice in Architectural, Engineering, and Construction sectors at the Theoretical, Methodological, and Technological levels.



Two top and bottom layers of continuous robotic tool-path, From Multi-Mode Hybridity project

TOC



TOC

TOC

2 HI-ARM: Definitions and Frameworks

ABSTRACT

This chapter includes four parts: introduction, definitions, frameworks, and conclusion. The introduction briefly explains the title of this research: HI-ARM (Hybrid Intelligence in Architectural Robotic Materialization), and it positions the research within the broader context of the architecture discipline and the building industry. Definitions, in six clusters, establish interrelations between major concepts and terminologies, which are related to this research. Each cluster of definitions is discussed with references to the literature, as well as short descriptions on original experiments. The frameworks introduce conceptual and methodical workflows for Integrated Computational Design and Fabrication Intelligence for Multi-Mode Robotic Production of Multi-Scale and Multi-Material Systems. The conclusion sets the goals for the more extended case studies on Porosity, Hybridity, and Assembly in the following chapters.

KEYWORDS

HI-ARM, Design to Production Intelligence, Architectural Robotics, Hybrid Materialization, Integrated Design to Robotic Production, Computational Intelligence, Material Intelligence, Fabrication Intelligence.

2.1 Introduction

To position this research within a broader disciplinary context, we introduce the four main elements of this dissertation, which are included in the title: 1) Hybrid, 2) Intelligence, 3) Architectural Robotics, and 4) Materialization. While in this section, the descriptions are provided with no reference to the background or specific case studies, the next section elaborates on the key definitions by giving references to the state of the art and certain considerations and findings of the associated conducted experiments.

2.1.1 Hybrid

Hybrid in the context of this research is twofold: Hybrid Material Systems and Hybrid Building Processes. Firstly, in terms of material, hybrid refers to the integration of two or multiple sets of material entities or systems. Associated case studies of hybridity focus on computation and production of hybridity in architectural design through the developed design methods and robotic fabrication technologies. Secondly, hybridization of building processes refers to multi-mode production systems where two or multiple robotic fabrication methods are combined. Multi-mode robotic production processes in this research mainly involve hybrid subtractive and additive manufacturing techniques. Therefore, the hybrid is considered both as a noun or the product and as a verb or the process where hybridity is introduced as a materialization solution in design and building, and hybridization implies multi-mode processes in production.

To a broader extent, but yet related to the background, the body, and the conclusion of the work presented in this dissertation, hybridization may refer to other pairs such as Hybrid of Human and Machine in Design and building processes, Hybrid of Analogue and Digital in design workflows, Hybrid of Physical and Virtual in design to production systems.

2.1.2 Intelligence

Intelligence in this research mainly refers to two types: Design Intelligence and Production Intelligence. Design intelligence implies the systematic application of integrated computational design workflows for data-driven and performance-oriented architectural design solutions. Production intelligence implies the integration of programmable robotic fabrication routines into the integrated design workflow where automation and materialization inform the design through a series of iterative feedforward and feedback loops.

2.1.3 Architectural Robotics

Architectural Robotics refers to an interdisciplinary field in which creative application and innovative development of robotics in architecture are pursued. The main focus of this research is achieving materialization intelligence using integrated design to robotic production systems. However, this research positions itself in a larger context of two main categories of robotics in the built environment:

- Robotic production of the built environment
- The embedded operational robotic systems in the built environment

The background of the first category with the focus on production is discussed throughout this dissertation. Application of embedded operational systems in architecture and structures are addressed and examined in research and practice. Prototypical examples of these applications are framed and discussed under terms and concepts such as Interactive and Programmable architecture (Inter al. Oosterhuis and Lénárd 2002; Oosterhuis 2012) or Adaptive Structures (Senatore, Duffour, and Winslow 2018; Sobek and Teuffel 2001). Here, what connects the two categories is the programmability and flexibility of robots as customizable machines, which, if applied creatively and purposefully, may improve the built environment's quality and performance core body of the work presented in this dissertation mainly focuses on developing customized technologies and workflows using industrial robotic arms for creative, efficient, and effective production processes.

2.1.4 Materialization

Materialization in this research refers to both digital and physical processes in design. Digital materialization implies computational design techniques such as modeling, simulation, and optimization to incorporate materiality or physicality in the digital design environment. This incorporation may include material computation to inform the digital model with material properties, such as structural, environmental, and fabrication related data. Moreover, digital materialization may also refer to

TOC

the process of modeling and computation of geometric features such as surface tectonics or volumetric structures in a digital model. Materialization, as a physical process, involves off-site or on-site production, fabrication, and assembly. In specific to the context of this research, it includes programmed and customized robotic production methods which are integrated into the computational design workflows.

2.2 HI-ARM Definitions and Discourse

Following the brief introduction of the title, definitions are discussed and elaborated in six clusters by giving references to the literature and the state-of-the-art plus short descriptions of different conducted experiments and case studies related to each cluster. Here the goal is not to provide a thorough historical and theoretical background review for each cluster. Instead, we aim to establish an initial discourse together with references from inside and outside of the discipline as well as the key findings of the explorations. In other words, these clusters are essential concepts beyond terminologies, which are instrumental in achieving computational, material, and fabrication intelligence.

Moreover, further references to the state of the art and domain-specific projects are given in the porosity, hybridity, and assembly chapters. Therefore, while these clusters are interconnected, they can be read independently, and in non-linear order. Through these definitions, we aim to introduce and elaborate the key ideas and terms for the development of Integrated Computational Design and Fabrication Intelligence for Multi-Mode (Subtractive-Additive) Robotic Production of Multi-Scale Multi-Material Systems. Following these clusters, we then introduce HI-ARM frameworks as conceptual, analytical, and operational tools, which are tested, exemplified, and prototyped in the case studies.

2.2.1 Cluster 1: Design Systems, Computation and Automation

Advancements in information technologies and cybernetics, as well as open-source robotics and accessible automation, are introducing new possibilities for the application of systems thinking in architectural design practices and the building industry. Systems thinking allows for developing integrated design systems to achieve design, material, and fabrication intelligence through computation and automation. Such embedded intelligence in design thinking and computational design to production systems can be understood and implemented as an emerging form of Architectural Intelligence (Inter al. Steenson 2017; Yuan et al. 2019). However, implementing systemic thinking does not necessarily involve design intelligence nor does it guarantee quality. Still, it may partially facilitate these as the design process, specifically for a multifaceted discipline such as architecture, is not a linear phenomenon. In other words, other modes of thinking, such as critical thinking, imaginative thinking, or even common-sense decision-making based on experience, are needed. Therefore, hybrid modes of thinking are required next to developing and applying integrated design systems, with embedded computation and automation modules, which are robust, consistent, reliable, and even in some cases repeatable and to a certain degree plug-and-play.

Developing design systems relies on both holistic or top-down design information modeling to study and establish the composition of sub-systems as well as bottom-up experiments and observation of sub-systems. Moreover, it is essential to acknowledge that developing design systems in architectural design and production may go beyond specific computational design tools or software and automation techniques or hardware. Therefore, the precedent to systems thinking in architecture may not be limited to Computer-Aided Design and Computer-Aided Manufacturing, as we may see in the work of many architects and researchers such as in “Note on the Synthesis of Form” by Christophe Alexander in 1964. In this context, we might be able to go even way back in history and argue that the systemic approach to design has been an integral part of design practice when it comes to bridging the gaps between design, production, and building processes.

As an example of this claim, we can take the ancient craft of carpet weaving, maybe as old as human civilization, and put it next to Jacquard’s Loom Machine with programmable physical punch cards, invented in 1804, which then revolutionized the textile industry in the 19th century [2]. Beyond the fact that such innovations have led to the implementation of punch cards in early computers of the 20th century, it is remarkable to see how a complex production process, with a high degree of freedom in design (i.e., in patterns, textures, and colors), can be translated into a programmable system which automates a complex and delicate manual craft (FIG. 2.1).

FIG. 2.1 Top: Carpet weaving craft example from City of Kashan, Tradition goes back to at least 400-500 BCE; Middle: Jacquard's Loom Machine for Textile weaving, Lyon 1804; Bottom: 80 Column Computer Punch Card for IBM Computers, Mid 20th Century.

TOC

Implementing systems thinking in design, using different state of the art approaches in computational-design such as data-driven analysis and simulation, parametric modeling, and generative design, are all benefiting from the four fundamentals of problem-solving through computational thinking: Decomposition, Pattern Recognition, Abstraction, and Algorithm Design (Inter al. Denning and Tedre 2019; Wang 2017). In this research, we discuss two further components and characteristics of design systems, which are essential in the development of HI-ARM frameworks and the realization of the case studies:

1. Determinism and Emergence in Design Systems
2. Feedforward and Feedback Loops

2.2.1.1 Deterministic, Stochastic and Multi-layered Models

Considering the nonlinearity and dynamics of architectural design processes, it is essential to acknowledge the differences between various types of computational design systems and their characteristics.

In terms of predictability, we can distinguish two types of models: deterministic and stochastic. In deterministic models, we can fully predict or determine the outcome by knowing the process. In other words, the same sets of input in the same condition result in a known or fully predictable output, all times with no deviation. While in stochastic models, there is a certain level of randomness, unpredictability, or emergent behavior in more advanced cases. In the context of this research, we can argue that most of the parametric design models can be categorized as deterministic. In contrast, other techniques such as generative models like the ones which are based on complex adaptive systems (CAS) (Holland 2006; Holland 2016) may introduce a certain level of unpredictability or emergent behavior. Again here, the point is not about one being better or more complete than the other. It is more about the fact that distinguishing these differences is essential in the successful development of an integrated design-to-production system.

Beyond the degree of predictability, it is essential to leverage interconnections between different architectural design layers and building scales in a coherent system. As it is leveraged by the frameworks and prototyped in the case studies, this multi-scalarity introduces flexibility and a certain level of unpredictability, which then needs to be considered, mapped, and controlled. Such multi-layer and multi-scale interdependencies allow for zooming out and zooming in, helping the system avoid having isolated sub-systems.

TOC

2.2.1.2 Feedforward, Process and Feedback

Processes plus their corresponding input and output data sets are the basis of a design system. Developing a design-to-production system relies on both feedforward and feedback loops. Through feedback loops, we can observe the output and adjust the process as required, while with feedforward loops, we monitor the input variation and adjust the process to compensate. These observations and monitoring can be automated, semi-automated, or be applied through human intelligence, i.e., designer, craftsman, and user.

Additionally, it is essential to acknowledge that we need to consider the non-linearities in the design throughout the process of the development of a design system. An implicit explanation of such non-linearity can be found in the description of feedback loops in biological and physical systems as Manuel De Landa (2000) elaborates:

“When a system switches from one stable state to another (at a critical point called bifurcation), minor fluctuations may play a crucial role in deciding the outcome. Thus, when we study a given physical system, we need to know the specific nature of the fluctuations that have been present at each of its bifurcations; in other words, we need to know its history to understand its current dynamical state.

And what is true of physical systems is all the more true of biological ones. attractors and bifurcations are features of any system in which the dynamic are not only far from equilibrium but also nonlinear, that is, in which there are strong mutual interactions (or feedback) between components.“

2.2.2 Cluster 2: Topology and Geometry, Tectonic and Component

Development in digital design interfaces has enabled the modeling and representation of complex forms. Beyond the visible complexity, it is essential to acknowledge the difference between topological and geometric modeling and the potential role each may play in digital design to robotic production systems. In other words, design computation and robotic production can lead to new ways of approaching topology and geometry in contemporary design materialization practices. Moreover, at building scale and in architectural applications, these new approaches result in an emphasis on the notions of tectonic and component. In this context, we further elaborate on the two following topics:

TOC

1 Topology of Fabrication
2 Component-Based Architecture

2.2.2.1 Topology of Fabrication: Tectonics and Families of Objects

In mathematics, topology is concerned with the properties of a geometric object that are preserved under continuous deformations, such as stretching, twisting, crumpling, and bending, but not tearing or gluing (Inter al. Edelsbrunner and Harer 2010; Zomorodian 2012; Pottmann et al. 2007). In contemporary architectural discourses, topological thinking can be traced back to notions and movements such as folding architecture (Lynn 1993), animate from (Lynn 1999), or extending the concept of Objective by Gilles Deleuze to Projectile by Bernard Cache (Perrella and Cache 2015; Cache 2010). From a digital 3D modeling point of view, the topology of a geometric digital object is defined with the quantities, properties, and correlation between points or vertices, lines or curves, planes, or surfaces.

Additionally, in fabrication processes, the topology of fabrication can refer to how the tooling and material processing are defined so that the production process is systematically repeatable and programmable with ranges of possibilities for variations or flexibility. While the bases of the topology of geometry are points, edges, curves, surfaces, etc., the topology of fabrication can be defined with sets of Cartesian plains associated with Tool-central points, working object reference points, and Robot operating reference points. In such a definition, each plane holds the coordination information, which in addition to the six required vector values for any given point in space (XYZ coordinates and Rx Ry Rz rotations), can have the fourth dimension, which is Time.

In various scales, Incorporating the topology of fabrication as an underlying driver or logic into the design-to-production systems leads to new definitions for architectural materiality and building processes.

In micro or material scale, the geometric qualities of design surfaces and volumes can be defined directly by how we set and control the topology of fabrication. For instance, the surface tectonics qualities can be achieved directly by altering the orientations and sequences in tooling in different fabrication and production processes such as milling, printing, and casting (FIG .2.2 & FIG. 2.3).

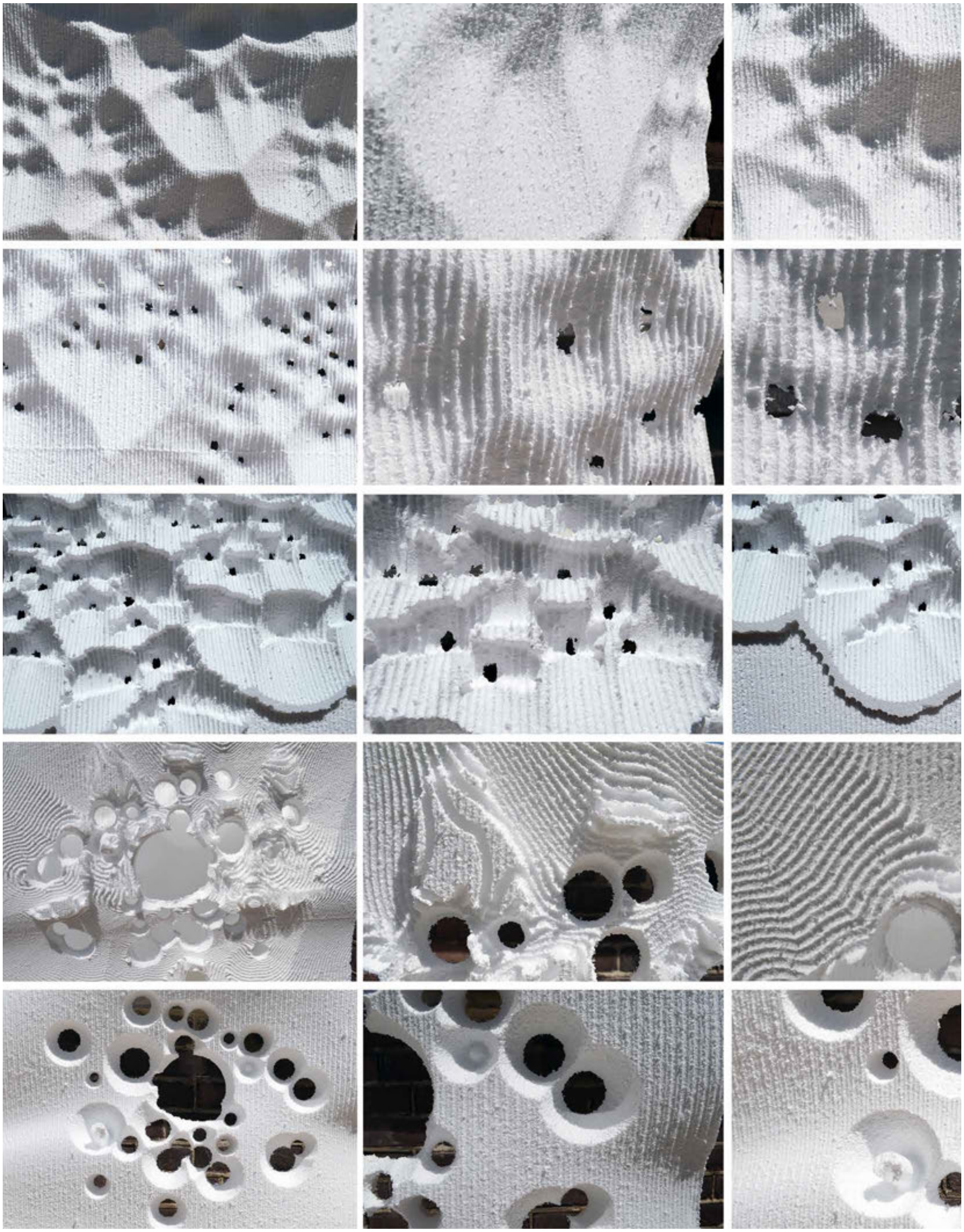


FIG. 2.2 Example of how the topology of fabrication affects the geometric qualities: surface tectonics and porosity exploration using Robotic 3D Milling.

TOC

FIG. 2.3 Example of how the topology of fabrication affects the geometric qualities, Left: A cast concrete element with linear traces of Robotic Hot Wire Cutting tool on the surface; Right: Glazed Robotically 3D printed prototype with layered finishing surface quality.

The design and production at meso-scale, or the scale that we commonly referred in practice and industry as building blocks and elements, can be radically changed and redefined using integrated design to production systems. Such changes can lead to what we can identify as new families of architectural components with embedded fabrication intelligence. Such intelligence can be achieved by incorporating the topology of fabrication within the design-to-production workflows and implementing production simulation techniques such as off-line kinematics simulation of the robotic setup (FIG. 2.4).

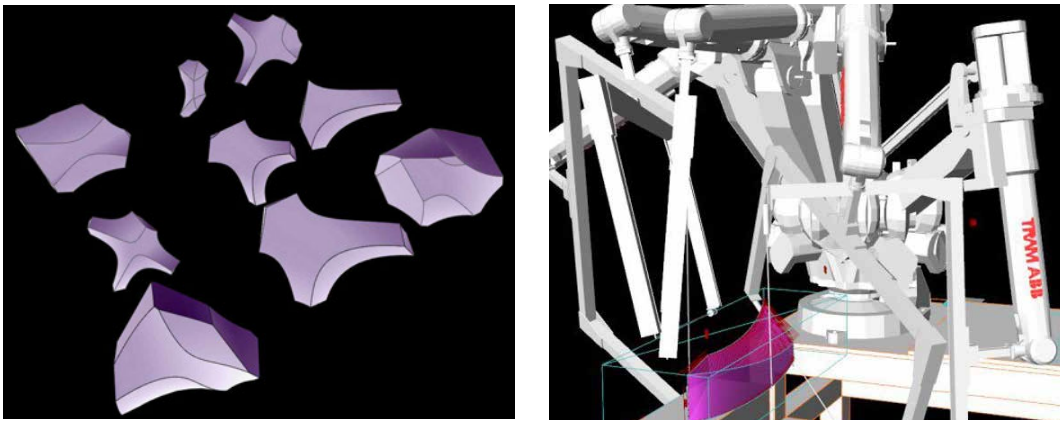


FIG. 2.4 Left: families of objects with the identical topology of fabrication as all components are the result of Boolean intersection operation of two twisted boxes with similar topology but varying in size, orientation, and the twisting angle; Right: A kinematic simulation of robotic production of a component with six sides to be cut.

The topology of both geometry and fabrication can be envisioned with different levels of abstraction. For instance, consider a twisted triangular prism with five developable surfaces. Such geometry is producible with five cuts using a line-based tool or robotic end-effector such as a bandsaw or a wire cutter. Applying another level of abstraction, we can consider a twisted triangular prism as an 'I' or a rope with two ends. All deformations of such topology are identical; hence we can design a generic fabrication and tooling strategy that allows for the systematic production of a range of deformations rather than providing ad-hoc solutions for each deformation.

Here, it is essential to mention that setting a generic solution that defines the topology of fabrication will not guarantee the constructability of all range of variations as there are several other factors involved, such as the design of the production setup and material affordances. On the one hand, implementing various abstraction levels allows for systematic and creative exploration in the design process. On the other hand, it results in the embodiment of fabrication intelligence as design outcome or product. For instance, back to the example of twisted triangular prism abstracted as an 'I', we can approach the design-to-production of more complex topologies such as 'V' and 'Y' with the same triangular profile and explore the constructability of a broader range of families of building components (FIG. 2.5 & FIG. 2.6).

FIG. 2.5 Example of topology of fabrication and families of components: Robotically produced branching prototype with three and four branching node components.

FIG. 2.6 An example of defining the topology of geometry and fabrication with different levels of abstraction that informs the exploration of design to production space and leads to computational and fabrication intelligence. Top: Families of robotically producible components with I and V topologies, Bottom: Robotic Hot Wire Cutting of a component with integrated connections.

TOC

2.2.2.2 Component-Based Architecture: Integration of Bone, Flesh, and Skin

Throughout the past and modern history of architecture and building construction, several proposed or prototyped models directly or indirectly suggest different materialization paradigms for the macro scale. In this context, the macro scale refers to the whole body of architecture or building with a clear strategy on how different pieces are assembled.

Before industrial 3rd and 4th revolutions, models for assembly in architecture were very dependent on the type of source material. Meaning that the inherent properties and characteristics of the material, on the one hand, and available and affordable approaches for accessing, processing, and tooling those materials, on the other, are influencing the way assembly or building models are defined. They frame materialization at macro scale defining the building's body and space as a whole. An example of such influence can be recognized if we compare the subtracting of the spaces out in the mountains like in a place in Kandovan to adding the stones next to each other in Stonehenge prehistoric monument (FIG. 2.7). While the subtractive one, in terms of geometry, usually results in a continuous mesh topology that defines the boundaries of the space and the building, the additive approach is constructed of discrete elements such as beams, columns, or blocks.

FIG. 2.7 Subtractive vs. Additive models of macro-scale materialization approaches in building processes, Left: Kandovan Village in North Iran as a subtractive example, Right: Stonehenge in England as an additive case.

Moreover, the model of assembly depends on how the correlations are defined between different sub-systems in architectural design and the body of the building. Architectural sub-systems can be seen as several layers of materiality in different scales, which may correspond to different desires, requirements, and performance criteria such as structural, functional, ornamental, environmental, etc. In day-to-day practice and state-of-the-art, these layers might be referred to as structure, façade, finishing, envelope, etc.

In the contemporary history of architecture, we can find several prototypical models when it comes to the interrelations between different building subsystems and material assembly. Here, we discuss three examples (FIG. 2.8):

1. The diagram of Dom-Ino house designed in 1914-15 by Le Corbusier
2. The Oblique Function in the format of series of sketches and studies by Claude Parent and Paul Virilio proposed in the ’60s
3. The Endless house by Friedrick John Kiesler which is prototyped in a maquette form in 1958–59

TOC

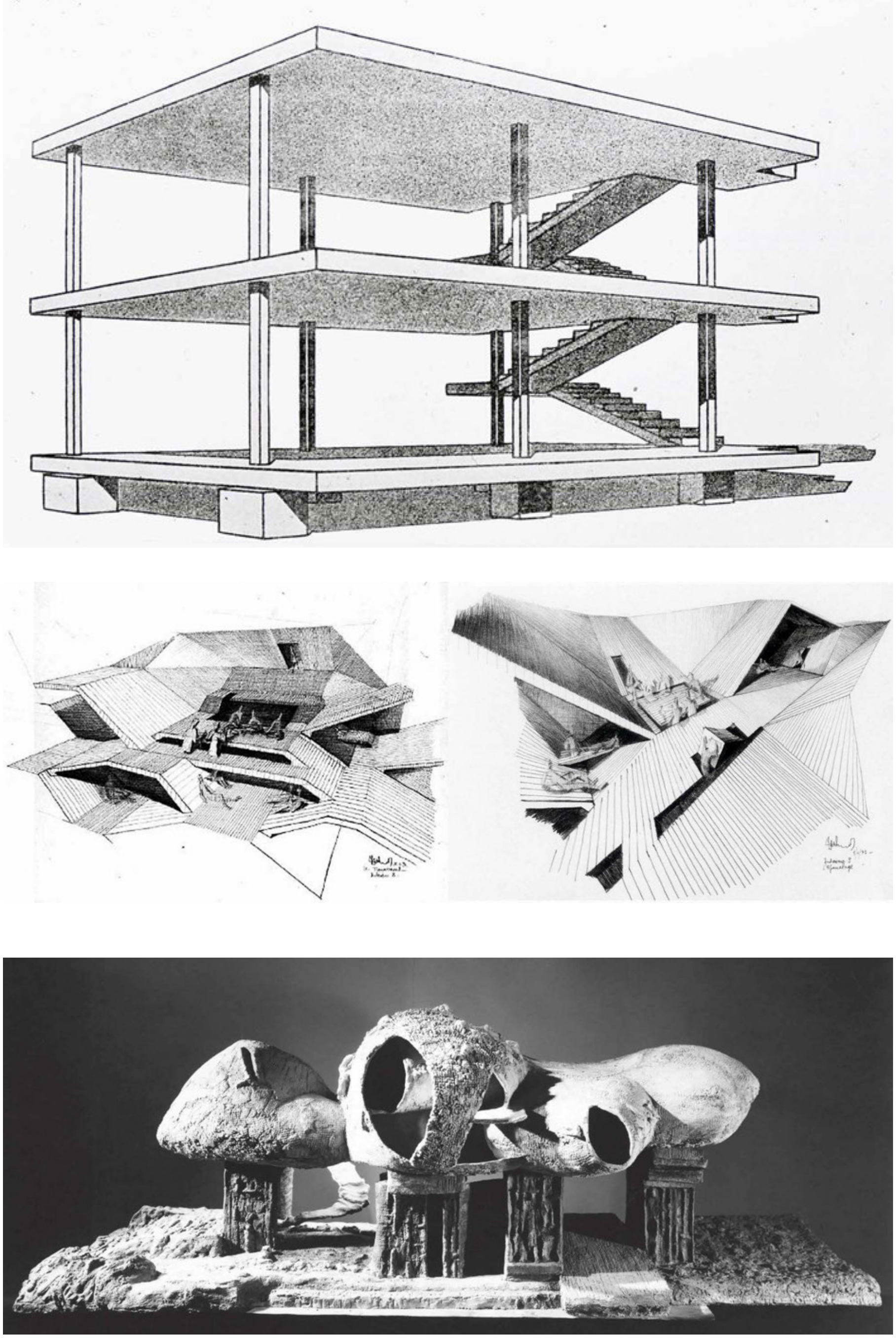


FIG. 2.8 Three prototypical models of macro-scale materialization in 20th CE, Top: Dom-Ino House; Middle: The Oblique Function; Bottom: Endless House.

In Dom-Ino house, we can identify the intended segregation of structure, circulation, floor, and façade. While a built example of such an idea is clearly manifested in buildings such as Bauhaus School in Dessau, designed by Walter Gropius and built in 1919, up until today, such models are widely adopted and used in many if not most of the projects globally, in various scales and functions in different contexts. They are sometimes, if not most of the time, are ignoring dissimilarities and diversities in available material resources and regional architectural cultures.

The second model, The Oblique Function, conceptually proposes a model where there is no distinction between structural elements, floors, and roofs. The integration between architectural elements is achieved through a geometric solution by rotating the elements avoiding the dominant 90-degree angles in design and construction. Realized example of such models can be seen in the Yokohama Terminal building designed by Farshid Mousavi and Alejandra Zaerao Polo, FOA office 2002, where the roofs, structures, and floors are intertwined.

As it is exemplified in The Endless House, the third category extends the idea of continuity even further by introducing continuous surfaces that seamlessly are defining the boundary of the space and the body of the building. This category is regularly discussed as blobby architecture as it is widely referred to as the first digital turn as opposed to the second (Carpo 2012; Carpo 2017). While this model is not fully implemented in many buildings, there are several pavilion and research scale examples of such model, especially with the advent and proliferation of additive manufacturing.

Bearing these references in mind, it is clear that there are different possible approaches to macro-scale materialization and building assembly. The applicability, feasibility, and efficiency of these models depend on various parameters. In this context, emerging computational design approaches, robotic fabrication, and assembly automation can significantly change these models. While here we do not advocate this idea that there is one best or universal solution in terms of macro-scale materialization and assembly, we are hypothesizing that a component-based architecture is one of the viable solutions.

Moreover, if we use the anatomy of the human body as a reference, by incorporating computational and fabrication intelligence, we are able to blur the boundaries between bones, flesh, and skin of architecture. Therefore, efforts and experiments that study and prototype such integration represent an area of research and development. However, again depending on the type of technique or material we use, separately studying and materializing an isolated building element such as a column will still be relevant to this research in particular as well as the practice and the industry on a larger scale in general. Such investigations may not radically change the assembly and materialization model, but they may lay down infrastructures advancement of technology in the industry. Therefore, this research finds both practices valuable while acknowledging the fundamental differences between the two.

2.2.3 Cluster 3: Digital-Physical Integration

Programmability and flexibility of robotic systems in architectural production and operation result in establishing connections and dynamic loops between the digital and the physical. Digitality, in this definition, refers to digital interfaces with all analytical, synthetical, modeling, and simulation capacities. Physicality refers to physical mediums that include materials and production, on the one hand, and operation or interaction that may consist of sensors and actuators.

Creatively and actively establishing bidirectional connections, feedforward, and feedback loops between the digital and the physical are key in designing and developing integrated design-to-production systems. These interrelations between the digital and the physical redefine materialization and production processes. In this research, several reasons can be enumerated for such integrations. Here we refer to the following three points:

1. Fabrication Intelligence
2. Immediate Materialization
3. Mass Customization

2.2.3.1 Fabrication Intelligence; Constraint and Potentialities

Fabrication intelligence is achievable by mapping the constraint and potentialities of production methods. Establishing connections between digital design interfaces and physical robotic production setups allows for the incorporation of fabrication constraints and potentialities within an integrated computational design to robotic production workflow. Facilitating such integration can be explored beyond a specific building material, i.e., robotic light 3D printing, to study the motion and pattern of material deposition in space (FIG. 2.9). In this process, both physicalization-of-the-digital and digitalization-of-the-physical are constructive. Physicalization-of-the-digital can be achieved through simulation techniques such as constraint-based modeling methods that use physics-based simulation, as well as kinematic simulation of the robotic production workflows with its constraints such as movements and

TOC

collisions. Digitalization-of-the-physical can be implemented by integrating scanners, sensors, and actuators within the production space as feedback from the physical to the digital.

FIG. 2.9 Top: Establishing connections between the digital and the physical; Bottom: Robotic Light Printing with color changing and blinking pattern according to the digital model.

2.2.3.2 Immediate Materialization: Redefining Digital Representation

Digital-physical bidirectional connections facilitate instant or immediate materialization. From an artistic expression point of view, immediate materialization can result in creative modes of translating different modes of imagination, expression, representation, and physical manifestation (Inter al. Lénárd 2019; Friedrich 2020). An example of such immediate materialization can be seen in the Sculpture City by Ilona Lénárd, Kas Oosterhuis and Menno Rubbens in 1994 (FIG. 2.10). In this project, the design-to-production workflow allows for translating 2D artistic abstract drawings to 3D robotically carve sculptures. Moreover, immediate materialization empowered by digital design to robotic fabrication facilitates data-driven art and production.

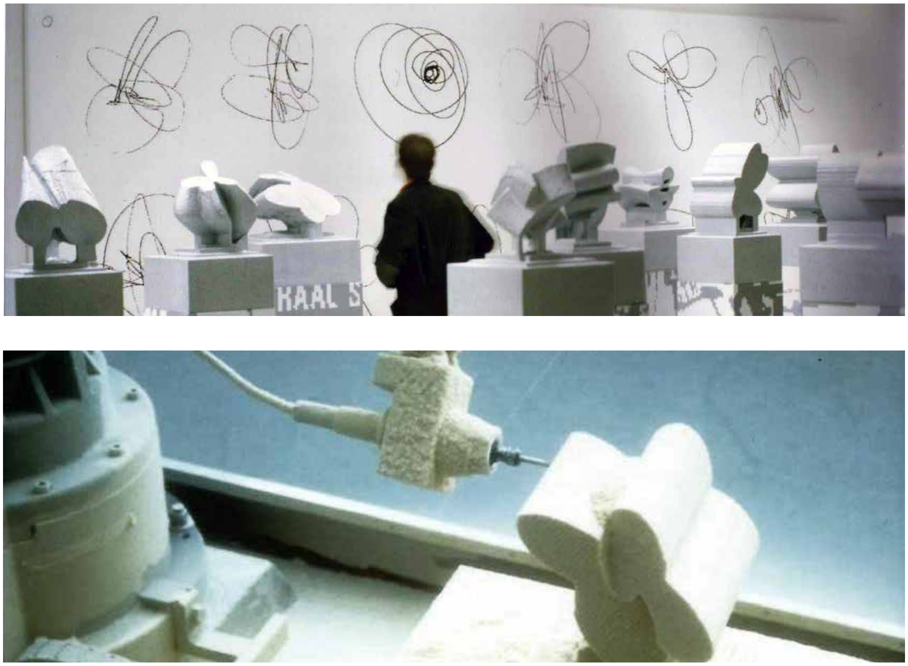


FIG. 2.10 Sculpture City, Ilona Lénárd, Kas Oosterhuis, and Menno Rubbens at RAM Gallery.

In the scale of architectural applications, immediate materialization can be used as experimental workflows and practices with certain levels of abrasion in order to study specific aspects of materiality such as tectonics and pattern in 2D and 3D (FIG. 2.11). Moreover, the direct connection between the digital and physical redefines the role of architectural design and documentation. The digital model is not merely a one-to-one copied version of the physical object. Instead, it may hold fabrication or materialization data such as a tooling path and sequence.

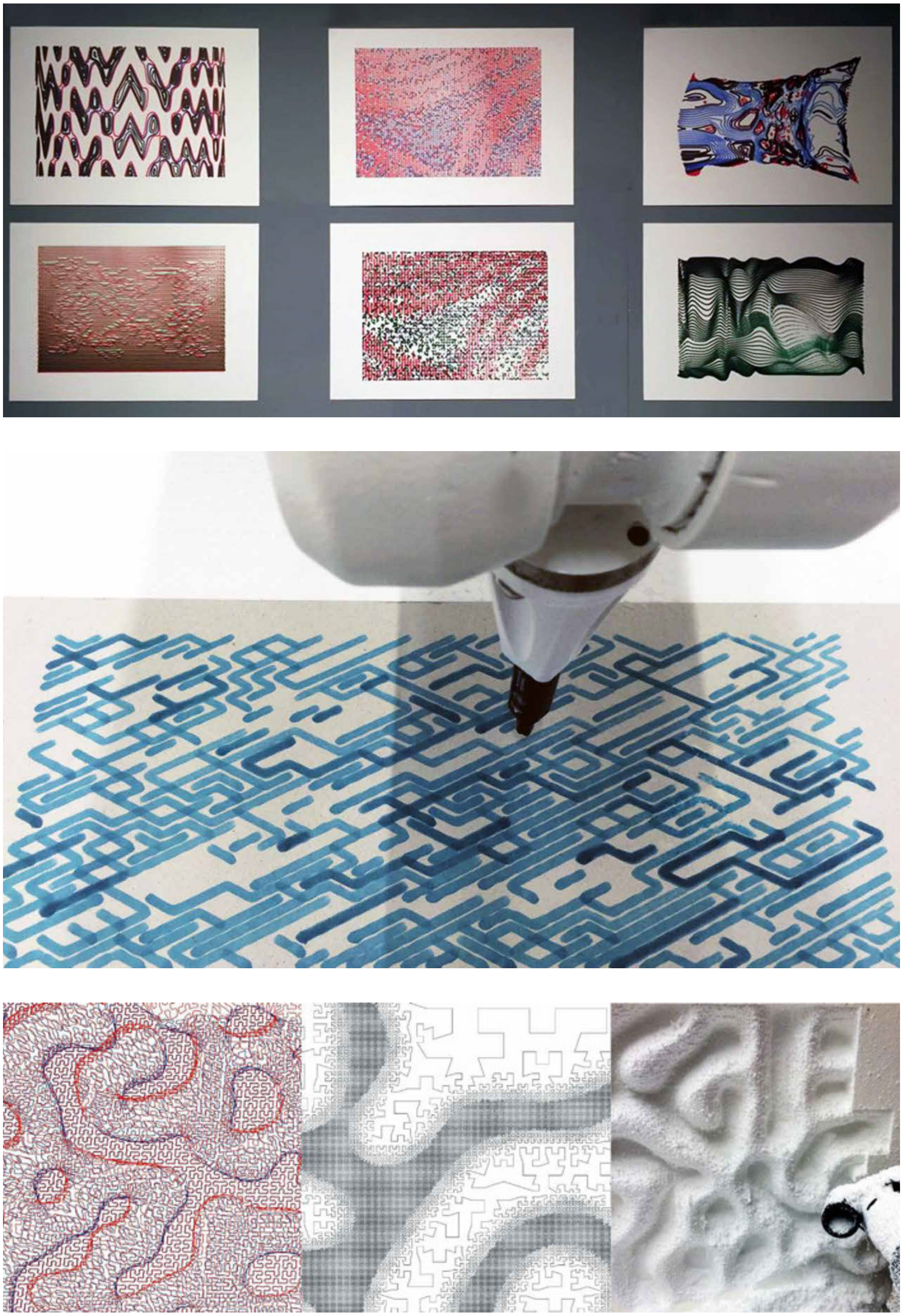


FIG. 2.11 Series of 2D and 3D studies using immediate materialization strategies for architectural applications such as porosity, material hybridity, and surface tectonics based on parametrically generated robotic toolpaths.

TOC

2.2.3.3 Mass Customization: On-Demand Production and Informed Resolution

Programmability and customizability of robotic production and operation systems allow for a high level of on-demand mass customization that can adapt to various requirements with different performance criteria in different contexts. Mass-customization can be achieved or deployed on various scales ranging from large-scale eco-systems to spatial scale configurations. A conceptual exemplar of such a programmable space and building system can be seen in the Architecture Machine group's installation in 1970, where a three-axis robot is changing the configurations of the stacked wooden cubes for imaginary habitats, in this case, mice (FIG. 2.12). Further, the recent implementation of automation in construction facilitates the on-demand design and mass customization at macro or building to meso or component scales that incorporate structural, environmental, and functional requirements such as joints, insulations, and integrated furniture. Within a similar framework, larger scales such as urban spaces can also be an area for innovative application of mass-customization and participatory design empowered by digitalization and robotization (Inter al. Del Signore and Riether 2018; Tsui et al. 2021).

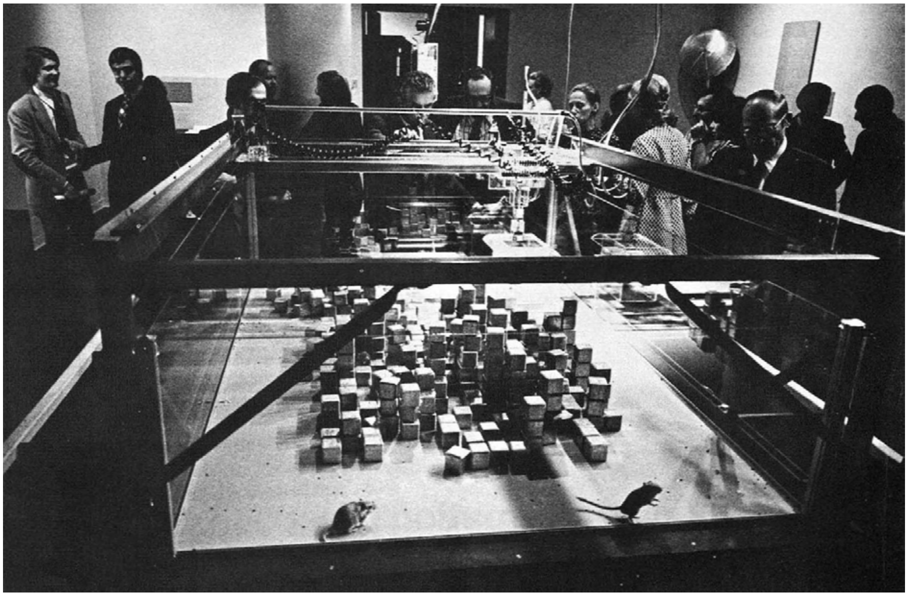


FIG. 2.12 SEEK, Installation by MIT Architecture Machine Group, Nicholas Negroponte, 1970.

Mass-customization is also achievable at a higher level of resolution by closing the gaps between the digital and the physical. Hence 2D or 3D engineered material design is realizable by developing customized design-to-production workflows which are operating at higher resolutions different robotic manufacturing techniques such as high-resolution milling and robotic 3D printing. (FIG. 2.13).

FIG. 2.13 Series of Robotic 3D Printing experiments studying different levels resolution for material deposition.

2.2.4 Cluster 4: Performance and Variation

Performance measurement, assessment, and evaluation of the digital models, physical prototypes, building products, and environments are essential parts of integrated design-to-production systems. We can think of various methods for pre-, concurrent- and post-evaluation of the design performance in design-to-production processes. While this research is not about providing and exploring a comprehensive taxonomy of performance-driven design, in relation to the goals and context of this research, the following three topics are central to the developed and implemented methods and frameworks in the case studies:

1. Design Exploration
2. Performance Criteria
3. Multi-Scalar Variation

2.2.4.1 Design Exploration: Sort, Search, Select

Regardless of the design methods and tools, a combination of synthetic and analytical routines and sub-procedures are required in a dynamic design process. Such methods can be integral parts of a parametric or generative system where through sorting, if-then structures, simulation, and optimization with specific criteria, the performance of a series of design instances or alternatives are measured to be then assessed or evaluated.

In this context, it is crucial to be aware of the type of computational design system in terms of when and how the performance evaluation can be applied during the design-to-materialization process. The assessment can be facilitated with linear post-analysis through sorting, ranking, simulation, optimization, and selecting or through more complex methods such as using of various types of Artificial Intelligence and generative design methods such as recursive methods with embedded if-then structures or complex adaptive systems like agent-based models (FIG. 2.14).

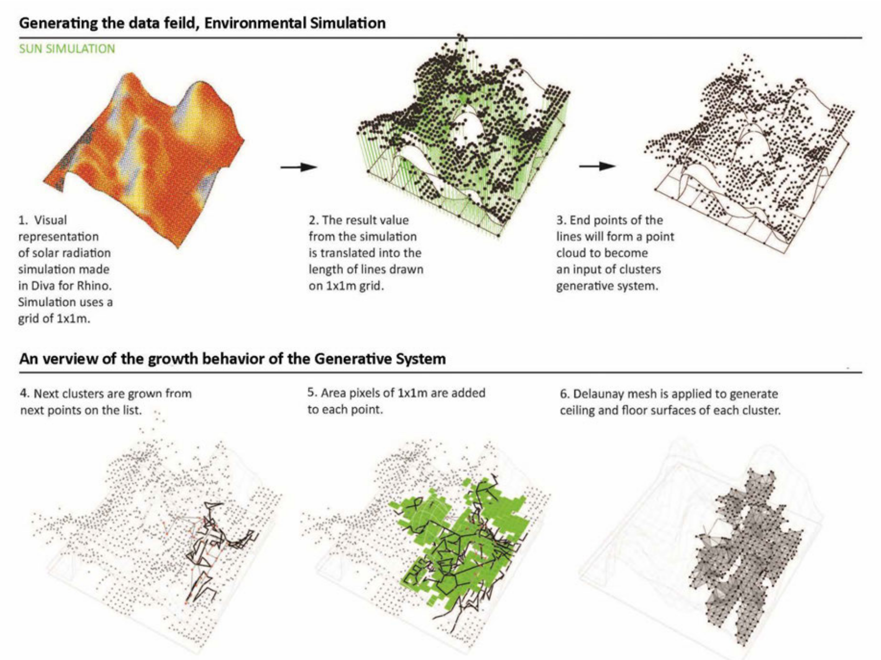


FIG. 2.14 Diagrammatic snapshots illustrating the growth of a generative system within an informed point cloud (M.Sc.3 studio Climatic Ecologies 2013), The point cloud is informed with multiple simulations (in this case, solar radiation analysis for different seasons).

In an integrated design-to-production process, we may implement a combination of various tools and techniques for performance measurement and evaluation. Here, it is important to establish and define the correlations between different retrieved and processed data sets that each may correspond to different measures and design objectives. Therefore, super-impositions and correlations between multiple layers of data such as function, structure, environment, and fabrication all together construct the backbones of data-driven design processes (FIG. 2.15).

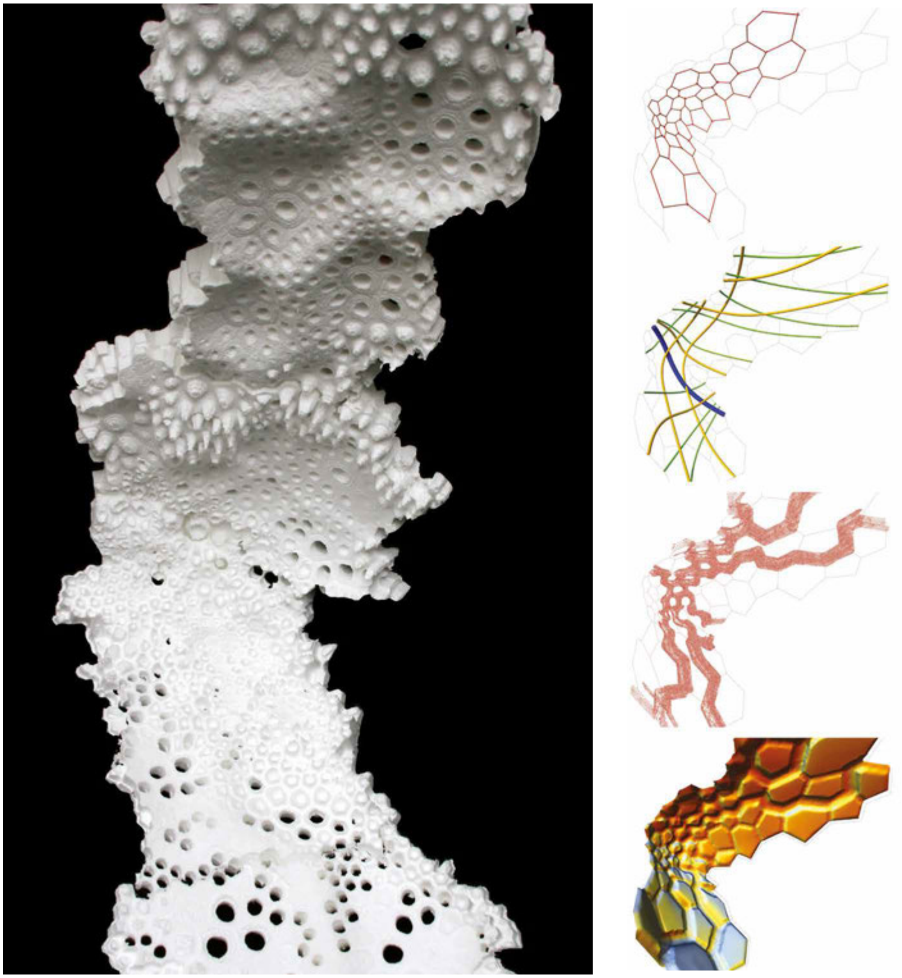


FIG. 2.15 Porous Assembly, Left: one-to-one mock-up of a section of the workshop project; Right: Multiple layers of data each corresponding to different performance measurement and criteria that all together inform the design locally at the scale of each cell and globally at the scale of components and assembly as well as the overall building envelope scale.

TOC

2.2.4.2 Multi-Scalar Variation: Modeling, Computation, and Production

In multiple scales, built environments and architectural spaces can be perceived and modeled as heterogeneous systems, which means that different requirements and properties might be needed in different coordinates within the space or void and the material body or the mass of the built environment. Simultaneously, multiple users of space might have various behaviors that will add to the heterogeneity of the system. The physical manifestation of such heterogeneous systems can be translated into topological and geometric variations in multiple scales.

Examples of purposefully benefiting from variation in architecture may go beyond the design and production techniques as we can find the precedents of such design intelligence through variation in buildings built prior to the advent of information technologies and digital fabrication. For instance, variation in the dimensions and shapes of cavities in The Music Hall space in Ali-Qapu in Isfahan (FIG. 2.16),1597 CE, result in a better acoustic performance of the scape as differentiation in depth, size, and shapes of the cavities correspond to different sound frequencies (Inter al. Hensel 2008; Azad 2012).

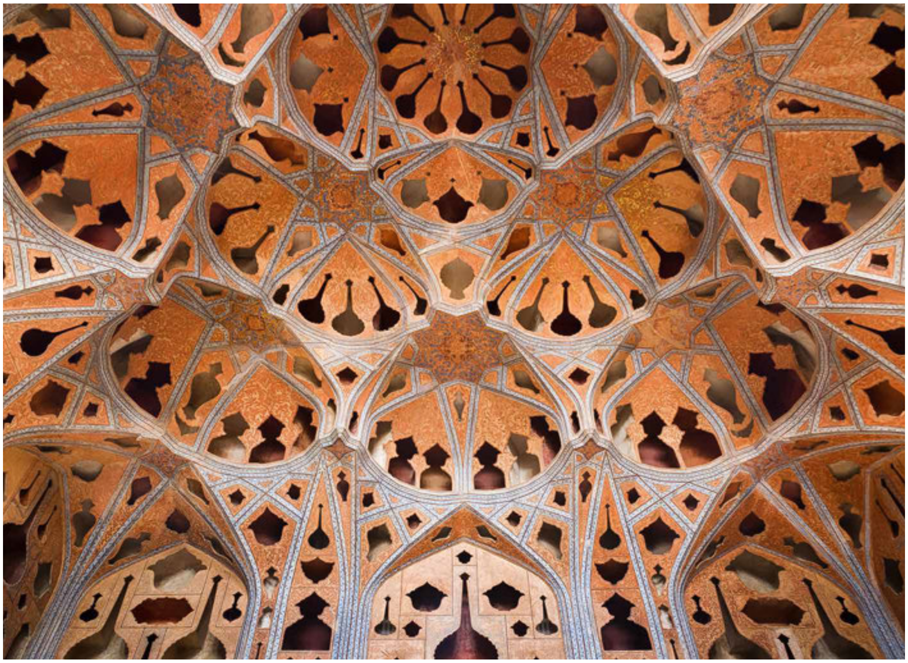


FIG. 2.16 Ali-Qapu, The Music Hall, Isfahan, 1597; Variations in size, depth, and shape of the cavities result in a better acoustic performance of the space.

Modeling and computation of variation can be continuous, i.e., a sine-curve graph with changing wave magnitude, or discontinuous, i.e., a free form surface discretized with voxels in varying sizes. Moreover, facilitating the systemic production of variation using digital fabrication and robotic production introduces new possibilities of benefiting from the complex yet buildable details and forms. In this context, revisiting different material systems to test and explore producible variation becomes a significant area for experimental research and development. An example of such an approach can be seen in a series of conducted experiments using incremental forming of flat aluminum sheets into free-formed surfaces. In these experiments, the differentiation in the depth of forming and surface engravings together improve the stiffness of the material (FIG 2.17).

FIG. 2.17 Incremental Sheet Forming of 1mm thick aluminum to free-formed surfaces with embedded engraves to increase and control stiffness; Result of experiments in a design-to-production studio.

2.2.4.3 Performance Criteria: Quantitative, Qualitative, and Mixed

Making the production of variation and complexity affordable allows us to explore a wider range of buildable design solutions that could meet the target performance criteria. In multiple scales for different performance measurements, these criteria can be quantitative or qualitative. Quantitative criteria can usually be explained and measured with quantitative data such as dimensions and forces, while qualitative criteria are mostly descriptive, which can be observed but are not directly measurable. In the built environment and architectural design, mapping solutions for both types of quantitative and qualitative criteria is required. Therefore, the parameterization process in an integrated design-to-production system may need to consider mapping various types of performance criteria, which are sometimes not measurable in the first place. While evaluation of a design considering the quantitative criteria such as structural stability might be more straightforward and easier to measure digitally, the qualitative criteria, for instance, flexibility and softness/hardness of finish material, might require an actual physical test or one to one feedback by the user (FIG. 2.18).

FIG. 2.18 Left: Undulating Cantilevered Brick Wall in Estación Atlántida, 1960, Uruguay, Eladio Dieste; Right: NJ-2, Rounds: Equal Weight, Unequal Measure, Rotate by artist Richard Serra; The curvature of the wall and variation in the horizontal section result in stability of the building and the large-scale sculpture.

Closing the gaps between digital design interfaces and programmable production techniques allows for a more dynamic and systemic way of measuring and evaluating quantitative and qualitative performance criteria of building systems and components. On the one hand, immediate materialization and prototyping complement the simulation routines, which are implemented with specific abstraction levels. On the other hand, a series of prototypes can be directly further evaluated using empirical methods, observation, physical tests, and direct feedback by the users (FIG. 2.19).

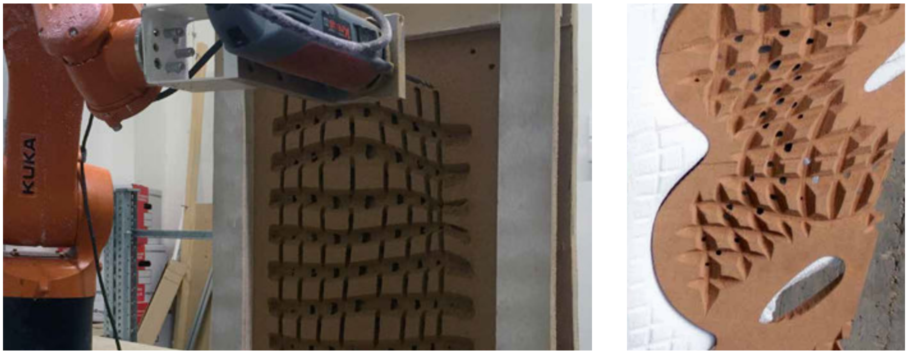


FIG. 2.19 Hybrid Assembly, The flexibility of the prototype is studied through prototyping in combination with the digital model that simulates the bending process of the 2D material into the desired 3D free form surface.

2.2.5 Cluster 5: Rationalization and Approximation versus Simplification

Design and architecture are multifaceted phenomena that are not explainable and assessable using merely measurable criteria. For instance, there might be a cultural reason or a societal value supporting the production or restoration of a very complex ornament in a building, which might require enormous digital fabrication and manual craft effort. Therefore, rationalization in broader disciplinary contexts does not equal less embodied energy required to design and materialize a building artifact. However, we may argue efficiency in the way we exploit our material and energy resources itself is a culture in architectural design and building processes. Such goals can be supported by developing innovative manufacturing workflows and adopting circular thinking on material use. These innovations redefine the role of ornamentation and materiality in design and architecture (Inter al. Picon 2013 and Picon 2021).

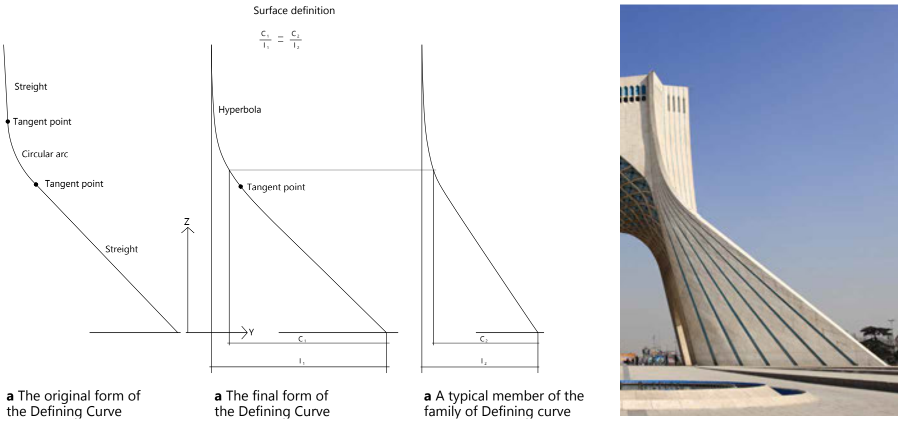
Bearing the definition mentioned above of what could be considered as rational in a larger context, in this research, rationalization is mainly concerned with achieving design and material intelligence through fabrication intelligence. Here, in order to incorporate such rationalization within the research frameworks and design methodologies, it is essential to elaborate further on the following topics:

1. Complexification versus Simplification
2. Approximation and Resolution

2.2.5.1 Complexification versus Simplification

It is necessary to acknowledge the difference between complex and simple in integrated and numerically controlled design-to-production processes. Meaning that the process of computing, automating, crafting, or in general, materializing a design or an artifact might be complex but affordable or simple to model and implement. Simultaneously, what may only visually look simple might not be easy to produce compared to a visually complex design with straightforward logic for production.

Prior to the advent and proliferation of digital fabrication and advanced construction technologies, mathematical and geometric logic was, and up until today is, one of the main forms of logic with which we could rationalize the materialization of complex forms. In such cases, abstraction plays an important role, as we can see in the classic example of Sydney opera house designed by Jorn Utzon in 1957 and engineered by Arup, where the complex shells of the building are all derived from a portion of a mathematically definable sphere (Arup and Zunz 1973). A similar approach is implemented in a monumental and cultural building in Tehran, designed by Hossein Amanat in 1966 and engineered by Arup for construction rationalization and structural design (Ayres 1970). In this example, we see how a visually complex curve might be more rational than a simplified version initially proposed in order to make the process of construction simpler, While the visually more complex hyperbolic curve is more rational as it is mathematically definable hence easier to find any given point on the surface in space using a simple formula (FIG. 2.20).



a The original form of the Defining Curve

a The final form of the Defining Curve

a A typical member of the family of Defining curve

FIG. 2.20 Monumental building designed by Amanat Architects 1966, Structural Calculation and construction rationalization by Arup.

Today’s technological advancements and state-of-the-art computational design techniques allow designers to incorporate mathematical formulas into their form-finding practices early in the design process. Therefore, In the past decades, there has been an increasing interest in the innovative application of mathematics and physics in architectural design processes (Liaropoulos-Legendre 2011; Burry and Burry 2012). Additionally, integrated design-to-production workflows open up new possibilities of materializing complexity that have affordable and rational programmable production routines, i.e., robotic fabrication toolpath and automated assembly processes. Consequently, new models and workflows for incorporating such logic are required. Additionally, integrated design-to-production workflows open up new possibilities of materializing complexity that have affordable and rational programmable production routines, i.e., robotic fabrication toolpath and automated assembly processes. Therefore, new models and workflows for incorporating such logic are required.

2.2.5.2 Approximation and Resolution

In a creative design process, where we consciously avoid enforcing a pre-made solution, it is inevitable and even desirable to implement various representation modes and techniques with different level-of-detail or abstraction. The buildability of such abstract models can be either achieved through approximation or by advancing a particular technology that could deliver the closest or highest possible degree of resolution or precision.

Moreover, it is essential to acknowledge that various materials and building systems may come with different tolerances in fabrication and construction. Therefore, fabrication and construction intelligence can be achieved by incorporating material tolerances and applying informed approximation methods. Such a strategy is implemented in the Soft Stone building, designed and built between 2014 to 2018 by SETUParchitecture studio [3]. In this project, the combination of two materials and developing a voxel-based approximation algorithm of curved surfaces, informed by curvature analysis, results in systemic materialization and construction efficiency (FIG. 2.21). Consequently, a maximum of 5 millimeters accumulated tolerance in 10 meters width is achieved through a hybrid of prefabricated bent metal voxels, with higher precision, which holds the manually precut natural stone prepared by craftsmen, which have less accuracy in production.

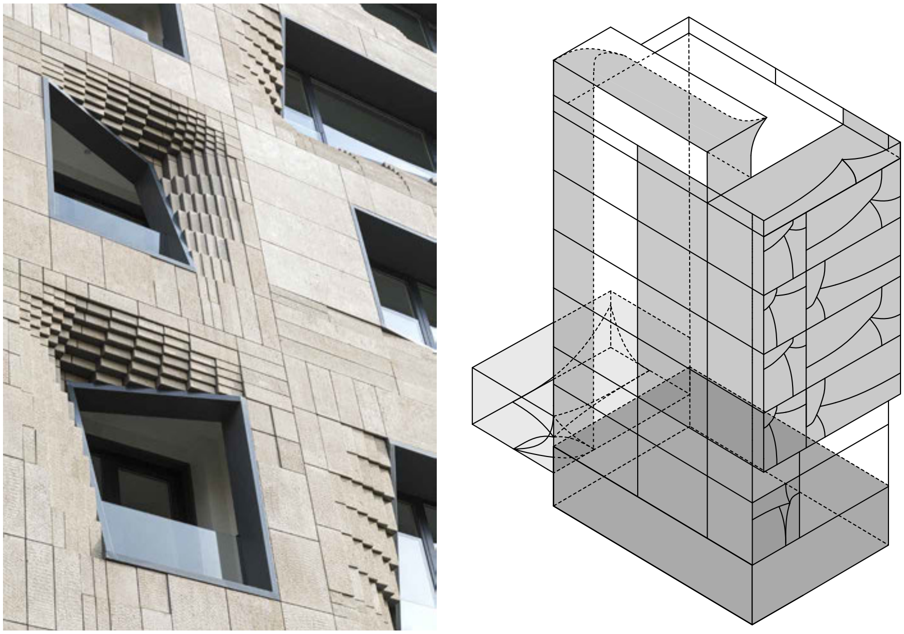


FIG. 2.21 Soft Stone office building designed By SETUParchitecture, Left: Built photo of Soft Stone, The curved surface is approximated using a recursive voxelization method which approximates the curvature with prefab stone components varied in sizes that are dry assembled on-site; Right: Diagrammatic representation of stone surfaces of the building modeled with NURBS surfaces.

Theoretically, it might be possible to develop and advance a tolerance-free production technology with absolute accuracy and precision for a specific project using a particular production technique. However, practically, especially at architectural scale, such an effort might be neither affordable nor needed. At the same time, if we could embrace and control the tolerances, we can benefit from imperfections and constraints in the production. On the one hand, embracing the production technique's precision would lead to the building process's efficiency and effectiveness. On the other hand, the imperfections and emerging material qualities might serve different quantifiable performances or qualitative aspects such as textures and tectonics.

In materialization processes, it is essential to identify and work with ranges of affordable resolution. This may apply to various digital manufacturing approaches such as additive, subtractive, formative, and modificative. Even in a particular manufacturing category, like in additive manufacturing, we may afford various resolutions using different material resources and technologies (Inter al. Khalili 1989; Khoshnevis 2004; Dini, Nannini and Chiarugi 2006) (FIG. 2.22).

FIG. 2.22 Resolution and production technology, Top: Sand Bag Shelter System by Nader Khalili, Cal-Earth Institute; Middle: Contour Crafting by Behrokh Khoshnevis; Bottom: Binder Jet Printing, by D-Shape, Enrico Dini.; Right column: close-up views of the same methods.

TOC

2.2.6 Cluster 6 Interdisciplinarity and Industrial Revolutions

Paradigm shifts in design and production methods can be mapped and explained alongside the industrial revolutions. The contemporary industrial revolution, also known as industry 4.0, is characterized by Cyber-Physical Production Systems, Internet of Things, Digital Twin, and Smart Factories that could support on-demand customized production. The AEC sectors need to prepare for such major advancement both culturally and infrastructurally. Such preparation demands the development of both implicit knowledge and explicit or applicable technology, which is empowered by interdisciplinary efforts. Here and throughout this research, we address and exemplify such interdisciplinarity on two intertwined fronts:

1. Research and Development
2. Discipline and Education

2.2.6.1 Research and Development

Cutting edge research and development in the field of computational design and architectural robotics can be perceived and assessed as a niche. Therefore, obsessively narrowing down the focus of a research project comes with both opportunities and challenges. One may argue that the smaller the focus, the better we can advance a particular technology such as 3D printing and develop communities of experts that could continuously explore and contribute to this and that specific emerging field of knowledge. An example of such contribution by this research can be seen in the project titled Continuous-Robotic-3D-Printing-of-Structurally-Optimized-Porous-Ceramic-Structures, which was exhibited as a part of the Imprimer Le Monde (Print the world) exhibition at Centre Pompidou in Paris (Brayer 2017) (FIG. 2.23). However, such efforts might lead to isolated technologies, which may eventually have also high technology readiness level, while there is not enough support culturally and infrastructurally in the society and industry to embrace such advancements. Therefore, in this research, while the case studies are digging deeper and stay focused on certain objectives to tackle, it is essential to constantly rethink the big picture through interdisciplinary approaches in education and practice.

FIG. 2.23 Imprimer Le Mond, Print the World Exhibition at Centre Pompidou, 2017. Projects in this photo from Left to right: Digital Grotesque [4], Smart Dynamic Casting [5], and Continuous Variation - Informed Robotic 3D Printing [6].

2.2.6.2 Discipline and Education

The integration of fabrication technology in architectural design practices promotes decentralized approaches in production processes and facilitates mass-customization. Open-source computation in design and production leads to the democratization of fabrication routines, effectively allowing both designers and users to access and operate industrial machinery on demand.

Such decentralization and democratization demand agile frameworks both in practice and academia that could continuously adapt to changes in culture and technology of design-to-production workflows. Since, from multiple points of view, such as economic and technological, the existing infrastructure in the industry is not fully ready to embrace such changes, the role of education is pivotal.

Co-creation, collative interdisciplinary effort, and hands-on explorative approaches are essential characteristics of such pedagogical models where in many cases, it goes beyond the conventional master-protégé model. Throughout this research, such frameworks have been designed and implemented in various locations, such as two days prototyping workshop in Los-Angeles at USC school of architecture in 2014, six days design-to-production studio in InDeSem symposium in Delft in 2015, sixteen days in Tehran at TRAM studio 2017, and fifteen weeks interdisciplinary project on Bioplastic Robotic 3D Printing in Dessau in 2018-19 (FIG. 2.24). These examples and many others have been installed in a day with deployable setups and became operational almost instantly in different locations with various glocal specificities. The production capacity of industrial robots equipped with different tools allows the production of customized building components. In most cases, the small programmable factory continuously has operated 24/7, with design and fabrication data being shared between parametric models and robotic workstations.

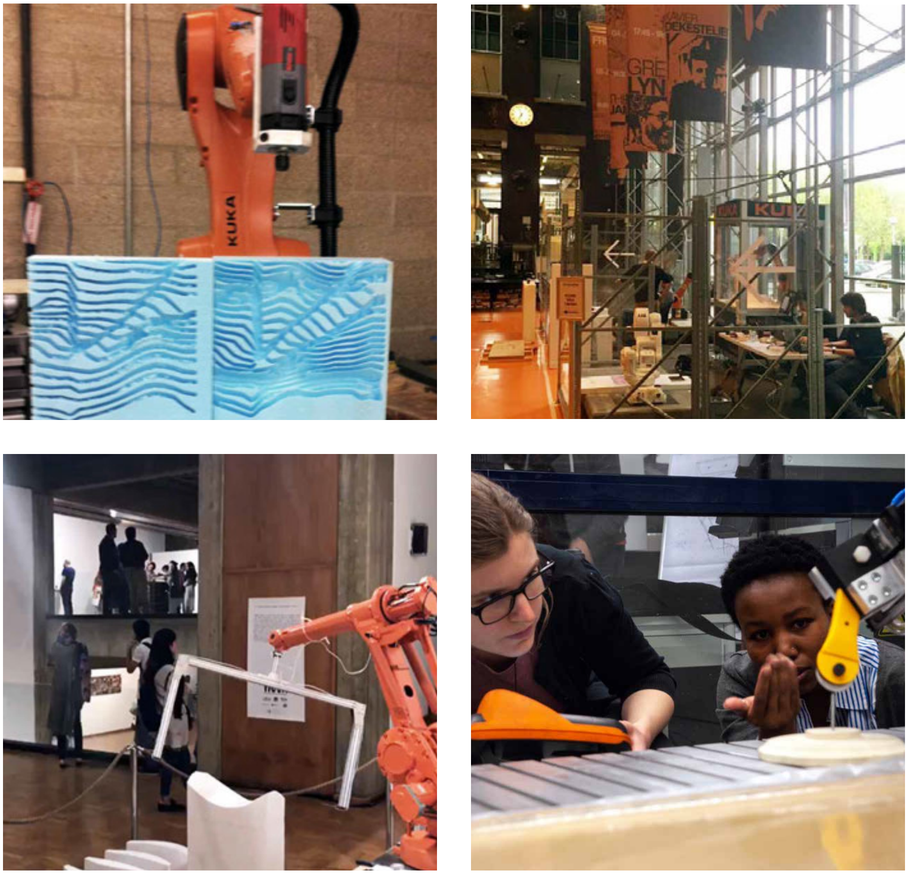


FIG. 2.24 Top Left: 2 days workshop and lecture at USC Los Angeles in 2014; Top Right: 6 days design to production workshop organized as a part of InDeSem Delft in 2015 [7]; Bottom Left: 16 Days TRAM studio and public exhibition organized in Tehran in 2017 [8]; Bottom Right: Interdisciplinary Bioplastic Robotic 3D Printing collaborative project between design and architecture departments in Dessau in 2018-19 [9].

2.3 HI-ARM Frameworks

HI-ARM frameworks outline the conceptual, analytical, and operational strategies in design-to-production processes. The frameworks are proposed based on the research objectives and previously elaborated definitions. Moreover, they are evolved through observations and conducted experiments in case studies. The four identified and developed HI-ARM frameworks are complementary, and they describe:

1. Interdisciplinary Domains Interrelations outlook
2. Design-Production-Material Space
3. Multiscale-Multimode-Multimaterial-Multicriteria
4. Design Materialization Model (Porosity, Hybridity, Assembly)

2.3.1 Framework 1: Interdisciplinary Domains Interrelations Outlook

HI-ARM outlook frames the interrelations between the major disciplinary domains (Computation, Automation, Materialization) with the goal to bridge the gap between design and construction in architectural practices and the building industry. HI-ARM outlook, as a whole, is considered as a backbone conceptual framework for case studies and developed design-to production methodologies. Further, the internal interrelations between the three domains are implemented as analytical and operational feedback in the integrated computational design to robotic production workflows to achieve design, production, and material intelligence (FIG 2.25).

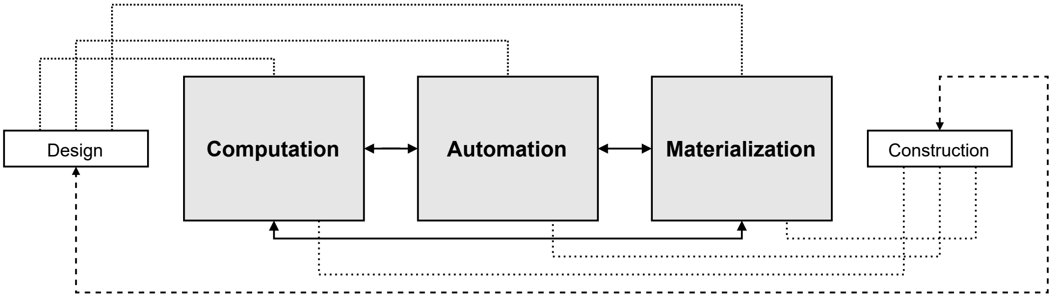


FIG. 2.25 HI-ARM Outlook, Interdisciplinary Domains Interrelations, Correlations and Feedback Loops between computation, automation and materialization to bridge the gaps between design and construction processes.

2.3.2 Framework 2: Design-Material-Production Space

Design-Material-Production space framework is a conceptual and operational tool in integrated design to production processes. The three interconnected spaces in this framework are Design-Space, Material-Space, and Production Space (FIG. 2.26).

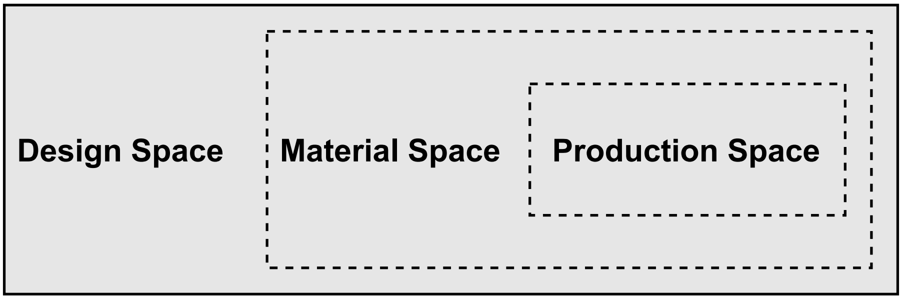


FIG. 2.26 HI-ARM Design-Material -Production Space Framework.

The Design-Space refers to all possibilities of design solutions for a given or formulated design problem. The instances within this space can be conceived and represented through different mediums and in various modes such as manual drawing, digital representation, associative parametric modeling, visualization, or geometric solutions. Naturally, all the instances within the Design-Space are not necessarily fully functional nor efficient as they can be immaterial and/or not producible.

The Material-Space includes all possible materials that can be considered or applied for a design instance or a set of solutions. The instances within the Material-Space have physical properties, behaviors, features, and tectonics. Materiality in this space is digital or physical; thus, possibilities can be explored through physical samples or physics-based simulations.

The Production-Space refers to all possibilities of accessing, processing, fabricating, assembling, and finishing a design instance or a set of solutions considering the constraints and potentialities of a given or developing production setup. In this space, the production setup includes the physical or virtual Cartesian space with all operational units such as robots, tools, and human or static elements such as working objects or material, obstacles, and boundaries.

For instance, to have a simplified example, being able to approach one target spot on the working object with a hundred different possible tooling directions and robotic arm configurations introduces hundreds of possibilities within the production space. In a simple example like this, changing the material properties by using ten different recipes for a specific purpose, the size of the material-production space expands to thousands of possibilities. For a particular design problem with 100 design instances in such material-production space, the overall options for that specific spot on the working object within the design-material-production space are a hundred thousand.

Beyond this simple example, the dynamic co-development of all these three spaces in an actual design process is nonlinear if not combinatorial or multiplicative, as certain combinations may result in emerging possibilities. Thus, the HI-ARM design-material-production framework is not only about quantifying the possibilities in a specific project. Instead, we implement this framework to understand and explain the co-relations and feedback loops between each of these spaces throughout an integrated design-to-production process.

2.3.3 Framework 3: Multi-Scale/Mode/Material/Criteria

The Multi-Scale/Mode/Material/Criteria framework is an operational tool for design materialization. The framework identifies and suggests four interconnected dimensions for integrated computational design to robotic production processes: Multi-Scale, Multi-Mode, Multi-Material, and Multi-Criteria (FIG 2.27).

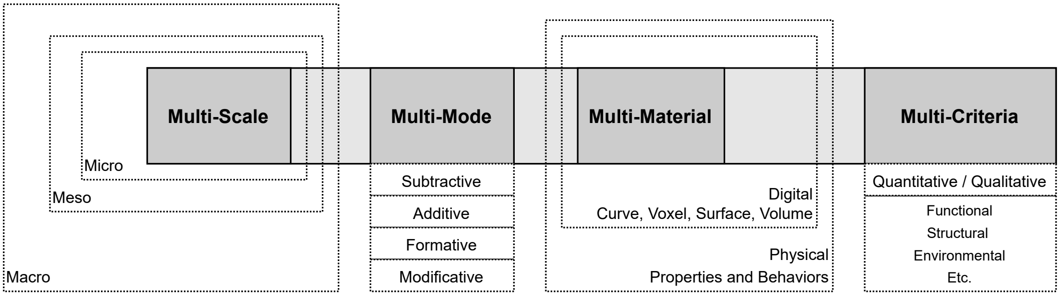


FIG. 2.27 HI-ARM Multi-Scale/Multi-Mode/Multi-Material/Multi-Criteria Framework.

Multi-Scale implies that there need to be cross-connections established between different scales of materialization for any given design problem at any given phase of design-to-production processes, e.g., ranging from Micro to Meso to Macro. Connections refer to direct or indirect associations and feedback loops between the compartments of an integrated system operating in different design scales. There are no fixed ranges of dimensions for Micro-Meso-Macro in this framework, as it depends on the design subject's overall scale. However, in this research, Micro can be mostly at the material and tectonic scales, Meso at the component and assembly scales, and Macro to spatial or building scales and beyond.

Multi-Mode refers to various production methods or robotic fabrication and tooling approaches such as subtractive, additive, formative, modificative, and combinations. In this framework, different modes of production are either pre-defined in a particular project are considered as potential production methods, which then will be chosen and co-evolved throughout the integrated design-to-production processes.

Multi-Material includes both digital and physical materialities. Digitally, Multi-Material refers to a set of possible modes of digital representation and geometric modeling techniques such as Curve-Based, Voxel-Based, Surface-Based, and Solid-Based or Volumetric and combinations. Physically, Multi-Material implies exploration and incorporation of sets of potential material properties and behaviors within the design-to-production workflow.

Multi-Criteria refers to quantitative and qualitative performance evaluation measures such as functionality, structure, environment, fabrication, etc. These criteria can be mapped in multiple scales, conceived through multiple materials, and produced using multiple production modes. Depending on the project objectives, one or a combination of these performance measures can be considered fixed or moving targets, which are then co-evolved and redefined throughout the design-to-production process.

2.3.4 Framework 4: Porosity-Hybridity-Assembly Materialization Model

Porosity-Hybridity-Assembly Materialization Model is a conceptional, analytical, and operational framework in computational design to robotic production processes. This framework is a comprehensive design materialization model as it covers the previously discussed three HI-ARM frameworks. The model advances robotic fabrication for multi-scale, multi-mode, and multi-material processes, applied to architectural design, in order to develop novel building systems. In this framework, porosity, hybridity, and assembly become design strategies fundamental to robotic materialization (2. 28).

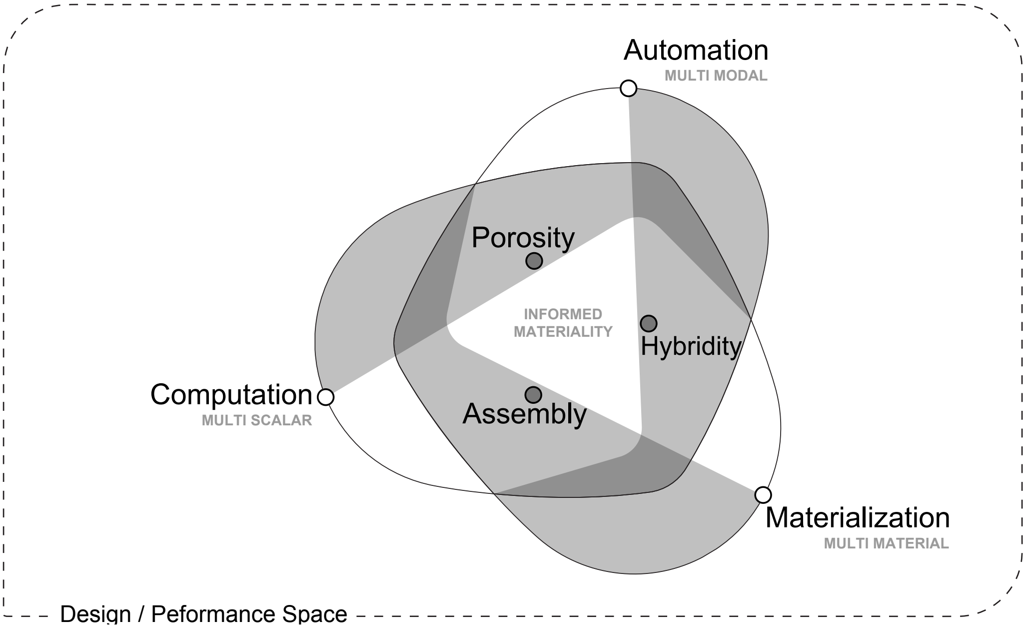


FIG. 2.28 HI-ARM Porosity-Hybridity-Assembly Materialization Model.

Porosity refers to a quantifiable relation between matter and void across different scales. It is about how today's materials can be totally designed at all scales and produced using robotic fabrication, achieving efficient material distribution with different resolutions. Hybridity, on the one hand, is the purposeful integration of various production modes, and on the other, implies multi-materiality. Through hybridization, the projects extend the capabilities of isolated fabrication routines and materials. Assembly refers to making connected topologies out of discrete parts. Furthermore, assembly is associated with component-based systems that allow the design to grow to a larger scale than that of the production setup. Further elaborations on the Porosity-Hybridity-Assembly materialization model is initially discussed in the book chapter on multi-scalar material architecture (Mostafavi and Anton 2018) in Towards a Robotic architecture Book (Daas and Wit 2018).

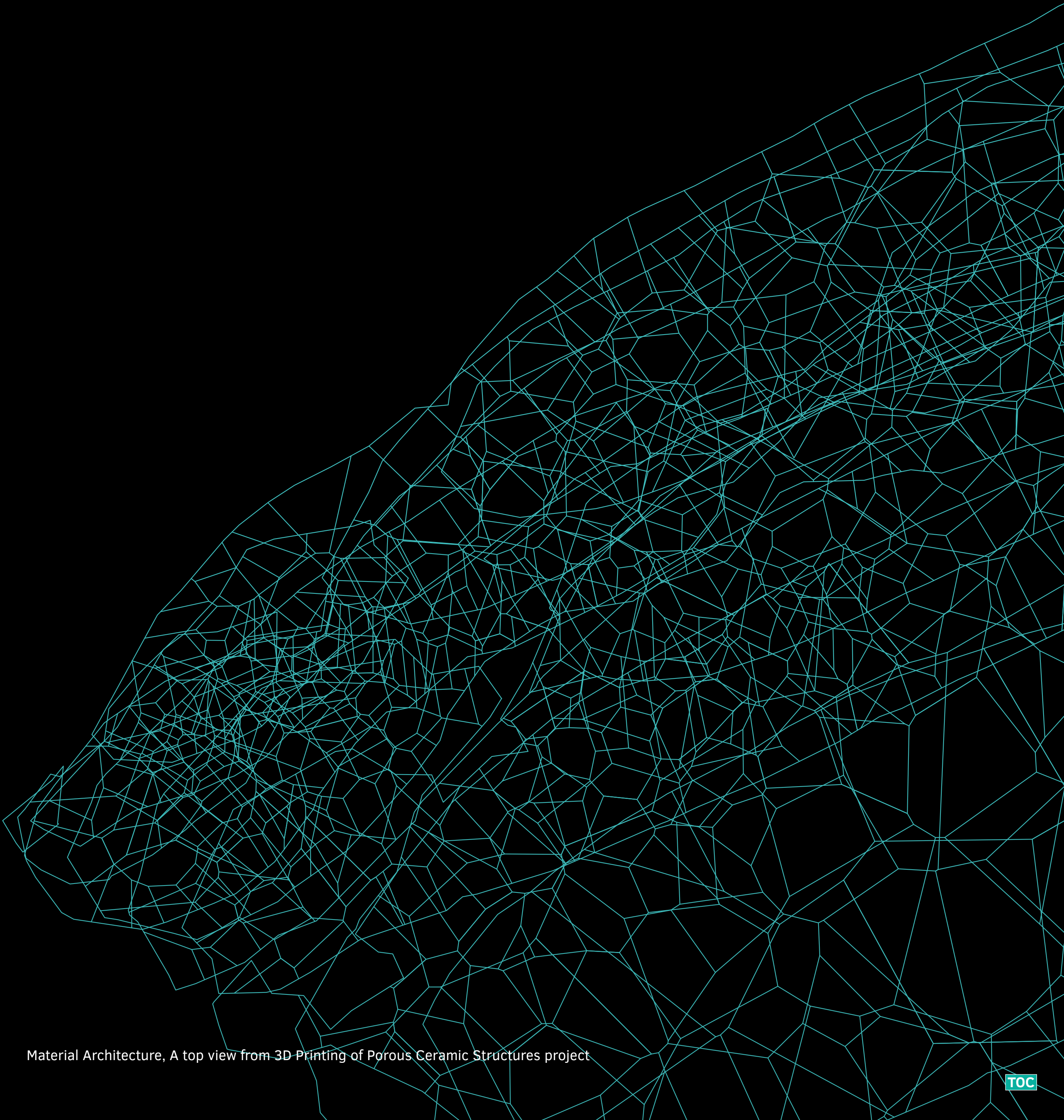
2.4 Chapter Conclusion

The first part of this chapter expands and explains the title of this dissertation: Hybrid Intelligence in Architectural Robotic Materialization (HI-ARM). While these short descriptions are specific to the research's context and content, each of these terms is further elaborated and exemplified both in this chapter and the other three following thematic chapters (Porosity-Hybridity-Assembly) with more extensively discussed case-studies.

The definitions in six clusters together with four frameworks construct and introduce the research outline and design-to-production methodologies in this work. In the following chapters, we will come back to the six clusters of definitions while we are drawing conclusions in each of the themes of Porosity, Hybridity, and Assembly. Therefore, redefining those definitions, the conclusion of chapters three, four, and five extends the developed discourses.

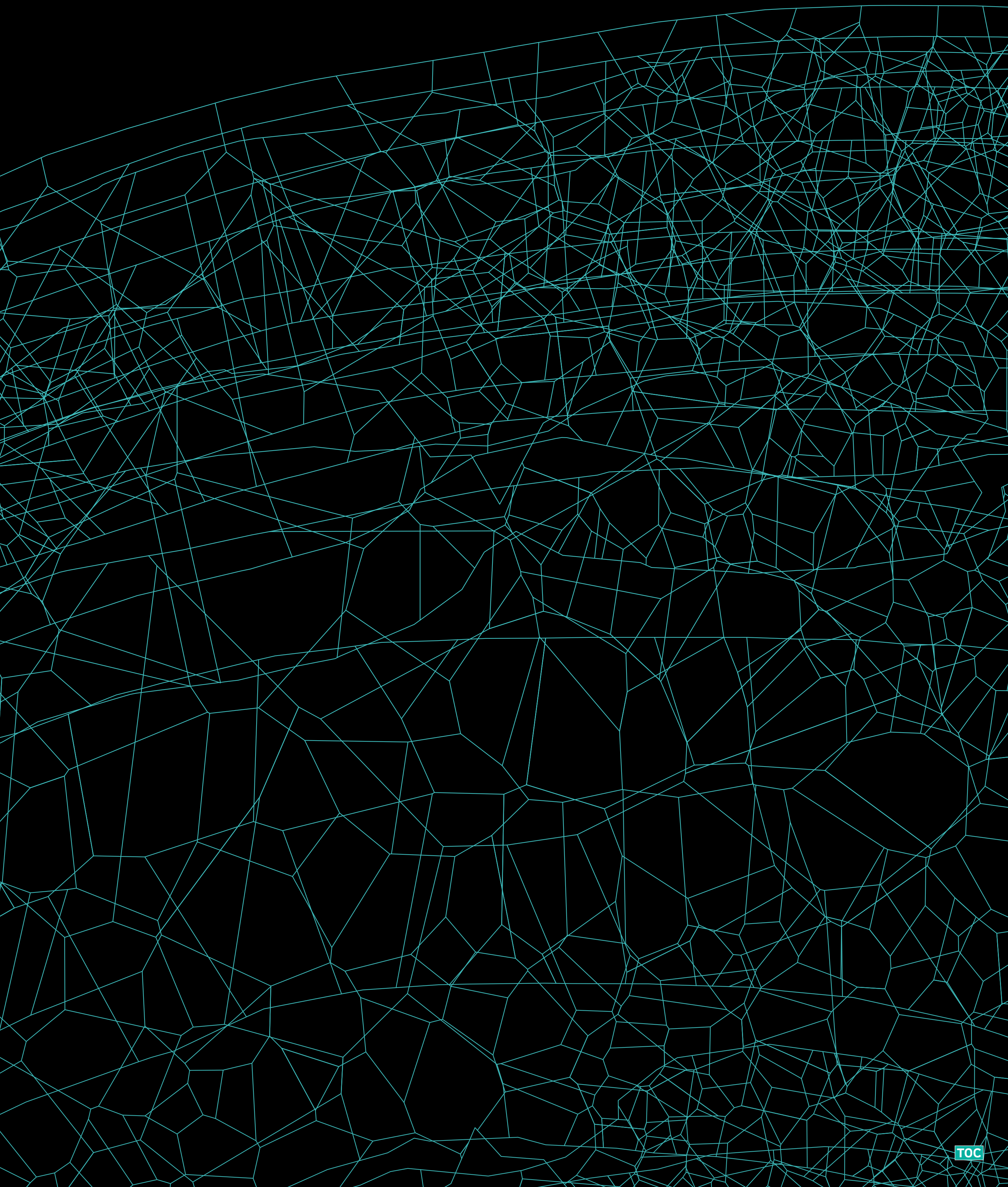
The extension and the degree of implementation of the case studies frameworks might vary from case to case. Meaning that while all four frameworks are considered the backbone of the design and development of the case studies in each case, considering the research objectives, we may use them differently and, hence, elaborate and explain them with different levels of detail.

TOC



Material Architecture, A top view from 3D Printing of Porous Ceramic Structures project

TOC



TOC

TOC

3 POROSITY: Computation and Production

ABSTRACT

This chapter focuses on the computation and production of porosity. Porosity within HI-ARM frameworks is introduced as a design materialization strategy for the intelligent distribution of matter and void in multiple scales. With an introduction to the objectives and applications of porosity, this chapter consists of two pilot case studies. The first case study mainly focuses on developing design systems as well as the integration of multiple disciplines such as architecture and structural design. This case study is an exemplar of developing integrated computational design systems by incorporating topology optimization methods within a bespoke computational design workflow. The second pilot project in this chapter focuses on the production of porosity, where an integrated design-to-production system is developed and tested for robotic 3D printing of ceramic structures. In this prototypical workflow, we discuss the methodologies of development of an Integrated Computational Design, which incorporates Material and Fabrication Intelligence.

KEYWORDS

Performance Driven Design, Design Information; Design Technology; Topology Optimization; Parametric Design. Informed Design, Robotic 3D Printing, Porosity, Material Architecture, Material behavior.

3.1 Chapter Introduction

Various reasons can be enumerated on why porous systems in design, architecture, and the built environment are relevant and applicable. Porosity can be implemented considering structural, functional, and environmental factors and performances. For instance, porous structures can have similar or better structural performance, while by being lighter, they can be less resource-and-processes-intensive and, hence, more environmentally friendly. The exact application of porosity and the scale of implementation might vary from case to case. Before being able to measure the accurate or absolute performance of a porous system, in the context of this research, it is important to be able to compute and produce porosity. Therefore, this chapter is mainly looking to integrated computational design and robotic production systems, which are developed for the digital and physical materialization of porosity in various architectural scales.

In this chapter, we discuss how computation and production of porosity are developed and implemented within the framework of HI-ARM. The focus is on two main case studies. The first project explores the computation of porous structures, and it discusses the methodology of developing integrated computational design systems where the goal is to incorporate material and structural intelligence into the design materialization workflow. What is important in this prototypical example is how multiple disciplines and objectives, such as structural design and material use optimization, are all integrated into a design system where input data, decisions, outputs, sub-procedures, interrelations, and feedback are all mapped, cross-related and integrated (FIG. 3.1).

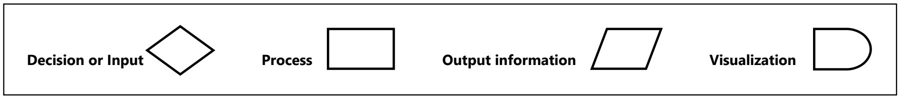


FIG. 3.1 Schematic diagram of flowchart elements of an integrated design system.

As a prototypical HI-ARM case study on Performance-Driven Design, the first project discusses that Design Information Modeling (DIM), Data Exchange, and interoperability in Design-Material-Production space are essential in developing an integrated design to production systems. Similar methods are further then applied as the bases in other case studies on porosity. Such as Porous Assembly, where multiple layers of data are generated and harvested based on environmental, structural, functional considerations, which informs the model and adds features to the designed and produced prototype (FIG. 3.2). Clearly, in other cases on Hybrid and Assembly, a similar methodology is applied as an underlining principle of HI-ARM projects.

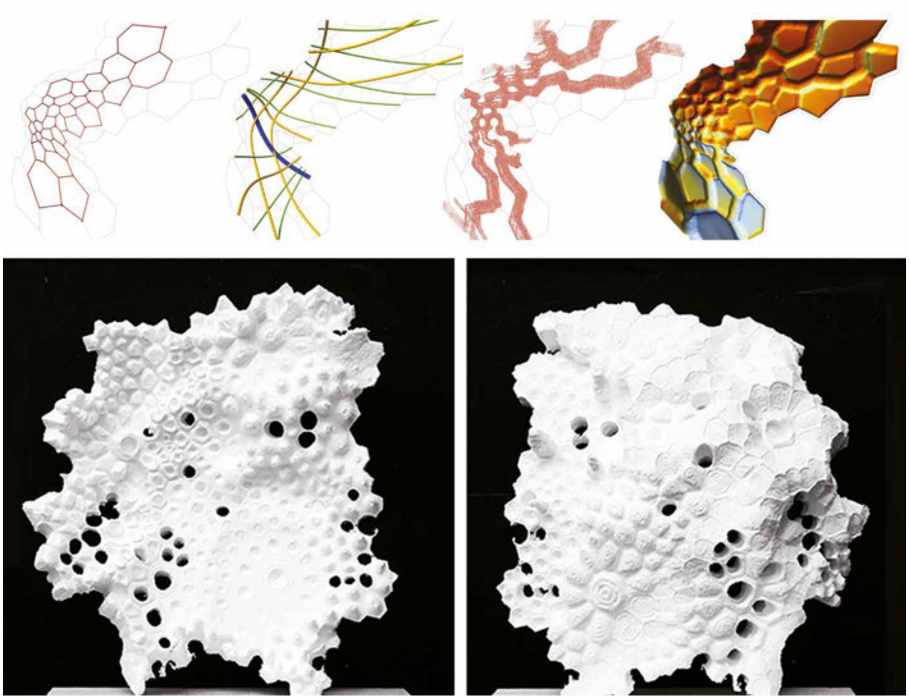


FIG. 3.2 Multiple Layers of generated and extracted design data in Porous Assembly project, Design Information Modeling is considered as the fundamental underlying principle of all HI-ARM projects.

The second part of this chapter is dedicated to the production of porosity, and it is exemplified through a case study on Robotic 3D Printing of porous structures (FIG. 3.3). In this project, the development process of the custom-made design-to-robotic-production setup is discussed, which then similar approaches are applied in the following projects on Hybridity and Assembly. Moreover, in this case on Additive Manufacturing, the HI-ARM approach into multi-scalarity in design ranging from micro to macro is discussed as an underlying framework for all projects where feedback from one scale iteratively informs other domains of research and design.

FIG. 3.3 Robotic 3D Printing of Porous Ceramics Structures.

Initiated as a research on additive manufacturing, the project looks at the development and implementation of 3D printing in architecture. The goal is to achieve optimized material distribution at multiple scales. Accomplishing this objective, porosity is introduced as a quantifiable means to measure and evaluate the performance of allocating matter both in digital and physical environments. Therefore, co-evolution of design computation strategies and material experimentation enables the customization of a numerically controlled production system in tune with the inherent characteristics of each unique building material. The incorporation of topology optimization output, considering robotic fabrication methods, leads to a distinctive material deposition approach to achieve porosity in compression-only structures.

TOC

3.2 Computation of Porosity: A Case study on Material Intelligence and integrated design[1]

Performance Driven Design and Design Information Exchange

Establishing a computational design methodology for parametric and performance-driven design of structures via topology optimization for rough structurally informed design models

ABSTRACT This paper presents a performance driven computational design methodology through introducing a case on parametric structural design. The paper describes the process of design technology development and frames a design methodology through which engineering, -in this case structural- aspects of architectural design could become more understandable, traceable and implementable by designers for dynamic and valid performance measurements and estimations. The research further embeds and customizes the process of topology optimization for specific design problems, in this case applied to the design of truss structures, for testing how the discretized results of Finite Elements Analysis in topology optimization can become the inputs for designing optimal trussed beams or cantilevers alternatives. The procedures of design information exchange between generative, simulative and evaluative modules for approaching the abovementioned engineering and design deliverables are developed and discussed in this paper.

KEYWORDS Performance driven design; design information; design technology; topology optimization; parametric design.

---

[1] The case study on the computation of porosity integrated into this chapter, titled Performance-Driven Design and Design Information, has been previously published in the following peer-reviewed paper (Mostafavi, Beltran and Biloria, 2013):
Mostafavi, Sina, M.G. Morales Beltran, and N.M. Biloria, 2013. “Performance Driven Design and Design Information Exchange.” In Stouffs, R and Sariyildiz, S (eds), Proceedings of the Education and Research in Computer Aided Architectural Design in Europe (eCAADe) 2013 conference, Delft, The Netherlands, vol. 2, pp. 117-126.

3.2.1 Introduction

One of the challenges in performance driven design methodologies is the way that designers can effectively integrate simulation and optimization techniques with parametric design and generative procedures (Oxman 2008). This challenge can also be attributed to as the lack of tools to support effective knowledge integration in Computer Aided Design (CAD) techniques and methods (Cavieres et al. 2011). In design practice, theoretically this gap is bridged via simultaneous consultations with engineers and specialists. However, for many design problems this concurrency might not be achievable and applicable. In this paper, as one of the directions towards achieving this concurrency we specifically focus on the implementation of optimization techniques in structural design, to see how they can be integrated with parametric design techniques. To be more explicit from a computational design point of view, and to the design methodology itself, the focus of the article is on design information modeling, exchange and interoperability. The paper structure here onwards addresses questions and objectives, the process, the tool and the methodology. Subsequently, the results from the examples and a case study are briefly reported and eventually the discussion focuses on performative design methodology, its supporting design technology, rough Building Information Modeling (BIM) systems (Eastman et al. 2018) and future directions.

3.2.2 Question and Objectives

Two Two major questions are the subjects of exploration in this research. The first one, which is more from a computational design perspective, questions the possibility to appropriately integrate optimization algorithms and procedures, -in our case, topology optimization, within a parametric design system. Pertaining to this question, the objective is to design a system with connected sub-procedures and feed¬backs with appropriate methods for design information exchange and translation from different CAD and programming platforms (operating as design decision support) for performance driven design (in this case is a truss structural system). The concurrency and consistency in extracting, generating, and structuring of geometric design information such as size, resolution, etc.- and non-geometric design in¬formation such as load conditions, Degree of Freedom (DOF), etc. will be discussed.

The second question is how to make the process of topology optimization more suitable for the scale of architectural design and what are the benefits of doing so? This method and in general Finite Element Analysis (FEA) have been widely used at the scale of industrial design for uni-body or monocoque structures like bike frames (FIG. 3.4a and 3.4b). However, for the scale of a building, while we usually have building elements like bars, beams, columns, and joints, directly using the discretized result of topology optimization might not be much applicable and might impose choosing in-site concrete casting (FIG. 3.4c and 3.4d). While in this research, we build on the assumption that it would be more relevant for designing a truss or frame structures, if we translate the finite geometry to a proper geometric system with nodes and bars (FIG. 3.4e).

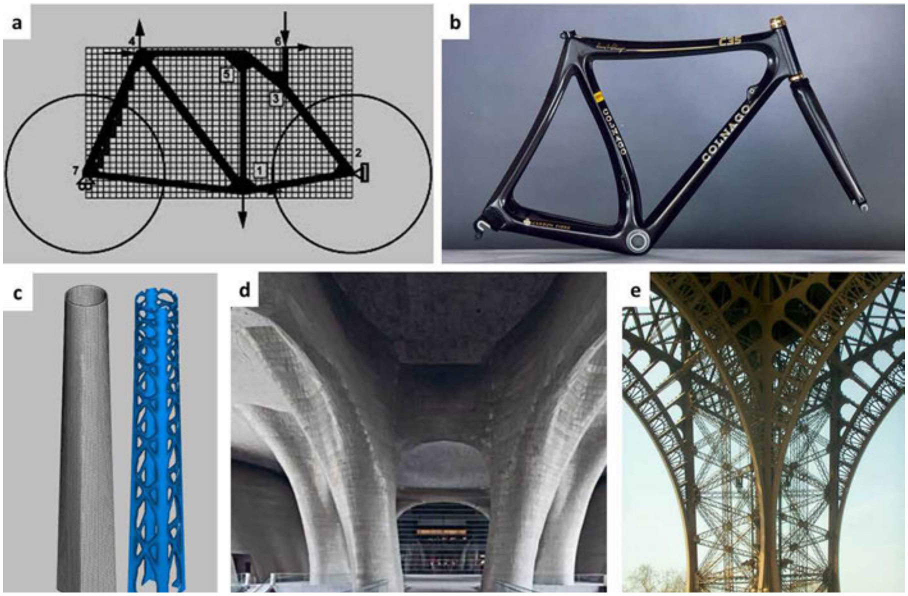


FIG. 3.4 a: Topology optimization method for designing of bicycle [10], b: COLNAGO monocoque bike frame designed using FEA, c: FEA applied in designing of a tower [10], d: Cast free form concrete column by Arata Isosaki in Shanghai, e: Close-up of Eiffel tower column with similar morphology with steel elements.

While to a certain extent the process is defined and developed as a generic design technology, the type of structural system is intentionally and precisely defined as a trussed beam or cantilever. Besides the developed algorithms, from a technical point of view, testing and developing of various methods for information exchange between software and platforms like MATLAB, Rhinoceros, Grasshopper plus some of its add-on plug-ins and the needed structural analysis software shall also be elaborated.

3.2.3 Design process and methodology

The process, as illustrated in the flowchart (FIG. 3.5), is a set of sub-procedures -A to D- such that the output, input and procedures are systematically correlated. In each sub-procedure there are four kinds of modules, which are decisions or inputs, processes, outputs, and visualizations. To make this technology-based design process an interactive, cyclic, and performative one, the following aspects have been taken into consideration:

- The decision(s) or input(s) of each sub-procedure are used as common inputs for more than one of the sub-procedures, whenever and wherever needed.
- The final translated output in each of the sub-procedures would automatically or semi-automatically be processed as the input of the next sub-procedure(s).
- After each single measurement or evaluation module there is either a visualization for alerting or a feedback loop to the previous stages.

The detailed descriptions of each of the sub-procedures are as follows:

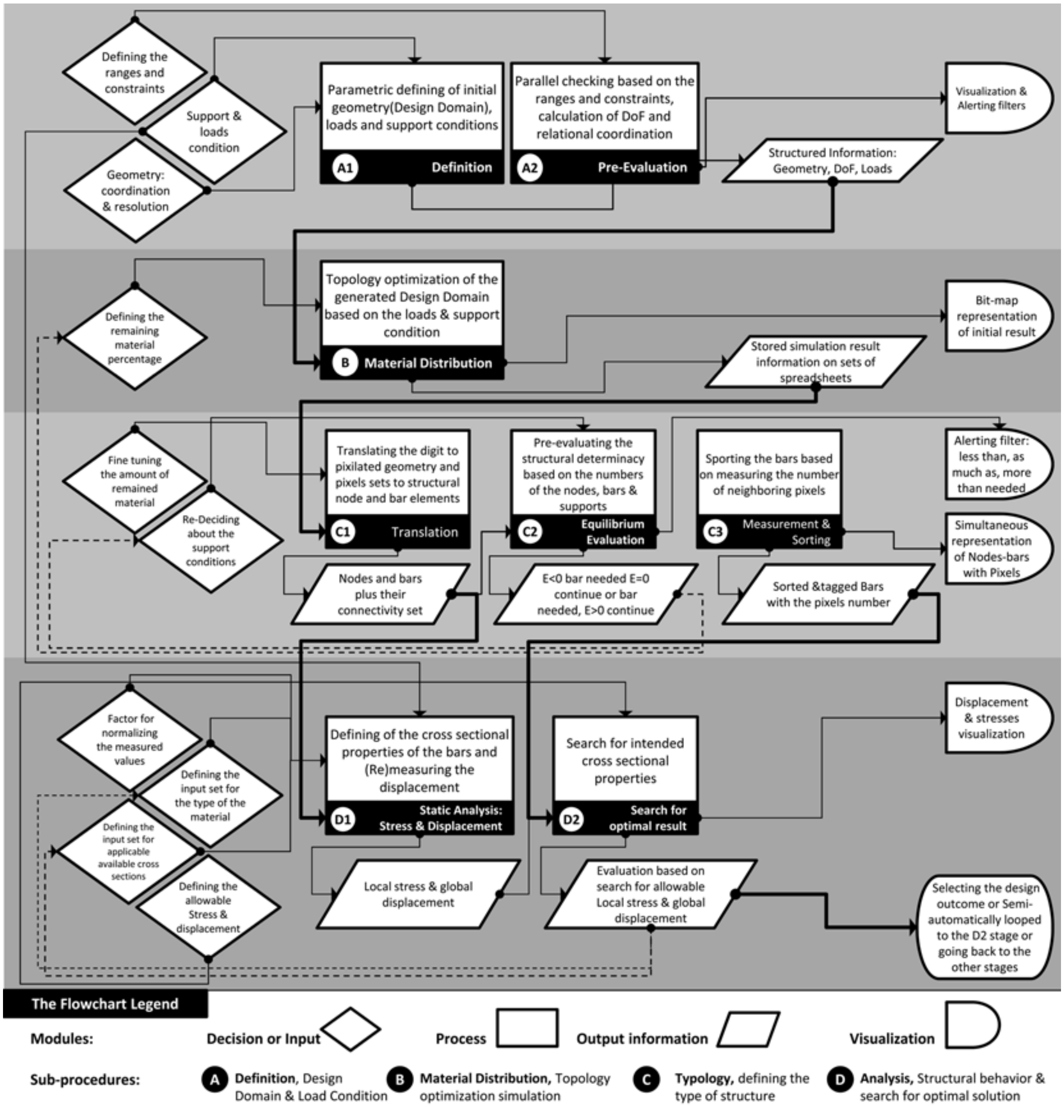
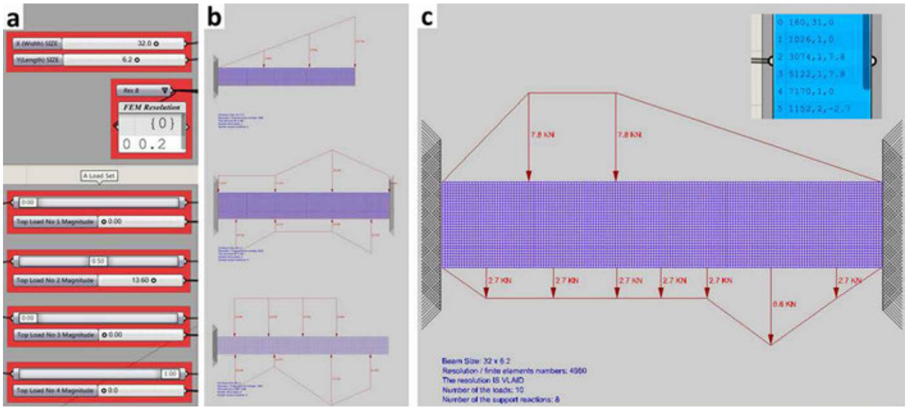


FIG. 3.5 The flowchart of the process, illustrating the correlated sub procedures.

3.2.3.1 Definition, design domain, discretization, and load condition [A]

In this phase, the designer defines the geometrical properties on which the supports and loads can be parametrically added and modified. These properties are, so far, the span and the height of a cantilever or a beam with either upper or lower distributed or point loads on sides. However, the process in this stage and other stages is designed in a way that more irregular initial shapes are also possible to implement, by just removing some portions of the initial planar design domain. The main inputs in this sub-procedure are the dimensions, the magnitude and coordination of loads, supports and the mesh resolution (FIG. 3.6a). Since this mesh resolution is indeed the discretization of the design domain for the following FEA, the acceptable resolution is a variable depending on the available computation time, power and the desired refinement. The output is a two-dimensional matrix or data list in *.txt* format that contains the relative dimensions of the geometry based on the discretization resolution, magnitude, the relative coordinates and calculated DOFs of each load positions based on the defined resolution. This step is done through visual programming using Grasshopper in Rhinoceros. The generated geometry attributes and alert messages (if either the geometry or resolution is not within some predefined range) are simultaneously visualized (FIG 3.6b and FIG. 3.6c).



X (Width) SIZE 32.0
Y(Length) SIZE 6.2
Res 8
FEM Resolution
{0}
0 0.2
0.00
Top Load No 1 Magnitude 0.00
0.50
Top Load No 2 Magnitude 13.60
0.00
Top Load No 3 Magnitude 0.00
1.00
Top Load No 4 Magnitude 0.0

```
0 160,31,0
1 1026,1,0
2 3074,1,7.8
3 5122,1,7.8
4 7170,1,0
5 1152,2,-2.7
```

Beam Size: 32 x 6.2
Resolution / finite elements numbers: 4950
The resolution IS VLAID
Number of the loads: 10
Number of the support reactions: 8

FIG. 3.6 a: Some of the input parameters, b: Variations in design domain definition plus load and support conditions, c: A case with its corresponding output set.

3.2.3.2 Material distribution (MD): topology optimization [B]

In this stage, the goal is to find the optimal material distribution of the discretized generated design. This step is in MATLAB and is based on the implementation and development of a topology optimization code, originally written by Sigmund (2001) with the purpose of solving linear compliance minimization using an optimizer and finite element subroutine. Modifications in the code are set up, with the objective of making it compatible with the input data files and supports interoperability of the output for the next sub-procedures.

The geometrical properties, DOFs and loads will be automatically called in the code and what has to be defined by the designer is the percentage of total remaining material. Consequently, two parallel results are the outputs of this phase, one a set of images that in real-time illustrates the results of material distribution simulation and the other, a set of excel spreadsheets, in which numerical values ranging from zero to one are stored. In the tested cases, four spreadsheets, respectively, with 30, 40, 50 and 60 percentage of remaining material have been the final outputs. In order to make this process more semi-automatic, further modifications can also be done in the code to predefine the range for remaining material in previous sub-procedures (FIG. 3.7).

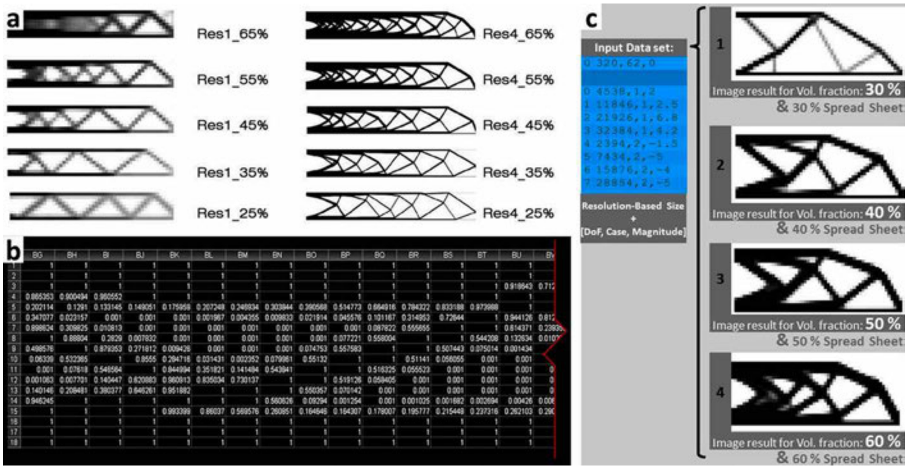
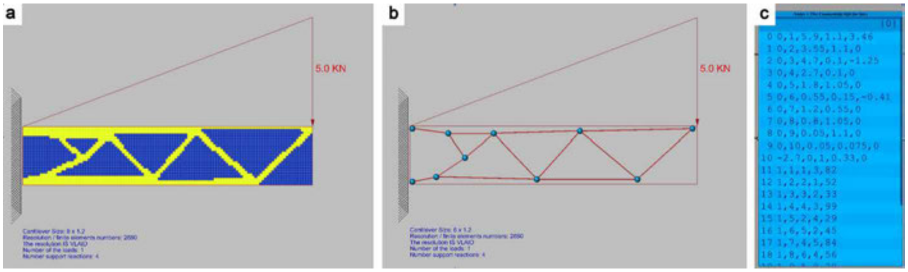


FIG. 3.7 a: Tests for finding proper resolution ranges, b: Close-up of a result spread sheet with digits from 0 to 1, c: An input set example and four different topologies of the same design domain and load and support conditions.

3.2.3.3 Typology, defining the type of structure [C]

The goal in this sub-procedure is to translate discrete or pixelated geometry, which is the result information from the topology optimization to a vector-based geometric system with nodes and lines (FIG. 3.8a and FIG. 3.8b). Although in the initial visualized topology the lines are detectable with the eyes of the designer, they are not automatically distinguishable for the CAD platform. So one of the main crucial challenges here was to extract the nodes and define the bars by using and developing appropriate algorithms in a way that the topologies do not change. This implies that if in a resultant image we see nine white polygons in the resultant vector geometry we should have also the same condition. Finally, the output is a matrix as .txt file with the required information of nodes, bars and load conditions in the desired format (FIG. 3.8c)



```
 0 0,1,5.9,1.1,3.46
 1 0,2,3.55,1.1,0
 2 0,3,4.7,0.1,-1.25
 3 0,4,2.7,0.1,0
 4 0,5,1.8,1.05,0
 5 0,6,0.55,0.15,-0.41
 6 0,7,1.2,0.55,0
 7 0,8,0.8,1.05,0
 8 0,9,0.05,1.1,0
 9 0,10,0.05,0.075,0
10 -2.7,0,1,0.33,0
11 1,1,1,3,82
12 1,2,2,1,52
13 1,3,3,2,33
14 1,4,4,3,99
15 1,5,2,4,29
16 1,6,5,2,45
17 1,7,4,5,84
18 1,8,6,4,56
```

FIG. 3.8 a: the converted spreadsheet to discrete geometry, b: extracted nodes and bars of same design domain, c: output set containing information on nodes, connectivity and load condition.

FIG. 3.9 illustrates the applied and developed methods for extracting the nodes from the resultant discrete geometry. After reading the float values on the spreadsheets and re-visualizing the results through using visual programming in Grasshopper, and tagging each cells with its corresponding zero to one value, a filter separates the cells into two lists of data. The reason for having this buffer is to let the designer find the appropriate continuous topology similar to the image result but this time composed of surfaces with the size of defined resolution. For instance, in the FIG. 3.9 this filter value is 0.3, which means that all values less than this would be within a list to create the negative shape and those cells with values equal or more than this threshold will create the positive shape (FIG. 3.9 a-c).

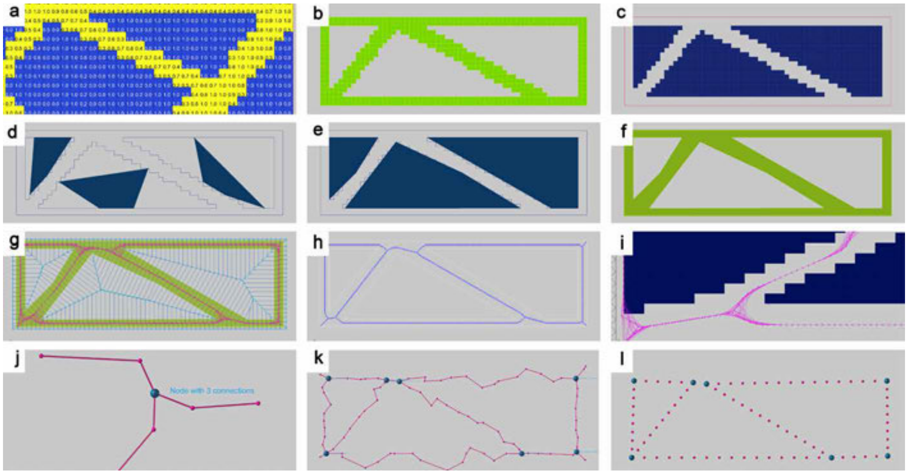


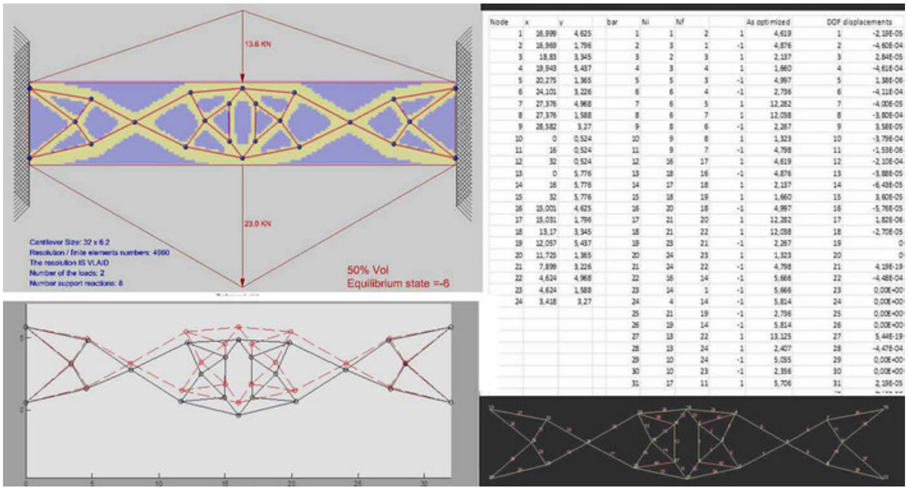
FIG. 3.9 The methods implemented for translating discrete to vector-based geometry with nodes and bars.

In the next step, after joining the negative shapes and retrieving the outer boundary curves, the goal is to transform the jagged edges of these shapes into straight lines extract polygons. This is done through minimizing the difference between the areas of shapes with straight lines from the original one with jagged edges. (FIG 3.9d and FIG 3.9e). This part is mainly done through visual and script based programming in Grasshopper, and Galapagos (evolutionary solver) for finding the shapes with optimum areas. By having the straight lines of the positive shapes (FIG. 3.9f), it would also be possible to develop and apply a skeletonization technique based on Voronoi algorithms (Aurenhammer and Klein, 2000) to get axial curves with similar original topology (FIG. 3.9g). Then by means of a Boolean gate the generated points through skeletonization algorithm can be achievable in a separate point cloud list (FIG 3.9h). After connecting the points to their neighboring, the nodes are those which has three or more connections. Therefore, another algorithm is developed to automatically detect nodes based on the numbers of connected neighbors (FIG 3.9i and FIG. 3.9j). Subsequent to this step another optional procedure is also developed in which the detected nodes would be anchor points of physical spring systems and other points will be stretched while having the fixed nodes as their supports. Therefore, with this method the poly-lines, which are not geometrically straight lines, will be stretched to form the bars.

Using this sub-procedure for all cases would allow us to have a persistent method to retrieve four set of nodes and bards for each of the volume fractions for any parametrically defined design domain with distinct load and support conditions in the first sub-procedure. After having the nodes and bars the structural determinacy of the each vector-based topologies will also be measured in advance through putting the numbers of the bars nodes and supports conditions in static equilibrium.

3.2.3.4 Structural analysis and search for optimal solution [D]

This stage starts with reading the input file in MATLAB with the information on nodes, bars and load conditions from the previous step coming from the Rhino/ Grasshopper. By having this information set for each of the four topologies, a static structural analysis will be run for obtaining local stresses and global displacement of the truss with the initial load and support conditions. Other variables such as material properties and available profiles can also be parametrically defined or extracted from a data set in this stage. FIG. 3.10 presents an overview of this sub-procedure for a beam case. Here, the generated data list store the results that will be used for further visualization and profile assignation in 3D design environment. Further information for evaluation and comparisons for different input parameters and topologies like total volume, maximum and minimum length of the elements can be extracted from the optimum result depending on the design requirements.



Node	x	y	bar	Ni	Nf		As optimized	DOF	displacements
1	16,999	4,625	1	1	2	1	4,619	1	-2,19E-05
2	16,969	1,796	2	3	1	-1	4,876	2	-4,60E-04
3	18,83	3,345	3	2	3	1	2,137	3	2,84E-05
4	19,943	5,437	4	3	4	1	1,660	4	-4,61E-04
5	20,275	1,365	5	5	3	-1	4,997	5	1,38E-06
6	24,101	3,226	6	6	4	-1	2,736	6	-4,11E-04
7	27,376	4,968	7	6	5	1	12,282	7	-4,00E-05
8	27,376	1,588	8	6	7	1	12,038	8	-3,80E-04
9	28,582	3,27	9	8	6	-1	2,267	9	3,58E-05
10	0	0,524	10	9	8	1	1,323	10	-3,79E-04
11	16	0,524	11	9	7	-1	4,798	11	-1,53E-06
12	32	0,524	12	16	17	1	4,619	12	-2,10E-04
13	0	5,776	13	18	16	-1	4,876	13	-3,88E-05
14	16	5,776	14	17	18	1	2,137	14	-6,43E-05
15	32	5,776	15	18	19	1	1,660	15	3,60E-05
16	15,001	4,625	16	20	18	-1	4,997	16	-5,76E-05
17	15,031	1,796	17	21	20	1	12,282	17	1,82E-06
18	13,17	3,345	18	21	22	1	12,038	18	-2,70E-05
19	12,057	5,437	19	23	21	-1	2,267	19	0
20	11,725	1,365	20	24	23	1	1,323	20	0
21	7,899	3,226	21	24	22	-1	4,798	21	4,19E-19
22	4,624	4,968	22	16	14	-1	5,666	22	-4,48E-04
23	4,624	1,588	23	14	1	-1	5,666	23	0,00E+00
24	3,418	3,27	24	4	14	-1	5,814	24	0,00E+00
			25	21	19	-1	2,736	25	0,00E+00
			26	19	14	-1	5,814	26	0,00E+00
			27	13	22	1	13,125	27	5,44E-19
			28	13	24	1	2,407	28	-4,47E-04
			29	10	24	-1	5,035	29	0,00E+00
			30	10	23	-1	2,356	30	0,00E+00
			31	17	11	1	5,706	31	2,19E-05

FIG. 3.10 An overview of analysis for a beam case for one of the translated vector-based topologies.

The fitness criteria in the search process are allowable stress of the bars and global displacement. The search process finds the minimum required cross sectional area from the defined input sets for each of the bar elements and simultaneously checking the allowable global displacement. This part of the process is mainly done implementing a code in MATLAB for cross sectional optimization. Moreover, in order to check the reliability of the process, some results have been compared with the results in the GSA suite. FIG. 3.11 represents an overview for a cantilever that has started from the discrete geometry to vector geometry with nodes and lines in which the cross sectional optimization results are directly used as input data for tubular profile assignment, results in differentiation in the size of each profile.

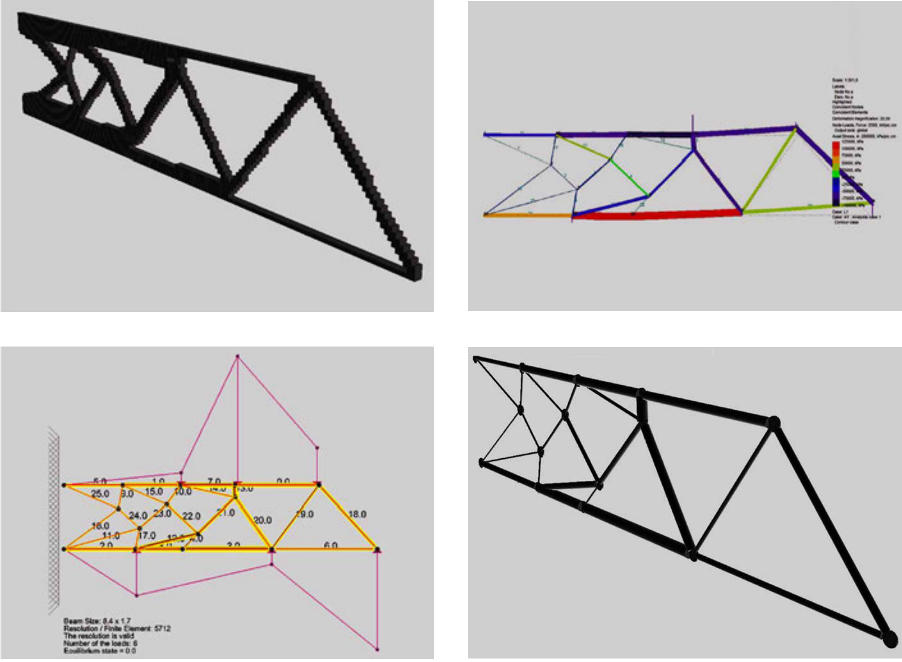


FIG. 3.11 An overview of the last sub procedure with on a cantilever truss under unequal point loads.

3.2.4 Tests and cases

In addition to separate examinations inside each of the sub-procedures to improve and test the functionality and generalizability of the applied methods are conducted, two A-to-Z cases have been tested which will be briefly reported and shortly discussed here. First one is a cantilever case with one point load at its end (FIG. 3.12). As it is illustrated here the results of optimization based on the initial design domain and load conditions are translated to a set of optimized truss structure. In this case and for any of its variation, besides the topological difference between the final topologies, the corresponding information sets pertaining to the structural performance and geometric properties of elements are also available for further evaluation and comparison.

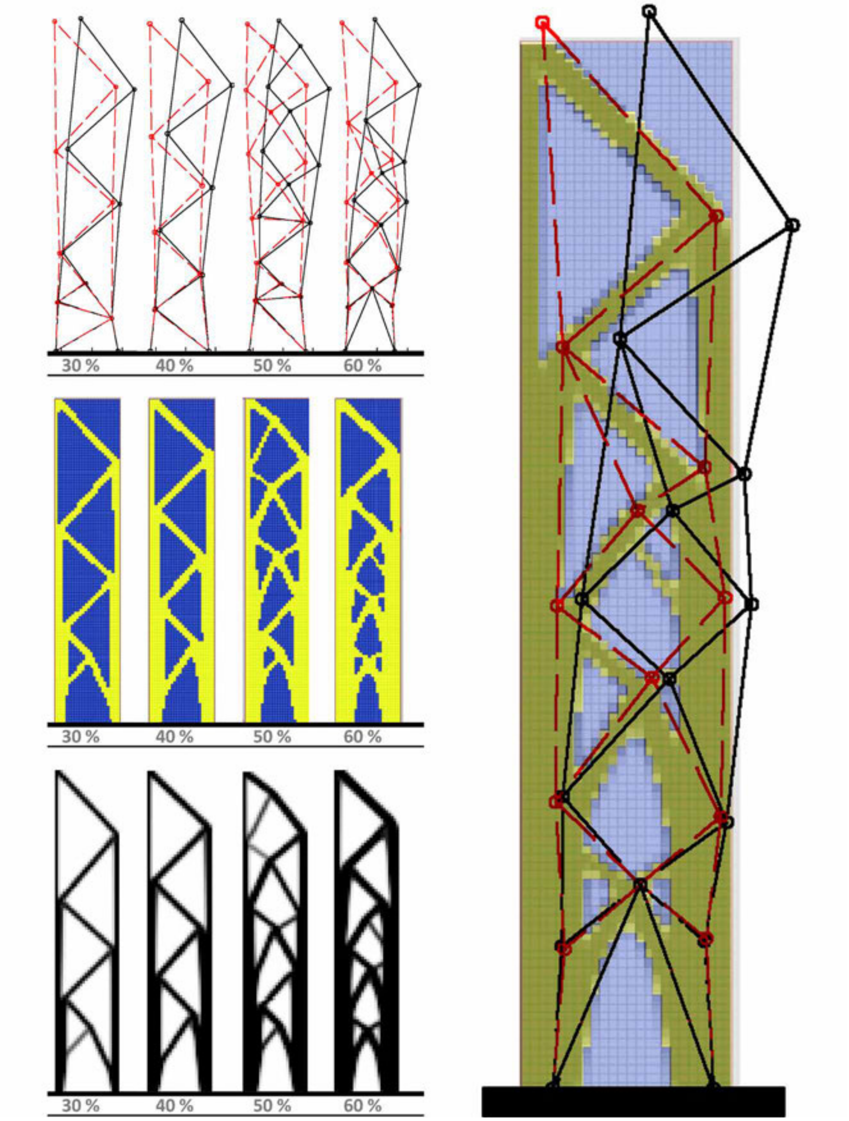


FIG. 3.12 An overview of tests on a cantilever case, Left: 30% to 60% volume fractions translated from finite or discretized to continuous or vector-based geometries, Right: An overlay of three methods on top of each other for a 60% volume fraction case.

The second case is a beam but in this case within a real world background design scenario for further validation of developed methods. This exercise builds upon a featured connecting bridges based project by Steven Hall Architects (FIG. 3.13).

TOC

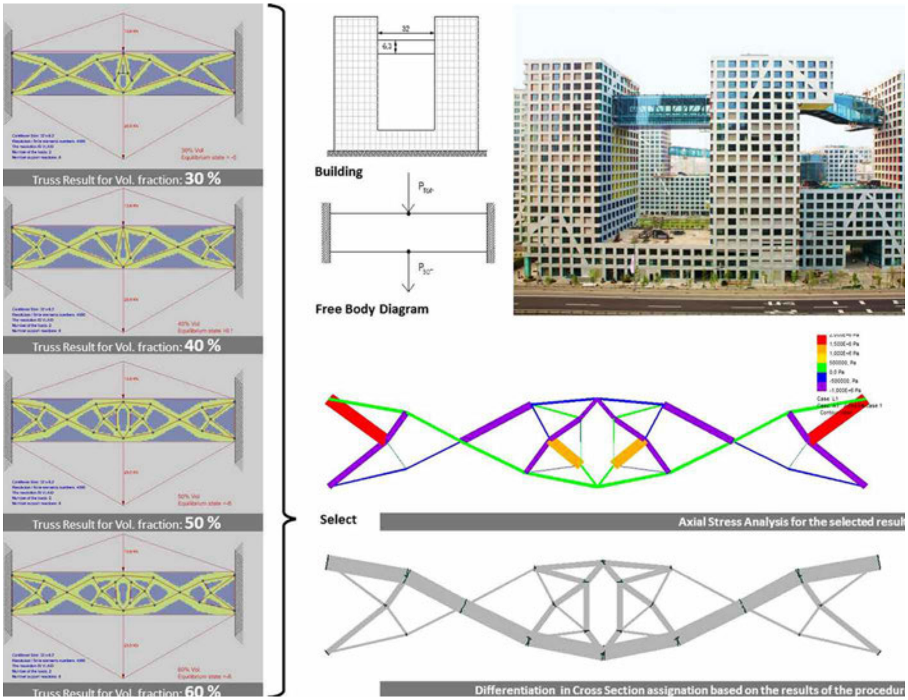
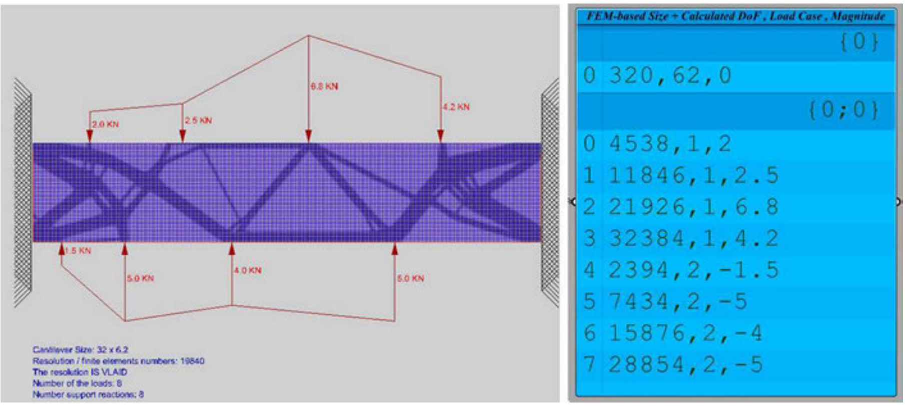


FIG. 3.13 An overview of a case study to facilitate a performance driven design methodology for bridges in a project like linked hybrid by Steven Hall architects. Photo from URL [11].

One of the benefits in this case is that there are similar design problems but with different sizes and proportions. This means that parametrically defining the initial design domain while having concurrent performance measurements would add to the efficiency of the design process itself. Additionally, as it is illustrated in FIG. 3.13, for each design domain with different load conditions we have four optimized topologies in vector format with nodes and bars that can be translated to steel, wood or any other profiles. Moreover, based on cross sectional optimization we will have a differentiation in profile properties which might be a source of new performance driven design idea for designers. In other words, in addition to automatic evaluations and comparisons based on the generated and stored quantitative information, the developed design system might also suggest some implicit hints based on the visualized information and rough performance estimation. For instance in this case the architects might decide just to have one support for the roof of the bridge at a specific coordinate and have lateral beams to support the walking deck at every six meters. With these presumptions, based on what the designer perceived from the way the algorithms lead to optimum solutions, he or she could alter the input parameters, go back to the very beginning stages, and find the optimum result with required conditions and acceptable proportions simultaneously (FIG. 3.14).



```
Cantilever Size: 32 x 6.2
Resolution / finite elements numbers: 19840
The resolution IS VLAID
Number of the loads: 8
Number support reactions: 8
```

```
{0}
0 320,62,0
{0;0}
0 4538,1,2
1 11846,1,2.5
2 21926,1,6.8
3 32384,1,4.2
4 2394,2,-1.5
5 7434,2,-5
6 15876,2,-4
7 28854,2,-5
```

FIG. 3.14 A feed-back attained through parametrically re-defining the initial conditions and the design domain for a similar case to retrieve another optimized topology plus needed geometric and non-geometric information for next stage.

3.2.5 Discussion

In terms of design methodology, the goal of this research is to address the integration of performance measurement and evaluation modules in a parametric design system by opening the black box of topology optimization, making it more traceable, specific, and applicable by designers, particularly at the scale of architectural design. Proposed algorithmic-design-information-exchange scenarios between different phases of the design procedure parallel to CAD and programming platforms have been considered and tested as an appropriate approach for this goal. Behind the benefits that can be implicitly and explicitly enumerated for this specific case, a conclusion is that knowledge integration in parametric design needs customized scenarios for integration and structuring of geometric and non-geometric information. The extent to which extraction and visualization of this information are needed depends on one hand on the user's knowledge as a designer, and on the other hand, on the design requirements and goals for a specific design problem.

From a design technology point of view, in addition to developed algorithms for solving the issues on interoperability or data exchange, what was peculiarly challenging in this research was developing and customizing a method for translating finite or discrete geometry to vector based and continuous topology. It is possible to deduce that the translation procedure can be considered as a more generic issue in parametric and performative driven design strategies. In addition to the process of FEA-based topology optimization methods in the realm of structural design, FEA methods are omnipresent in the basis of many simulation techniques. Considering this fact, it might be beneficial to facilitate performance driven design methodologies with methods, tools and strategies for such translational procedures. The implementation of skeletonization and node finding methods can be considered as some of these cases for such translational algorithms. Future cases need to be defined with similar methodological schemes to test their generalizability and functionality.

3.3 Production of Porosity: A case study on Fabrication Intelligence and Robotic 3D printing[2]

Materially Informed Design to Robotic Production

A Robotic 3D Printing System for Informed Material Deposition

ABSTRACT This paper presents and discusses the development of a materially informed Design-to-Robotic-Production (D2RP) process for additive manufacturing aiming to achieve performative porosity in architecture at various scales. An extended series of experiments on materiality employing robotic fabrication techniques has been implemented in order to finally produce a prototype on one-to-one scale. In this context, design materiality has been approached from both digital and physical perspectives. At a digital materiality level, a customized computational design framework has been implemented for form finding of compression only structures combined with a material distribution optimization method. Moreover, the chained connection between the parametric design model and the robotic production setup has enabled a systematic study of specific aspects of physicality that cannot be fully simulated in the digital medium. This established a feedback loop not only for understanding material behaviors and properties but also for robotically depositing material in order to create an informed material architecture.

KEYWORDS Informed Design, Robotic 3D printing, Porosity, Material Architecture, Material Behavior.

---

[2] The case study on the production of porosity integrated into this chapter titled has been previously published in the following peer-reviewed paper (Mostafavi and Bier 2016). Further information on this project is also accessible in another publication (Mostafavi, Bier, Anton, and Bodea, 2015) and a video, titled Continuous Variation - design to the production studio, which is accessible on the URL link [6].
Mostafavi, Sina, and Henriette Bier. 2016. “Materially Informed Design to Robotic Production: A Robotic 3D Printing System for Informed Material Deposition.” In: Reinhardt D., Saunders R., Burry J. (eds) Robotic Fabrication in Architecture, Art and Design 2016. Springer, Cham. https://doi.org/10.1007/978-3-319-26378-6_27.

3.3.1 Introduction

Materially informed Design-to-Robotic-Production (D2RP) systems explore the extents to which rapid and flexible robotic fabrication methods can inform and enhance established generative design to materialization and production practices.

In the case study of this paper, the focus is on experimentation with optimized material deposition for a compression-only computationally derived topology. The study has explored the possibilities of designing and fabricating material architectures with various levels of porosities, ranging from architectural (macro) to material (micro) scales. By employing performative and generative design methods, industrial robotic production techniques and material science experiments, the D2RP aims to close the loop from design to 1:1 scale fabrication. With this goal, the main research components of the presented case study deal with specific aspects of materiality in relation to design computation and robotic 3D printing. In this context, the chosen fragment of a computationally designed pavilion required translation of the optimization results from a finite geometry into a continuous robotic path for material deposition in order to create an applicable material architecture.

The integration of physical material properties into design by means of digital design interfaces and computational design methods has been explored in both practice and academia (Inter al. Borden and Meredith 2011; Kolarevic and Klinger 2008; Gramazio and Kohler 2008). The historical survey with respective related cases and paradigms is not within the scope of this paper but relevant to the goals of the presented case. In order to position this project in this larger field of research two major types of approaches have been identified. One presents cases in which, in order to study design materiality, the design system relies only on virtual modeling, simulation, analysis, and abstraction of physicality through implementation of certain computation methods such as Finite Element Method (FEM), Computational Fluid Dynamics (CFD), Particle Systems, etc. The other one presents material experimentations, and the design system focuses mostly on constraints and potentialities of certain material and/or fabrication method that is integrated into digital modeling platforms, i.e. parametric design models. The proposed D2RP system establishes a feedback loop between the two approaches. In order to achieve this goal, at digital materiality level, a systematic and chained strategy for design information exchange is established by designing and implementing a customized parametric form finding system for compression-only structures combined with topology optimization. At physical level, the direct connection to the robotic production system, in addition to improving the production method has led to the direct study of certain aspects of physicality that cannot be fully modeled inside the digital design platform. Therefore, the production system becomes not only a means of fabrication but also simulation.

TOC

Recent advances in both robotics and 3D printing have introduced new approaches towards architectural materialization and production. Considering materiality and architecture at multiple scales, there are a few projects that successfully bring the two together. In some examples a scaled-up printing machine is employed to horizontally deposit layer-by-layer building material (Inter al. Khoshnevis 2004; Khoshnevis et al. 2006; Kestelier 2011; Dini, Nannini and Chiarugi 2006). The explored and presented robotic 3D printing project proposes an alternative method of material deposition aiming to create a multi-dimensional material architecture (FIG. 3.15). This is achieved while taking the behaviors and properties of the implemented material into consideration, which in this case is ceramics, as well as by integrating material optimization routines in the D2RP system.

FIG. 3.15 3D model continues robotic single robotic path and emergent material architecture.

D2RP consists of four main research components: Design computation, tooling/production set-up, robotics, and materiality. Each set of experiments and design exercises presented in the following section, explores possibilities of integration by establishing feedback loops between the four components. Parallel to the lab-based explorations for the development of the D2RP a studio design project was considered as a pilot case study. In this project architectural and material porosity at various scales is considered as the main design driver (FIG. 3.16).

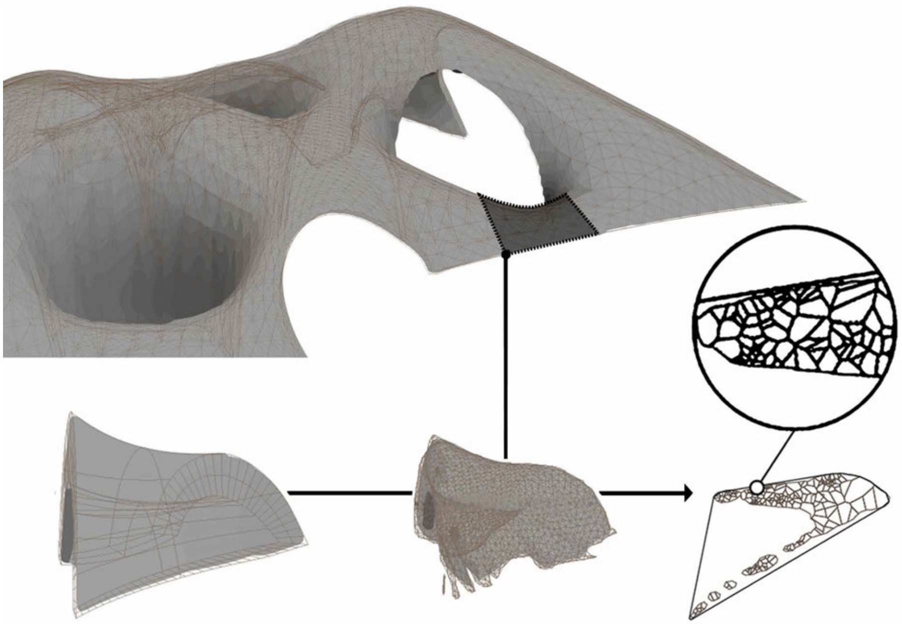


FIG. 3.16 D2RP explores multi-scalar porosity at building, component, and material levels.

3.3.2 D2RP Development

The D2RP proposes a roadmap for development and improvement of a robotic 3D printing technology for fabricating 1:1 building components. The roadmap includes three initial case studies, concluding with creating a direct link between design and production: multi-colored light robotic 3D printing, robotic pattern studies, and ceramic robotic printing.

Multi-colored light robotic 3D printing involves mounting a color changing light source on the robotic arm. This project addresses the connection established between motion and information extracted from the virtual 3D model. Being able to study the three-dimensionality of robotic motion contributed to developing a new approach to 3D printing, different from the slicing-in-layers printing technique. This provided possible directions for defining a 3D printing method, in tune with the structural characteristics of the final prototype.

The study of robotic motion defines the boundaries of the digital design-space in relation to the physical solution-space. This informs the parametric setup with ranges of reachability and optimized orientations. It also contributes to being able to maximize the overall space used. In addition, by numerically controlling the on-off light pattern and light colors by means of an Arduino micro-controller, the team reached the goal of further extending design possibilities in such a way that multiple materials can be deposited at certain coordination based on the information extracted from the virtual 3D geometry. As the first step, any given curve, in digital, is reproduced, in physical, with multi-colored light curves captured by means of long exposure-time photography. Later this approach is tested on the compression-only designed pavilion represented by a network of curves (FIG. 3.17).

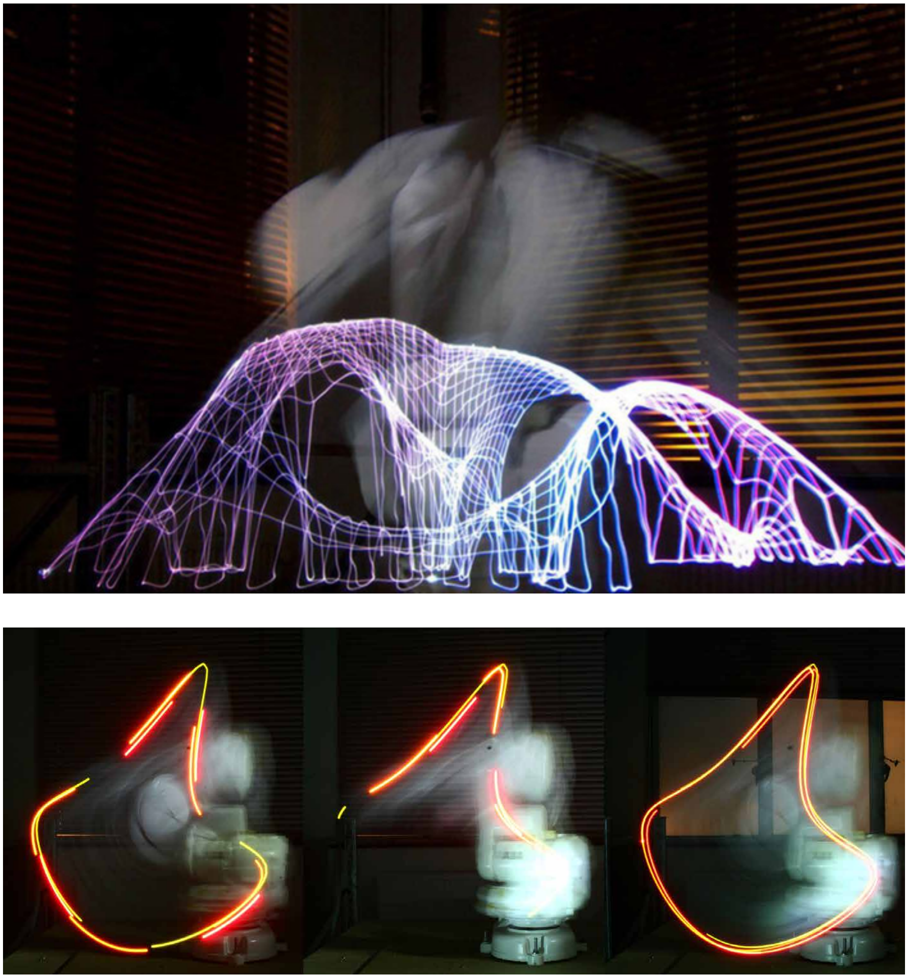


FIG. 3.17 Multi-colored Robotic 3D Light Printing.

As part of the second set of preliminary studies, the robotic pattern project focuses on drawing geometric patterns that explore variation in densities and resolutions to reach the desired porosity. This informed the design of robotically controlled routines for material deposition to reach a functionally graded structure (Oxman, Keating and Tsai 2011). The established parametric system, derived from these experiments, involved size of the overall shape, thickness of nozzle for material deposition, number of targets to describe the robotic motion and the method of approaching defined targets. As a consequence, the team formulated two categories of material deposition: Continuous flow and on/off numerically controlled flow patterns (FIG. 3.18).

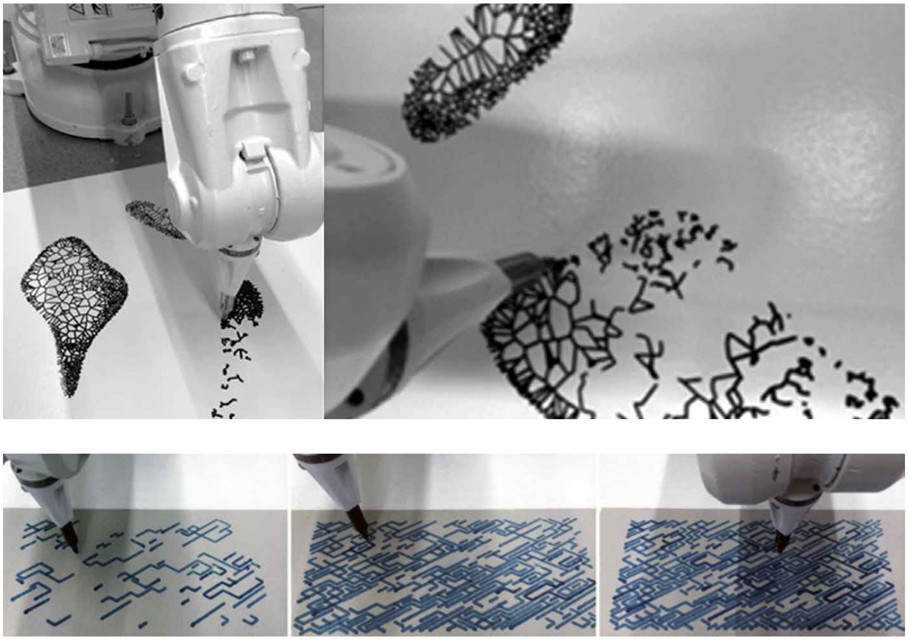


FIG. 3.18 Differentiated porosity tests at material/micro scale (Top), Pattern and material architecture studies: on-off material architecture tests (Bottom).

The ceramic robotic printing explores possibilities of production of 3D printed building parts and establishes a production method where all parameters are calibrated for the developed physical set-up. The team designed an extruder connected to an end-effector mounted on the head of a robotic arm, where the material source was exterior to the robotic arm to maximize the freedom of movement, in order to achieve an optimum multi-dimensional material-architecture. Initial experiments range from simple layer-by-layer material deposition to study material flow to 3D dimensional printing on doubly curved surfaces (FIG. 3.19).

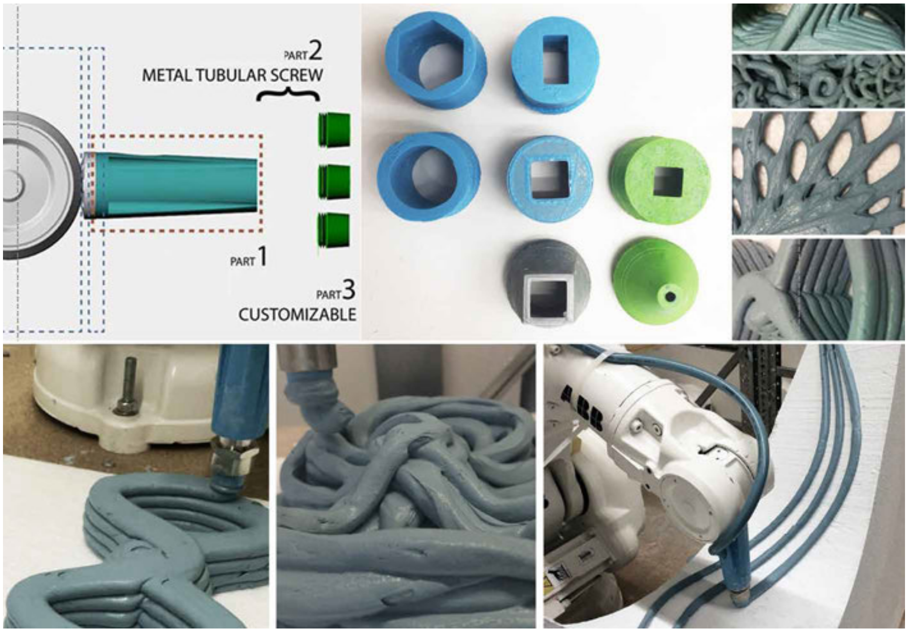


FIG. 3.19 Robotic 3D printing: Nozzle/resolution customization, tests on curved surfaces.

Considering the fact that natural materials are not fully predictable several material properties like plasticity, viscosity, flow rate and short-term material behavior were investigated and documented at different robot-motion speeds in order to provide complete information sets for the next prototyping phase.

3.3.3 Design and Prototype

In order to develop a coherent computational design system specific to this project, the first step was to implement methods for form finding of compression-only structures, derived from the innate characteristics of the material. In addition to eliminating tension forces in the derived topology, this part of the design system was implemented as a parametric strategy to define the porosity at macro or architectural scale to fulfill certain functional and locational requirements. Furthermore, in order to achieve the micro porosity level, a finite element method for material distribution optimization was implemented on a part of the designed pavilion. The optimization also considered local and global load and support conditions. To implement a generic and repeatable method on other parts of the topology, the challenge was to be able to parametrically change the method of finite-mode geometric representation like point cloud and mesh to a vector based or NURBs (Non-Uniform Rational Basis-Spline) geometry. This was achieved by applying a segmental system in the very initial topology, retrievable at different stages of form finding and parametric geometric transformation (Mostafavi, Morales and Biloria 2013; Mostafavi and Tanti 2014). By applying the computational design system several configurations were generated, in each distributing the compression only material where needed and as needed, while taking the structural performance at both macro and micro scales into consideration.

The challenge of the next step was to materialize these differentiated densities by creating unified topologies that express structural loads consistent with the design approach and robotic fabrication potentialities and constraints. At this stage, various algorithmic form finding and optimization techniques, mostly in the Rhino-Grasshopper platform and Python scripting-language, were applied. This allowed the systematic exploration and evaluation of design alternatives in the design-solution space, eventually providing the required information for production, path generation and kinematics simulation with the ABB-Robot studio. Simultaneously, the initial material experiments and information sets informed the design process, design materiality and robotics. This was achieved through step-by-step documentation of a series of purposeful design-to-robotic production experiments with fixed and variable parameters. Specific to this project, the resulting dataset provides information on the possibilities of the developed D2RP system for robotic ceramic 3D printing, such as maximum angle of cantilevering, maximum length of bridging material without supports, minimum and maximum size of the nozzle, material flow, motion speed, etc.

For production purposes, the topology of the pavilion was sub-divided into unique components. As the research progressed it became apparent that due to the significant variety of customized building components featured in the design, the robot manufacturer's software functionality needed further customization. For this purpose, a link between the design and the simulation environments (Rhinoceros platform and its add-ons) and the rapid code interpreter of Robot Studio has been implemented. This direct link between the design model and robot controller enabled the implementation of a greater range of unique, longer, continuous tool paths (FIG. 3.20).

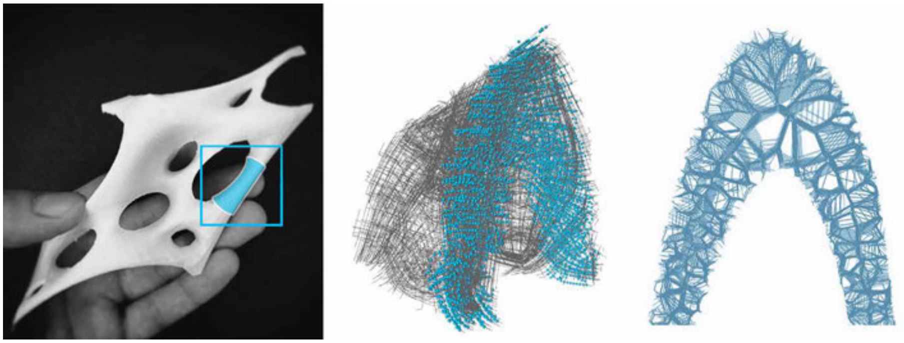


FIG. 3.20 Left to right fragment chosen for 1:1 fabrication, informed point cloud chosen fragment, the computed continuous curve as toolpath.

As a construction material, clay-ceramics is commonly used for compression-only structures. The structures based on compression perform through stability due to significant mass and specific geometry. What the study aimed to prove was that by controlling the geometry and the material deposition, compression structures could become lighter, and significantly improve their material cost and their thermal insulation performance. A way of achieving material deposition optimization is by controlling the parameters of the production setup. This is briefly described as follows: The extruder system designed and built by the D2RP team manages a plunger-based mechanical extruder of a paste of ceramic-clay, water and a specific water-based color pigment that increases gluiness. The numeric control of clay extrusion was experimented and valuable results for dynamic extrusion were recorded, while implementing a discontinuous porous pattern. But due to shifting research objectives, only continuous clay extrusion was used for the fabricated prototype. Therefore, a custom design routine was developed in order to extract a continuous motion path to generate the designed material architecture.

To achieve continuous material deposition, similar to the challenge of translating mesh to NURBs in macro scale, in micro level a generic parametric system is developed to translate the discrete result of optimization to continuous curves (FIG.3.21). In brief, the method involved picking a starting point and recursively searching in the extracted point cloud to generate a continuous spline. From topological and computational point of view, this helped the system to directly and efficiently provide an applicable tool path, considering material properties and behaviors and hardware-software specifications of the developed D2RP system.

TOC

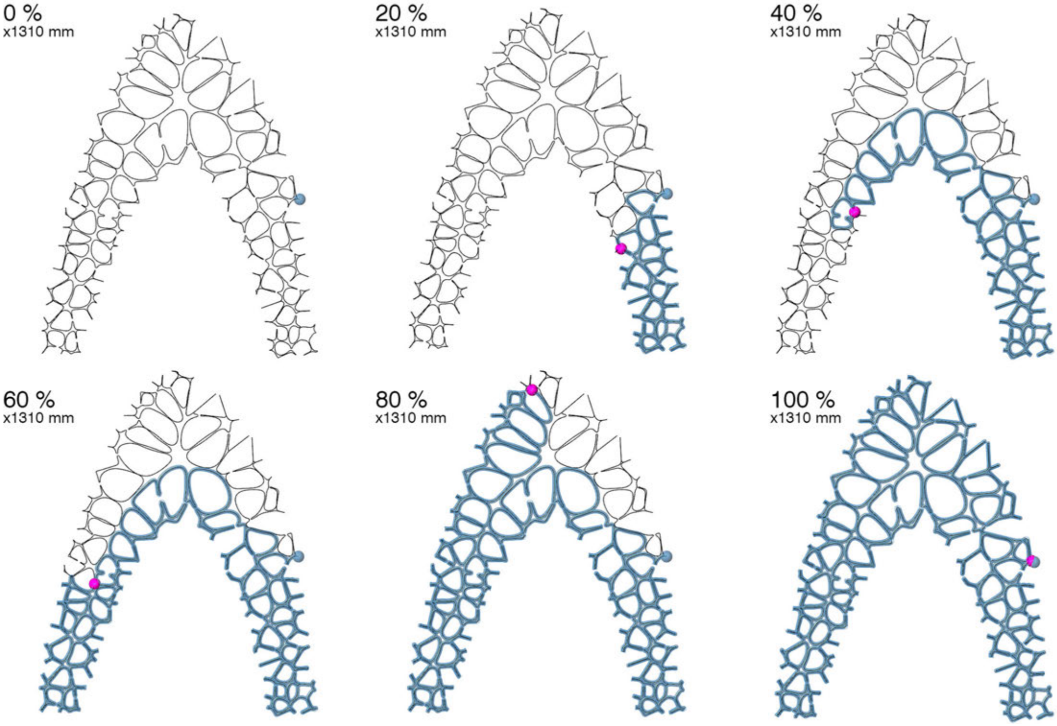


FIG. 3.21 Deposition process on one of the driven continuous curve from the discrete result.

controlled through line-size and nozzle customization at the tip of the robot end-effector. We experimented with nozzles of various profile sizes and shapes. For the fabricated prototype, a nozzle featuring a square 1 cm^2 aperture was used. Finally, within the study's agenda of 1:1 fabrication and architectural performance aims, it can be concluded that the prototype achieves both improved 3D printing speed and reliability.

3.3.4 Prototype

According to the design brief, the architectural object was relating to the surrounding environment via pores of varying in size according to functional, and structural requirements. The fabricated fragment explores these connections, materializing a piece of structurally optimized compression only urban furniture at 1:1 scale (FIG. 3.23 and FIG. 3.24). While developing a customized design-to-production setup, the team achieved optimization in motion path generation.

Common 3D printing techniques employ non-differentiated routines for slicing and ordering material layers into motion paths. The prototype was produced embedding fabrication potentialities and constraints into the design. It must be noted that, although the computational 3D model comes close to the actual prototype, the two entities remain different mainly due to emergent material properties. Differences between virtual and material exemplify emergent aesthetics inherent to the material behavior. The emergent aesthetics inherent to the prototype are as much due to the 3D layering technique as to how material extrusion varies along the path (FIG. 3.22).

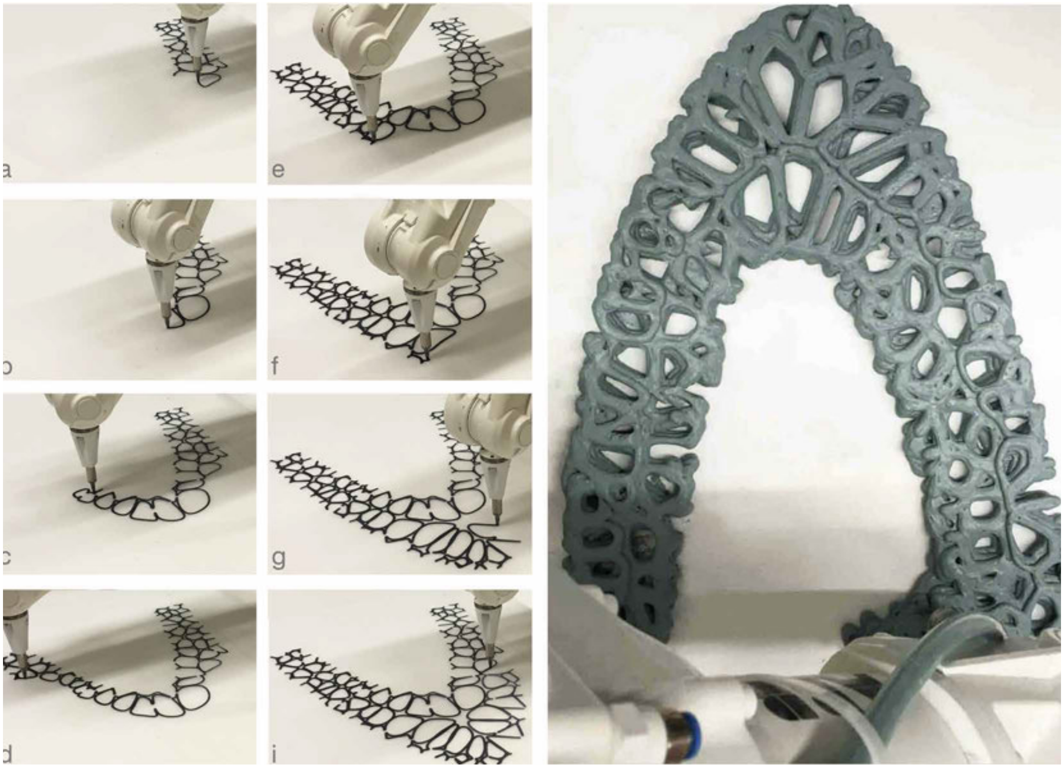


FIG. 3.22 Left: Test of the material deposition method (left), robotic 3D printing of the one-to-one prototype (right).

3.3.5 Conclusion and Discussion

Advancements in robotic building as presented in this paper indicate that future building systems are customizable and increasingly robotically produced and operated. The presented D2RP system demonstrates that informed porosity in additive manufacturing is relevant for the development of materially informed architecture. Porosity at macro (building), meso (skin), and micro (material) scales implies optimization of spatial configurations and material distribution. Using this approach we strive not only to control mass-void ratios but also to achieve an integrated design, from overall building configuration to the architectural material. In the context of the third and fourth industrial revolutions (Anderson 2012), the flexibility of such D2RP system can be understood with respect to the interaction between designers, users, and NC systems aiming to produce highly customizable and on-demand building components. Robotic Building (RB) eliminates the current problem of missed optimization opportunities due to a fragmented and sequential process of architecture— engineering—manufacturing. In a larger context, the additive D2RP approach presented in this paper is part of the Robotic Building (RB) project, which focuses on linking design to materialization by integrating multiple functionalities (from functional requirements to structural strength, thermal insulation, and climate control) in the design (Bier 2013, 2014) of building components.

Scaling up the technology of 3D printing from object to building was the specific goal of the presented case study. This was achieved by integrating the technology in an informed, chained design-to-production system, in which the 3D printing and robotics are not only ways of manufacturing but also methods and tools for simulation and testing of certain aspects of materiality, which lead to new opportunities for design exploration and creation. For the authors, it was important to develop the technology not as an isolated node but as an integrated working-operating module connected to a real-life design problem. The main consideration in architecture and building construction is that the factory of the future will employ building materials and components that can be robotically processed and assembled. This requires the development of multi-materials, -tools, and -robots for D2RP processes that will be implemented incrementally in the next phases of this research.

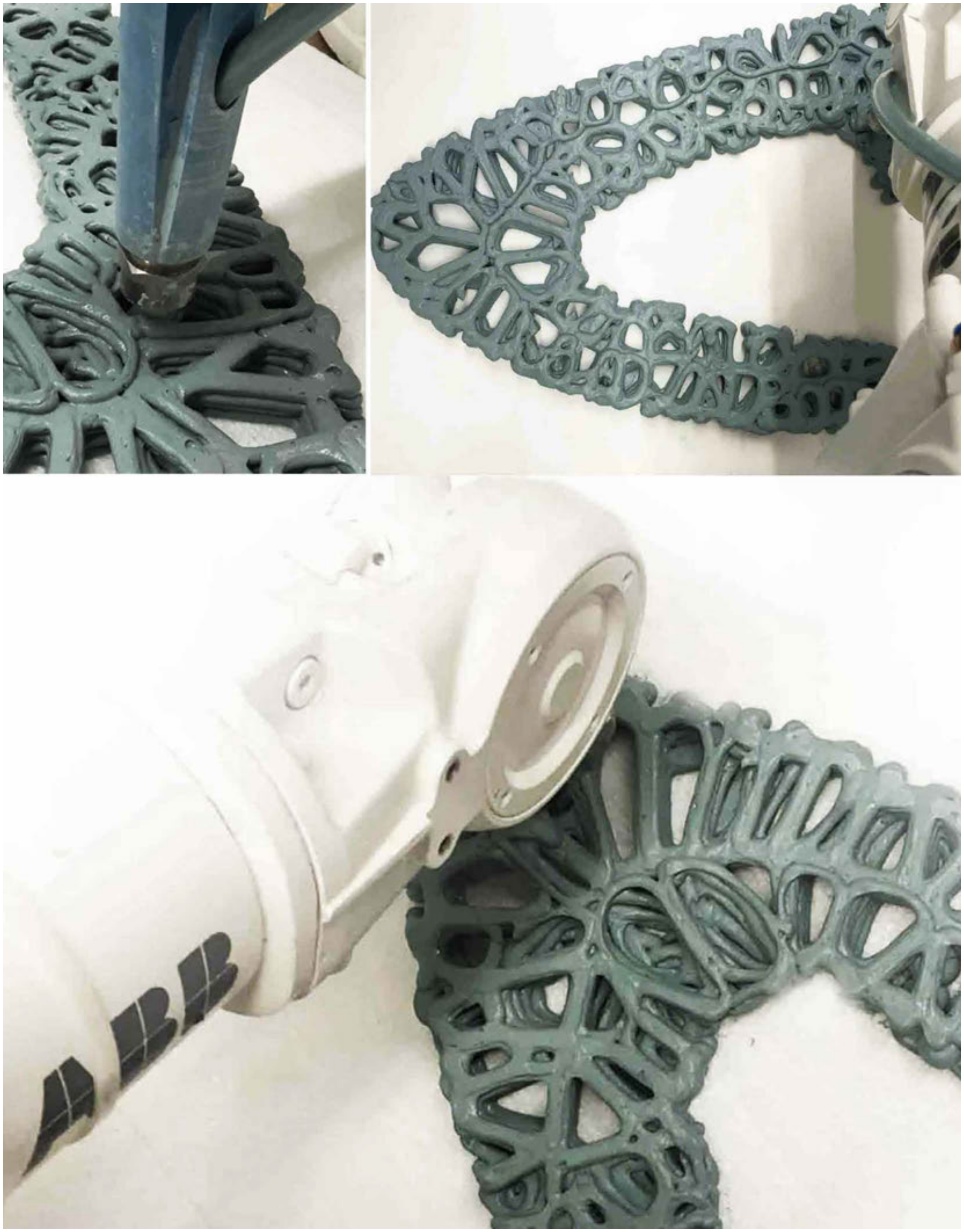


FIG. 3.23 Close ups of continuous Robotic 3D printing process of porous structures.

TOC

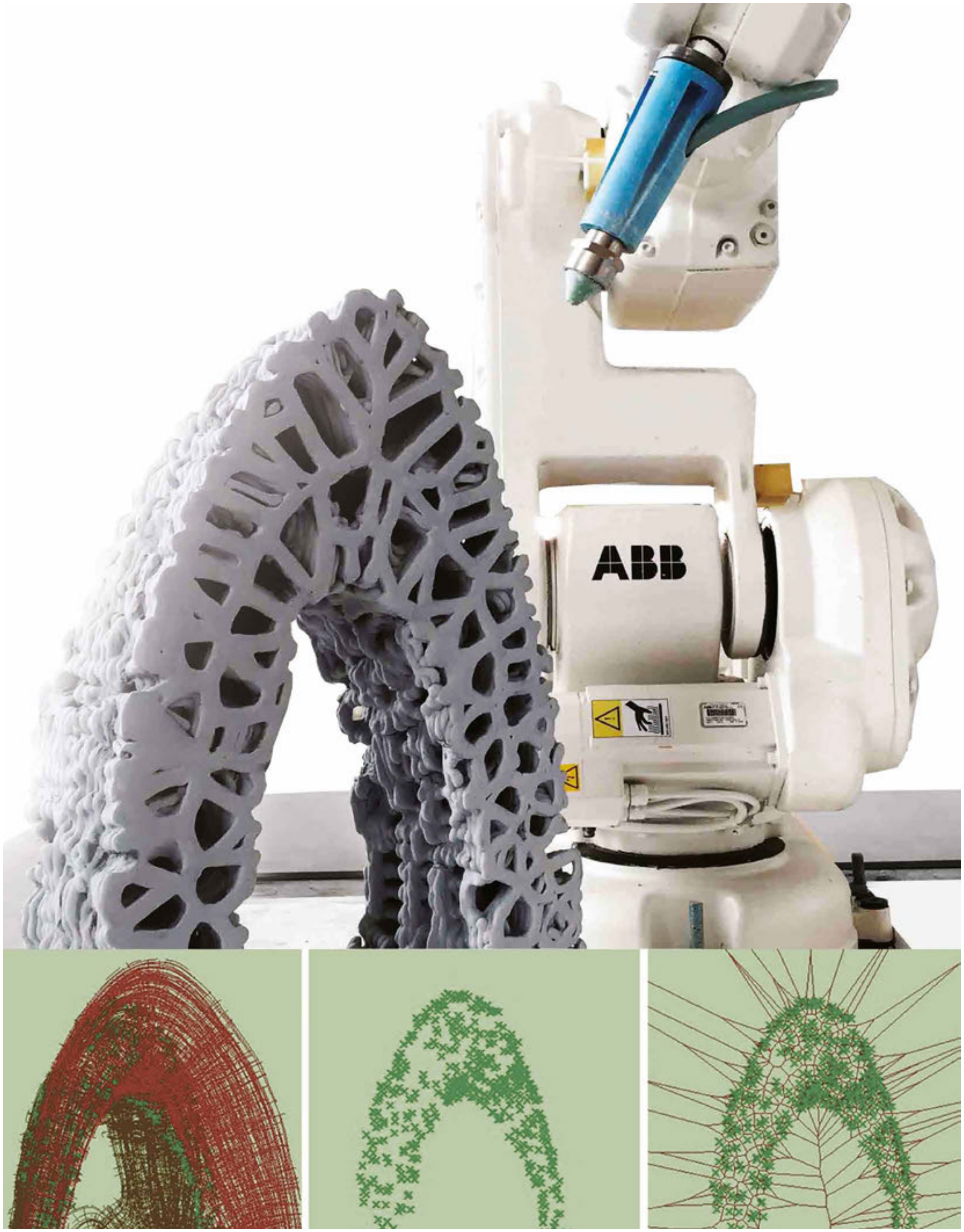


FIG. 3.24 One-to-one prototype of the robotically 3D printed structure (top); Discrete 3D point cloud generated based on the FEA method, to be then translated to a continuous robotic 3D printing tool path.

TOC

3.4 Chapter Conclusion

Focusing on computational and fabrication intelligence in design materialization processes, the objective of this chapter is to present the developed workflows and methods for computation and production of porosity. The two central case studies are one on material computation and design information exchange and the other one on developing and applying robotic 3D printing within architectural design workflows.

While both cases are mainly centered on material or micro-to-meso architectural scales with structural considerations as the main performance criterion, the methods of computation and production of porosity in this chapter can be extended and become applicable for larger scales. By extendibility, we mainly refer to the method of integrated design materialization systems for computation and production of porosity in different scales. Based on the research outcomes of these two cases, the findings on porosity in relation to the previously discussed definitions and frameworks in chapter two are summarized as follows:

1. **Porosity / Design Systems, Computation and Automation:** Developing integrated design to production systems to materialize porosity for architectural applications and lightweight structures requires the integration of multiple disciplines such as architecture, structure, material science, computation, and robotics. These integrations demand a systemic design of decision-support systems that are beyond the available tools and methods; hence they can be customized for different applications. Interoperability between different computation design platforms and the programmability of robotic production setups allows for higher customization levels.

2. **Porosity / Topology and Geometry: Tectonics and Component:** A new level of resolution of porosity can be computed and produced using the developed HI-ARM methodologies as prototyped in the presented case studies. This new level of detail requires advanced computational geometric modeling where we may go beyond a purely surface-based approach to a more volumetric point cloud or voxel-based geometric systems. This may radically change the definition of conventional architectural elements such as walls or windows, where the thresholds between mass and void are blurred in multiple scales.

3. **Porosity / Digital-Physical Integration:** The second case study in this chapter on Robotic 3D printing of porous structures exemplifies the iterative process of developing an integrated design-to-production system, where a direct translation of

digital representation to numerically controlled physical production is tested. This immediate link between digital design and robotic production is a crucial component in the materialization of porous structures. Working with natural materials such as ceramics and learning from the process and the outcomes, through systemic documentation and objection of result establishes feedback loops which then are used to inform and update the digital model in particular or design in general.

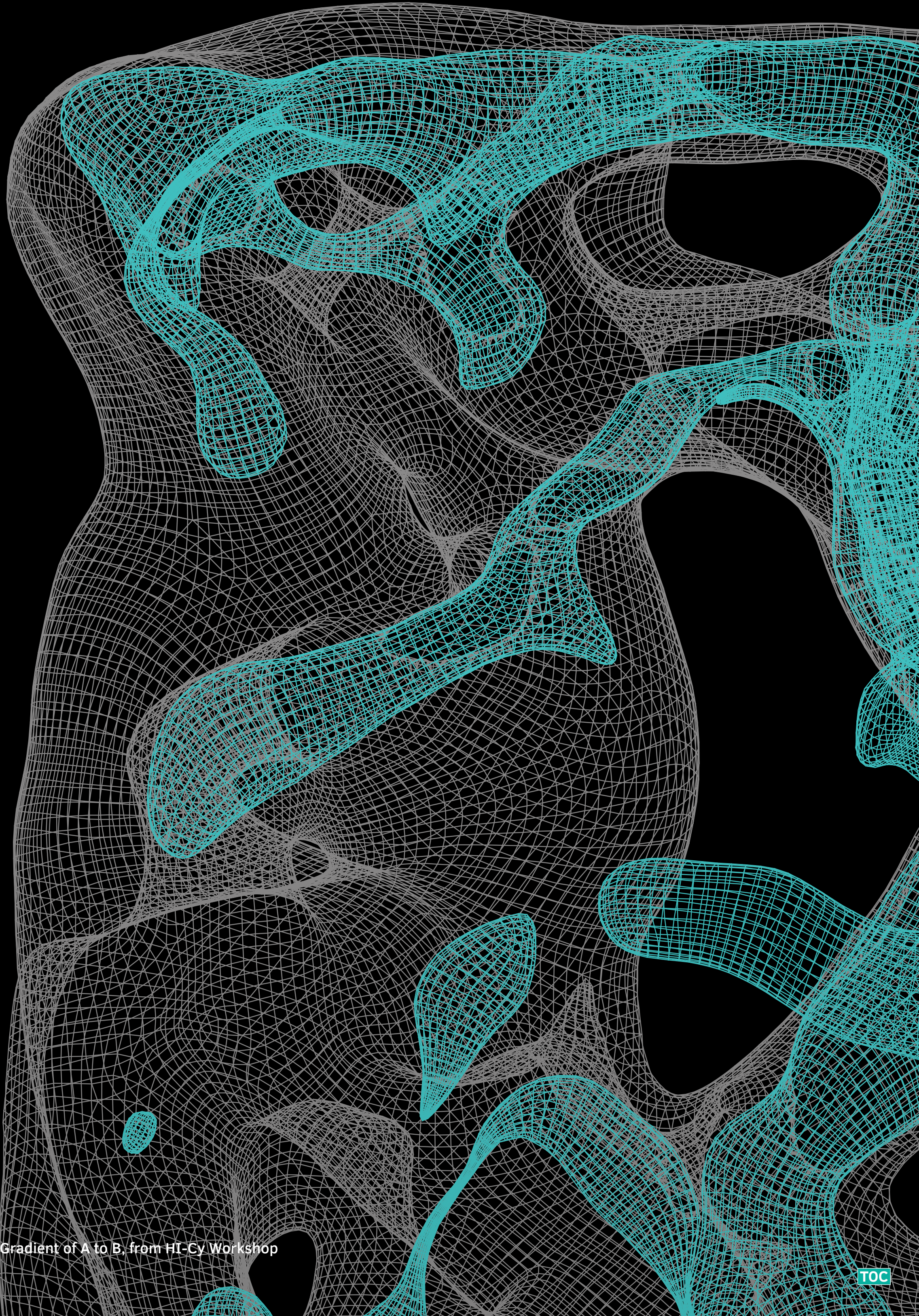
4 **Porosity / Performance and Variation:** Multi-scalar computation and production of porosity in architectural design materialization processes provide opportunities for making building systems structurally, environmentally, and functionally more efficient. While the numerical evaluation of this efficiency is fundamental to develop a relevant and applicable design-to-production system, yet being able to facilitate computation of porosity itself is a crucial area of research investigation. The two cases studies exemplify how porosity as a design materialization strategy can be computed and produced for better structural performance while other performance criteria can also be considered in justification and evaluation of porous systems with a high level of producible topological complexity and geometric variation.

5 **Porosity / Rationalization and Approximation versus Simplification:** Applying Integrated Computational Design Fabrication Intelligence to materialize porosity may result in geometrically complex solutions. The producibility of such porous outcomes may not only be judged based on the resulting visual complexity. Therefore, the role of customized computational design to robotic production workflows is important to evaluate and improve the constructability of the design. Moreover, each fabrication method, such as additive manufacturing, may require different strategies for generating rational or affordable toolpath for production, which may result in complex geometries and emergent material qualities.

6 **Porosity / Industrial Revolutions and Interdisciplinarity:** A crucial dimension of making the computation and production of porosity applicable in broader industrial and social contexts is achievable through introducing interdisciplinary approaches in design and building processes. In the context of this research, as it is exemplified in the two case studies, innovation in material and structural design play essential roles in the informed materialization of porous building systems.

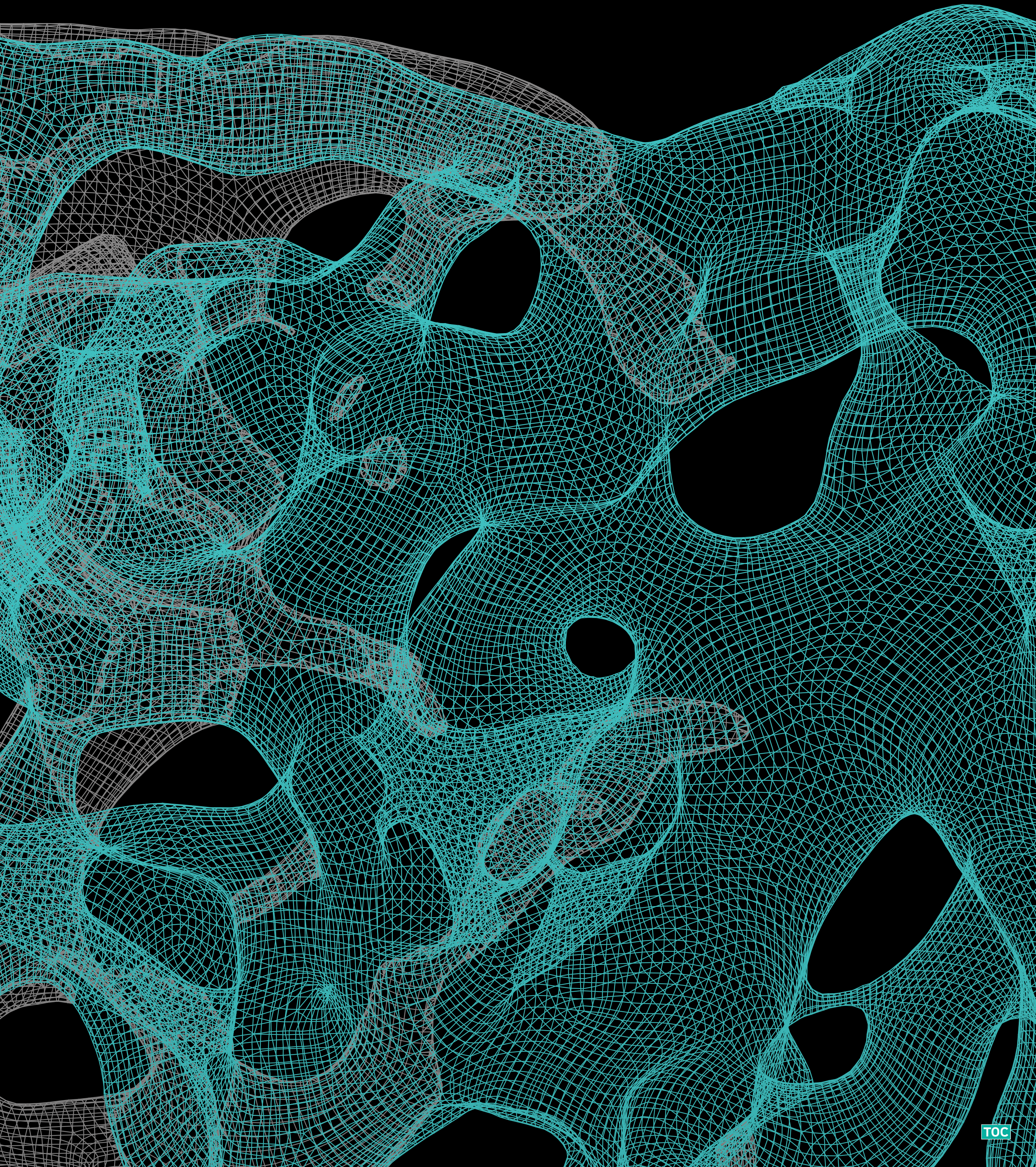
While the three main subjects in this research are porosity, hybrid, and assembly and they can be studied independently and read in a non-linear way, porosity is introduced and researched as the first subject as it is applicable and valid when it comes to the other two topics of hybridity and assembly. Therefore, most of the research findings and the developed methodologies are naturally a part of the following projects in chapters four and five.

TOC



Hybrid Material System: Gradient of A to B, from HI-Cy Workshop

TOC



TOC

4 HYBRIDITY: Multi-Mode and Multi-Material

ABSTRACT

Building upon the previously developed methodologies in the porosity chapter, this chapter addresses hybridity from two main angles. Firstly, the hybridization of robotic fabrication methods or multi-mode robotic production addresses the challenges and potentialities of integrating multiple robotic production techniques. Secondly, hybridity refers to multi-materiality, where two or more materials are combined, modeled, computed, and produced using integrated computational design to multi-mode production systems. With a series of short case study descriptions and experiments on hybridity, the introduction discusses Computational Intelligence, Material Intelligence, and Fabrication Intelligence as bases of multi-mode materialization of multi-material systems. The chapter's main body, Materializing Hybridity in Architecture, presents three core case studies in more detail: Hybrid Cork, Hybrid Concrete, and Hybrid Silicone. The cases exemplify multi-mode robotic production methods such as subtractive-subtractive using Robotic Hot Wire Cutting and Robotic Milling or Subtractive-Additive using Robotic Hot Wire Cutting and Robotic Milling combined with Robotic 3D printing. The chapter concludes with a set of key findings and propositions on hybridity, which are centered on the definitions and frameworks of HI-ARM.

KEYWORDS

Hybridity, Multi-Mode Robotic Production, Multi-Materiality, Subtractive-Additive, Robotic Hot Wire Cutting, Robotic Milling, Robotic 3D Printing, Hybrid Cork, Hybrid Concrete, Hybrid Silicone, Hybrid Chair.

4.1 Chapter Introduction

There are several reasons why the built environment is required to consist of multiple materials as for instance buildings consists of various systems ranging from bare structure to Heating Ventilation and Air Conditioning (HVAC), Mechanical, Electrical and Piping (MEP) and drainage, etc. Hence, architectural design materialization processes need to address multi-materiality both digitally and physically on different scales. Similar to natural formations, the built environment incorporates a multitude of subsystems, each with diverse and sometimes conflicting objectives and properties. In the discipline of architectural robotics, it is essential to acknowledge that these subsystems can manifest into fusions of multiple geometric instances and matters to be produced with different techniques of production, such as additive, subtractive, and formative. The property pallet may include materials with fully quantifiable behaviors and unpredictable ones that together may create novel hybrid intelligence in architectural systems when combined. Consequently, the introduced and explored approaches to hybridity in architecture utilize robotic fabrication that incorporates multiple techniques with multiple materials.

Implementing the HI-ARM frameworks, we discuss how computational intelligence, Fabrication Intelligence, and Material intelligence can be integrated within the design-to-production workflows in order to materialize multi-materiality. The chapter introduction on hybridity extends with three sets of brief descriptions of case studies and experiments, which are addressing Computational, Fabrication, and Material intelligence in design to production processes. The chapter’s main body is titled Materializing Hybridity in Architecture, where we discuss three main projects: Hybrid Cork, Hybrid Concrete, and Hybrid Silicone. Since in terms of computational design approaches and workflows, there are several overlaps between the case studies previously presented in the porosity chapter, in this chapter, the main focus of the discussions is centered on Fabrication Intelligence in the form of Multi-Mode Robotic Production strategies and Material Intelligence in the form of Multi-Materiality.

4.1.1 Computational Intelligence and Hybridity

Regardless of the production methods and the building materials, developing and applying computational design systems to digitally materialize hybridity is challenging and an area of research in itself. Several researchers have developed methods and conducted experiments with a focus on the computation of hybrid material systems for design and architectural applications (Inter. al Panagiotis and Payne 2016; Grigoriadis 2019; Yu and Xie 2021). The contribution of this dissertation to this research area is developing workflows and methodologies of digital modeling and computation hybrid materials systems which are informed by constraints and potentialities of robotic fabrication methods.

This research and chapter's core objective is not centered on delivering generic computational design toolkits for multi-material design modeling. However, through a series of experiments and sets of case studies on hybridity, a collection of tools and approaches are developed and tested. As an example, four designed hybrid prototypes, as shown in FIG. 4.1, formalize four different possible topological integrations between two matters, which are 3D printed in two different colors: White (Material A) and red (Material B). The four types of topologies of two materials in this study are:

1. Gradient of A – TO – B
2. Penetration of A – IN – B
3. Distribution of B – ON – A
4. Intertwine of A – AND – B

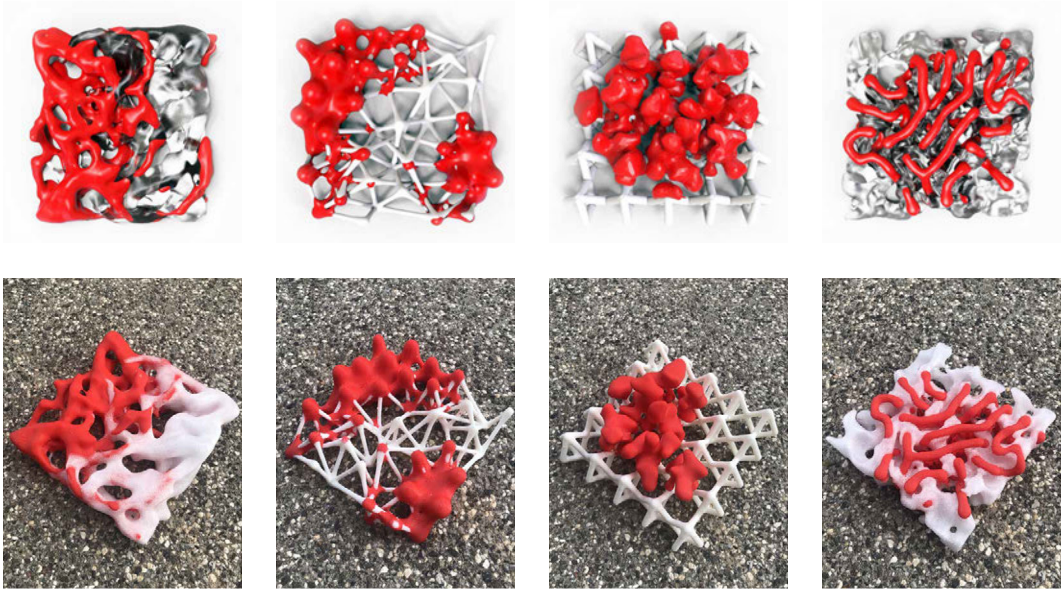


FIG. 4.1 Computational modeling of four topological types of Multi Materiality. Top layer digital models, bottom layer 3D printed prototypes; Pairs from Left to Right: Gradient of A-to-B, Penetration of A-in-B, Distribution of A-on-B, Intertwine of A-and-B.

The categorization mentioned above is conceived for an advanced computational design workshop, with the goal of providing initial generic topological and geometric solutions of modeling multi-materiality for then to be implemented in specific design projects organized at Digital Futures international workshops (Mostafavi, Kemper and Khaeez, HI-Cy workshop at DigitalFUTURES world 2020; URL [12] & [13]). While a categorization like this can be extended or altered to be comprehensive and consider different design objectives and case-specific requirements, this research will mainly address the challenges of computational modeling of multilateral systems as an integral part of the case studies to follow.

Similar to the developed and tested approaches in the porosity projects, voxel-based modeling is a promising method when it comes to volumetric modeling and additive manufacturing. However, as this research proposes multi-mode robotic fabrication building solutions, a combination of surface-based and volumetric computational modeling according to the fabrication constraints and potentialities is required.

In addition to topology and geometry, performance-driven solutions based on multi-material systems require novel material computation methods. There are several potential performative design applications of multi-material systems, such as in structures where two different materials may take compression and tension forces correspondingly (Yu and Xie 2021) or in other architectural applications where two materials can be combined for more qualitative reasons. The chapter will elaborate more on the developed computational intelligence implemented in the main case studies.

4.1.2 Fabrication Intelligence and Hybridity

The hybridization of production methods introduces novel possibilities in design materialization. Programmability and customizability of robotic fabrication technologies allow for the integration of multiple techniques of production. This research develops different multi-mode robotic production methods that are tested and explained within the frameworks of HI-ARM.

Multi-mode robotic production techniques, hypothetically and practically, will expand the production space in an integrated computational design-to-production system. Moreover, by being able to handle multiple materials at the same time or in sequence, the material space will also expand. However, like many other fabrication technologies, each production method, such as subtractive, additive, formative, and modificative, has its own constraints and capacities. Therefore, the presented methodologies exemplify the challenges of developing and integrating multi-mode robotic production techniques within the design processes. The main developed multi-mode robotic production methods in this research are designed by combining different subtractive and additive processes. However, a similar approach can be extended to other forms of material handling and fabrication, such as formative and modification. In summary, a general description of four types of process is as follows:

1. **Additive:** Adding material on the previously placed matter or objects; In this research, an additive process may refer to placing discrete elements in the production space such as in pick-and-place methods, or it can be continuous depositions and hardening of matter in techniques such as Robotic 3D Printing, Weaving, Fused deposition Modeling, or Selective Laser Sintering.

2. **Subtractive:** Removing material from an existing mass or matter of an object or input material; In this research, a subtractive process may refer to volumetrically removing chunks of matter without crushing the material such in Robotic Hot wire Cutting or grinding the matter layer by layer in processes such as Robotic Milling.

3. **Formative:** Changing the initial form and size of the input material; In this research, a formative process may refer to transforming the input material or an object using physical force such as stretching or Incremental Sheet Forming of metal plates or using other forms of energy such as thermal or chemical to change the shape of the matter like using a heat gun to melt hence change the initial state of the input material.

4. **Modificative:** Making changes on the input material without changing the size or mass; In this research, a modificative process may refer to cutting an input material without removing the matter, such as Robotic Cutting of plate material with a mounted knife tool or Robotic Steam Bending of wood timber.

The categorization is proposed considering the objectives and the frameworks of HI-ARM, while other classifications are conceivable considering different points of view. Moreover, numerous combinations of these types of production approaches are conceivable, while this research is mainly centered on two cases: 1) Subtractive – Subtractive and 2) Subtractive – Additive.

Here, before getting into the details of this chapter’s core case studies (Hybrid Cork, Hybrid Concrete, and Hybrid Silicone), we discuss three core concepts and strategies developed and applied in multi-mode robotic materializing processes.

TOC

4.1.2.1 Multi-mode, volumetric design, roughing and finishing

Hybridization of production processes by implementing multi-mode robotic production methods allows for volumetric design compared to commonly-used surface-based design in digital modeling and computational design, where layers of materials are usually sandwiched on top of each other. This approach is tested in Multi-mode Hybridity (FIG. 4.2), where two distinct subtractive robotic fabrication methods are combined: volumetric cutting and milling. On the one hand, this results in the efficiency of subtractive production processes by rapid volumetric material removal, followed by high-level detailing processed through milling from both sides, which is perpendicular to the surface and it creates porosity

FIG. 4.2 Multi-mode Hybridity - volumetric cutting and milling are used together as a hybrid production strategy implementing two subtractive robotic fabrication methods.

Multi-mode hybridity is prototyped as part of larger architectural design projects. The overall morphology in macro scale, componential logic in meso-scale and surface texture, and internal porosity in micro-scale are informed by implementing an integrated computational design to robotic fabrication workflow. The volumetric cutting using the Robotic Hot Wire bracket tool follows the compression lines extracted from structure analysis. Respectively, the milling pattern follows internal structural tension stress-lines and external light penetration, controlled daylighting, and the mitigation or intensification of solar radiation as needed (FIG. 4.3).

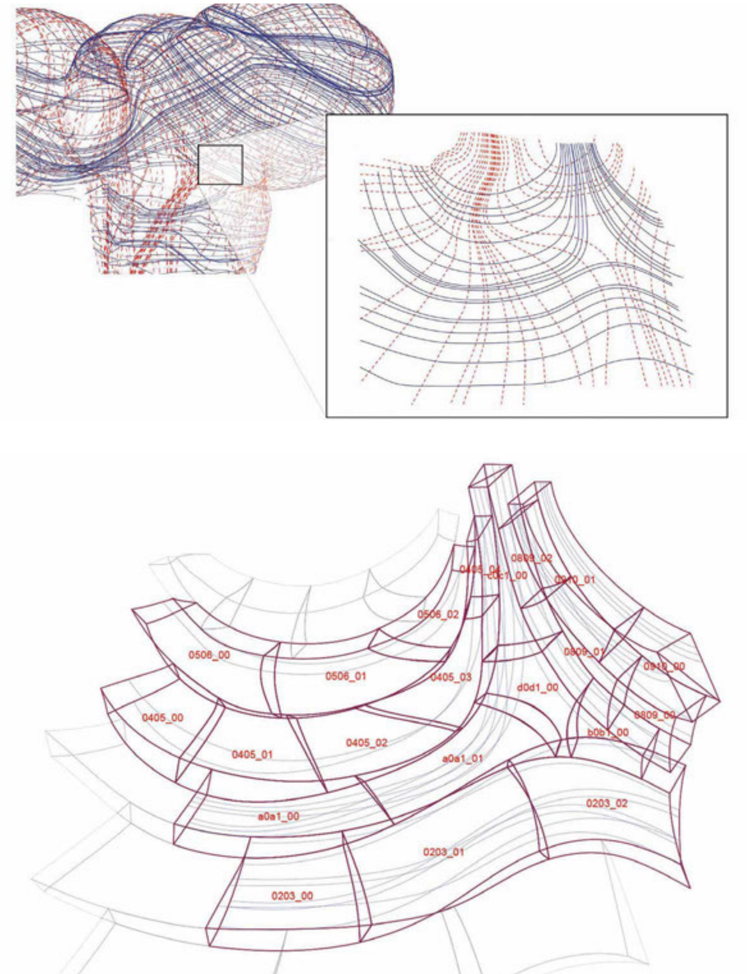


FIG. 4.3 Multi-mode Hybridity - the hybrid nature of the manufacturing method is developed based on how complex components work in compression and tension. All components are produced with six cuts except the d0d1_00 in the middle on the saddle point of the surface where the curvature direction changes.

The hybrid nature of the manufacturing method allows for the realization of complex components. The assembly logic is derived from the structural analysis and the affordances of both implemented robotic production techniques. In order to keep the topology of fabrication similar for all pieces, the overall body of each component is produced with six cuts. An exception to this rule is the component in the middle where the curvature of the surface changes its direction. Acting like a saddle point, the middle customized component, or the keystone in a masonry system, ensures the smooth transition between different curvature directionalities. Consequently, such a strategy for assembly results in creating an approximated doubly curved shell. The approximation is grounded in the fact that all faces of the components are ruled surfaces produced by hot-wire cutting. Furthermore, to fine-tune and produce a fully curved shell, robotic milling shapes the edge areas to match the neighboring components (FIG. 4.4). Therefore, the robotic fabrication strategy enables the production of a highly curved geometry while optimizing the required manufacturing effort. Although the same project could be created through the use of only robotic milling, the isolated use of one technique is materially uneconomical and time-consuming in terms of production.

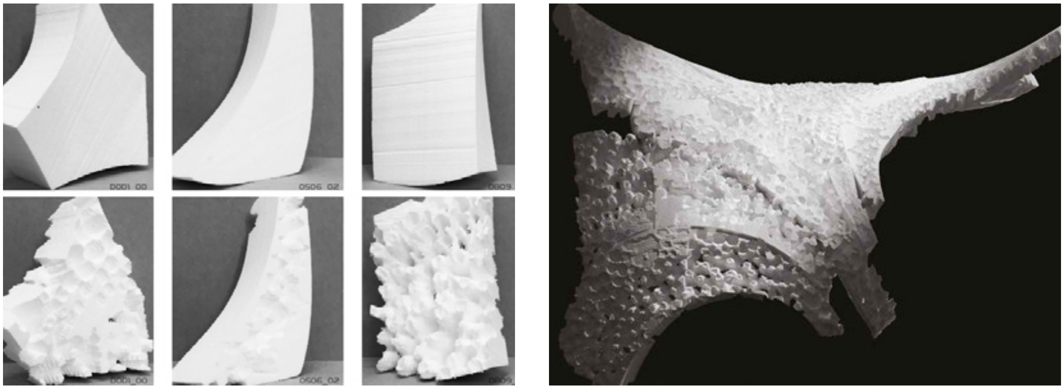


FIG. 4.4 Multi-mode Hybridity - The manufacturing method is developed based on how components work in compression and tension; Left: Robotic Hot Wire Cutting followed by Robotic Milling on both sides; Right: Assembled prototyped.

4.1.2.2 Multi mode, internal porosity and external surface quality

The combination of two subtractive processes (Robotic Hot Wire Cutting and Robotic Milling) is further approached differently in another project where subtractive manufacturing fully benefits from the multi-directional access for tooling in a seven-axis robotic production setup (FIG. 4.5). The double-layered envelope prototype with an internal cavity is designed in such a way that all the surfaces of volumetric components are developable surfaces. Therefore, the prototype revisits the frequently used approach in treating surface finishing using subtractive manufacturing, which usually results in non-porous solid pieces. In such a conventional CNC manufacturing routine, hot wire cutting might be combined with milling. This leads to roughing, or crushing the material layer by layer, followed by higher resolution finishing.

In this example, the sequence and combination of two subtractive methods are re-examined. Firstly, the outer surfaces and the internal cavities, all with developable surfaces, are rapidly removed using hot wire cutting. Then from both sides of the component, the holes with developable conical shapes are removed by milling so that the axis of the milling spindle follows the outer surface of each o the holes. Consequently, there is no roughing or material crushing in the milling process, making the whole routine more efficient in terms of fabrication effort and required energy for production.

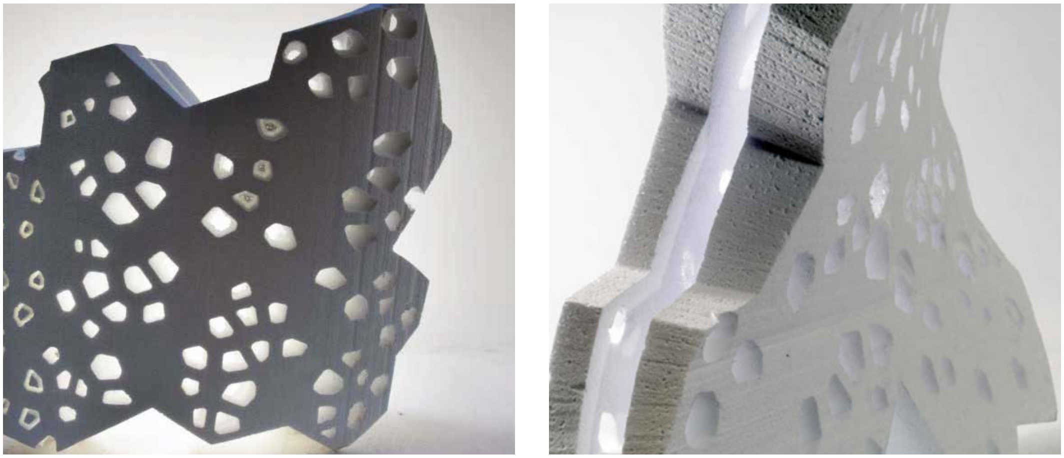


FIG. 4.5 Creating internal cavities using multi-mode hot wire cutting robotic milling; one-piece component produced with seven-axis production setup with multiple end-effectors without crushing the material as all surfaces are developable.

Rationalizing the design according to production methods may not necessarily mean the simplification of geometry, for instance, turning all double curvature surfaces into developable surfaces. An example of this claim is tested in a project on volumetric architecture, where the finishing surface of the monocoque structure seamlessly combines both double curvature and developable surfaces (FIG. 4.6).

FIG. 4.6 Robotically Produced Fiber Glass Music Stage Table, Implementing Robotic Hot Wire Cutting combined with Robotic Milling where needed and as needed results in a smooth transition from curved to developable surfaces.

The Melt Rey fiberglass table project is part of a 360-degrees performing stage, designed and robotically produced as the result of a Design and Robotic Production studio for the Ferropolis festival and 100 Years Bauhaus Anniversary events.
In a 3700x1700x1450 mm bounding box, the free form produced one-to-one prototype is a volumetric spatial complex monocoque structure with variation in the thicknesses of the elements (FIG. 4.7). The thickness is decided based on structural analysis as well as functional requirements. The interrelations between compartments of the design-to-production algorithm are derived based on the user requirements, such as a deck for one large and one medium instrument, which could bear the load up to 100kg. Moreover, built-in integrated speakers and integrated light design are considered. Consequently, 21 unique components are cut one by one and tagged for the assembly. The table’s overall volumetric free form body is coated with two layers of fiberglass reinforced with resin.

FIG. 4.7 Top view of robotically produced free form monocoque fiberglass table.

The project is implementing computational design and multiple robotic production methods, such as hot-wire cutting combined with robotic milling, which all inform the design materialization of a geometrically complex volumetric structure. The design of the table is evolved through a series of procedural modeling routines and computational design techniques such as curvature analysis. Moreover, the subdivision logic of the monocoque structure into smaller components is developed based on the constraint and potentialities of the multi-mode robotic fabrication method. This integrated design-to-production approach results in a new aesthetic of continuous surface quality, which seamlessly combines developable surfaces with double curvature patches (FIG. 4.8).

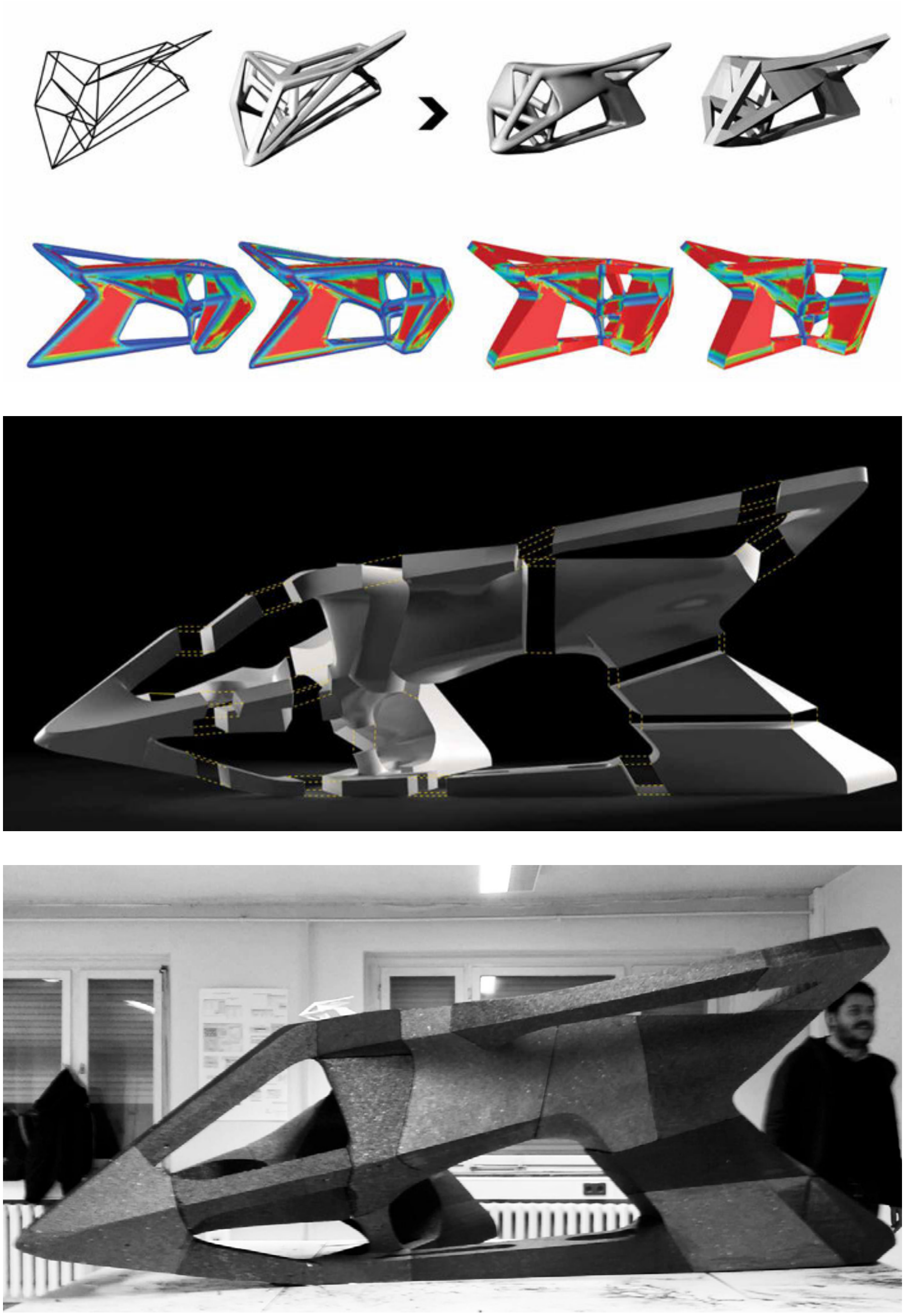


FIG. 4.8 Top: Procedural modeling of the free form fiberglass table and series of curvature analysis feedback informing the design to seamlessly combine double-curved surfaces with developable faces; Middle: Exploded view of the table; Bottom: Robotically produced table before coating with fiberglass reinforced resin.

4.1.3 Material Intelligence and Hybridity

Another explored dimension of hybridity is using and processing multiple materials with varying properties. In material science, the potential of hybridity depends on the selection of materials, their volumetric percentage, their configuration, and the way they connect (Ashby and Bréchet 2003; Ashby 2013). In addition to these quantifiable parameters, architectural design may employ perceptual and aesthetic aspects of multi-materiality. Therefore, the choice and production of hybrid systems go beyond mechanical properties. In this context, various hybrid properties and behaviors might be conceived and become producible using multi-mode robotic production methods such as:

- Hybrid of Hard and Soft
- Hybrid of Rough and Smooth
- Hybrid of Solid and Porous
- Hybrid of Transparent and Opaque
- Hybrid of Thin and Thick
- Hybrid of Dark and Bright Colored
- Hybrid of Natural and Artificial
- Hybrid of Elastic and Plastic
- Hybrid of Structural and Insulative
- Hybrid of Conductive and Non-Conductive
- Hybrid of Absorptive and Reflective
- Hybrid of Compressive and Tensile resistant
- Hybrid of Homogeneous and Heterogeneous
- Hybrid of Hydrophilic and Hydrophobic

The above-mentioned pairs can be implemented as design materialization strategies, and naturally, cross combinations of these and more conceivable hybrid material intelligence are hypothetically possible. In this research, we study hybrid materiality as an integral part of prototypical case studies, which are discussed in this chapter's main body. Therefore, the goal in this chapter is not to provide a comprehensive palette of all physical and mechanical possibilities. Instead, the hybrid logic is conceived and developed according to the specific design requirements and research objectives. However, prior to elaborating on the case study's details, here we further explain two major concepts about material intelligence using Multi-mode robotic production methods:

1. Hybrid Material Properties
2. Hybrid Material Behaviors

Hybrid Properties: In multiple scales, multi-mode robotic production methods allow for architecting different material properties in building components and structures by combining complementary material processing methods. Such combination is pre-tested in a subtractive-additive process as part of the Scalable Porosity project (FIG. 4.9), where a series of experiments is conducted to propose hybrid methods of production for volumetric cutting combined with additive manufacturing. Achieving an adequate tolerance at the building scale, this project deposits ceramic clay, an earth-based, natural and unpredictable material, on free-form polystyrene components with high curvature variation. This employs the manipulator's full-motion capacities and creates a tectonic in line with the logic and production sequence. This method is further extended in the Hybrid Silicone project, where the rigid properties of hard foam are combined with silicone's soft and adhesive properties.

FIG. 4.9 Scalable Porosity - series of experiments conducted to develop hybrid methods of production: volumetric cutting combined with additive manufacturing.

Hybrid Behaviors: multi-mode robotic fabrication allows for selective modification and adjustment of material behavior. As a part of the hybrid cork project, a series of experiments are conducted using multi-directional robotic milling where slits of material are removed from rigid boards of cork (FIG. 4.10). In this project, the incorporation of expanded polystyrene and cork boards into a building system enhances the individual materials' physical properties. Even if both chosen materials share similar attributes, such as rigidity, granulation, and density, the robotic production system manipulates physical behaviors in favor of the desired design performances. In the case of cork, carving the planar rigid board from multiple sides results in a doubly curved element with engineered flexibility, which is then structurally supported by polystyrene components. The final prototype exhibits built-in hybrid behaviors, such as controlled elasticity, where the second material does not fully support the cork, and stiffness in areas where the two perfectly overlap. Robotic fabrication also enables variation in thickness, pattern densification, angle, and depth of penetration, creating an overall topological continuity of the two materials.

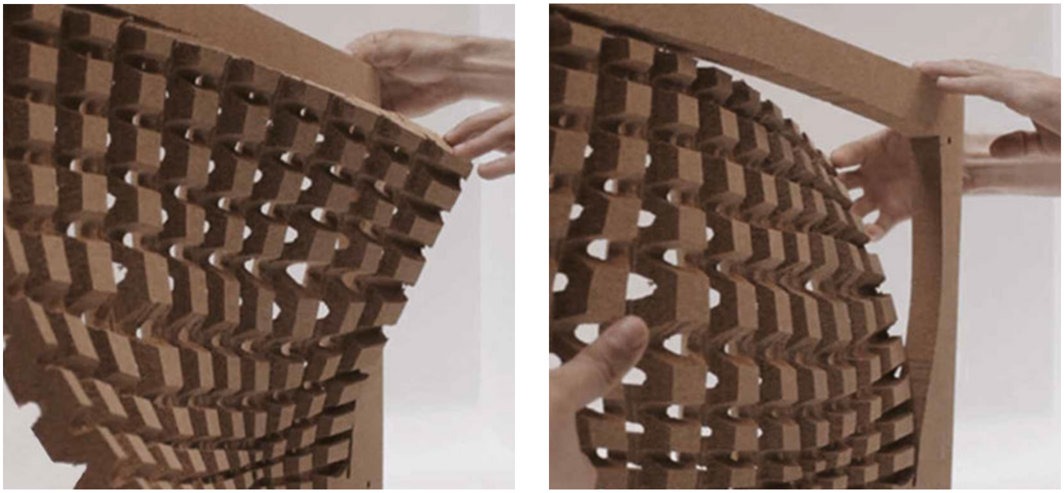


FIG. 4.10 Hybrid Assembly - Modifying the properties of rigid cork boards through multi-directional robotic milling of a differentiated pattern with varying depth and angle to control the flexibility and intertwine two sets of hard and soft materials.

4.2 Materializing Hybridity in Architecture[3]

Materializing Hybridity in Architecture

Design to Robotic Production of Multi-Material and Multi-Scale Building Resolutions

ABSTRACT

This paper discusses methods of modeling and robotic production of hybridity in various building scales in architecture. It specifically explains prototypical case studies of applying multiple materials and different robotic production methods to materialize performance driven hybridity. The methods demonstrate the potentialities of robotic production to provide alternative means of building systems with multiple materials. Consequently, the paper provides a design materialization framework of hybridity, porosity, and assembly for architectural applications in which digital modeling, computational design, and the feedbacks from production processes are tested and elaborated. Three projects are discussed in detail: a hybrid of flexible cork and rigid polystyrene, a hybrid of structural concrete with an intertwined permanent mold, and a hybrid of soft additively deposited silicone and subtractively produced hard polystyrene. Each project has specific performance criteria, with which a certain a level of geometric complexity and variation is accomplished. Additionally, the customization of the robotic production method according to the design; and concurrent design development according to the potentialities and constraint of each materialization strategy are discussed. The research concludes on how the multi materiality which is achieved through multi-mode robotic production methods introduces a higher, on-demand and performative resolution in building systems.

ABSTRACT

Hybridity; Multi-Mode Robotic Production; Multi-Materiality; Subtractive-Additive Manufacturing; Material Architecture, Hybrid Cork, Hybrid Concrete, Hybrid Silicone, Hybrid Chair.

---

[3] The following section, titled Materializing Hybridity in Architecture, has been previously published in the following peer-reviewed paper (Mostafavi, Kemper and Du, 2018):
Mostafavi, Sina, Benjamin N. Kemper, and Chong Du. 2019. “Materializing Hybridity in Architecture: Design to Robotic Production of Multi-Materiality in Multiple Scales.” Architectural Science Review 62(2019: 424-437, Issue on Means, Methods and Machines in Architecture, Taylor & Francis. https://doi.org/10.1080/00038628.2019.1653819.

4.2.1 Introduction

Buildings consist of subsystems, each with different requirements to be achieved by the assembly of multiple materials. In many contemporary practices in the construction industry, the sequential assembly of building elements, usually in multiple layers, results in the segregation of structure, finishing details, and other functional components. To provide alternative solutions for design to production of this inevitable multi-materiality, this research prototypes hybrid material systems that are produced with different robotic production methods. The presented case studies' emphasis on how robotically producible hybridity can improve different building performances. Moreover, the projects elaborate how these alternative materialization solutions require specific computational design and digital modeling approaches. Therefore, there are three main scopes in this research: material hybridity, robotic production and design computation.

Surveying the state of the art, there are projects in which the topic of multi materiality is studied. In "flow-based fabrication" numerically controlled composition of liquids create gradients of solidified materials which are additively deposited. (Duro-Royo, Mogas-Soldevila and Oxman 2015). In this reference, as demonstrated in the produced prototype, creating gradients in microscopic scales radically differ from the conventional layer by layer assembly of multiple materials, which is dominating in building processes. In this paper materializing hybridity at architectural scales benefits from the customizability and programmability of robotic production setups in order to create multi-materiality in multiple scales.

The ability to integrate multiple methods of robotic fabrication allows for the integration of multiple materials. Relevant to the body of this research are projects such as "Multi-mode production" methods (Mostafavi, Kemper and Fischer 2018) in which two or more methods of fabrication processes are combined introducing potentialities of materializing hybridity. Examples are Wiggle Wall in which fast printing of foam is followed by robotic milling (Pigram and McGee 2011), "Compound Fabrication" in which a subtractive routine follows an additive method for finer refinement of the surface quality (Oxman and Keating 2013), and a 6-axis hybrid additive-subtractive manufacturing equipment with changeable head tools (Li, Haghighi and Yang 2018). Next example in a larger scale is an all-purpose construction system with additive, subtractive, and assembling techniques which is proposed as Digital Construction Platform that utilizes a mobile system (Keating, Spielberg, Klein and Oxman 2014).

To produce hybrid material systems, in addition to the Multi-mode nature of production techniques, methods of digital modeling and computation of multi materiality is a fundamental aspect. In this respect, the process of translating a digital representation model into a production routine, which is customized for certain techniques, is studied in several projects. In Materially Informed Robotic Ceramic 3D Printing, a recursive system is developed through which a continuous robotic toolpath is computationally generated, in order to create a porous ceramic structure (Mostafavi and Bier 2016). Further Computer Aided Modeling methods, that facilitate production of hybridity, propose voxel-based representation techniques for complex material distributions (Panagiotis and Payne 2016). The voxel-based modeling approaches allow for higher resolution application of additive manufacturing. While using robotic manufacturing at architectural scales, further compound digital modeling approaches are required in which the nature of robotic tooling is considered. Therefore, production routines provide feedback to design materialization processes and digital modeling approaches. This integration of fabrication constraints within the architectural design process opens the possibility for direct and instantaneous feedback between fabrication constraints and design intent (McGee and Pigram 2011).

The case studies in this paper present a framework of design computation to robotic production methodology with the focus on multi materiality in various architectural scales. The three projects discussed in detail are: hybrid of flexible cork with rigid polystyrene, hybrid of structural concrete with an intertwined permanent mold, and hybrid of soft additively deposited silicone with subtractively produced hard polystyrene. The third case study is explained in more detail as a conclusive project on design to robotic materialization of hybridity.

4.2.2 Case Studies: Design to robotic production of hybridity

Each presented prototype in this paper is a part of a larger design project with specific architectural performance criteria such as structural, functional, and environmental. The core subject in these case studies is multi materiality. The hybridity is explained from three perspectives: the physical and architectural properties of the hybrid material systems; feedback loops from robotic production informing the design materialization processes; and methods of computer-aided modeling, digital representation, and computation of multi materiality. The objective, on one hand is to construct applicable building systems that are informed by specific architectural performance parameters, and on the other hand is to develop and test customized design to robotic production processes.

4.2.3 Hybrid Cork

FIG. 4.11 Hybrid Cork.

The hybrid components consisting of flexible porous cork and hard polystyrene is a one-to-one prototype which is a part of an indoor stage structure with sound absorptive capacities (FIG. 4.11). It focuses on the integration of two different materials by using subtractive robotic production. The materials used are rigid cork board and Expanded Polystyrene (EPS). In the design proposal, the cork is placed in areas requiring either comfortable seating surfaces or sound absorption properties. During the first production stage, the thickness variation in the EPS components is decided considering structural and functional requirements. Moreover, a sound reflection analysis informs the overall geometry as well as the distribution of cavities between the two materials. The EPS components are produced with robotic milling from multiple sides. Specific patterns are three-dimensionally milled into plates of rigid cork to achieve flexibility and double curved bending (FIG. 4.12), to fit them onto allocated areas of the EPS components.

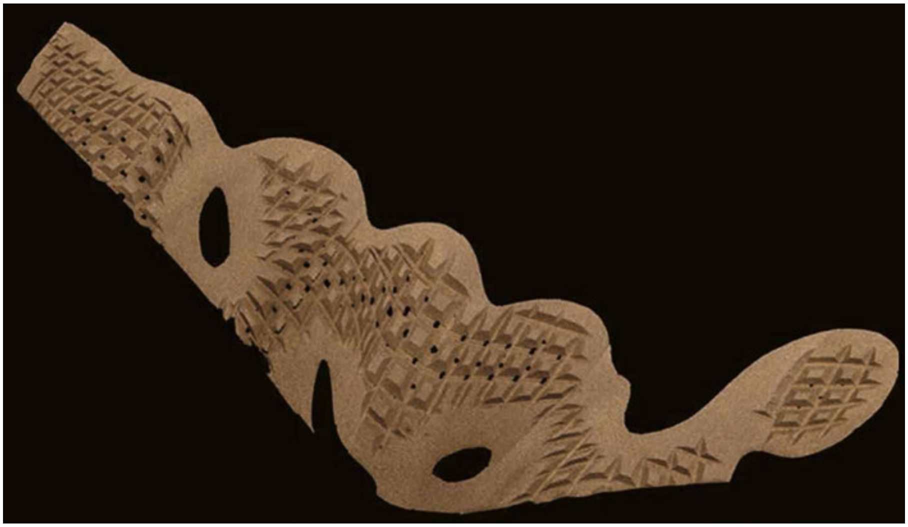


FIG. 4.12 Unrolled patch of cork components, Cork gains intended flexibility and double curved bending.

The most challenging aspect of this research is to estimate the three-dimensional bending behavior of the two-dimensional robotically produced cork boards. This unrolling process is evaluated through a series of digital simulations and physical prototypes with different milling patterns. Although the virtual simulations provide the initial guidelines on unrolling strategy, a series of prototypes is necessary to evaluate the actual bending in the physical world. This is mainly due to the level of detail in the simulation model wherein is not feasible to represent the thickness of the material in mesh format as it is a computationally heavy process.

While the first milling operation on EPS follows a common layer-by-layer roughing approach of removing material, the second subtractive manufacturing method on the cork works differently (FIG. 4.13). In order to achieve the intended bending behavior, notches of material are removed from both sides of the rigid cork boards. This results in a multi-directional flexibility in order to match the target curvature of the design. In a final step, the EPS components are connected to the two-dimensional cork plates, which are three-dimensionally bent and fixed onto the intended contact areas (FIG. 4.11). The EPS components and cork boards are incorporated into a building system, which enhances individual physical properties. Even if both chosen materials share similar properties, such as rigidity, granulation and density, the robotic production system changes physical behaviors in favor of the required design performances. In the case of cork, carving the planar rigid board from multiple sides, results in a double curvature element with flexibility, while being structurally supported by the polystyrene. The final prototype has a built-in hybrid behavior that introduces controlled elasticity where the cork is not fully supported by the second material and stiffness in areas where the two perfectly overlap.

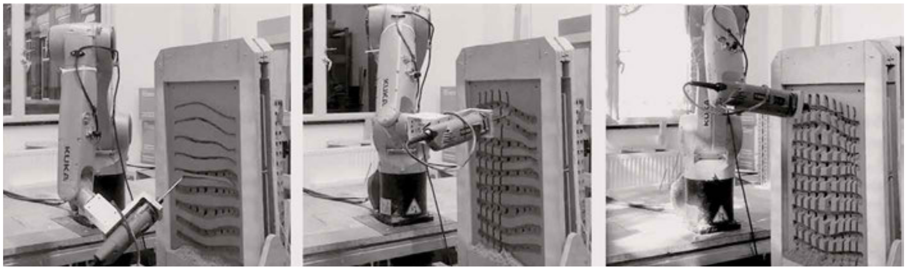


FIG. 4.13 Carving out the notches in multiple angles from rigid cork boards.

4.2.4 Hybrid Concrete

The hybrid of concrete intertwined with permanent parts of the mold is a multi-material system with concrete as structure and EPS as the second functional material (FIG. 4.14). Unlike the common two-sided mold for casting, the mold for this cast consists of four robotically produced components. Therefore, certain EPS parts are functioning as temporary casting mold elements, while some other permanent parts are intertwined with concrete to act as insulation and finishing. The prototype is extracted from a building skin that is designed according to structural and environmental analyses. The result of these analyses is an information point-cloud with values extracted from stress analysis and environmental simulation. The distribution of the structure in this discrete point-cloud originates from a topology optimization routine while the distribution of the second material is controlled according to other functional and environmental factors. Beyond the architectural design considerations, the main research objective is to produce components in which two material are integrated. As a result, both materials are closed volumetric continuous topologies, which are interlocked together three-dimensionally.

Considering the properties of both concrete and EPS, the minimum to maximum dimensions and variations in thickness are defined. From a point of view of digital modeling of a hybrid system, this project presents challenges with respect to the translation of voxelized or discretized results of material computation into a producible strategy toolpath generation. Hence, the design is rationalized according to the reachabilities and collisions in the robotic tooling process. This implies avoiding unreachable overhangs on the finishing surface of the mold. The core finding, from a geometric point of view in this study, is to model the overall topology of the component in relation to a middle surface. As a result, both concrete and EPS surfaces, which are generated based on the point cloud, are then rationalized according to an offset from the middle surface. This rationalization assures us that each part of the mold is robotically producible.

TOC

FIG. 4.14 Hybrid Concrete.

FIG. 4.15 Concrete branch prototype, with robotically produced formwork with two temporary mold parts.

The first prototype is cast in concrete only (FIG. 4.15). This iteration is to determine the ranges of producible dimensions of fiber reinforced concrete to be cast in a two-part formwork. In this prototype, the method of production and parametric toolpath generation with KUKA|prc in Rhinoceros® Grasshopper 3D is tested and verified (FIG. 4.16 and FIG. 4.17). In the second prototype, unlike a common two-sided mold for casting, the mold consists of four robotically produced elements.

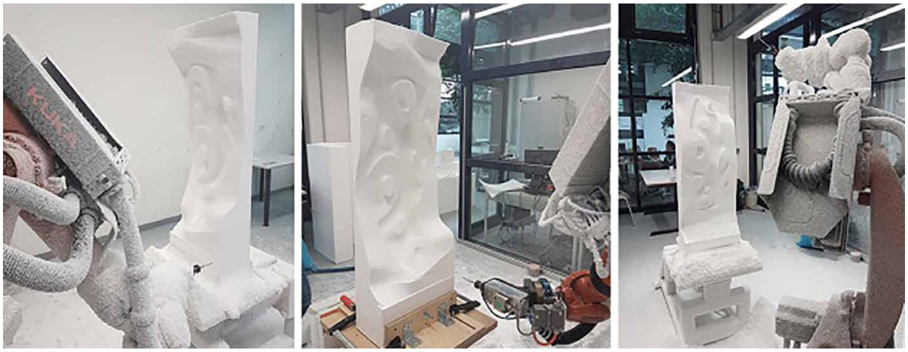


FIG. 4.16 Milling process of the test mold for concrete casting with two parts.

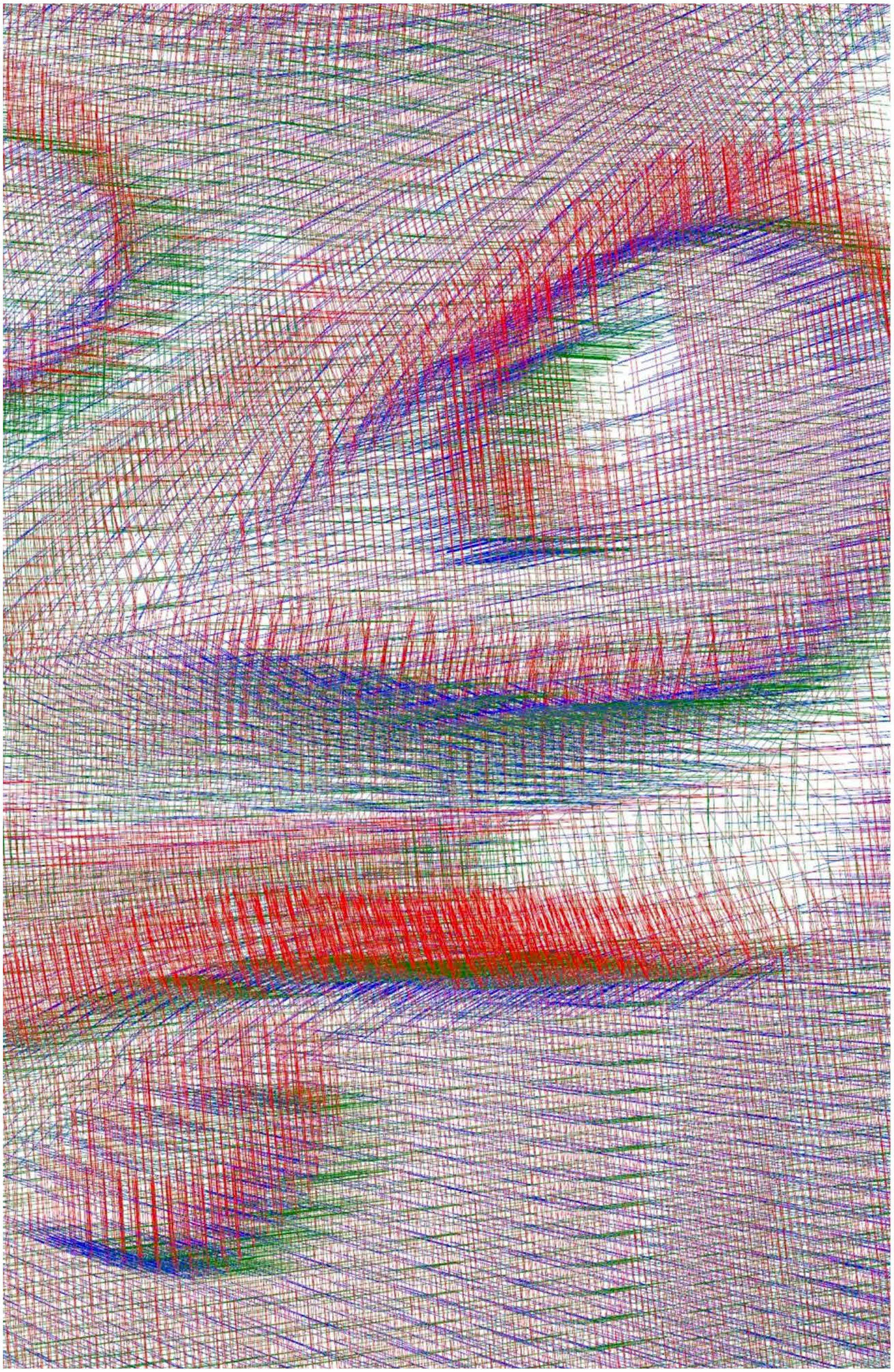


FIG. 4.17 A close-up of the robotic toolpath planes with varying orientations on the concrete surface.

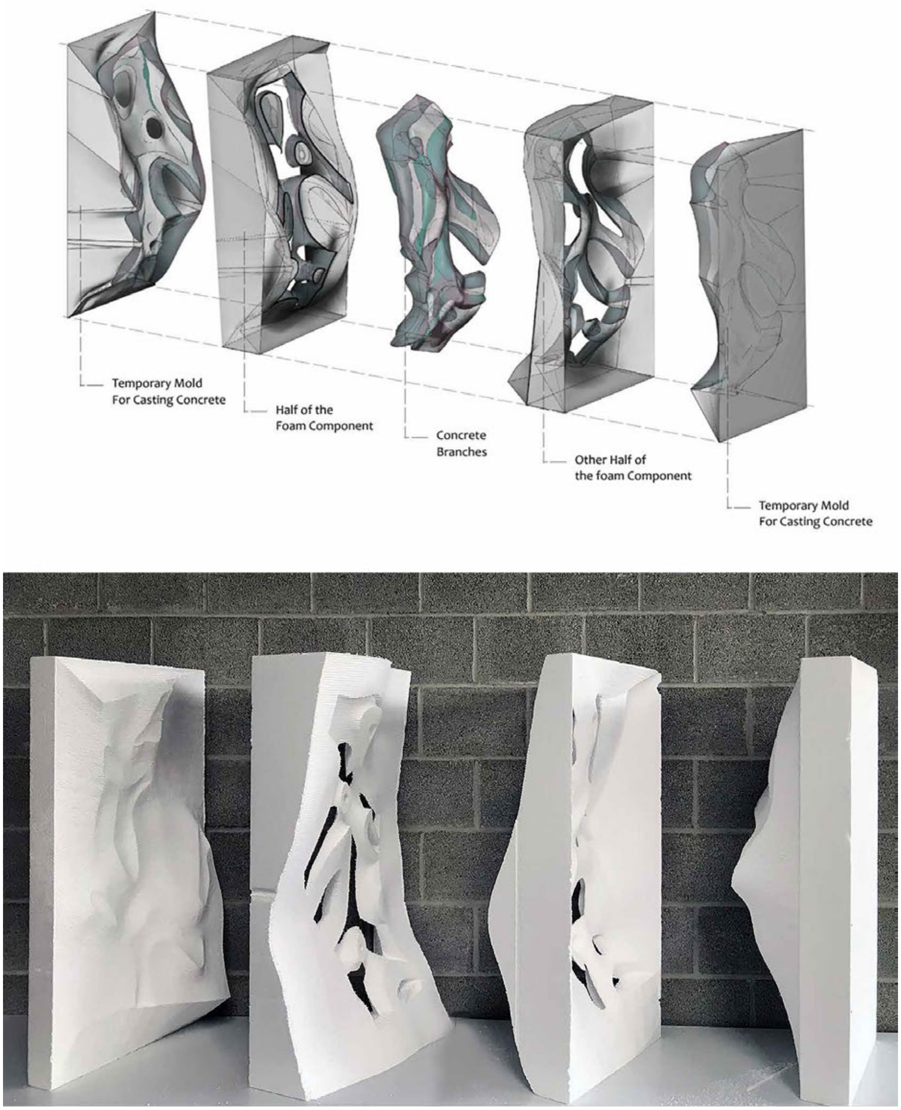


FIG. 4.18 The robotically produced four part mold of Hybrid Concrete prototype.

Out of these four elements, two are closer to the concrete core and remain in place after stripping the formwork (FIG. 4.18). Two outer EPS blocks are taken part away, and the side boundary surfaces of the overall hybrid component are produced with three hot wire cutting routines. The finished surface is mainly EPS as protection or insulation with a softer texture, and exposed harden concrete parts which are extruded out in certain areas. The range of diameters of the concrete branch varies from 22mm to 65mm. The thickness of the EPS ranges from 8mm to over 300mm. The sizes of the openings or the porosity integrated into the component range from 20mm to around 200mm. The permanent EPS elements stay interlocked in place without any use of glue. This is due to the three-dimensionality of the concrete structure that tightly keeps the two EPS elements in place (FIG. 4.19). An overview of design-to-production of the Hybrid Concrete prototype is presented in a video accessible on URL [14].

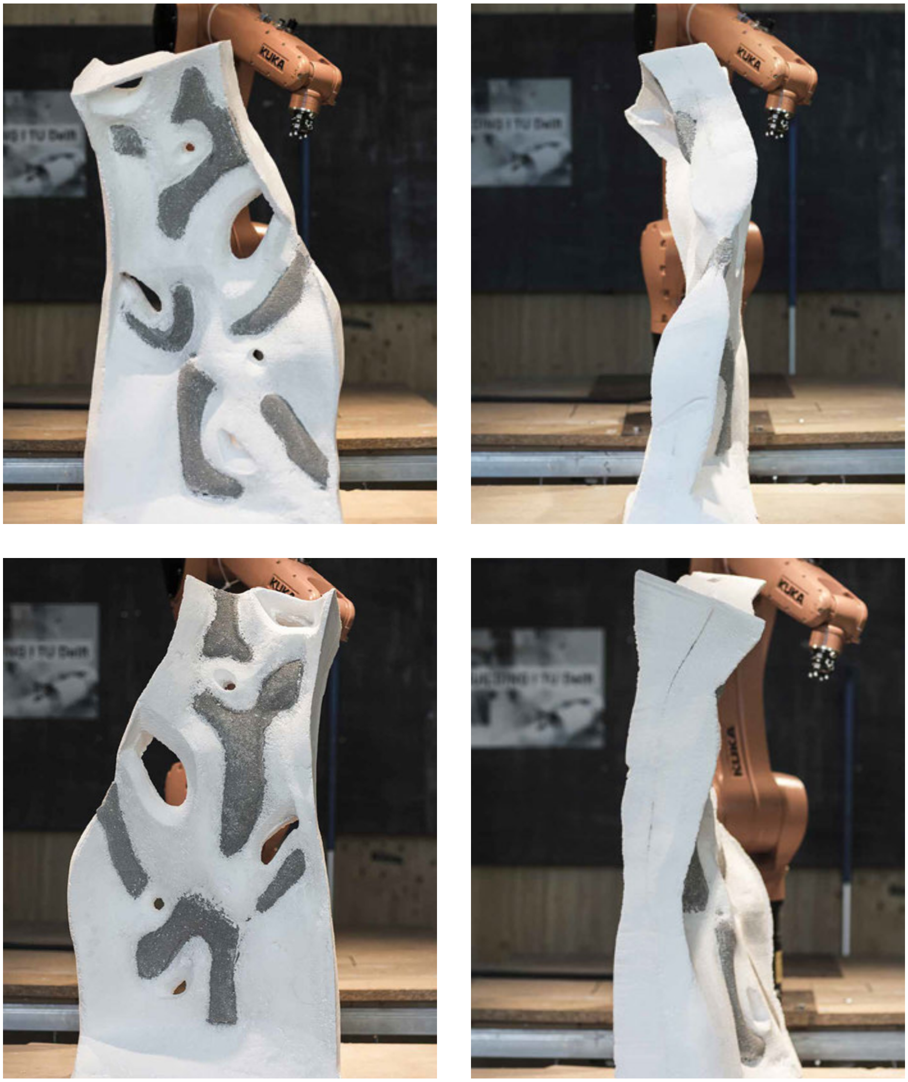


FIG. 4.19 Side views of Hybrid Concrete prototype.

4.2.5 Hybrid Silicone

The Hybrid Silicone is implementing a Multi-mode subtractive-additive robotic production method. This multi-material system consists of additively deposited soft silicone and subtractively produced hard polystyrene (FIG. 4.20). The objective is to merge materials with different properties, such as softness and hardness together, to create a hybrid system corresponding to different design requirements. The research evolves along a series of experiments on silicone behavior to develop an additive production method for an elastic material, and to estimate the outcome properties and performance of the printed prototypes. Moreover, from a design perspective, the objective is to compute the density distribution of silicone and evaluate the morphology of the printed geometries for specific functions. An overview of the multi-mode robotic production process of the Hybrid Chair is available on the URL [15]. The Video is previously published in Rob|Arch 2018 in Zurich and The Common Inn Exhibition at NAi Het Nieuwe Instituut in Rotterdam.

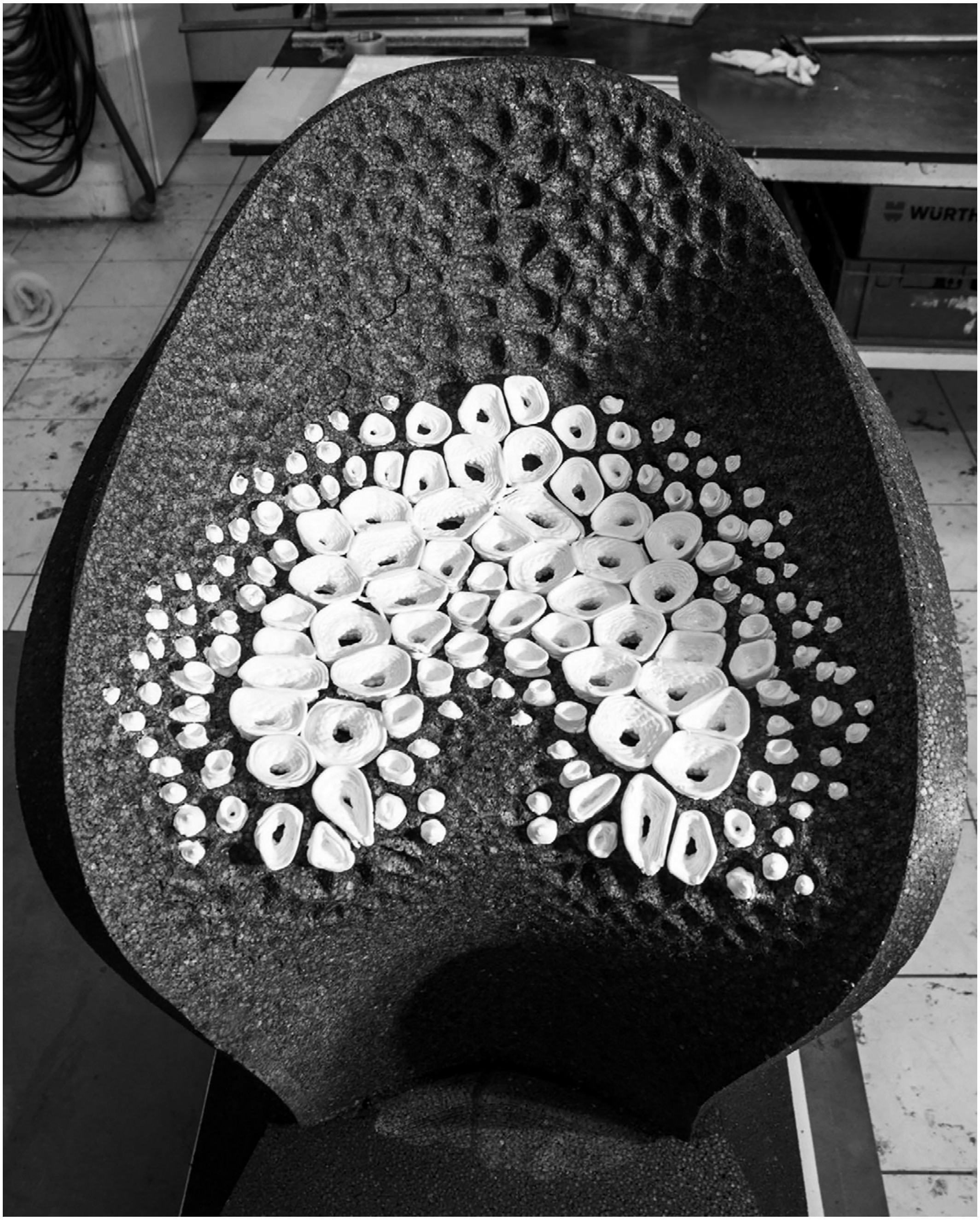


FIG. 4.20 Hybrid Chair produced with Hybrid Silicone materialization method.

4.2.6 Subtractive-Additive

In addition to the background research on Multi-mode robotic production mentioned in the introduction, there are related projects that employ a combination of subtractive and additive production methods. Woven Clay is a project in which a previously milled foam is temporarily used as an undulating printing bed where the clay is deposited from a distance above the surface (Friedman, Kim, and Mesa 2014). A similar combination of subtractive and additive manufacturing methods is tested in Materially Informed 3D Printing Project where the deposition toolpath fully follows the surface geometry of the component produced with robotic hotwire cutting (Mostafavi, Bier, Anton and Bodea 2015) (FIG. 4.21). In most of the additive production processes such as Fused Deposition Methods, Selective Laser Sintering, Stereolithography, or even casting, the physical state of the material changes from one state to another. The phase change makes it difficult to simultaneously or progressively combine two processes of subtractive and additive manufacturing. The hybrid project presented in this paper uses silicone as an adhesive material that it is able to permanently stay in place, and it does not need heat or a different source of energy to solidify.

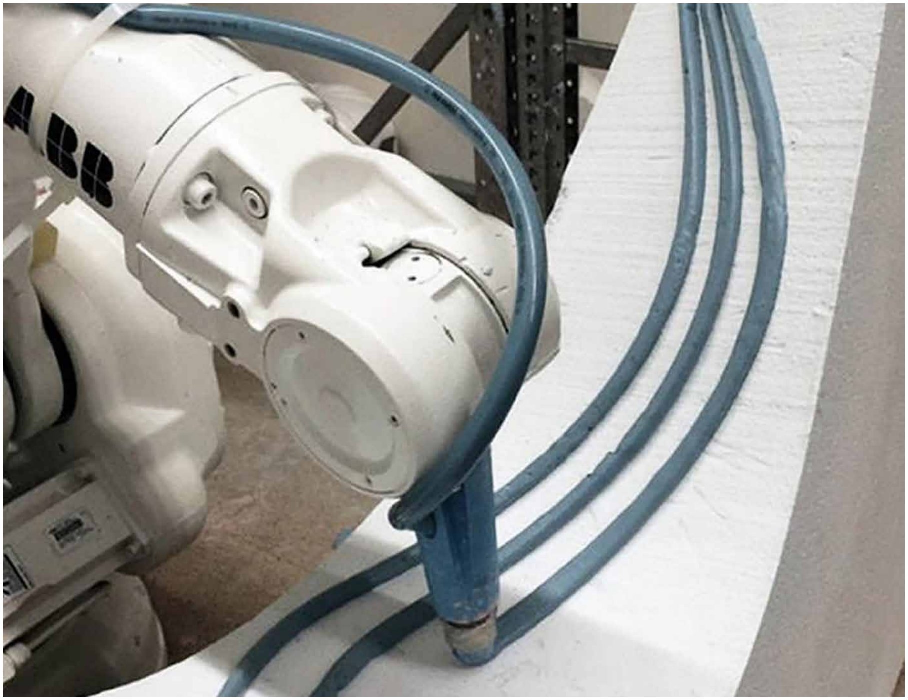


FIG. 4.21 Robotic 3D printing on a freeform surface.

As the goal is to incorporate two production methods, sets of additive experiments are tested on freeform surfaces. The results of these feedbacks are first, understanding the constraints and correlation between material capacities and second, the movement range of the arm and printing angles with no support structure required. Moreover, the elasticity of various shapes and thicknesses is studied, documented and evaluated for different potential design applications. With these objectives, a customized extruder for printing silicone is designed. Exploiting the movement capacity of a six-axis arm, the extruder with two changeable material containers, i.e., translucent and opaque silicone is located on top of axis three of a KUKA Agilus KR 10 robotic arm. Therefore, the specific design of the extruder allows for a short connection to the nozzle, directly on the tip of axis six. Between the calibrated tip of the tool and the flange, a ball bearing is integrated that allows for rotation of the slender funnel. Consequently, the connecting pipes from the cartridges to the nozzle faces upwards during the movement. On the one hand, this short connection enables higher ranges of three-dimensional movement of the nozzle on complex surfaces and on the other hand, a lower pressure is required to push or stop the extrusion (FIG. 4.22).

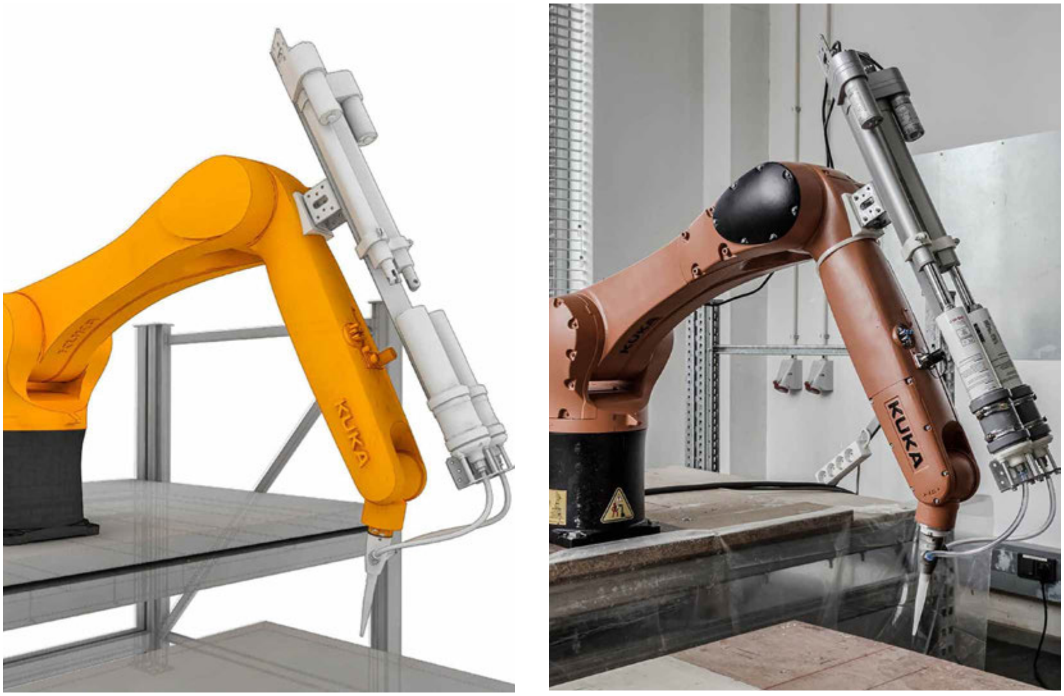


FIG. 4.22 Parametric simulation with in KUKA|prc with integrated digital model of the extruder(left); Robotic additive manufacturing setup for silicone printing with KR10-1100 (right).

TOC

Two main categories of cellular and linear silicone robotic toolpath and ranges in between are tested. Categories of experiments in detail are:

- Linear printing on double curved fabric with continuous toolpath using an external fixed extruder (FIG. 4.23 top): This resulted in determining the values for working robot speed, the material flow, the vertical distances between layers, clarification of the silicone properties, pot life, hardening duration, viscosity.

- Flat cellular printing on double curved fabric results in extruder modification (FIG. 4.23 middle); This concluded in reducing the distance between the external extruder and the printing fabric, which is resulted in a shorter tubing system. The solution is a custom build extruding system mounted on top of the robot to provide the shortest distance of tubes as possible.

- Medium to large size cellular printing on flat fabric with five types of toolpath with the mounted extruder on the manipulator; printing of angled and cantilevered cells with internal reinforcement; diameter and height ranges of the printed cells are: 25mm < D < 105 mm and 11mm < H < 125 mm (FIG. 4.23 bottom); This iteration also is a feedback for estimation of the maximum angle for cantilever printing, heights and wall thicknesses. This experiment resulted in sufficient printing quality of medium to large cell shapes and a verification of the previous tested specific printing values.

A selected set of process-demonstration videos, including 360-degree views of the designed extruder, kinematic simulation, robotic arm maneuvering, printing tests, and multi-mode subtractive-additive experiments, is available on the URL [16].

FIG. 4.23 Robotic silicone printing experiments, linear continuous printing (top); cellular printing on a free form fabric (middle); prototype testing height, cantilevering and size ranges (bottom).

Through these experiments, the overall printing quality is improved. The nozzle has a diameter of 3mm, which results in a print layer height of 2.4mm. The maximum printing angle can exceed 45 degrees. The printing angle is in correlation to the following factors: viscosity, wall thickness, stickiness of the silicone type, overall topology, and the mass of material to be printed on top. Therefore, an exact value is always specific for a certain shape. As seen in iteration three, the material and printing technique has the potential to print cantilevered parts. Silicone reacts with air after extruding and within 15 minutes the shape begins to harden. Furthermore, fully hardened silicone can be welded together with fresh silicone. These attributes allow for taller prints with maximum cantilevering angles.

FIG. 4.24 A test sample as a proof of concept prototype integrating subtractive robotic manufacturing applied on EPS and additive deposition of silicone with robotic arm.

To test and evaluate the proposed Multi-mode robotic production method, a proof-of-concept prototype with polystyrene foam and silicone is produced (FIG. 4.24). The dried outcome of the printed cells demonstrates the desired elastic behavior while it firmly stays glued to the foam. Further tests are also conducted in which by introducing a sine wave in the toolpath the contact area of the two materials, as well as the printing layers, is effectively increased (FIG. 4.25). This micro-scale manipulation results in an efficient deposition printing method.

FIG. 4.25 Fortifying sine wave toolpath for silicone printing to increase the stability of printed material.

4.2.7 Design to fabrication workflow and prototyping of the Hybrid Chair

The workflow is extended, explored, and demonstrated in the design-to-fabrication process of a prototype Hybrid Chair (FIG. 4.26). This process considers the key topics discussed with regard to subtractive production in combination with the opportunities of silicone printing. The integrated workflow establishes interconnected feedback loops between digital modeling, design computation, material properties, and a Multi-mode robotic production method. The project proposes a hybrid system composed of high-density polystyrene as a hard and silicone as a soft material. The macro scale geometry of the chair is designed in foam with developable surfaces. In micro scale, a distribution pattern in relation to the human body is applied while considering robotic milling, which is linked to the additive manufacturing process of the soft material.

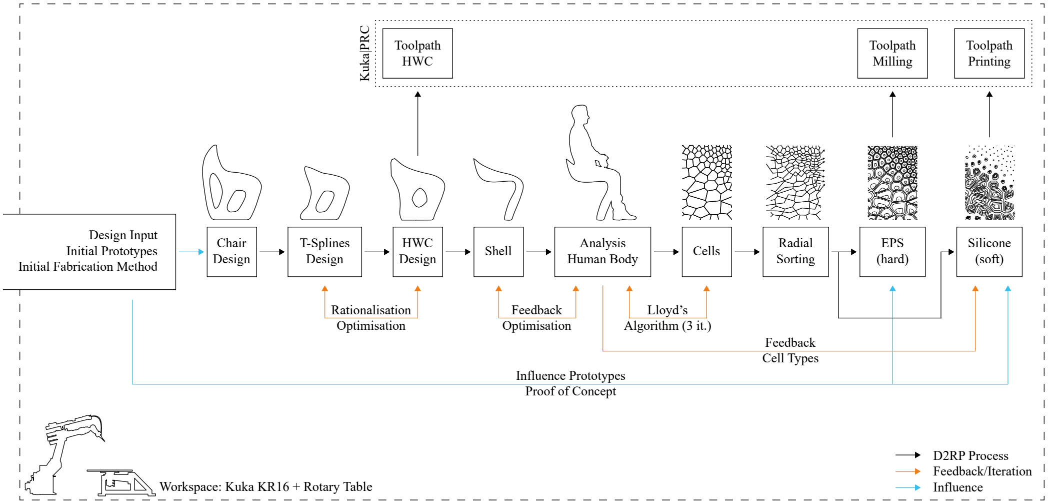


FIG. 4.26 Hybrid Chair, design-fabrication flowchart with rationalization and optimization feedback loops.

The form-finding to design materialization methodology of the Hybrid Chair includes three main feedbacks from the Multi-mode robotic fabrication (FIG. 4.27). As these three processes are considered and simulated in one seven-axis setup: six-axis robotic arm with a sliding rail, it is essential to iteratively evaluate the constructibility of the design by examining the overlaps between the optimum production-space of each method. The distribution of the silicone cells with differentiated sizes and typologies is implemented according to contact with the human body as it pertains to the seating and leaning areas on the front side of the chair. In similar scales, multi-materiality is explored and tested in chair design projects. Among them are the Gemini chaise (Oxman et al. 2014) with a focus on acoustical performance and the multi-colored multi-material ZHA chair (Bhooshan, Fuchs, and Bhooshan 2017) with an emphasis on structural efficiency gained through multi-material printing in a layer-by-layer printing fashion with high resolution. In the Hybrid Chair presented in this paper, flexible material with a feasible resolution for silicone printing is considered to be robotically deposited directly on the subtractively produced volume with three-dimensional surface tectonics, which is produced with robotic milling.

The macro-scale design is an iterative exercise implemented with Autodesk T-Splines in Rhinoceros 3D. The output of this modeling process is one digital model, which is then rationalized to four continuously developable surfaces that approximate the design (FIG. 28). The result of this approximation is then translated to an initial parametric model, which is linked to the robotic production simulation that allows for minor parametric customization of the design in the macro scale. To decrease the volume weight of the chair an internal hole with an adjustable three-dimensional twist is introduced.

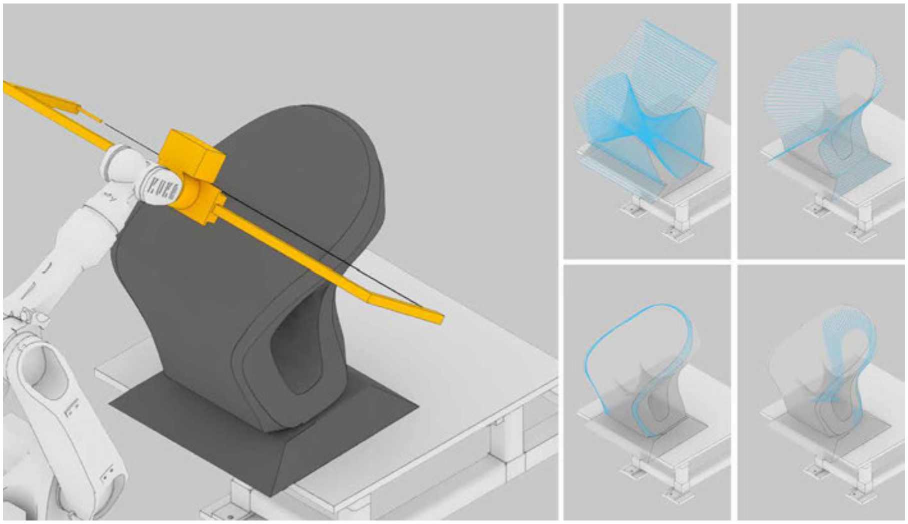


FIG. 4.27 Robotic Hot Wire Cutting of overall form, with only four cuts out of which one side will be milled for more elaborated required details where needed.

FIG. 4.28 Robotic Hot Wire Cutting of the developed surfaces of the Hybrid Chair.

The next mode of production is robotic milling on only the concave curvature of the front face of the Hybrid Chair (FIG. 4.29). While the macro design shape is produced by hot wire cutting, milling is used to further define the seating area. Roughing is necessary and only applied in this area to speed up the process. The robotic milling toolpath follows the cellular logic of the front surface that varies in size and depth according to the distribution of the soft silicone cells. To stay as perpendicular as possible to the surface during the milling process, the toolpath is parametrically generated based on the original cellular logic of the geometry. Each cell has a local entering and exiting safe point above the surface to be followed by radial incremental material removal. In this process, instead of a conventional line-by-line removal, the milling follows the cellular and thus a radial logic (FiG 4.30, FiG 4.31 and FiG 4.32 82).

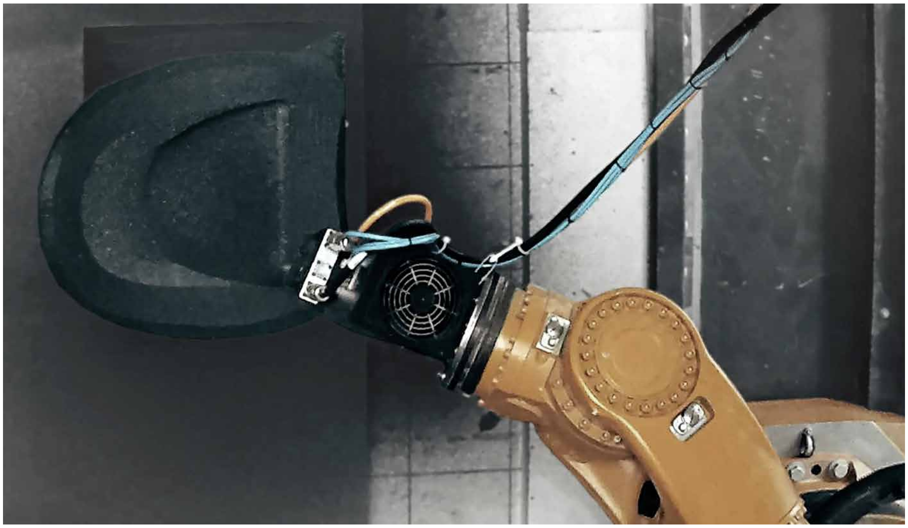


FIG. 4.29 Concave curvature surface robotic milling of the Hybrid Chair.

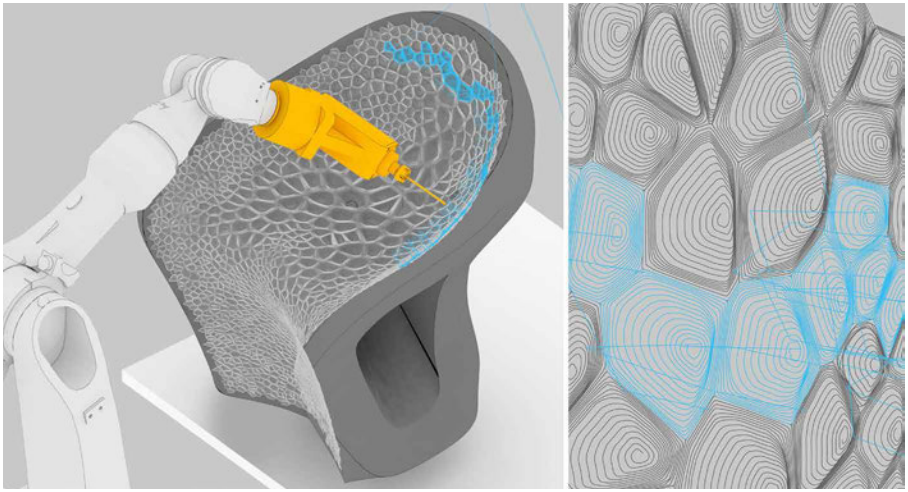


FIG. 4.30 Simulation of robotic milling on the concave part of the Hybrid Chair (left); incremental radial material removal strategy to fabricate the cellular pattern (right).

FIG. 4.31 Process of milling the cell in higher resolution perpendicular to the geometry that results in a refined surface quality and increases the friction between two materials.

These two subtractive processes are followed by an additive method. Silicone cells with varied sizes, depth, and typologies are distributed on top of the three dimensional concave front surface of the chair (FIG. 4.32,FIG. 4.33, and FIG. 4.34). The printability of the cells is decided based on a series of experiments on the fabric as well as the tests on EPS. The toolpath generation follows a similar cellular logic applied in robotic milling in the previous step. In this process, the continuity of the printing path is essential. Continuity in this stage of production means that after finishing the printing of one cell, the toolpath always continues to print a neighboring cell and avoids hovering above the surface until all cells are produced.

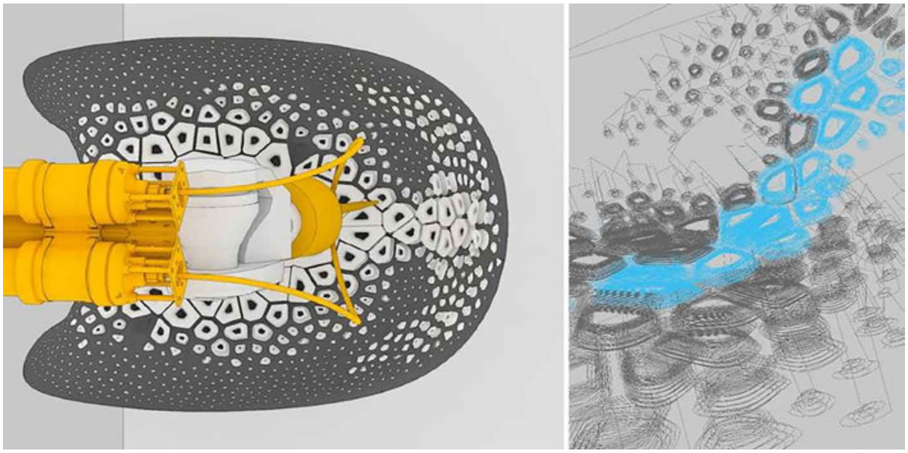


FIG. 4.32 Robotic 3D printing of silicone on subtractively produced front concave surface of the Hybrid Chair (left); continuous printing toolpath (right).

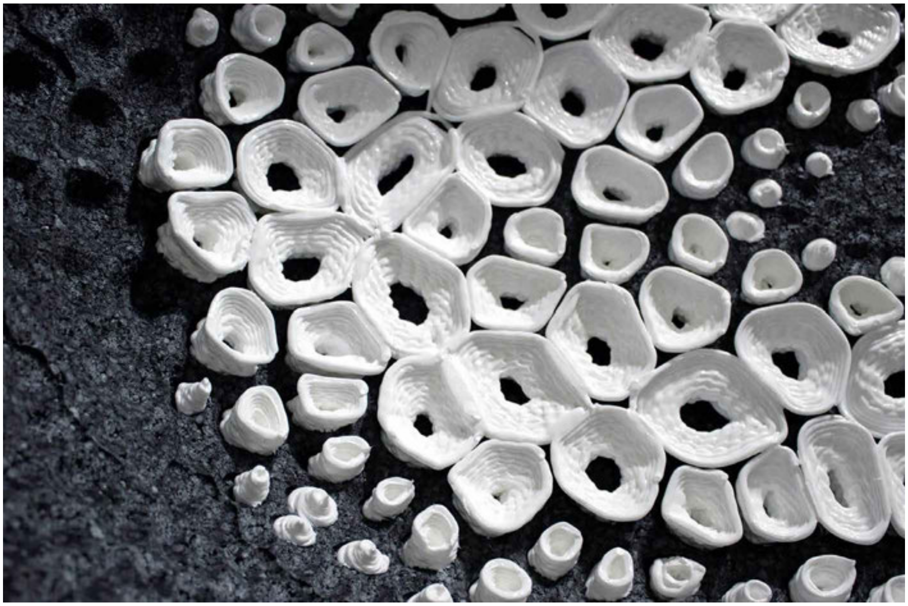


FIG. 4.33 Silicone cell on EPS surface, a zoom in view of the Hybrid Chair.

FIG. 4.34 Silicone cell on EPS surface, The fortifying sine wave smoothly disappear as the print reaches the tip of cantilever.

The production time of high-resolution milling and printing is reduced by an optimized robotic milling toolpath. Due to the difference in the numbers of neighboring cells and the gradient in size, a one-directional sorting technique is not applicable. The nature of cell distribution on the Hybrid Chair demands for a customized sorting approach that results in a continuous sorting with short travel time. Therefore, the outer edge of the chair shell is considered as reference for a radial sorting from outside to inside (FIG. 4.35). Since both subtractive and additive processes are executed in one setup, it is essential to inform the design through robotic simulation of both processes. As each of these processes has different optimum workable production space, it is important to know the overlap between these optima.

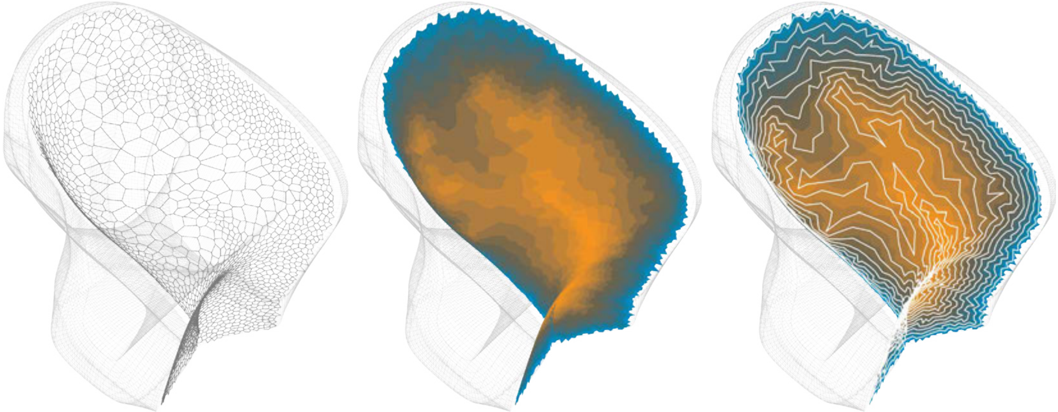


FIG. 4.35 Resulting cell distribution pattern based on human body analysis (left); toolpath optimization following a radial logic (middle); continuous toolpath travels through all cells without hovering above the surface to avoid tool and object collision during production (right).

4.2.8 Conclusion

The methods of design to robotic production of hybridity presented in this paper explore interrelations between different design scales, multiple fabrication methods, and various building materials. The approaches specifically define architectural robotics as a field of feedback and feedforward routines between three key research domains which are computation, automation, and materialization. Focusing on multi-materiality, each of the three prototypical case studies in this paper highlight certain challenges with regards to each of these domains that are summarized in the conclusion table (table 4.1). According to the description of the case studies, as well as the comparison provided in the table, following conclusive points and future directions can be discussed.

TABLE 4.1 Multi Materiality, Robotic Production, Modeling and Computation, Geometry and Performances of the hybrid projects summarized and compared.

Subject		Project		
		Hybrid Cork	Hybrid Concrete	Hybrid Silicone
Multi Materiality		– Hybrid of hard Expanded Polystyrene with flexible cork – Raw materials: EPS volumetric blocks and rigid cork boards	– Hybrid of hard Expanded Polystyrene with reinforced concrete – Raw materials: EPS volumetric blocks and concrete mixture	– Hybrid of hard Expanded Polystyrene with elastic solidified silicone – Raw materials: EPS volumetric blocks and liquid silicone mixture
Robotic & Production		– Two processes: robotic milling and robotic carving – Volumetric subtractive manufacturing on EPS and multi directional carving out notches from rigid cork boards – Assembly of the bendable cork interlocked in place on milled EPS	– Two processes: robotic milling, casting followed by robotic hot wire cutting – Volumetric subtractive manufacturing and casting the mixture – Two permanent parts of the EPS mold are assembled together without glue as they are intertwined with concrete	– Three processes: robotic hot-wire cutting, robotic milling and robotic 3D printing – Multi-mode of subtractive – subtractive - additive, roughing is applied only on the concave surface – Assembly of printed cells directly on the surface controlled with a higher resolution milling in contact areas and the adhesive properties of silicone
Modeling & Computation		– Modeling the details of the pattern directly with controlling the angles in robotic milling toolpath – Simulation as guideline for unrolling 3-dimensional cork into flattened surfaces using a physics engine	– Modeling the component according to a middle guiding surface that all of its boundary surfaces are generated as an offset of this guiding surface – Topology optimization of structure and translating the discrete point cloud into producible meshes	– Procedural modeling workflow with feedback from multi-mode robotic fabrication and toolpath optimization – Modeling the geometry of silicone cells with toolpath represented as curve – Computed continuous toolpath for milling and printing that includes all cells, avoids collisions and minimizes the total hovering traveling time
Design	Geometry	– Volume + Surface: Volumetric component with thickness variation interlocked with thickened surface with multi directional pattern that integrates porosity and varied notches	– Volume + Volume: Volumetric concrete element with varied diameters of branches intertwined with volumetric EPS elements that are both topologically continues volumes	– Volume + Curve: Volumetric EPS element designed with rationalized developable surfaces and mesh geometry of the concave seating area with continuous curves that are representing the cells
	Performance	Acoustic and surface quality	Structural and functional requirements	Comfort in seating area and surface quality

Materializing multi materiality in architecture, using robotic manufacturing requires customized design to robotic production models and workflows. An applicable and coherent model facilitates the design and production of porosity, hybridity, and assembly, as three essential operational components (Mostafavi and Anton, 2018). Starting from an application-based research, which evolved towards concepts and methodologies for robotic implementation, the studies show how novel material architectures can be conceived and produced. In this context, material architecture refers to a new multi-scalar system that ranges from micro to macro according to the inherent constraints and potentialities of innovative production methods. The proposed innovation is dependent on how computation, automation, and materialization are formulated and integrated. The outcomes of these customized processes are efficient building products with multiple materials. The achievable hybridity expands the physical property-space of materials that are producible hence implementable in design.

The design space is characterized and informed with the method of robotic production and through a set of feedbacks that implies customized methods of digital modeling, representation, and computation. Consequently, in addition to dominant surface based and boundary representation modeling methods, alternative modes of volumetric, curve-based and more fabrication methods of computer-aided design are needed. These alternative modes of modeling to production are introducing volumetric approaches to design, which are implementable through both subtractive and additive methods of manufacturing such as hot wire cutting, milling, and printing. In such approaches, in order to develop an operational design materialization methods, simulation and computation of the tooling process are essential, through which the sequences and combination of multiple techniques is re-examined.

Being able to design and customize different types of end-effectors to be integrated into a robotic production setup introduces gradients of varying material handling and processing approaches for building applications. With a focus on subtractive and additive approaches, the case studies in this paper are providing a set of prototypical projects on Multi-mode robotic production and a concluding design-to-prototyping process of the Hybrid Chair. The projects emphasize how the process of design materialization is influenced by the established feedback loops of robotic fabrication and how both subtractive and additive methods combined are approached or customized differently for more effective production. Moreover, the efficiency of the produced building systems is extended with the potentialities of a higher resolution and multi-material architecture that Multi-mode robotic production methods provide. The new resolution which is multi-scalar in nature and it is about simultaneous design to production in multiple scales, ranging from micro to macro.

TOC

4.3 Chapter Conclusion

Focusing on hybrid production and hybrid materiality, this chapter's objective is to present the developed workflows and methods for computation and production of hybridity in architecture. The chapter's three core case studies are Hybrid Cork, Hybrid Concrete, and Hybrid Silicone, where computational intelligence, fabrication intelligence, and material intelligence are discussed as an integral part of design-to-production systems.

Introduced Multi-mode methods of robotic production are subtractive-subtractive such as volumetric Robotic Hot Wiring Cutting and Robotic Milling, and subtractive-additive such as Robotic Hot Wire Cutting and Robotic Milling combined with Robotic 3D Printing. Eventually, further hybridization of production techniques using formative, modificative strategies is possible with the developed and prototype HI-ARM frameworks. To draw further conclusions on hybridity, based on the research outcomes of the case studies, we summarize the key findings in relation to the previously discussed definitions and frameworks in chapter two, which are applicable to the subject of hybridity:

1 **Hybridity / Design Systems, Computation and Automation:** Developing workflows for design computation of multi materiality and effective implementation of multi-mode robotic production processes requires an integrative approach to interoperability between different design platforms and the utilization of robotic setups' programmability. Both hypothetically and practically, the use of multiple production methods and multiple materials expands the production space's potentialities and possibilities in the material space. These expansions make the development of design-to-production processes more challenging yet with more opportunities for establishing integral feedback loops in design materialization processes.

2 **Hybridity / Topology and Geometry, Tectonics and Component:** Concerning topological and geometric modeling of multi-materiality, novel computational design methods that incorporate fabrication intelligence are required. The novelty may lie in how the design system may go beyond conventional visualization-oriented digital design approaches and move more towards data-driven and fabrication-aware computational representation methods. Moreover, similar conclusions made on computational modeling of porosity, such as the importance of volumetric modeling techniques such as voxel-based approaches, are critically relevant when it comes to the digital materialization of hybridity. Eventually, multi-mode robotic production

TOC

techniques and advanced design computation methods question the dominant layer-based approach of sandwiching layers of materials on top of each other. This opens up new possibilities for the materialization of hybrid systems in various architectural scales and building applications.

3 **Hybridity / Digital-Physical Integration:** Digitalization of the physical and physicalization of the digital are essential processes in materializing architectural hybridity using multi-mode robotic production technologies. The digital design interfaces need to be more informed in terms of the physicality of the material as well as the robotic building process using kinematic simulation. Moreover, using multi-mode methods such as subtractive-additive may demand dynamic updates from the physical to the digital. These automated feedback loops are helpful when working with materials with less fully predictable behaviors or heterogeneous properties during the fabrication.

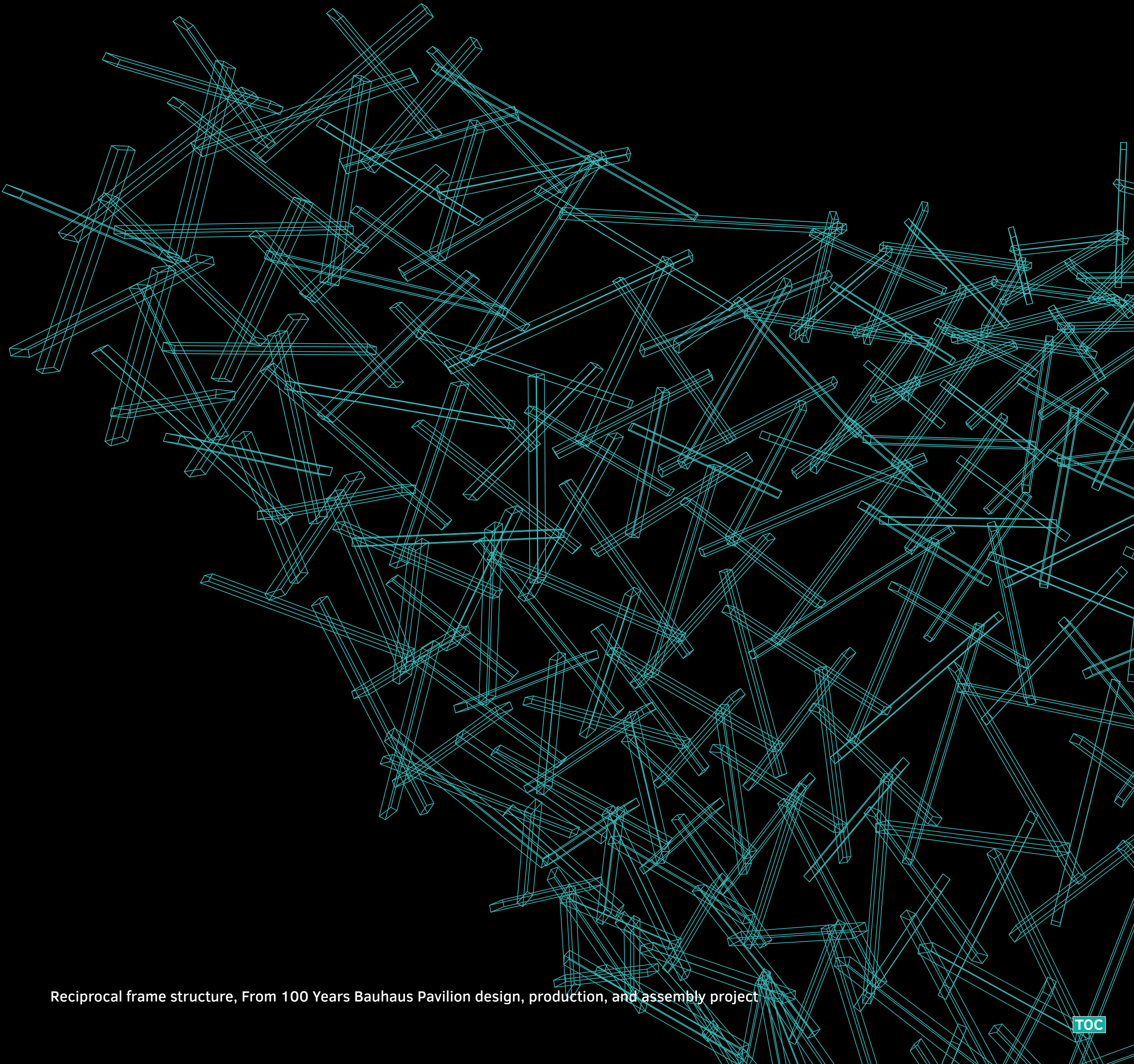
4 **Hybridity / Performance and Variation:** Incorporating multiple material properties and behaviors in hybrid systems allows for navigating a larger design-to-production space. Therefore, hypothetically and practically, there are more probable performance-driven design solutions which are producible using customized multi-mode robotic production technologies. However, evaluation of the actual performance of multi-material systems z may require the application of computationally heavy or complex systems. In this context, a series of purposeful design-to-robotic production experiments to study and document the materiality is an important feedback loop to inform the design process with the goal of finding performative solutions that simultaneously consider material, fabrication, and computational intelligence.

5 **Hybridity / Rationalization and Approximation versus Simplification:** Hybridization of the production process makes the materialization of complex multi-material systems possible. Therefore, new topological and morphological configurations can be implemented as rational choices using customized multi-mode robotic production techniques. Cases like Hybrid Concrete presented in this chapter, where two complex volumes of foam and concrete are three-dimensionally intertwined and interlocked, exemplify how rethinking the production process allows for the materialization of complex geometries with multiple materials.

6 **Hybridity / industrial Revolutions and Interdisciplinarity:** Similar to computation and production of porosity, efficient and effective materialization of hybridity requires an interdisciplinary effort. In Hybrid Cork, Hybrid Concrete, and Hybrid Silicone, we have emphasized the way hybrid material behaviors can be studied by integrating computational design and digital simulation processes together with robotic

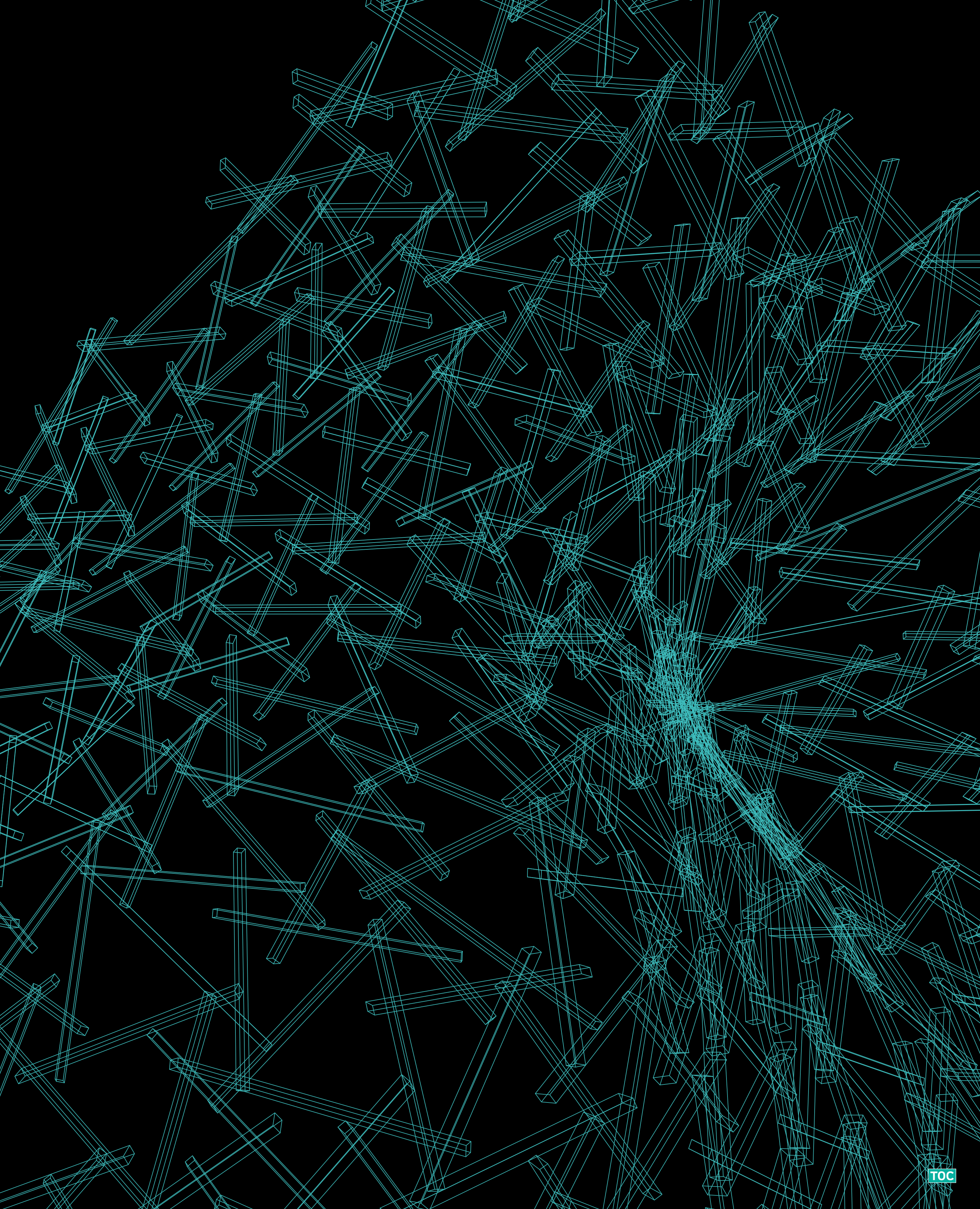
production experiential routine routines. These examples prove how disciplines such as material science, structural design, robotics, and production automation are fundamental bases of interdisciplinarity in architectural materialization.

TOC



Reciprocal frame structure, From 100 Years Bauhaus Pavilion design, production, and assembly project

TOC



TOC

TOC

5 ASSEMBLY: Component and Sequence

ABSTRACT

This chapter is centered on Assembly as the third subject explored and framed in this research next to Porosity and Hybridity. Assembly addresses the challenges of putting materials, building elements, and architectural components in various scales using integrated computational design to robotic production workflows. In the introduction, three major assembly concepts are discussed with a series of experiments and briefly presented projects: Connection, Component, and Sequence. The core case study of this chapter is focused on Design-to-Robotic-Production of Free-Form Reciprocal Frame Wooden Structures. The produced one-to-one prototype exemplifies a multi-directional approach to Assembly where the constraint and potentialities of production inform the design in terms of fabrication and assembly intelligence. The chapter concludes with a set of key findings and propositions related to Assembly, which are presented in reflection on HI-ARM definitions and frameworks.

KEYWORDS

Assembly, Connection, Component, Sequence of Production, Sequence of Assembly Reciprocal Frames, Wood Assembly, Reciprocal Tessellation, Free Form Structure.

5.1 Chapter Introduction

There are various reasons why dividing the building systems as a whole into smaller parts is an inevitable and essential consideration in architectural materialization processes as for instance the produced object is larger than the production space. Therefore, discretization is one of the implicit practices of architectural design and construction. On the one hand, internal factors are related to material constraints, design rationalization, and computation. On the other, external parameters include tooling capacities, transportation, and on-site building processes. Architectural robotics introduces a new spectrum of possible strategies for assembly intelligence.

Similar to porosity and hybridity, the assembly can be studied in various architectural scales ranging from micros such as material scale to macros or building units or spatial scale. In this chapter, the main focus is on the meso or componential scale. However, through the lens of the experiments' findings and the frameworks, we try to question and address larger-scale assembly challenges in the conclusions.

Implementing the HI-ARM frameworks, the briefly presented projects plus the core case study of this chapter discuss how assembly intelligence is informing the design in various phases, from conception to construction. Here, focusing on assembly in the meso-scale, three core concepts related to assembly are discussed in two sections:

1. Connections and Component
2. Sequences in assembly

5.1.1 Connections and Component

By developing and implementing integrated design-to-production workflows, this research proposes a component-based architectural design materialization and building systems with embedded connection details. Component-based design materialization questions the Element-based approach in design processes where predefined categories of building elements such as walls, columns, ceilings, windows, doors, etc., which are given instances of the body or the mass of architecture to be assembled. Therefore, the conducted and presented experiments redefine major assembly related concepts in construction processes such as building blocks, modularity, prefabrication, dry, and wet joinery systems.

With regards to component and connection, this research identifies two primary focus and design strategy in relation to integrated computational design to robotic fabrication systems:

1 Multi-Layered Intertwined Volumetric Components
2 Multi-Directional Distributed Connections

The volumetric approach to component-based design and assembly is tested in a double-layered building envelop (FIG. 5.1 and FIG. 5.2). The double-layered building envelope is a robotically produced one-to-one prototype that materializes a multi-layered assembly system for volumetric building skins. The prototype is a part of a larger designed project and consists of five interlocking components, each with varying sizes, integrated cavities, porosities, and surface tectonics. The project exemplifies how robotic fabrication results in an assembly intelligence where volumetric and highly detailed components can be interlocked together. The fabrication and assembly logic has informed the tessellation of two layers, internal and external, in such a way that there is a three-dimensional puzzle-like system with shifted cells.

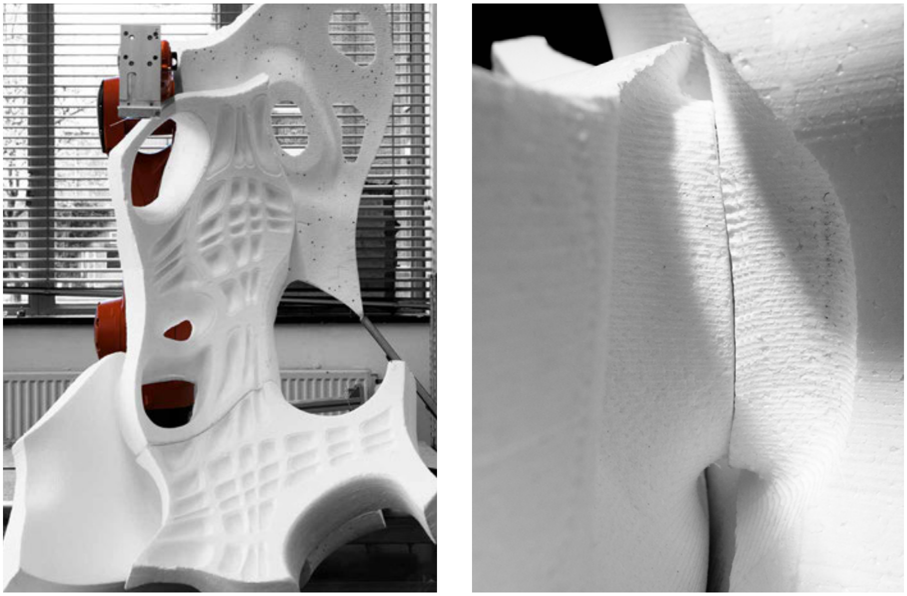


FIG. 5.1 Volumetric Component-Based Design Example, Double-Layered Building Envelope one-to-one Prototype, Left: five components assembled in two layers; Right a close up of the connection areas between two components inside the envelope.

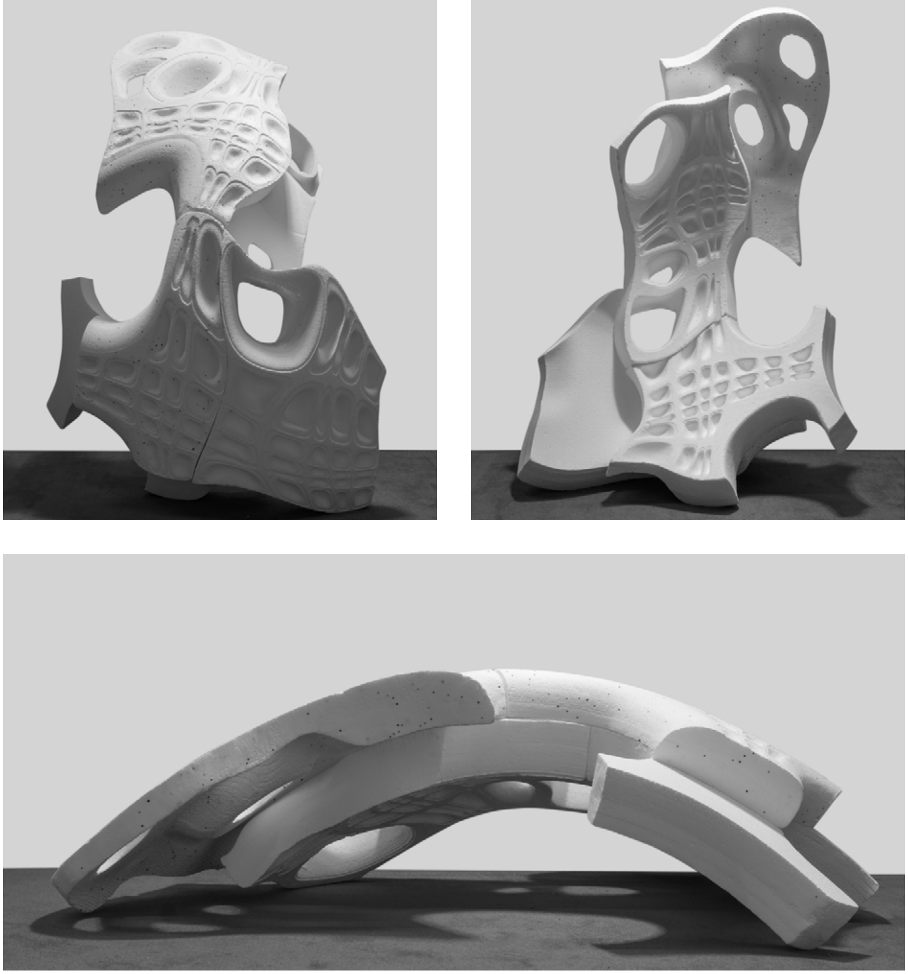


FIG. 5.2 Double-Layered Building Envelope, Top Left: Exterior view; Top Right: Interior View; Bottom: Sectional Side View.

The multi-directional distributed connection approach is prototyped in the Porous Assembly project, where components are coming together in order to shape a seamless and continuous building body (FIG. 4.3). With the aim to explore performative porosity at different scales, ranging from micro levels to meso, the one-to-one robotically produced prototype is a part of a designed pavilion and introduce a unique interlocking system for assembly of components, each with different size, thickness variation, curvature, surface tectonics, and level porosity.

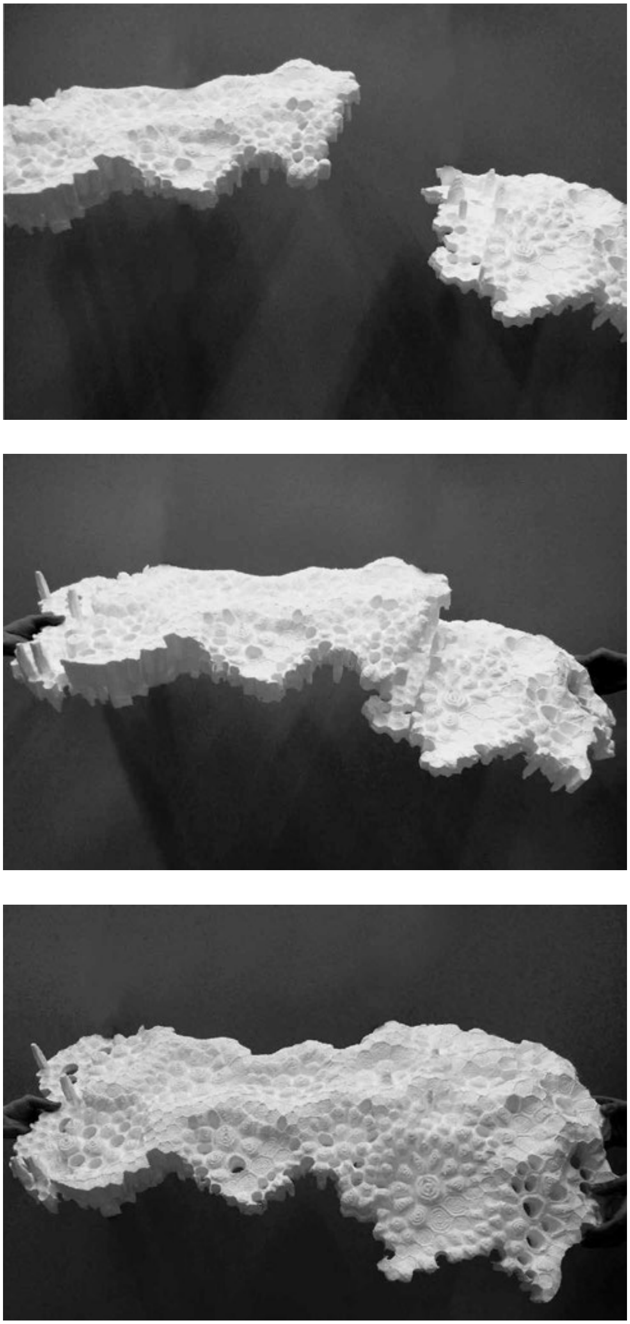


FIG. 5.3 Porous Assembly - the multi directional finger-joints create a prototype where the connections between different components are seamlessly integrated in overall surface tectonic.

In Porous Assembly, by introducing multi-directional finger-joints, an assemblage of customized components constructs a prototype in which the connections are seamlessly integrated into overall surface tectonics. Applying a localized assembly approach means only specific cells are targeted to perform as joints. Moreover, as the cellular topology stems from porosity logic, it makes the interlocking performance of the joints controllable through matching positive and negative elements for each target cell. Therefore, the “degrees of freedom” of the assembly at any given joint can be blocked through different geometric constraints. Here, robotic fabrication extends the production capacities of complex connections with different geometric features. This flexibility in production introduces a larger design to production space that allows for having ranges of the numbers, directions, and placements of pins onto the stepped connection with its jagged edges (FIG. 5.4).

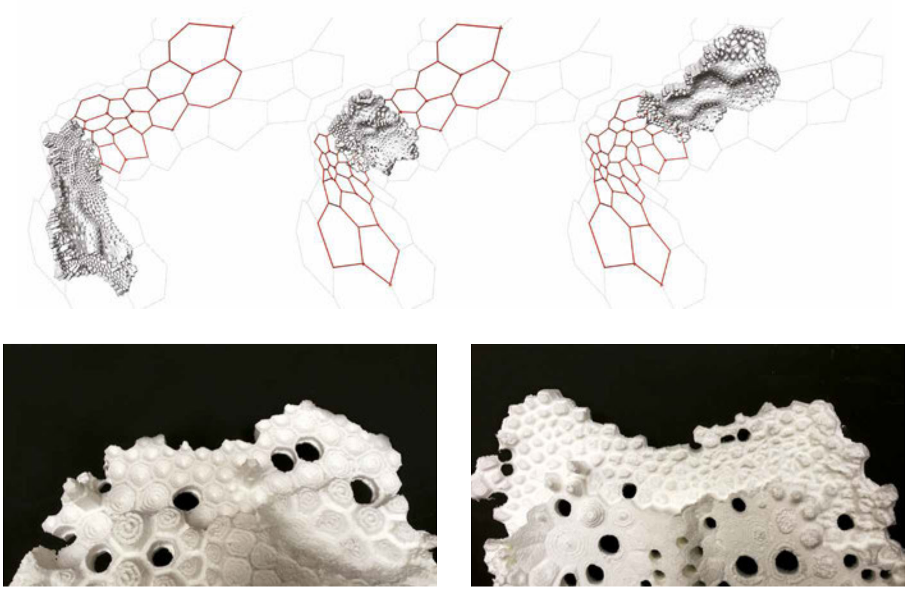


FIG. 5.4 Porous Assembly - robotic fabrication allows for the production of complex finger-joint connections that incorporate pins, distributed on surface connections with cellular edges.

5.1.2 Sequence of Assembly

The sequence or the order of the assembly of building components is an important but neglected part of fabrication and construction in the early stages of design processes. The flexibility and programmability of robotic production setups allow the rethinking of assembly strategies in multiple architectural scales, hence establishing a feedback loop to inform the design-to-materialization process. Introducing the factor of time, integrated computational design to robotic production processes afford the integration of assembly logic through incorporating geometrical and physical constraints as well as automated fabrication potentialities.

The sequence of assembly is studied in a Robotic Stacking project with the goal to develop a workflow for the assembly of non-pyramidal structures (FIG. 5.5). The project showcases an integrative approach for stacking discrete architectural parts with varied sizes in multiple directions. Several processes of parametrization, structural analysis, and robotic assembly are algorithmically integrated into a design-to-production method. This method is informed by the systematic control of density, dimensionality, and directionality of the elements while taking environmental, functional, and structural requirements into consideration in larger architectural and spatial design scales. The process benefits from the integration of robotic kinematic simulation that is enabling the materialization of a multidirectional and multidimensional assembly system.

FIG. 5.5 Robotic Stacking, Dry Assembly of Non-Pyramidal Structure: Assembly of layers and sub-layers follows an informed sequence based on constraint-based modeling, which allows for cantilevering and combination of large and small profiles.

Robotic stacking as an additive construction method has been extensively explored in architecture (Bonwetsch et al. 2006; Gramazio, Kohler and Oesterle 2010; Pérez 2017; Retsin, Jimenez and Soler 2017). The proposed Design to Robotic Production and Assembly approach combines the advantages of both known approaches by exploiting the dimensional flexibility of the continuous approach as well as the spatial freedom and multi-sized discrete parts (Chiang, Bier, Mostafavi 2018).

Furthermore, certain physical constraints are also affecting the arrangement of elements: The spacing between elements should allow the gripper to work and in order to prevent collision between elements, the elements' length (l), width (a), tilting angle (θ), the radius of curvature (ρ) and the distance between the center points (d) should meet the constraint indicated in FIG. 5.6. Since the discretized shell as part of a larger building envelope in this case study has a non-uniform thickness, longer and shorter elements are introduced (FIG. 5.7). The length of elements is limited when the orientation of elements is not parallel to each other, and the limit of the length is identified with an adjusted distance (d2, shown in FIG. 5.6).

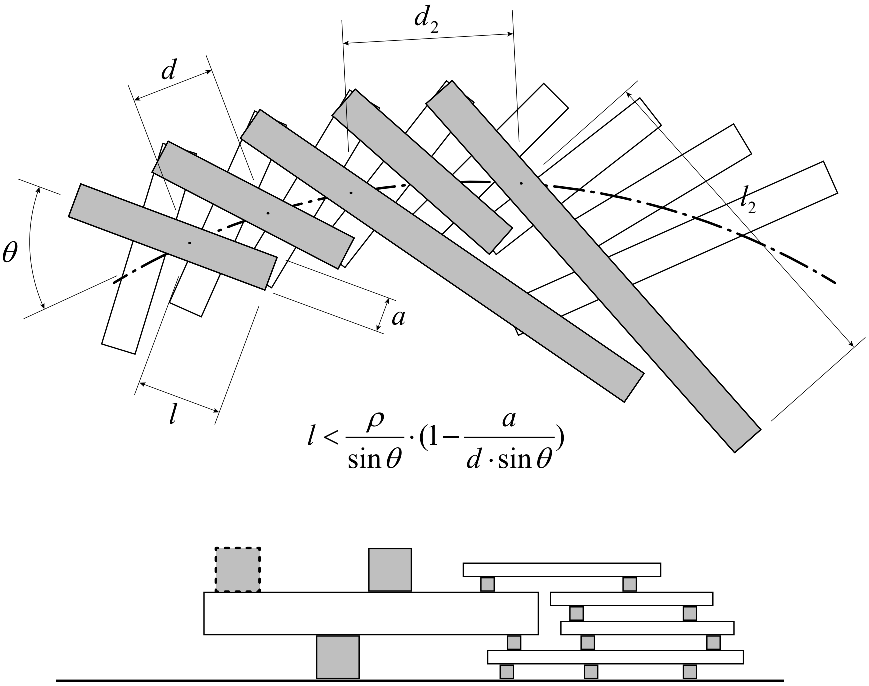


FIG. 5.6 Constraint-based parametric design-to-assembly system by introducing gradual variation in the angles between elements to control collisions between elements and the tool, and constantly checking the stability of the whole assembly during the assembly process.

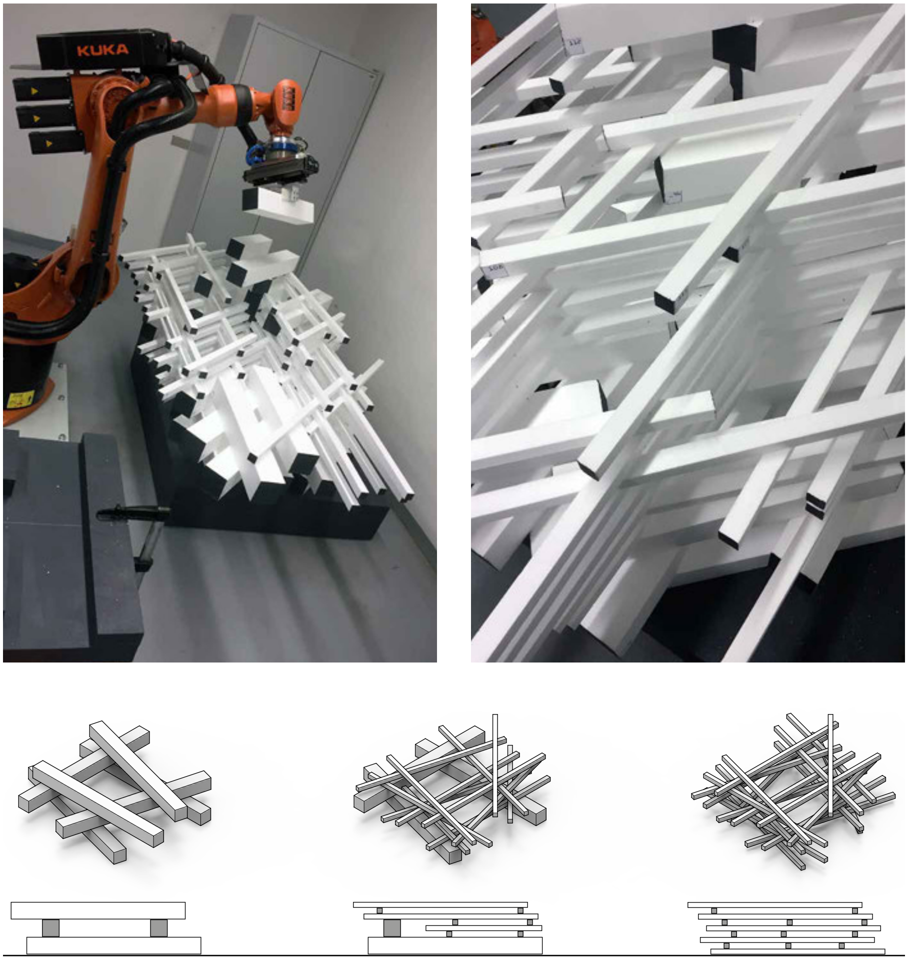


FIG. 5.7 Robotic Stacking, Dry Assembly of Non-Pyramidal Structures, Top Left: Robotic Stacking; Top Right: A close up of the assembly with elements with varied profile and length dimensions; Bottom: Diagrammatic representation of layering with different profiles.

Moreover, the ratio between large and small elements should be an odd integer, in order to keep the layering arrangement simple. If the ratio of large to small elements is 3:1, when three layers of small elements are placed at the side of one layer of large elements, the elements' main axis can be parallel at both top and bottom surfaces. This feature allows that every contact between elements in different layers stays cross-wise.

The stacking produces a fragment that has a mild curvature and cantilevers in multiple directions. Furthermore, the process is a human-assisted robotic staking example where the input elements' precutting and placement with varying sizes are done manually as the first step toward human-robot collaboration, which is necessary for implementing construction at building scale and needs to be explored further (The process documented in URL [17]). Moreover, a series of Multi-mode (gripping, drilling, placing) is conducted to explore further the automation of robotic assembly procedures of spatial structures (FIG. 5.8). In contrast with this prototype, which is a 2D layer by layer stacking of discrete elements, the next case study in this chapter introduces a more three-dimensional approach by focusing on multi-directional joinery systems based on reciprocal frame structures.

FIG. 5.8 A multi-mode assembly experiment, Gripping, Drilling and Placing.

5.2 Design to Robotic Production of Free-Form Reciprocal Frame Wooden Structures[4]

Design to Robotic Production of Free-Form Reciprocal Frame Wooden Structures

A Case study on Multi-Directional Assembly, 100 Years Bauhaus Pavilion

ABSTRACT

In a reciprocal frame structure, at any given joint, there are only two members connecting to each other. Therefore, the joints in a standard reciprocal structure are topologically identical. Due to these topological similarities between the joints, the parametric modeling of a reciprocal frame structure applied to a geometrically regular surface, such as domes and symmetric shells, is practical, and it has been explored in several projects previously. In this context, this paper presents an integrated computational design to robotic production process of a free form wooden pavilion with a non-uniform tessellation pattern with differentiated cell sizes. The case study, on the one hand, elaborates on the challenges of solving reciprocal tessellation on complex geometries, and on the other hand, discusses the chosen and developed robotic production approach as a feedback loop that informs the design process.

KEYWORDS

Reciprocal Structure, Wood Assembly, Design to Robotic Production, Reciprocal Tessellation, Free Form Structure.

---

[4] The following section, titled design to Robotic Production of Free-Form Reciprocal Frame Wooden Structures, has been previously published in the following peer-reviewed paper (Mostafavi, Kastrati, Badr and Mazlan, 2020):
Mostafavi, Sina, Valmir Kastrati, Hossam Badr, and Shazwan Mazlan. 2020. "Design Computation to Robotic Production Methods for Reciprocal Tessellation of Free-form Timber Structures." In Werner, L., Koring, D (eds.), Anthropologic – Architecture and Fabrication in the cognitive age - Proceedings of the 38th eCAADe Conference – Technical University of Berlin, Berlin, Germany.
More diagrams and information on the design development, computational design methodology, and robotic production to the assembly process are available on the URL [18] (Recorded presentation of the conference paper in eCAADe 2020).

5.2.1 Introduction and Background

Advancement in digital design and production technologies allows for efficient and effective use of wood as a potentially carbon-neutral material. Beyond automation of building processes in wood manufacturing, the programmability and customizability of robotic fabrication methods provide opportunities for design and assembly of complex structures. In this context, the design-to-production of reciprocal frame structures is studied. The reciprocal frame structure can be defined as structures consisting of linear flat or inclined elements, which support each other and are arranged in a way to form a closed circuit or unit (Larsen 2014). In particular, in wooden reciprocal structures, the joint design between intersecting elements is challenging in free-form geometries.

While inspiring references of complex wooden joint design can be found in traditional Japanese architecture or Scandinavian woodworks, usually with repetitive geometries, the methods of manual craft and carpentry are not directly applicable and scalable for automated construction. Moreover, architectural scale examples of wooden structures that implement reciprocal systems are few yet enough to be described in three categories in relation to this research. The first category is Regular Wooden Reciprocal Structures, such as symmetric domes by Shu and Kengo Kuma (Mellado et al. 2014) or even older examples of Da Vinci’s self-supporting bridge concepts (Bowie 1959). The second category can be mentioned as Reciprocal Tessellation of Irregular Geometries, like Mount Rokko-Shidare Observatory, designed by architect Hiroshi Sambuichi and Ove Arup and Partners (Goto 2011). The third type can be categorized as Wooden Architectural Elements or even waffle-like structures with cross-halved joints. Examples of this type can be seen in exterior elements of Bamboo Basket shop in Tokyo or Starbucks cafe in Fukuoka-shi by Kengo Kuma, where connections between elements may not be fully considered as a typical reciprocal structure, but yet there are visual resemblances as well as similarities in the method of assembly.

Contemporary applications of digital design and fabrication technologies in wood manufacturing provide examples of moving from repetitive elements and connections to more differentiated components with complex joinery systems (Inter al. Willmann et al. 2016; Anastas, Rhode-Barbarigos and Adriaenssens 2016; Menges, Schwinn and Krieg 2017). One of the early uses of robotic pick-and-place assembly is “The Sequential Wall” where timbers are laid down on top of each other, with no physical intersection between the elements which have varying length sizes (Gramazio et al. 2010). In “Robotically assembled joints for topology optimized structures”, the produced prototype provides a more complex connection between the ending points of the timbers. In this multi-directional spatial structure, more than two elements are meeting in one single point, which results in three-dimensional cuts at the end of the wooden profiles (Søndergaard et al. 2016). Lastly, in Timber Shell-Nexorade Hybrid, by combining timber elements and plywood panels, a hybrid system is introduced in such a way that avoids complex connection detail design and production (Mesnil et al. 2018).

The research objective of the presented case study is to rethink the design and production of free-form reciprocal wooden structures by developing and implementing integrated computational design to robotic production processes. In terms of connection design, one the one hand, the goal is to benefit from the potentialities of robotic production and, on the other hand, consider two elements per joint as the constraint or guiding principle of reciprocal systems. Among various possibilities of tooling such as nailing, screwing, gluing, milling, and spatially connecting (Eversmann 2019), multi-dimensional robotic milling is explored in order to achieve the required complexity in material removal from the reciprocal elements. This paper introduces and discusses the tessellation methods of free-form surfaces with varying sizes of cells and elements as the key research problem and design challenge.

5.2.2 Case Study: 100 Years Bauhaus Pavilion

As a part of 100 Years Bauhaus anniversary event in the City of Dessau, and by studying the historical impact of Arts and Craft movement in architecture, the case study of this research is a wooden pavilion structure. The pavilion is designed based on a reciprocal frame structural system using digital design and production technologies. The following section elaborates on the developed computational design, robotic production, and assembly methodologies. The descriptions are provided in three sub-topics: Reciprocal Tessellation of Free Form Structures, Architectural and Structural Form-Finding, and Robotic Fabrication. The two first topics are explored and developed in parallel, while the third domain provides feedback for materialization, which means that the research behind solving the tessellation in the micro-to-meso-scale is as important as macro-scale design, such as structural and architectural form-finding procedures. Therefore, the tessellation method is explained first as the primary research challenge of the project, and the other two sections are written in such a way that they can be read independently.

5.2.3 Solving the Tessellation of free form reciprocal structures

In order to solve the reciprocal tessellation of free-form surfaces, the research is conducted on two scales. The first scale is the micro-to-meso, which is concerned with each reciprocal frame in relation to the neighboring cells. The second part is the macro-scale, for which two strategies are developed to populate reciprocal frames on any given free-form surface.

Different topologies such as triangle, square and hexagon are studied as 2D planar cells. Reciprocal frames have overlapping members in such a way that each intersection receives only two elements. To parametrically model reciprocal frames, firstly, edges are divided equally with n-numbers of points, which result in a list of indices associated with each edge of the cell. Secondly, to construct the reciprocal elements as lines between two points, shifting patterns in the indices are studied. By connecting each initial index [0] to the shifted index [i] of the adjacent edge, a line is constructed as the reciprocal element. The higher the shift step, the deeper the intersection and smaller surface area in the middle (FIG. 5.9).

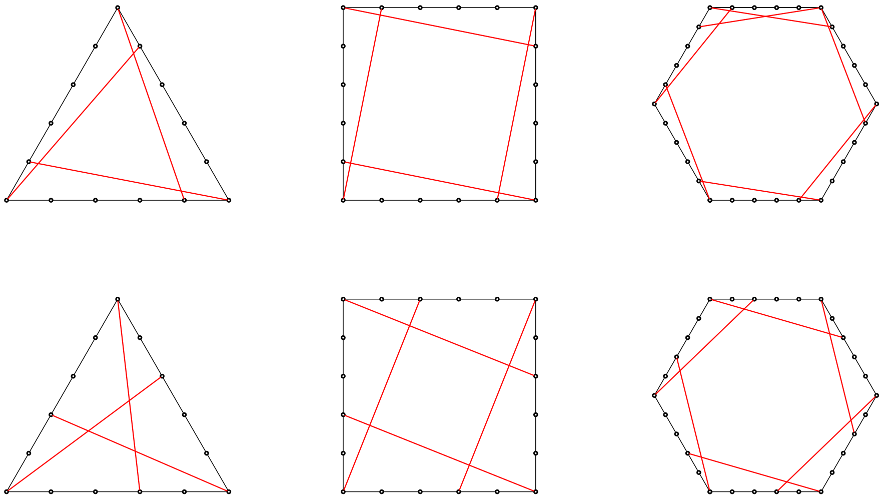


FIG. 5.9 Parametrization of reciprocal frames with different topologies, reconstructed lines based on shifted indices as points on the divided edges.

The next step is the 3D rotation of each element using the midpoints of the shifted edges as the center of rotation. On each planar reciprocal cell, the axis of the rotation is the perpendicular vector to each element. The angle of the 3D rotation is decided based on the type and the thickness of profiles in such a way that overlaps in case of tubular metal profiles, or sufficient physical intersection in case of wooden timbers, between elements is achieved. As an example, with the 60x46mm timber profile and cell size of 600mm in diameter, angles between 6 to 13 degrees are acceptable (FIG. 5.10).

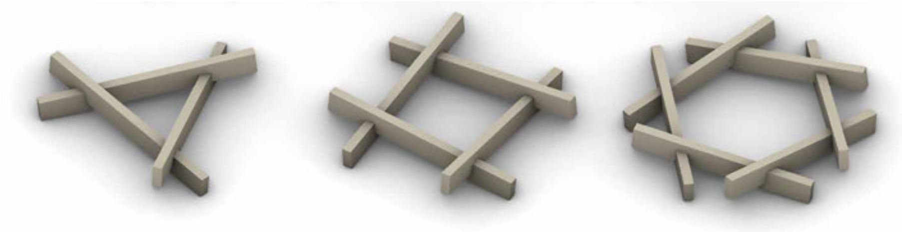


FIG. 5.10 3D rotations around the normal planar axis that results in acceptable intersections between reciprocal cell elements.

To further set the sizes and proportions of reciprocal units, two prototypes are robotically fabricated. In the first try, the notches are applied to only one of the intersecting elements, which results in less tooling time with the robot. In the second prototype, the intersecting elements share the total required depth of the penetration equally. While both methods result in stiff reciprocal units, the second approach is chosen. This decision is considering the physical assembly of the elements with minimal difficulties as well as the fact that in the second approach, the probability of fracture is lower as the material removal is less per element. Moreover, by extending both ends of each profile, the required strength of the elements is achieved. The extension is important, especially where the connections are close to the endpoints of the profiles. This initial fabrication feedback provides the required information for materialization in the following phases of the design process (FIG. 5.11). More information is provided in the third sub-topic of the case study.

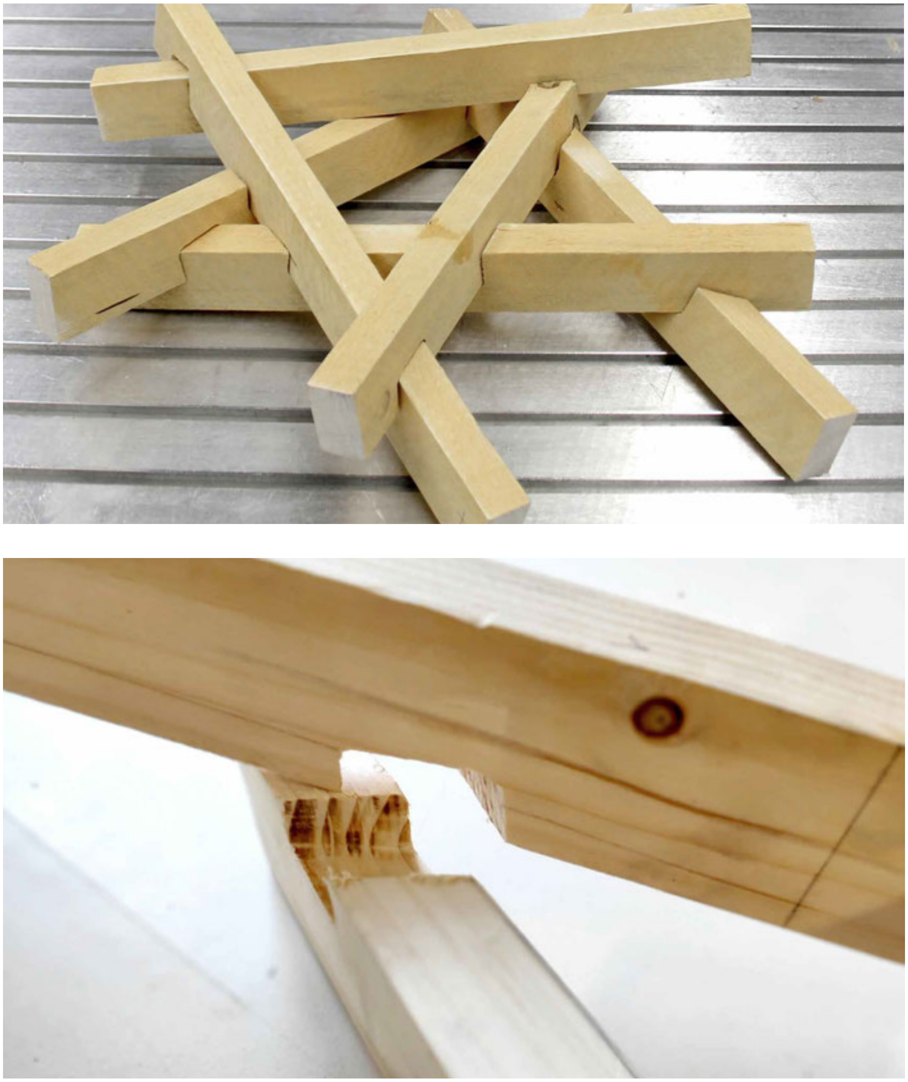


FIG. 5.11 Top: Robotically fabricated prototype of the first two reciprocal cells; Bottom: a reciprocal connection in which the notches are introduced on both members.

In the next phase of solving the tessellation, two approaches are tested on the macro-scale. While the first method is mainly based on Curvature Analysis of free-form surfaces, the second method Recursively Grows the reciprocal cells on the surface, taking multiple design considerations and assembly constraints into account.

TOC

The method based on curvature analysis takes a free-form surface as an input. While the subdivided surface that holds cells is a triangulated mesh, the input to be used for curvature analysis is required to be a NURBS. First step is the 2D shifting routine which is applied to the three edges of each triangle as it is previously explained in FIG. 5.9. Secondly, the mid-points of each shifted edge is projected to the NURBS surface, and the curvature values of the surface associated with the projected points are retrieved. The mid-points are projected to the surface considering the closest distance. Then, these values are used for 3D rotation of the elements in order to construct the reciprocal members with physical intersections (FIG. 5.12).

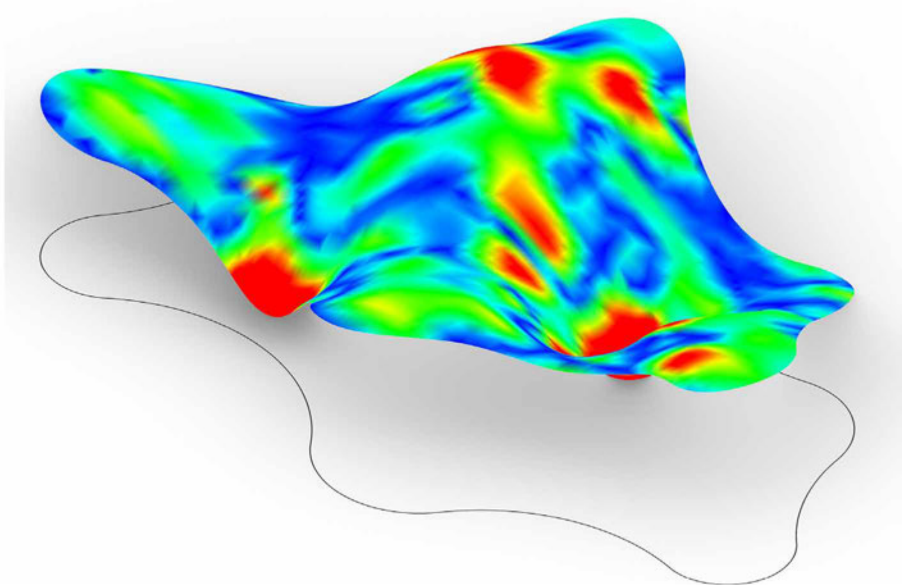


FIG. 5.12 Values extracted from curvature analysis of free form pavilion surface to be used for solving the reciprocal tessellation.

On a free form surface, elements in the areas with higher curvature require less rotation, while elements in the areas that have lower curvature take more rotation to obtain the necessary physical intersection between reciprocal neighbor elements. Therefore, the absolute mean curvature values, which are different for each edge, are remapped to the target range of rotation angles in such a way that all timber elements intersect appropriately. While this method is promising and applicable on a variety of free-form surfaces, yet in some cases, such as surfaces with kinks or complex anticlastic surfaces, the desirable intersection might not be achieved between all elements.

In the second method, instead of starting with the edges, the process begins with the vertices of triangulated mesh with varying face sizes that approximate the free-form NURBS surface. Then, on each of the vertices, circles are generated with radii corresponding to the surface area of each mesh face. The orientation of each circle is aligned with the tangent plane of the NURBS surface at the evaluated point. The evaluated points are the same as the circle centers and the same as the vertices of the mesh faces. Here, the axial lines of reciprocal elements are generated based on these circles in such a way that all lines are tangent to a pair of corresponding neighbor circles. In the next step, the generated lines are used as the Z vector of the Cartesian planes that set the orientation of the rectangular wooden profiles. In this case, the XY values of the generated Cartesian planes, which control the orientation of the profile around the axial lines of the wooden elements, may not necessarily result in proper connections between the intersecting wooden elements, since the axal lines are three-dimensionally oriented. (FIG. 5.13).

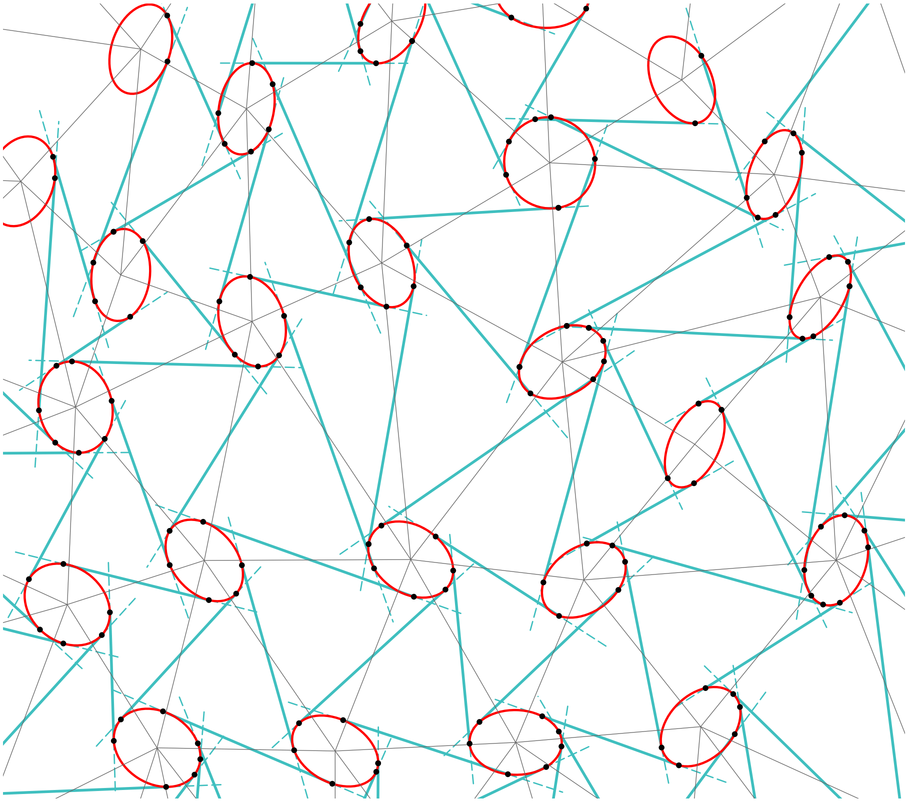


FIG. 5.13 The second method based on circles on the vertices of the triangulated mesh.

In order to adjust the orientation of the profiles, a recursive evaluation routine is developed. Meaning that the evaluation process may start from one joint in the structure, check and adjust the connection, rotate the profile as needed and move to the next neighbor element, and recursively repeat the same evaluation routine until all connections meet the criteria. The fitness criteria consider the fabrication method as well as having equal shared notches between the intersecting elements. This strategy suggests that each slit ends up with three faces, as it is proven to be practical in the second prototype shown in FIG. 5.11. In this process, the criterion of having three faces per connection is checked geometrically, while in order to force the profile closer to each other at the intersections, the Kangaroo Physics solver in Grasshopper Plugins of Rhinoceros® is used. In the final surface of the designed pavilion, the recursive loop starts simultaneously from the three anchor points, adjusts the connection, and moves toward the upper peripheral edges of the free-form pavilion surface (FIG. 5.14).

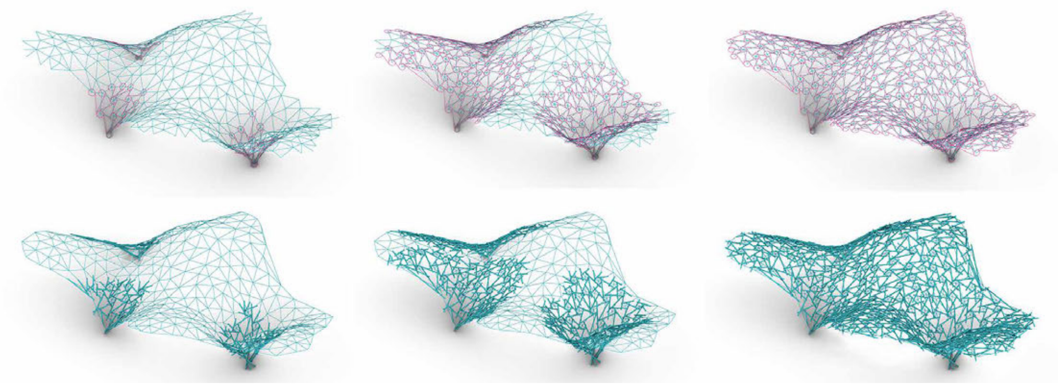


FIG. 5.14 Recursive method of solving tessellation for the free-form reciprocal pavilion.

5.2.4 Multi-Scalar Form Finding and Materialization

On the macro scale, the parametrization of the design-space simultaneously takes multiple architectural and structural factors into consideration. Meaning that while the overall configuration of the pavilion canopy is informed based on contextual parameters such as physical obstacles as well as human movements and interactions, the structural form-finding routine is implemented in parallel. The outer free-form peripheral curve of the pavilion is bounded inside a 6.5m x 10m plot. In order to define the main pathways towards the plot and position the internal activities, the outer peripheral curve is parametrically adjusted according to on-site observations as well as isovist analysis that considers surrounding buildings and obstacles (FIG. 5.15).

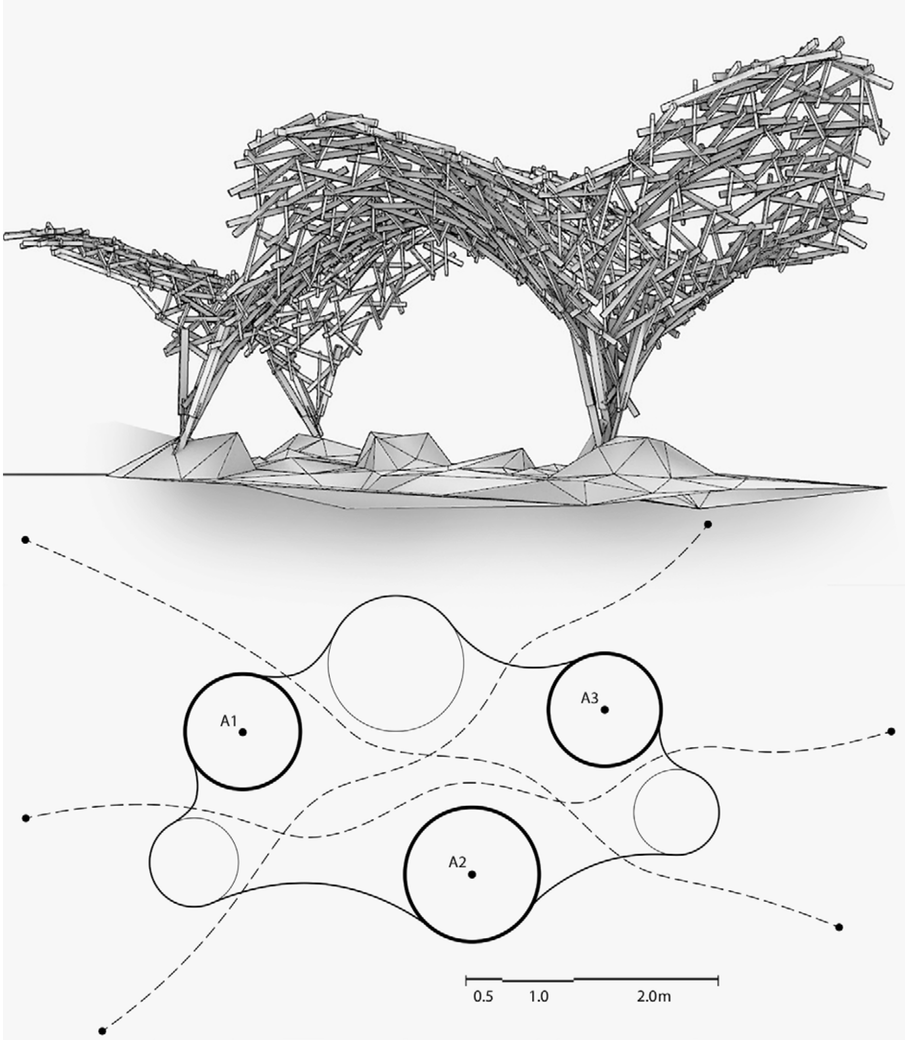


FIG. 5.15 Parametrization of the peripheral freeform curve of the pavilion and the overall architectural configuration.

The next phase of parameterization is transforming the 2D projected surface of the pavilion boundary into a free-form 3D mesh surface with the right resolution. Moreover, three anchor points are introduced as supports within the projected boundary area in order to hold the structure. These anchor points can freely move on the 2D surface inside the pavilion boundary, avoiding the obstacles and considering the activities under the canopy. A dynamic mesh relaxation method based on counter gravity force is implemented where the anchor points are fixed in Z and free in the XY plane, the points on the peripheral curve are fixed in XY and free only in Z, and all the other vertices of the mesh are free to move in all XYZ directions. The reason behind moving the vertices on the peripheral curve only in the Z direction is to avoid drastic deformation and to maintain the boundary shape of the pavilion during the 2D to the 3D relaxation process.

Additionally, the initial resolution of the triangulation of the 2D surface influences the mesh relaxation process. The final resolution is set with 300 populated points on the 2D surface, considering two main sets of factors. Firstly, parameters such as the feasible size range of reciprocal units, total quantities of elements, and fabrication effort are taken into account. Moreover, the resolution influences the dynamic mesh relaxation process in terms of the required computational processing power as well as the quality and topology of the resulting mesh, especially on the peripheral edges of the relaxed mesh.

With these three parametric systems being set, which are: 1) adjustable anchor points, 2) changeable mesh resolution, and 3) dynamic relaxation of the topology, the parameters of the design-space are defined. Moreover, a structural analysis routine is linked to the parametric model in order to evaluate the structural stiffness of every possible outcome generation in the design-space. The preliminary cross-section material for all the elements is set to be a type of wood that can hold Fy=1.3kN/cm2. Further, a set of predefined wooden profiles are considered as the input timber profile options. In this project, considering the material supply and fabrication effort, the number of options is reduced to two, which are 50mm x 120mm and 50mm x 70mm. This results in a variation of cross-section profile through the pavilion, as it is shown in one of the design generations in FIG. 5.16.

TOC

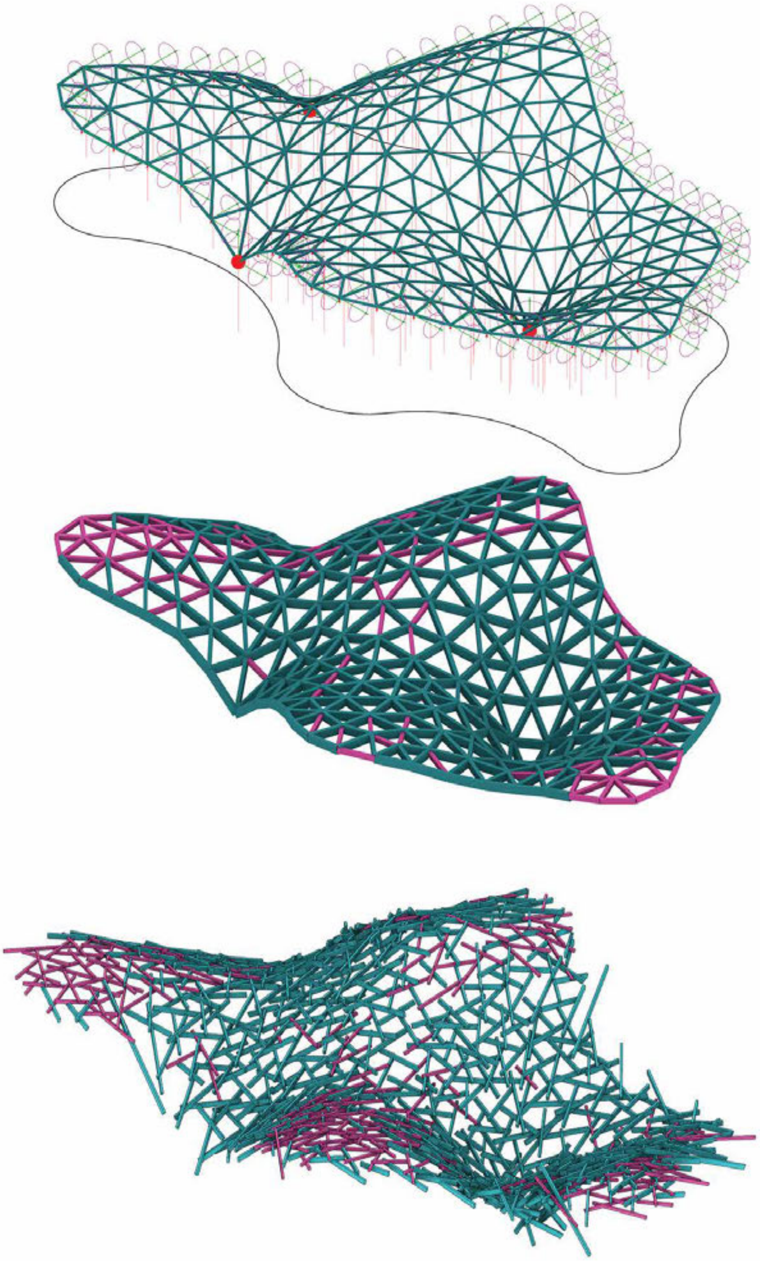


FIG. 5.16 Top: Parametrization of the design-space defined with the adjustable anchor points, changeable mesh resolution, and free-form mesh to be dynamically relaxed; Middle: Materialization of the cross-section with varied profile sizes; Bottom, Applying the second reciprocal tessellation method.

TOC

The following step is to explore the design-space using a Multi-Objective Optimization (MOO) solver in order to find the optimal configurations. The objectives are: the mass to be minimized, the total accessible average height to be maximized, the total structural displacement on all vertices to be minimized, and the total internal elastic energy to be minimized. The add-on plugins used in Rhinoceros®-Grasshopper3D are Wallacei as the MOO solver and Karamba3D for structural analysis and profile assignment. Eventually, among the multiple optimal generations, the most fitting one is chosen for further fabrication and design development (FIG. 5.17).

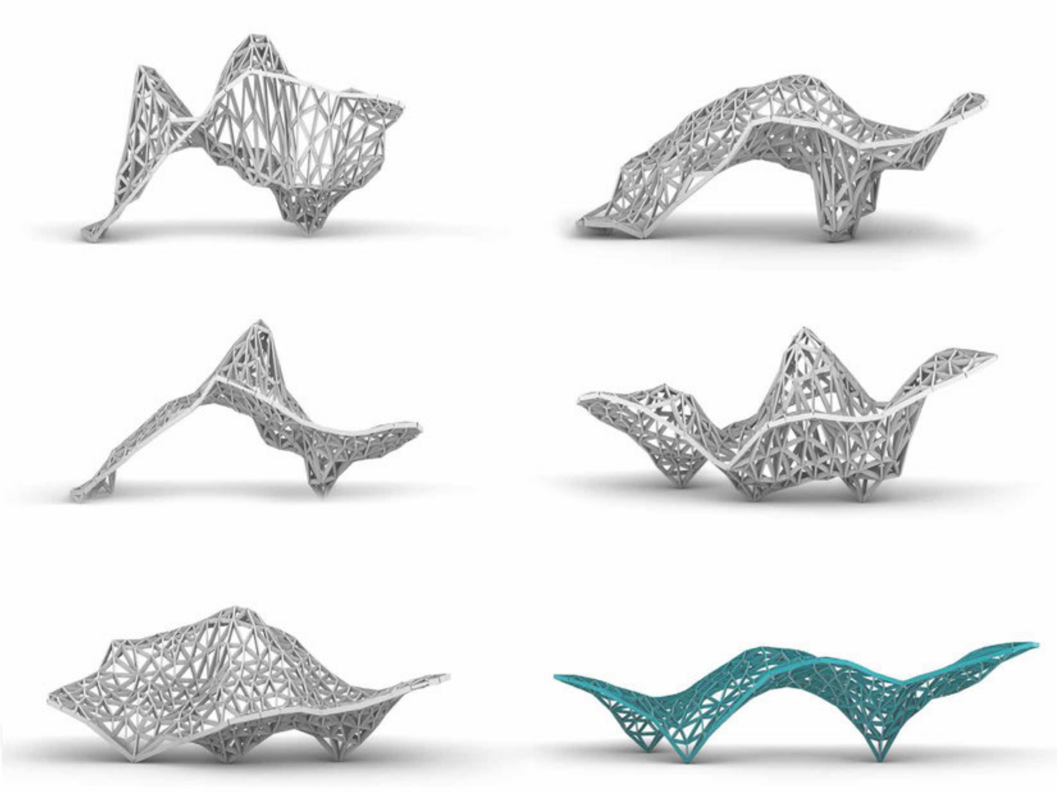


FIG. 5.17 Exploring the design space using Multi-Objective Optimization to find the optimum solutions (Performance criteria explained in the text).

5.2.5 Robotic Production and Assembly

Parallel to the computational design workflow, several prototypes of reciprocal structures are produced and different methods are tested. In order to establish a generic system that considers the variations in the dimensions of the profiles, the numbers of the connections per element, and the angles and depths of the cuts, a parametric design-to-robotic production method is developed. Incorporating the inverse kinematics simulation of the robotic production process suggests two types of material removal approach. The first approach is the Layer-by-Layer removal method, where the orientation plane of Tool Central Point (TCP) at the tip of the milling bit is aligned with the orientation plane of the bottom surface of the cut. The second tooling routine is Perimeter Removal, which directly cuts the perimeter of the slit, without crushing the whole material inside the joint, by aligning the direction of the milling bit to the three surfaces of the cut. While the second method is faster, for some ranges of angles, the first method is required. Using the second method results in round edges between the surfaces of the cut, which may prevent the two elements interlocking perfectly together. The radius of the fillet depends on the diameter of the milling bit. Therefore an offset towards outside of the cut for all three surfaces is required to control the fabrication tolerances (FIG. 5.18).

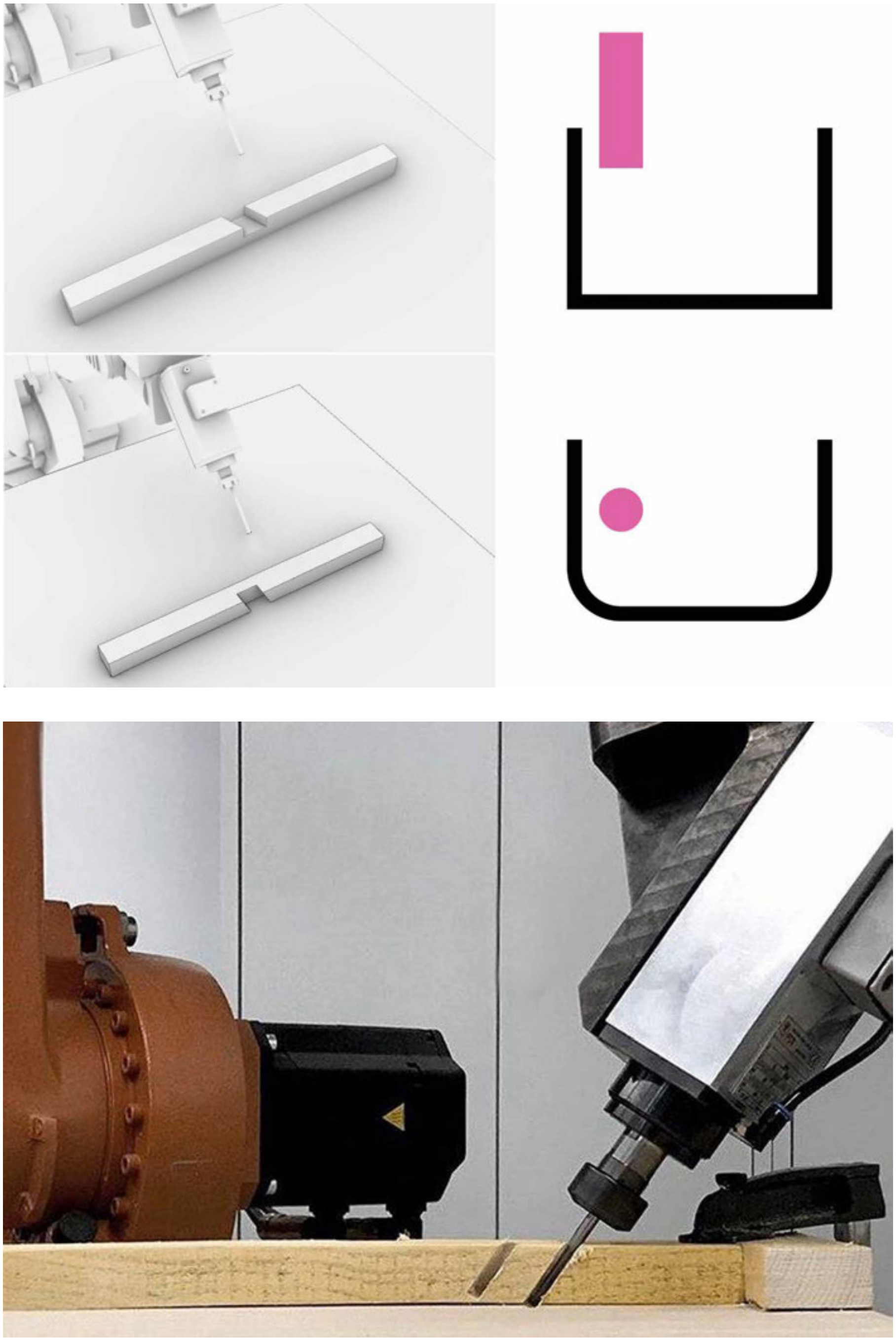


FIG. 5.18 Two methods of toolpath generation for material removal: Layer by Layer removal on the top and perimeter removal without crushing the material in the middle and bottom.

By using the developed robotic toolpath generator, three initial tests are produced before the final pavilion prototype. In the first case, the focus is on one reciprocal unit where a 30mm x 60mm wooden profile is used, and cuts are only introduced on one of the intersecting members. The second case uses the same type of detail for intersections, where multiple units are produced and assembled together to form a larger mock-up with hexagonal reciprocal cells. Instead of wooden profiles, 50mm x 70mm Expanded Polystyrene (EPS) elements are used for faster production and testing the proportions of the final designed pavilion. While the production effort is considerably less with this type of intersection, the assembly process is challenging as there are no reference contact points on the corresponding reciprocal elements. Therefore, the halved joint detail is tested in the third case as well as the final pavilion prototype to overcome the assembly challenges and reduce the risk of fracture of the elements.

The final presented prototype in this paper consists of 78 reciprocal wooden elements with varying sizes in length ranging from 500mm to 1700mm that together form 26 reciprocal cells. The prototype is a segment of the designed pavilion, and it is taken out from the areas around one of the anchor points to produce a reciprocal structure that has high surface curvature. The profile cross-section is set to 26mm x 50mm by considering the available material resources, the applicable payload of the KUKA KR-16 robotic arm, as well as the estimated time for the production and assembly. In order to double-check the structural stability of the prototype, the model is analyzed by implementing the same structural analysis routine developed for the form-finding and materialization. The total time of producing all the joints with an 8mm milling bit is roughly 12 hours, which includes supervision and the positioning of pre-cut elements in front of the robotic arm. Most of the elements are receiving two cuts. However, in some cases, there are three or four notches where the extended ends of reciprocal elements collide with more than two nearby elements. Cuts are mainly produced using the perimeter cutting method, and few cases are produced using the layer-by-layer approach. Therefore, zip ties are used to stiffen the connections (5.19).

TOC

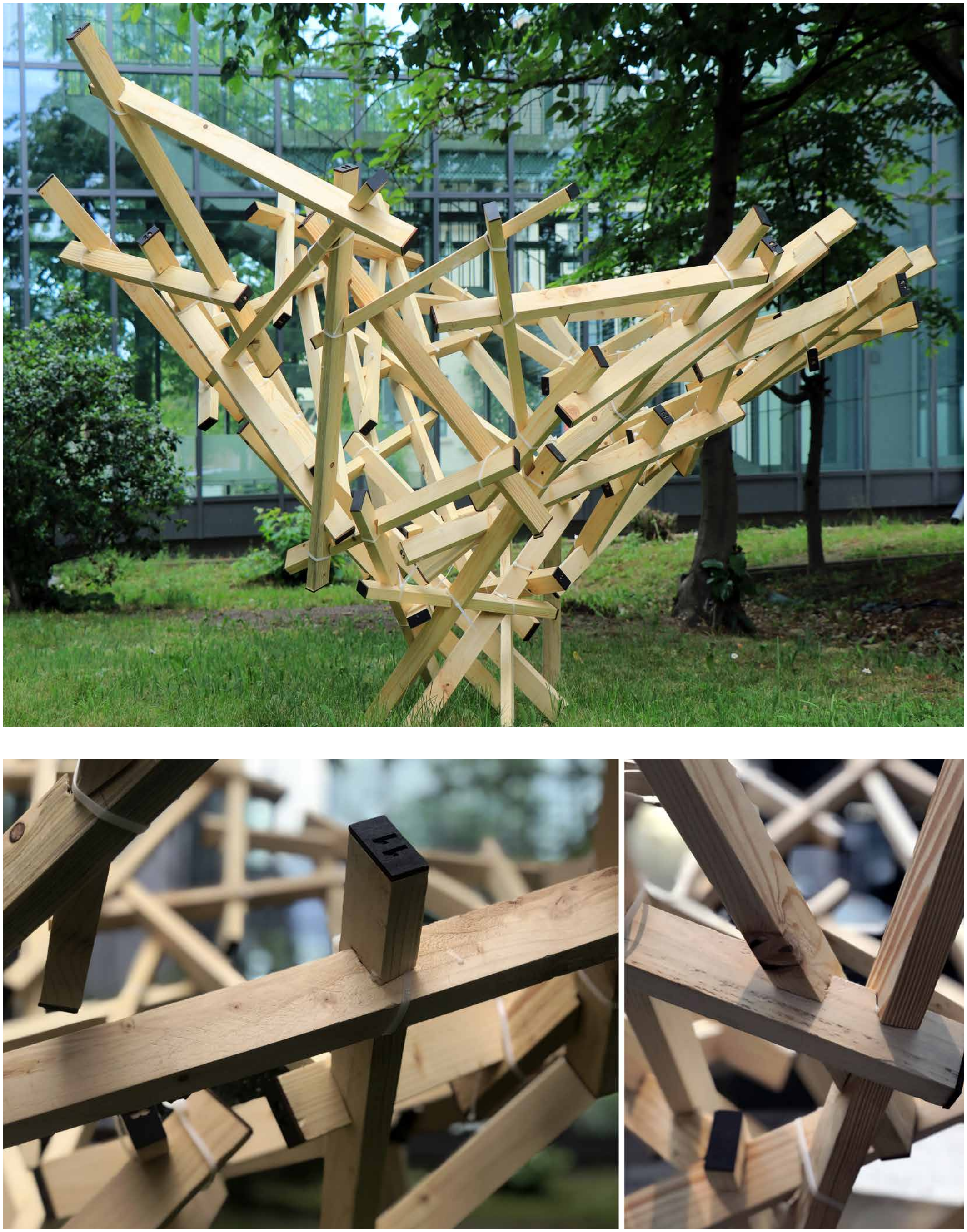


FIG. 5.19 Top: The final prototype with 78 reciprocal elements varying in size ranging from 500mm to 1700mm Bottom: Close up of the connections.

TOC

5.2.6 Conclusion and Discussion

This project presents the development of a computational design to robotic production workflow for reciprocal wooden frame structures. Computationally solving the tessellation of free form surfaces, while considering all the required geometric constraints and fabrication potentialities, appears to be a key factor in this research. The proposed methods for tessellation provide solutions for a variety of complex geometries. Further improvements can be made for free-form surfaces with multiple opposing curvature directions like anticlastic surfaces. An instant solution for extreme curvatures is to increase the tessellation resolution, which then results in larger quantities of elements hence more fabrication effort. Therefore, in this project, the size variation of reciprocal cells is explored and tested. Defining the cell sizes based on the surface curvature, on the one hand, may result in interesting architectural qualities and, on the other hand, may structurally explain the differentiation of profile cross-section. Theoretically, it is possible to vary the profile section of every single reciprocal element to optimize the structural performance further. However, practically a balance between the availability of material resources, quantitative performance measurements, qualitative design objectives, and fabrication strategy is required. In this context, one of the future directions for this research might be the integration of robotic pre-cutting of elements with varied shapes and dimensions.

Reciprocal systems are a type of self-supporting structure which are introducing a range of opportunities to develop alternative assembly strategies of free-form wooden structures. While providing the freedom to produce complex joint design using robotic tooling can influence the assembly logic, further explorations can be conducted to automate the process of connecting the elements together. This may suggest the development of robotic assembly setups with multiple manipulators or human-robot collaboration where augmented reality could assist the assembly processes and inform the design accordingly. Learning from the manual assembly process of the final prototype, it is worthy of mention that the basket-like shape of the prototype provides stability while connecting the units together. Moreover, as the tagging sequence follows the very same order of recursively generating the reciprocal members starting from the anchor points, the structure remains self-supporting during the assembly process.

5.3 Chapter Conclusion

In micro-to-meso scales or material-to-component scales, integrated computational design to robotic production systems provides varieties of opportunities for efficient and effective architectural materialization approaches. These ranges of scales are mainly addressed and discussed as a part of projects on porosity and hybridity. This chapter looks into how we can benefit from the framework of this research with the goal of developing alternative methods of assembly in architectural design and building processes. Therefore, with the focus on meso-scale design and prototyping, the goal is to see how we can address larger-scale assembly challenges, allowing us to think and go beyond the dimensions production setups.

Components, Connections, and Sequences are identified and discussed as three fundamental concepts and strategies to achieve assembly intelligence in design-to-production systems. Further, this chapter's extended case study is a one-to-one prototyped reciprocal wooden structure that introduces an integrated design-to-robotic-production of Free-Form Reciprocal Structures. The process discusses how the fabrication constraints and potentialities of multi-directional connections in micro-scale inform the multi-directional assembly of elements with varying sizes, hence establishing feedback loops to the computational design form-finding workflow in the macro-scale and tessellation logic in meso-scale.

To draw further conclusions on assembly, based on the research outcomes of the case studies, we summarize the key findings in relation to the previously discussed definitions and frameworks in chapter two, which are applicable to the subject of assembly in design-to-production processes:

1 **Assembly / Design Systems, Computation and Automation:** Developing integrated design to design-to-production systems for efficient and effective assembly methods requires the innovative implementation of computational design and automatization of building processes. In this research, incorporating fabrication to assembly constraints and potentialities within the design computation workflow is identified and explored as one of the key strategies and challenges to tackle. Moreover, the sequence of assembly or conceiving and computing a time-based workflow is suggested and prototyped in the experiments and case studies. In terms of automation for assembly, in addition to Multi-mode robotic production techniques and multi-tooling, which result in robot-robot collaboration, future human-robot collaborative workflows and scenarios are required for a larger extent implementation of robotics in larger-scale fabrication and potentially in construction scales.

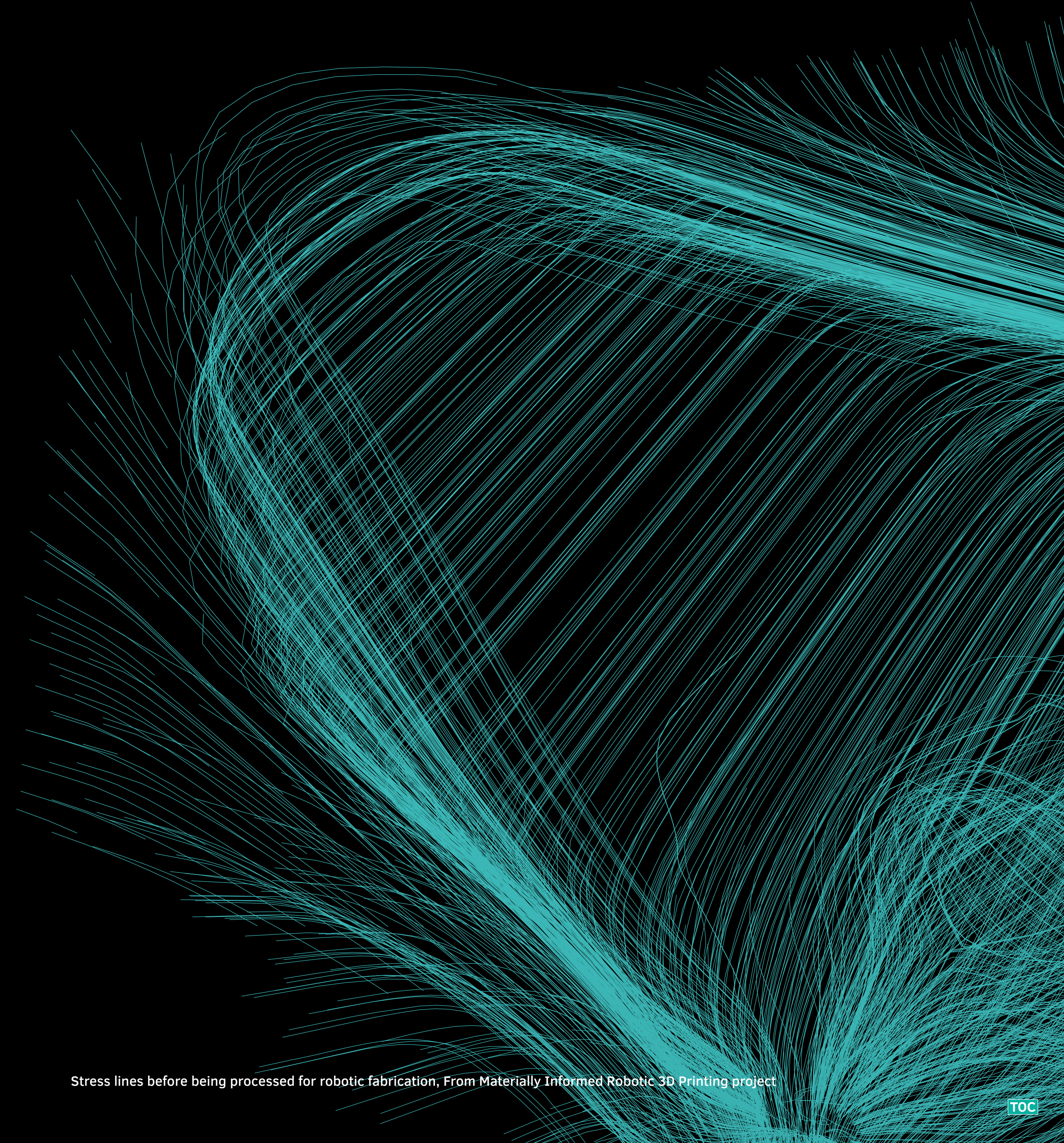
2. **Assembly / Topology and Geometry, Tectonics and Component:** Enabled by integrated computational design to robotic production systems, the developed frameworks and methods exemplify how alternative strategies for assembly introduce a wide variety of volumetric approaches next to surface-based modeling. In the context of assembly intelligence, for topological and geometric modeling of building components, a combination of discretization of volumetric 3D components and tessellation of free-form surfaces is required. Moreover, being able to access the material from multiple sides informs and justifies the design of complex joints and assembly details that are producible using robotic fabrication.

3. **Assembly / Digital-Physical Integration:** The automation of assembly demands development of integrated design-to-production strategies for controlling the accumulative tolerances during the assembly. The tolerance is specifically critical when we go larger than available production space for a specific robotic setup. Therefore, feedback from the physical to the digital through scanning and survey of the operating space can partially control the fabrication accuracy, repeatability, and assembly precision. However, as it has been discussed and exemplified in this research, the very hybrid nature of architectural design materialization and building systems may require a combination of automated, semi-automated, and manual approaches where we could benefit from both machine and human capabilities and intelligence. In this context, virtual space as a medium can play an instrumental role in bridging the digital and physical as well as the machine and human.

4. **Assembly / Performance and Variation:** Advanced computational modeling and robotic fabrication allow for the materialization of complex joints and multi-directional connections, which can perform structurally and effectively. Therefore, the application of integrated design to production systems results in incorporation of the connections in building components with varying dimensions that can take multiple functional, structural, and environmental criteria into account. Further, the aggregated components' structural performance, or computing the sequence and evaluating the stability during the assembly process, is an important area of exploration and further investigation.

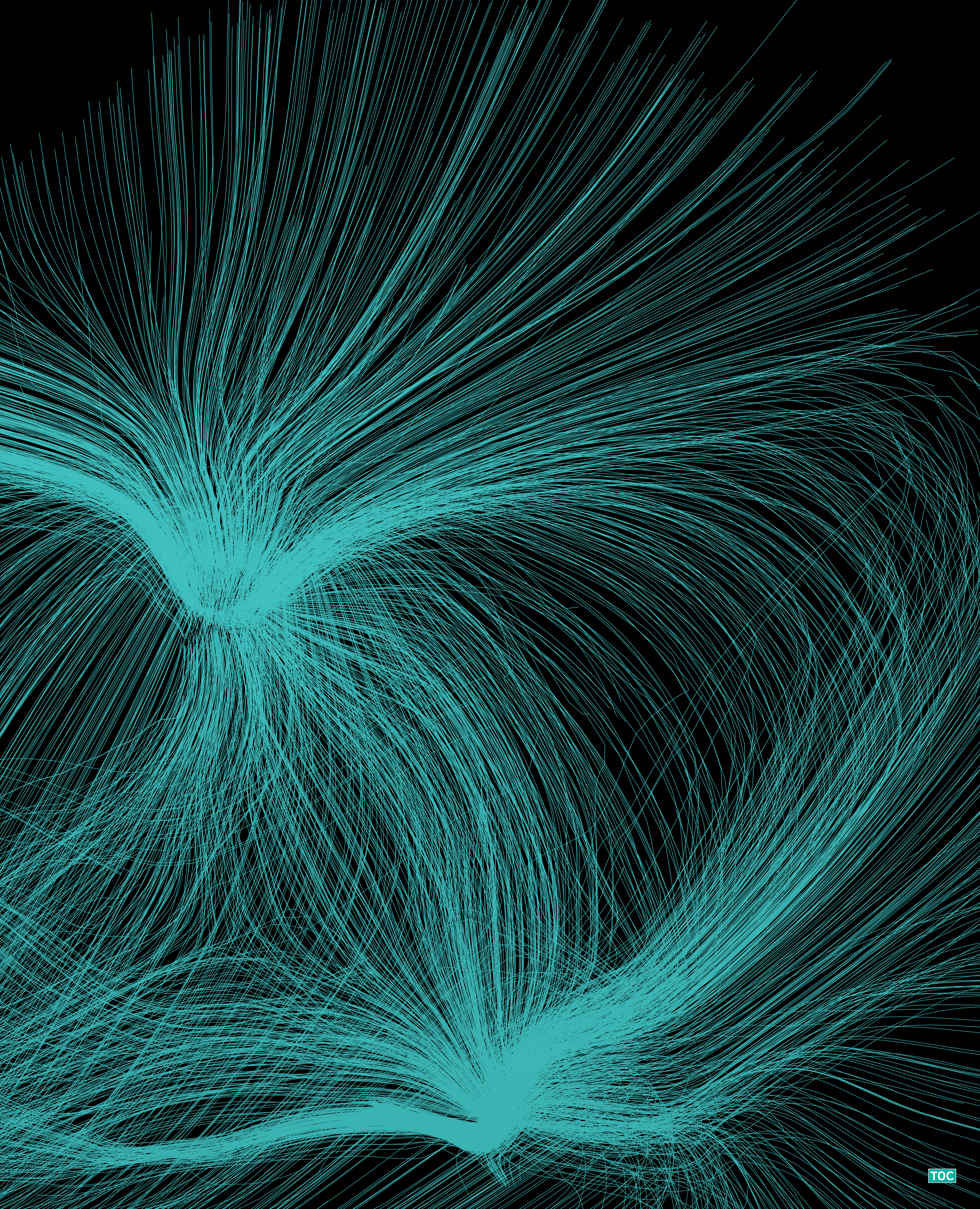
5. **Assembly / Rationalization and Approximation versus Simplification:** Integrated computational design to robotic production systems allow for the production of complex joinery details and assembly procedures. The connections can be geometrically and topologically complex. However, they can be rational and efficient in terms of production and assembly of the component in multiple directions, considering the robotic arm tooling and maneuvering spaces' flexibility and reachability.

6 **Assembly / industrial Revolutions and Interdisciplinarity:** Like computation and production of porosity and hybridity, efficient and effective assembly in architectural scales requires an interdisciplinary approach. When it comes to assembly, architectural robotics, as a relatively young, emerging, and extending field of study, is very much influenced by the existing manufacturing approaches in other industries with a strong automaton culture. For instance, while we can learn to from the existing approaches in assembly lines of the automotive industry, designing and developing bespoke assembly approaches tailored for architectural scale applications are still required. Therefore, an assembly line for building scale may consider the very multi-scalar, multi-material, and multi-performative nature of architecture where, for most of the cases, the to be produced object is larger than the production space. In this context, the fusion of human intelligence with automated fabrication and assembly processes is an essential next step in architectural robotics. Enabling such coexistence, developing various monitoring methods plus surveying and scanning the assembly space on the one hand, and augmentation of digital design to the robotic fabrication process using the virtual space, on the other hand, are key areas for further research investment.



Stress lines before being processed for robotic fabrication, From Materially Informed Robotic 3D Printing project

TOC



TOC

TOC

6 Conclusion

ABSTRACT This chapter includes four parts: introduction, results and contributions, reflection and futures work, and final remarks. The introduction opens the conclusion by referring back to the main question and objective. Results and contributions recap the sub-questions corresponding to each of the four main chapters. The third part of this chapter provides sets of reflections and elaborates on the potential impact and future directions of this work and related fields in research, education, and practice. The final remarks close this dissertation by providing some concluding thoughts on the why, the how, and the what of the path that has been taken.

6.1 Introduction

This research started with a passion for creative and innovative applications of technologies in architectural design and building processes. This dissertation is discussing the what and the how of the developed design materialization model. Narrowing down the scope of the research, the main research question has been formulated as follows:

- **How can we develop and deploy integrated computational design to robotic production systems for efficient architectural materialization and effective building?**

A new materialization model has been developed for architectural applications in various scales using computational design and robotic production techniques and methods to answer this question. In summary, addressing the how part of the main research question, Hybrid Intelligence in Architectural Robotic Materialization (HI-ARM) introduces and employs three modes of intelligence: Computational Intelligence, Fabrication Intelligence, and Maternal intelligence to achieve efficient architectural materiality and implement effective building processes. In this respect, new definitions and frameworks are provided. Further, the ‘what’ of this research is concerned with three thematic subjects: Porosity, Hybridity, and Assembly. These three topics are discussed as a part of the solution through prototypical case studies, conducted design-driven experiments, and produced physical prototypes. Moreover, in order to position this research in the larger context and discuss the 'why' or the research relevance, a background question has moved the research forward:

- **How emerging technologies are transforming the experience and the practice of architecture and the building industry?**

As it has been previously discussed in chapter one, four major domains are identified to answer this question: process, product, context, and cognition. While the major body of this dissertation book has been dedicated to the process and product (How and what), in this chapter, in addition, to discuss the research finding and limitations, further elaborations are provided on technological, societal, and environmental research relevance in the following sections.

6.2 Results and Contributions

Results and contributions review the research findings and deliverables of the four main chapters (chapter 2-3-4-5). By providing a brief response to each chapter's corresponding sub-questions, the goal here is to define and assess how each chapter's result contributes to the body of domain knowledge in specific and larger contexts in general. Each part is concluded by introducing the limitations of this research to then address future work in the following section of this chapter.

6.2.1 Chapter 2: HI-ARM

Chapter two constructs the theoretical and methodological basis of Hybrid Intelligence in Architectural Robotic Materialization (HI-ARM) in two parts, HI-ARM definitions and HI-ARM frameworks:

1 **HI-ARM Definitions** has laid down the basis for the discourse that this dissertation has produced and contributed to the field by introducing and expanding identified key concepts and terminologies in six clusters. These definitions are central to the advancement and application of integrated computational design to robotic production workflows and technologies. A conclusion based on the six clusters is as follows:

Cluster 1: Design systems, Computation, and Automation

With an emphasis on systems thinking, HI-ARM considers computation and automation at the core of developing an integrated design-to-production workflow. Therefore in architectural materialization processes, it is important to systemically establish relations between sub-procedures and identify and apply feedforward and feedback loops between various stages and components of design-to-production systems.

Cluster 2: Topology and Geometry, Tectonics and Components

Besides benefiting from parametric geometric modeling, computational design, and generative systems, it is essential to model the topology of fabrication or the logic of tooling and assembly. It was concluded that by integrating simulation of the production process, new geometric qualities and material properties will become realizable. As a result, new models of component-based building systems are developed with ranges of families of robotically producible components with embedded computational and material intelligence.

Cluster 3: Digital-Physical Integration

By establishing connections between digital design interfaces and physical production setups, this research has exemplified the integration of constraints and potentialities of different fabrication methods in different design stages, ranging from conception to construction. The case studies have illustrated computation and automation redefine the role of digital and analog representation and physical model making in creative architectural design and materialization processes. As a result, digital-physical integration results in effective and on-demand mass-customization of building components with high efficiency.

Cluster 4: Performance and Variation

Producing variation in multiple architectural scales, potentially at no extra cost, introduces challenges and opportunities for developing and applying performance-driven design workflows and methodologies. On this front, in addition to developing computational design systems, this research has illustrated how robotic production not only can be a way for producing complexity and differentiation but also can be a means for exploration and assessment of both quantitative and qualitative performance criteria. The case studies also emphasize on the importance of multi-scalar approaches in designing and prototyping performative solutions where orchestration of multiple layers of data in different design stages is required.

Cluster 5: Rationalization and Approximation versus Simplification

The definition of constructability in design changes radically by applying integrated computational design to robotic production systems. This research illustrates how by incorporating computational, fabrication, and material intelligence, rationalization does not necessarily mean simplification. Therefore, constructible architectural components and building systems might be visually or geometrically complex but simple, affordable, or even efficient in terms of fabrication and assembly. Consequently, while continuous advancement in novel digital fabrication technologies may facilitate zero-tolerance construction, creative and innovative design-to-production workflows may embrace and purposefully design with affordable tolerances using particular robotic fabrication and assembly systems.

Cluster 6: Interdisciplinarity and Industrial Revolutions

This research has positioned interdisciplinary effort and approaches at the center of the design and development of integrated design-to-construction systems. While three major domains of computation, automation, and materialization are introduced as key areas of investigation, further complementary studies that could expand the reach and richness of this research in the context of the contemporary industrial revolution are required. In this chapter, further suggestions are made to address how research, education, and practice can be more agile to culturally, technologically, and methodically facilitate and embrace such changes in the future of discipline and industry.

2 **HI-ARM Frameworks** has outlined the conceptual, analytical, and operational design materialization strategies with the goal to incorporate and achieve computational intelligence, material intelligence, and fabrication intelligence within the design-to-production systems. A conclusion of the results and contributions related to the four frameworks is as follows:

Framework 1: Interdisciplinary Domains Interrelations

The domains-interrelations-framework identifies computation, automation, and materialization as three key realms of investigation, knowledge, and expertise required in developing and applying integrated-design-to-robotic-production systems. Therefore, the case studies and experiments in this dissertation develop and exemplify the feedback and feedforward loops between these domains to bridge the gap between design and construction at the early stage of architectural design.

TOC

Framework 2: Design-Material-Production Space

Design-Material-Production Space framework has been developed and applied as an underlying principle in the experiments and case studies presented in this dissertation. The framework aims to break the linearity of design materialization processes to incorporate and achieve computational, material, and fabrication intelligence in design-to-production processes. In this context, a linear design materialization process may start from drawing, representation, and modeling to material selection from an existing catalog to then eventually choose a production technique. Therefore, this research in multiple scales and phases of the design has challenged this linearity.

Framework 3: Multi-Scale/Mode/Material/Criteria Design-to-Production System

The Multi-Scale/Mode/Material/Criteria framework has been formed and implemented as an operational tool for intelligent design materialization. This framework has been tested and evolved in various projects where either all or purposefully only some specific dimensions are explored and applied. The four dimensions are scale, mode of production, Material, and performance criteria. In conclusion, a thorough and iterative application of the Multi-Scale/Mode/Material/Criteria framework is required to develop an integrated design-to-production system and achieve a solution with computational, material, and fabrication intelligence. However, in research-oriented experimental projects focusing on one or some of the four dimensions might be required, thus justifiable.

Framework 4: Porosity-Hybridity-Assembly Materialization Model

The porosity-Hybridity-Assembly framework has been developed and implemented as a comprehensive materialization model for integrated computational-design-to-robotic-production systems. The model targets the fundamental physical properties and material behaviors of architectural products and the automation of building processes. In this research, the three thematic subjects of this framework have been considered complementary in a large-scale construction of the built environment project, while each of the three themes is independently investigated in sets of corresponding computational-design-to-robotic-production case studies. In conclusion, the porosity-Hybridity-Assembly materialization model suggests a more volumetric approach to materiality as opposed to a surface-based approach where bone, flesh, and skin are separate entities and segregated sub-systems. Moreover, the case studies are illustrating how structural, environmental, and functional efficiencies can be achieved by engineering material distribution, benefiting from multi-materiality, and designing for intelligent assembly.

6.2.2 Chapter 3: Porosity

Porosity in this research is concerned with the computation and production of porous systems in various architectural scales such as micro or material, meso or component, and macro or spatial. Through the case studies, several porous material systems are explored and delivered with the purposeful distribution of mass and void to achieve quantitative and qualitative design objectives. Various performance criteria such as structural, environmental, and functional are considered in the conducted experiments. In this dissertation, the two main case studies have mainly focused on structural criteria while mapping the other performance criteria in the overall design system. The contributions and limitations of the developed methodologies and technologies for computation and production of porosity can be summarized as follows:

Computation of Porosity: Abstraction, modes of representation and resolution

Computation in an integrated design-to-robotic-production system requires novel techniques and workflows that consider the constraint and potentialities of fabrication plus properties and behaviors of different materials. Simultaneously, various degrees and modes of abstraction are needed in various scales in different design phases. Therefore, this research has identified data exchange and integration between different computational design platforms as essential in developing integrated design-to-production systems to effectively produce efficient porous material systems.

Interoperability: Developing Design Materialization Systems

A prototypical case study on interoperability focusing on the computation of porosity is delivered to interlink topology optimization method with the parametric design of a trussed-beam. The domain-specific contribution of this case study in terms of computational design is the way a sub-process based on a skeletonization technique is developed and coupled with the Finite Element Method in order to systematically translate the finite or discrete results of material distribution to continuous or vector-based geometry, which then represent the materializable bars in a trussed-beam structure. The project lays down the backbones for further case studies of this dissertation in terms of systemic development and application of workflows with multiple disciplinary knowledge required for a dynamic and interactive design parametrization and materialization. Future research may focus on coupling 3D printing or automated assembly with the developed design materialization system.

Production of porosity: Fabrication intelligence and new material affordances

Production of porosity is becoming more affordable by developing and applying intelligent robotic fabrication and assembly methods. This research has implemented different techniques such as subtractive and additive for the materialization of porosity. As a general conclusion, additive manufacturing allows us to materialize more volumetric or three-dimensional porosity versus surface-based porosity, which is more affordable using subtractive fabrication methods. Therefore, Lattice-type structures are identified as an important type of porous structures to be computed and robotically produced. On this front, this research search has contributed to the computational design and robotic production of both volumetric and surface-based porosity. The contribution is twofold, firstly by technology integration through advancing robotic 3D printing setups and secondly by developing systemic design-to-production workflows to materialize porosity in different design and architectural scales.

Continuous Robotic 3D Printing of porous ceramic structures

The leading case with the focus on the production porosity is a project on robotic 3D printing of porous ceramic structures. Building upon the previous case study's research findings on design system development, the robotic 3D printing project has explored and exemplified the challenges of introducing feedback loops from fabrication to design. One of the key contributions of this project is how the translation of optimized material distribution according to structural topology optimization to continuous robotic 3D printing toolpath is researched and implemented. This example again has emphasized the importance of translating the discretized geometry to continuous pass for robotic fabrication. Consequently, an important research finding is how the resolution of computation and production need to be addressed in an integrated design-to-production system considering the fabrication potentialities and material affordances. Moreover, the pavilion design case study out of which the produced prototype is extracted exemplifies the multi-scalar approach in design-to-production processes which is widely implemented in most of the experiments and case studies in this dissertation.

6.2.3 Chapter 4: Hybridity

Hybridity in this research is explored and delivered on two fronts: Hybridization of the Production Processes by integrating multiple robotic fabrication methods and Hybrid Materiality of the Product by using multiple materials. Therefore in this dissertation, multi-mode robotic production methods have exemplified the process-side of hybridity and multi-materiality in the product-oriented aspect. Conceptually, porosity can also be considered as a type of hybridity of matter and void. Therefore the research findings and conclusions on porosity to a large extent are applicable to the topic of hybridity. Hence they are further advanced and implemented in the case studies, and methods pertained to hybridity. The contributions and limitations of the developed methodologies and technologies related to hybridity will be summarized as follows:

TOC

Hybridization of production methods: Multi-mode subtractive-substrative and subtractive-additive design to robotic production systems

This research contributes to the field of architectural robotics by developing sets of multimode robotic production systems. The experiments and the prototypes illustrate how expanding the production-space by utilizing customized robotic production strategies such as subtractive-subtractive and subtractive-additive results in novel workflows for materialization in different scales.

Consequently, the case studies have exemplified how the inherent differences between production techniques may inform the design materialization process and how they can be complementary to each other while considering the constraint and potentialities of multiple robotic production techniques and properties and behaviors of multiple materials are mapped. Examples of the delivered multi-mode methods are subtractive-subtractive techniques such as Robotic Hot Wire Cutting and Robotic 3D Milling or subtractive techniques combined with additive approaches such as Robotic 3D Printing.

Multi-materiality and computation of hybrid topologies: Curve, surface, voxel and volume

Implementing multi-mode robotic production methods that incorporate production-space capacities and limitations demands new digital geometric modeling and computational design approaches. Such approaches may go beyond merely focusing on the advancement of manufacturing technologies like increasing the resolution of voxel-based multi-material 3D printers. Therefore, this research has developed workflows in which the topological characteristics of different robotic tooling strategies become a design driver for informed and intelligent production of multi-material systems. Consequently, this research has illustrated how the robotic production systems' capacities, such as geometric and physical features of the mounted tools or end-effectors and reachability, inform the integrated design-to-production system.

Hybrid material systems: Cases of Hybrid Cork, Hybrid Concrete and Hybrid Silicone

In this dissertation, hybrid material systems are exemplified with prototypical case studies where at least two materials are combined. Each combination has offered alternative approaches to materializing hybridity for different architectural applications. The three multi-material prototyped systems are Hybrid Cork, Hybrid Concrete, and Hybrid Silicone. Each of these three cases has been conceived as a part of a larger design-to-production systems and design research project to employ Computational, fabrication, and material intelligence within the design-production-material space. The cases illustrate how multiple performances can be mapped, and purposeful variation can be achieved by hybrid material properties and behaviors such as a hybrid of soft and hard, hybrid of structural and insulative, etc.

6.2.4 Chapter 5: Assembly

Assembly in this research focuses on the design and production challenges of connecting material units, building blocks, and architectural components. Moreover, assembly is about extending beyond the dimensionalities of raw input material or the designed building component and growing beyond the reachability of specific production setups. This research contributes to the field by focusing on two topics: component and sequence in assembly. The subject of assembly has initially been explored with series of design-to-production experiments. Consequently, a more comprehensive case study on assembly in this dissertation has focused on the design and robotic production of reciprocal wooden structures with robotically produced connections. The conclusion on the contributions and limitations of the developed methodologies and technologies related to assembly is as follows:

Towards new modes of assembly intelligence through Integrated design-to-robotic production systems: Component, Connection and Sequence

The developed integrated design-to-robotic production systems have introduced alternative assembly approaches in architectural design and building processes. The experiments and prototypes have illustrated how the design-to-production of a component-based architecture with embedded connection systems can result in assembly intelligence. Prototypical solutions include distributed embedded robotically produced multi-directional finger joints, intertwining volumetric components, and experiments on pick-and-place robotic stacking with the goal to explore the notion of sequence and stability during the assembly. Thus, design for assembly and disassembly plus automation of assembly processes are the key future areas for further research to explore efficient and effective building systems.

Design for Assembly: A case study on multi-directional assembly and Integrated Design-to Robotic Production of Free-Form Reciprocal Wooden Structures

The extended case study of chapter five focusing on assembly has delivered a methodology for design-to-robotic production of free-form reciprocal wooden structures where fabrication constraints and potentialities inform the design at various scales. To a considerable extent, this project summarizes the integrative and multi-scalar approach in design-materialization developed and discussed in this dissertation. While tolerance-free manufacturing in built environment scales is hypothetically possible, this project outlines how fabrication and assembly tolerances can be practically incorporated in an integrated design-to-production process. In this context, design for assembly and disassembly, autonomous assembly, and automation of assembly processes in construction scales are among subjects that this research considers extremely relevant for future investigations.

6.3 Reflections and Future Work

This research exploits the customizability and programmability of robotic production methods to frame and achieve what is titled hybrid intelligence in materialization for various architectural scales and applications considering multiple performance criteria. Intelligence in this dissertation is multifaceted, and it specifically focuses on three forms of embedded intelligence both in the process and product: computational Intelligence, fabrication Intelligence, and material Intelligence. Therefore, by fundamentally challenging the existing approaches for design and production in ABE research fields and AEC sectors, the overarching goal is to bridge the gaps between design and construction. In the following paragraphs, further reflections are made as a set of twelve interrelated and complementary concepts and topics in three categories: research, education, and practice.

6.3.1 Research

Based on the developed and delivered methodologies and technologies, and considering the limitation of this research, the following areas and topics are identified as research follow-ups to the work presented in this dissertation:

1 Cyber-physical design to production and operation systems

This research has delivered workflows, tools, and frameworks for cyber-physical design-to-production systems, which can lead to increased user-oriented and data-driven design and materialization of the built environment (Chapters 2, 3, 4, 5). Further exploration can be done to develop open-source and web-based platforms to allow for a higher level of mass-customization supported by multi-modal and multi-nodal factories-of-the-future. Such models may target the goal of democratization and decentralization of design and production, and eventually, more efficient use of resources and effective operation and maintenance of the built environment in various scales. Therefore, to achieve this objective, future investigations are required on remote control systems and building automation. Building automation in this context refers to the process of digitalization and robotization of production as well as embedding programmable operational devices such as interactive and responsive components within the built environment.

2 Advanced methods of computation of porosity and hybridity

In this dissertation, several methods have been developed for the computation and production of porous and hybrid material systems as an integral routine for advancing customized design to robotic production workflows (Chapters 2 and 5). As a general reflection regarding computing building components and systems with material and fabrication intelligence, the importance of innovation in computational modeling of both discrete and continuous topological and geometric systems has been identified and explored. In this context, facilitating the translations from one mode of digital modeling to another guides future research on material and fabrication-aware modes of digital representation and fabrication. Beyond the explored computational design techniques such as advanced parametric modeling, multi-objective optimization, Finite Element Methods, and swarm intelligence, developing and implementing domain-specific artificial intelligence, i.e., for 3D image processing, in the generative computation of porosity and hybrid is another area of this research that extends the reach and applicability of this research.

3 Adaptive fabrication, sensing and physical to digital feedbacks and feedforwards

A major focus of this research has been on the development of integrated design materialization and building systems by establishing connections between the digital design and computation interfaces to physical robotic production setups (Chapters 2, 3, 4, 5). In the context of this research, such connections are more from the digital to the physical. Future research can highly benefit from establishing meaningful connections from the physical to the digital. Early attempts for updating the digital information through 3D scanning and photogrammetry have been made in some of the follow-up experiments to some of the multi-mode case studies (Chapter 4). In order to advance emerging fabrication technologies to their full potential, integrated scenarios are required for adaptive fabrication where new models of design thinking and materialization are supported through sensing, learning through Computational and Artificial Intelligence and real-time feedforward and feedback loops between the digital and physical.

4 Automaton in assembly, scaling up beyond the macro, multiple robots, and Human Robot Collaboration (HRC)

Assembly is introduced and explored as one of the three pillars of HI-ARM (Chapters 2 and 5). Further research can be conducted as a continuation of this dissertation, emphasizing design to robotic assembly processes. This can happen by coupling multimode robotic production workflow such as subtractive additive with automated assembly in construction scales, which may go beyond a particular fabrication setup's reachability. Therefore, developing scenarios for assembly space for architectural applications requires further research where several types of robots are orchestrated as part of an integrated design-to-production-to-assembly multi-dimensional system (4D+, i.e., X,Y,Z, Mx, My, Mz &Time) . In addition to multi-dimensional and multi-player systems, developing human-robot collaboration scenarios is an area for future research to achieve assembly intelligence in design and construction.

5 Immersive environment for design and materialization, Virtual and Augmented realities in design-to-production and assembly systems

Envisioning an active human agency in design and materialization processes demands research on immersive environments. Therefore, as a continuation to this research, future work can be dedicated to Human-Computer Interaction (HCI) technologies and methodologies for semiautomated co-design to co-production and assembly processes. In this context, the human may refer to designers, builders, and users who are in close co-existence with the robotic production and assembly setups. Such integration can be facilitated by research on the application of Augmented Reality and Virtual Reality in computationally and robotically supported design-materialization and building processes.

6 Contextualization, redefining glocal crafts through Hybrid Intelligence

The core technological front of this research, such as advancing computation and automation, can be considered as a global or site-less contribution to the science. However, as exemplified in the case studies, innovation is very much dependent on how multiple environmental and socio-cultural parameters are incorporated as active components of the design to production and operation system. Additionally, new human agencies can be assigned by extending and augmenting the active role that designers, users, and builders may play in redefining design and building craftsmanship. Consequently, future work can focus on learning from the past and present diverse local methods of building technologies, structural systems, and crafts in different regions. Such efforts may result in a higher level of individualization and contextualization in art, design, architecture, and fair and resilient post-industrial building culture.

7 Material intelligence, scaling down beyond the micro, circularity, embodied energy, smart and bio-materials

Material intelligence is identified and explored as one of the three key forms of intelligence in this dissertation, next to computational and fabrication intelligence (Chapters 2, 3, 4). In most of the experiments, specifically in additive processes, parallel research in material design and experimentation is central in developing and implementing design-to-production systems. With the goal to extend the material palette of design and architecture to smart materials and multi-material systems, further thorough research can be done with a focus on material innovation and design with a goal to search for more circular and recyclable building solutions with less embodied energy. In line with this goal, initial collaborative research has been conducted on biodegradable materials. Several workflows and methods are developed and tested for bioplastic robotic materialization, including robotic 3D printing of bio-plastics. While this direction as future research may impact the larger scale by designing and engineering the smaller scales, it also emphasizes the importance of interdisciplinary and transdisciplinary research in architectural robotics.

6.3.2 Education

This research has considerably benefited from establishing purposeful overlaps between research agendas and educational curricula. The designed and taught courses and studios serve as testbeds for iterative evaluation and advancement of the theoretical frameworks, design methodologies, and production technologies. Moreover, these experiences have demanded the rethinking of existing models in design education. Consequently, while the case studies in this dissertation are not necessarily discussed from a pedagogical point of view, there is a considerable body of tacit knowledge gained through the experience and observation in education for which the following points are drawn as reflections and areas for future investigations:

8 Research embedded design education, collaborative and transdisciplinary efforts redefining the master and protégé model

Integrating emerging and disruptive technologies such as computation and automation within the design education curriculum requires innovative collaborative and transdisciplinary research and design models. Such models may go beyond the traditional structure where students will learn about the boundaries of specific disciplines, and then they learn that the research and design in the built environment involve multiple experts such as architects, structural designers, mechanical and electrical engineers, manufacturers, and contractors. Therefore, at an organizational level, this may change the way we could departmentalize the research and education in architecture and the built environment faculties. Consequently, educational setups need to adapt to these paradigm shifts both physically in terms of access to the tools and technologies in an open-source and creative common world to move beyond the dominant existing model that we have mainly inherited, in many cases at its best, from the second industrial revolution. Within the studios and courses, the hierarchical master and protégé model may need to be redefined as students can be considered as co-researchers in research-embedded educational projects. In line with this reflection, future research is viable to be done on comparative and critical studies on the past and present of design and architectural education to explore and introduce innovative pedagogical models at bachelor and graduate levels.

9 Hands-on approach, research by design, hacking and making

The hands-on approach has been a dominant strategy for education and advancing the research in almost all of this dissertation's experiments and case studies. In this context, hands-on refers to research by design, scripting, hacking, making, and prototyping. Conceptually speaking, this approach results in moving beyond designing with representation and diagrams, which usually result in staying in the two-dimensional picture-planes, i.e., in the format of drawings and renders. These new modalities of teaching require one-to-one interaction and engagement from both mentors and students to redesign the mediums through which we operate as researchers and designers, and architects. Future research can be done on the way we could assess creativity and innovation in such models where the outcome of the experience is not merely design products by genius individuals, but it is very much about the process, collaboratively advancing the project and plugging it in the bigger picture.

10 Self-awareness about the extreme and complex, beyond technophilia or technophobia, mass-customized design education

As discussed in chapter two, one of the main reasons to explore and materialize topologically and geometrically complex designs and prototypes is to advance integrated design to production technologies by identifying the limitations and potentialities of different systems. Moreover, it is also discussed that informed complexity and variation may result in better performance. However, based on the observations made during this research in the educational context and considering digital design trends in progressive design education, we might be able to argue that exploring the extreme and the complex may come with its threats and opportunities. To move beyond technophilia or technophobia, members of the studio may need to be self-aware about why we may need a radical approach towards design and materiality and how we position the work in a larger socio-cultural and interdisciplinary context, both in the short and long run. Simultaneously, it is in the hand of studio coordinators and mentors to find the fine line for each design and research brief by keeping the experience serious and playful plus diverse and inclusive while considering that all members of the studio are exploring new territories.

6.3.3 Practice

The core body of the work presented in this dissertation has been developed within academic research and educational contexts. However, both in research projects and design-to-production studios, there has been a strong drive to establish both conceptual and applied connections to the practice. Here, practice refers to both design disciplines and manufacturing and building processes in AEC sectors. Therefore, the following points with regards to the future of practice are made which can have implications in creative industries, the discipline of architecture, and the building industry:

11 Emerging models of knowledge-based design-to-production creative practices, entrepreneurship and new modes of agency for designers, users and builders

Through series of experiments and case studies, this research exemplifies how new models of materialization require interdisciplinary approaches in research and education. Within the context of contemporary industrial revolutions, similar fundamental changes that could facilitate collaborative working cultures and structures are expected due to ubiquitous digitalization and automation. Building upon the research findings in the dissertations and extending its impact in practice, future research may focus on two interrelated domains: Emerging models of design-to-production creative practices and new modes of agency for designers, users, and builders. The first domain may require the activation and application of research in practice through spinoffs and developing new management models of emerging startups. While the early advent of CAD-CAM technologies has changed the working culture inside the offices, such emerging models of knowledge-based practices may radically change the service-based model of architectural design practices to more

TOC

integrated process-based and on-demand product-driven models. By addressing the societal impact of this research and related fields, the second area demands redefining the roles of multiple players within the design-to-production practices. Consequently, on the one hand, it is required to educate designers and architects to practice entrepreneurship by developing and deploying new business models, and, on the other hand, facilitate the engagement of users and builders to play an active role requires fundamental research and applications in practice and industry.

12 Infrastructural innovations in construction industry: demand-supply chains, new material palettes, customization and intelligent production and assembly

Assessing the short-mid and long-term impact of digitalization and automation in the building industry is essential for future investigations in order to demand and make infrastructural changes in the construction industry. Therefore, in addition to maximizing the technology readiness level of the developed design-to-production systems, it is indispensable to invest in facilitating the integration of new methods and models of materialization in the construction industry. Innovation in this front may focus on redefining the damand-supply chains in design and construction in such a way that the whole system could be more flexible and intelligent for mass customization. Finally, the definition of raw and pre-processed input materials needs to change radically, as advanced computation and automation in design and construction allow for working with bespoke and innovative material palettes.

TOC

6.4 Final remarks

HI-ARM has been aimed at seamless integration of design computation and automated production in architectural design and building practices. Therefore, theoretical, methodological, and technological goals are identified and achieved to rethink and redefine novel design materialization tools and workflows. On this journey, it has been important for the author to go beyond a specific technical niche and try to develop a holistic materialization model which not only would facilitate design efficiency and utilize effective production but also allow us to think and act differently during all phases of design to construction ranging from reinventing design conceptualization to disrupting the contemporary building industry practices.

In the early development of the body of this research, the main focus has been on material computation which then moved towards robotic fabrication. However, throughout the progress, the focus has been shifted back and forth from design to production and from material scale to building scale. This iterative and multi-scalar approach in conducting this research has resulted in the successful framing of an integrative architectural design materialization model with three core thematic subjects of porosity, hybridity, and assembly. While it could have been possible to merely focus on one of these three topics, bringing these three under one umbrella has allowed this research, and its implementations in education and practice, to be more cohesive while disclosing potential research to be done more extensively on each of the three thematic subjects in the near future.

This research documents a journey on how enhanced feedback and feedforward loops can be established between design and production through systemic thinking and interdisciplinary research. This is done by framing interdependencies between computation, automation, and materialization. Therefore, through technology integration and advancing computational design and robotic fabrication, this research has delivered explicit and implicit knowledge of innovative design-to-production workflows to explore and materialize high-performance solutions. In this context, this research identifies as crucial to contribute to the growing open-source culture where in addition to acknowledging what can be delivered as innovative design and building production, the documenting of the procedures of how such generic or fully tailored processes and solutions can be developed and deployed plays an important role.

Concurrent expansion and exploration of design-material-fabrication space results in mapping and achieving multiple modes of design intelligence at different scales. On the one hand, this concurrency is redefining key notions of the materiality and materialization of architecture such as ornament, structure, component, and assembly, and on the other hand, it allows for the integration of multiple subsystems in the built environment, such as functional, structural, and environmental. In this context, in addition to retrofitting a particular emerging technology, this research has tried to illustrate how the integration of computational and robotic technologies may go beyond plug-and-play automation solutions in design and construction.

Eventually, beyond the addressed technological and environmental relevance, this research lays down the foundation for the societal expected impact of the contemporary industrial revolutions in architectural design and materialization practices. By envisioning hybrids of human, artificial, and natural intelligence, such impact can be further investigated through redefining the socio-environmental agency of designers, makers, builders, and users to co-think, co-decide, and co-act with robots.

TOC

References

Alexander, Christopher. 2002. Notes on the synthesis of form. Cambridge, Mass: Harvard University Press.

Anastas, Yousef, Landolf Rhode-Barbarigos, and Sigrid Adriaenssens. 2016. “Design-to-Construction Workflow for Cell-Based Pattern Reciprocal Free-Form Structures.” Journal of the International Association for Shell and Spatial Structures. Vol. 57 (2016) No. 2 June n. 188, pp. 159-176(18). DOI: 10.20898/j.iass.2016.188.737.

Anderson, Chris. 2012. Makers: The New Industrial Revolution. London: Random House.

Arup, Ove, and Zunz Jack. 1973. “Sydney Opera House.” The Arup Journal, Vol. 8 No. 3 October 1973. Published by Ove Arup & Partners Consulting Engineers, London

Ashby, Mike F., and Yves J.M. Bréchet. 2003. “Designing Hybrid Materials.” Acta Materialia 51 (19). Pergamon:5801–21. https://doi.org/10.1016/S1359-6454(03)00441-5.

Ashby, Mike. 2013. “Designing Architectured Materials.” Scripta Materialia 68 (2013): 4 – 7. https://doi.org/10.1016/j.scriptamat.2012.04.033.

Aurenhammer, F. and R. Klein. 2000. “Voronoi Diagrams.” Handbook of Computational Geometry, 5, 201-290. (2000). DOI:10.1016/B978-044482537-7/50006-1.

Ayres, Peter. 1970. “The geometry of Shahyad Ariamehr.” The Arup Journal, Vol. 5 No 1 March 1970, Published by Ove Arup & Partners Consulting Engineers, London.

Azad, Hassan. 2008. “Ali Qapu: Persian historical music room”. Proceedings of the Institute of Acoustics. 30 (PART 3): 98-102.

Bernstein, Phillip G. 2018. Architecture, design, data: practice competency in the era of computation. https://doi.org/10.1515/9783035610444.

Bhooshan, Vishu, Mathias Fuchs, and Shajay Bhooshan. 2017. “3D-printing, topology optimization and statistical learning: a case study.” In Proceedings of the Symposium on Simulation for Architecture and Urban Design (SIMAUD ‘17). Society for Computer Simulation International, San Diego, CA, USA, Article 12, 1–8.

Bier, Henriette and Sina Mostafavi. 2015. “Structural optimization for materially informed design to robotic production processes.” American Journal of Engineering and Applied Sciences 8, issue 4 (2015): 549-555. DOI:10.3844/AJEASSP.2015.549.555.

Bier, Henriette. 2014. “Robotic Building(s).” In Oosterhuis K. (ed.), Next Generation Building 1(1), p. 83–92. doi:10. 7564/14-NGBJ8.

Borden, Gail Peter, and Michael Meredith. 2012. Matter material processes in architectural production. New York: Routledge.

Bowie, Theodore. 1959. The Sketchbook of Villard de Honnecourt. Bloomington and London Indiana University Press.

Brayer, Marie-Ange. 2017. Imprimer le monde. Print the world exposition at Centre national d’art et de culture Georges Pompidou (Paris). Orléans : Ed. HYX.

Burry, Jane, and Mark Burry. 2012. The new mathematics of architecture. London: Thames & Hudson.

Cache, Bernard. 2010. Projectiles. Architectural Association London.

Carpo, Mario. 2012. The digital turn in architecture, 1990-2010. Chicester, West Sussex: John Wiley & Sons.

Carpo, Mario. 2017. The Second Digital Turn : Design beyond Intelligence. Cambridge, Massachusetts : The MIT Press.

Cavieres, A., R. Gentry and T. Al-Haddad. 2011. “Knowledge-based parametric tools for concrete masonry walls: Conceptual design and preliminary structural analysis.” Automation in Construction 20 (2011): 716-728. DOI: 10.1016/J.AUTCON.2011.01.003.

Chiang, Yu Chou, Henriette Bier and Sina Mostafavi. 2018.. “Design to Robotic Assembly: An Exploration in Stacking.” Frontiers Digit. Humanit. 5 (2018): 23. DOI: 10.3389/fdigh.2018.00023.

Creswell, John W., and J. David Creswell. 2018. Research design: qualitative, quantitative, and mixed methods approaches, Thousand Oaks, California : SAGE Publications.

Cross, Nigel. 1999. "Design Research: A Disciplined Conversation." Design Issues 15, no. 2 (1999): 5-10. Accessed March 5, 2021. doi:10.2307/1511837.

Culkin, John Macaulay. 1967. A schoolman's guide to Marshall McLuhan. New York: Saturday Review, Inc. Bottom of Form

Daas, Mahesh, and Andrew John Wit. 2018. Towards a robotic architecture. Novato, CA : Applied Research and Design Publishing, ORO Editions.

De Landa, Manuel. 1997. A thousand years of nonlinear history. New York: Zone Books.

Del Signore, Marcella, and Gernot Riether. 2018. Urban machines: public space in a digital culture. [Trento]: LISt Lab.

Denning, Peter J., and Matti Tedre. 2019. Computational thinking, Cambridge: MIT Press.

Dini, E, Nannini, R and Chiarugi, M 2006, Methods and Device for Building Automatically Conglomerate Structure, WOPatent WO2006100556.

Duro-Royo, Jorge, Laia Mogas-Soldevila and Neri Oxman. "Flow-based fabrication: An integrated computational workflow for design and digital additive manufacturing of multifunctional heterogeneously structured objects." Comput. Aided Des. 69 (2015): 143-154. DOI: 10.1016/j.cad.2015.05.005.

Eastman, Charles M., Paul M. Teicholz, Rafael Sacks, and Ghang Lee. 2018. BIM handbook: a guide to building information modeling for owners, managers, designers, engineers and contractors. Hoboken, New Jersey: Wiley.

Edelsbrunner, Herbert, and John L. Harer. 2010. Computational topology: an introduction. Providence: American Mathematical Society.

Eversmann, Philipp. 2019. "Concepts for Timber Joints in Robotic Building Processes Introduction: Computational Development of Timber Structures and Joining Techniques." In Rethinking wood. Future dimensions of timber assembly, edited by Hudert, Markus, and Sven Pfeiffer. Basel: Birkhäuser.

Frazer, John. 1995. An Evolutionary Architecture. Architectural Association.

Friedman, Jared, Heamin Kim, H., Olga Mesa. 2014. "Experiments in Additive Clay Depositions." In W. McGee & M. Ponce de Leon (Eds.), Robotic Fabrication in Architecture, Art and Design 2014 (pp. 261-272). New York, NY: Springer International Publishing. DOI: 10.1007/978-3-319-04663-1_18

Gehry, Frank, Lloyd Meaghan, and Shelden Dennis. 2020. "Empowering Design: Gehry Partners, Gehry Technologies and Architect-Led Industry Change." Architectural Design 90, no. 2 (March 2020): 14–23, https://doi.org/10.1002/ad.2542.

Grigoriadis, Kostas. 2019. "Computational blends: the epistemology of designing with functionally graded materials". The Journal of Architecture. 24 (2): 160-192.

Goto, Kazuma, Ryota Kidokoro, and Takeshi Matsuo. 2011. "Rokko Mountain Observatory, Kobe, Japan." The Arup Journal 2: 20–26. Published by Ove Arup & Partners Consulting Engineers, London.

Gramazio, Fabio and Matthias Kohler. 2008. "Digital Materiality in Architecture", in Gramazio and Kohler, Lars Muller Publishers, Boden.

Gramazio, Fabio, Matthias Kohler, and Silvan Oesterle. 2010. "Encoding Material." Architectural Design, 80(4), pp. 108-115. https://doi.org/10.1002/ad.1114.

Groat, Linda, and David Wang. 2013. Architectural Research Methods. New Jeresy: y John Wiley & Sons, Inc.

Hensel, Michael. 2008. "Performance-Orientated Design Precursors and Potentials". ARCHITECTURAL DESIGN. 78 (2): 48-53. https://doi.org/10.1002/ad.641

Hensel, Michael. (Ed.). 2012. Design Innovation for the Built Environment: Research by Design and the Renovation of Practice (1st ed.). Routledge. https://doi.org/10.4324/9780203129746

Hensel, Michael. 2013. Performance-oriented architecture: rethinking architectural design and the built environment. Chichester: Wiley.

Holland, John Henry. 2006. "Studying Complex Adaptive Systems." Journal of Systems Science and Complexity 19 (2006): 1-8.

Holland, John Henry. 2014. Complexity : A Very Short Introduction. Oxford University Press.

Horváth, Imre. 2007. "Comparison of Three Methodological Approaches of Design Research." Guidelines for a Decision Support Method Adapted to NPD Processes (2007): International Conference On Engineering Design, Iced'07, Cité Des Sciences Et De L'industrie, Paris, France.

Horváth, Imre. 2008. “Differences between ‘research in design context’ and ‘design inclusive research’ in the domain of industrial design engineering.” Journal of Design Research 7 (2008): 61-83. DOI:10.1504/JDR.2008.018777.

International Federation of Robotics. 2016. “Executive Summary World Robotics 2016 Industrial Robots.” Frankfurt am Main: Author. Available online at: https://ifr.org/img/uploads/Executive_Summary_WR_Industrial_Robots_20161.pdf

Keating, Steven, and Neri Oxman. 2013. “Compound fabrication: A multi-functional robotic platform for digital design and fabrication.” Robotics and Computer-integrated Manufacturing 29 (2013): 439-448. DOI: 10.1016/J.RCIM.2013.05.001.

Keating, Steven, Nathan A. Spielberg, John Klein and Neri Oxman. 2014. “A Compound Arm Approach to Digital Construction.” In: McGee W., Ponce de Leon M. (eds) Robotic Fabrication in Architecture, Art and Design 2014. Springer, Cham. https://doi.org/10.1007/978-3-319-04663-1_7.

Kestelier, Xavier De. 2011. “Design Potential For Large-Scale Additive Fabrication: Free-Form Construction.” In Fabricate 2011: Making Digital Architecture, by Glynn Ruairi And Sheil Bob, 243-249. London: UCL Press.

Khalili, E Nader. 1989. “Lunar Structures Generated and Shielded with on-Site Materials.” Journal of Aerospace Engineering 2 (3):119–29. https://doi.org/10.1061/(ASCE)0893-1321(1989)2:3(119).

Khoshnevis, Behrokh, Dooil Hwang, Ke-Thia Yao, Zhenghao Yeh. 2006. “Mega-scale fabrication by Contour Crafting.” International Journal of Industrial and Systems Engineering 1 (2006): 301-320. DOI: 10.1504/IJISE.2006.009791.

Khoshnevis, Behrokh. 2004. “Automated Construction by Contour Crafting-Related Robotics and Information Technologies” Automation in Construction, vol. 13, no. 1, pp. 5–19. DOI: 10.1016/J.AUTCON.2003.08.012.

Knight, Terry and George Stiny. 2015. “Making grammars: From computing with shapes to computing with things.” Design Studies 41: 8-28. DOI: 10.1016/J.DESTUD.2015.08.006.

Kolarevic, Branko, and Ali. Malkawi. 2005. Performative Architecture : Beyond Instrumentality. Spon Press.

Kolarevic, Branko, and Kevin R. Klinger. eds. 2008. Manufacturing material effects: rethinking design and making in architecture. New York: Routledge.

Kolarevic, Branko. 2004. Architecture in the digital age: design and manufacturing. New York: Taylor & Francis

Koskinen, Ilpo, John Zimmerman, Thomas Binder, Johan Redstrom and Stephan Wensveen, 2011. Design Research Through Practice: From the Lab, Field, and Showroom. Morgan Kaufmann Inc. San Francisco

Larsen, Olga Popovic. 2014. “Reciprocal Frame (RF) Structures: Real and Exploratory.” Nexus Network Journal, vol. 16, no. 1, 2014, pp. 119–134, doi:10.1007/s00004-014-0181-0.

Laurel, Brenda. 2003. Design research: methods and perspectives. Cambridge, Mass: MIT Press.

Liaropoulos-Legendre, George. 2011. Mathematics of space. London: Wiley. doi/10.1002/ad.v81.4/issuetoc.

Lénárd, Ilona. 2019. Powerlines, Paintings. Blurb.

Li, Lin, Azadeh Haghighi and YiranYang. 2018. “A novel 6-axis hybrid additive-subtractive manufacturing process: Design and case studies.” Journal of Manufacturing Processes 33 (2018): 150-160.

Li, Yu, and Yi Min Xie. 2021. “Evolutionary topology optimization for structures made of multiple materials with different properties in tension and compression”. Composite Structures. Vol. 259, https://doi.org/10.1016/j.compstruct.2020.113497.

Lynn, Greg. 1993. Folding in Architecture, Architectural Design. Willey.

Lynn, Greg. 1999. Animate Form. Princeton Architectural Press.

McGee, Wes and David Pigram. 2011. “Matter and making.” In R. Glynn & B. Sheil (Eds.), In Fabricate: Making Digital Architecture (pp. 74-85). London: Riverside Architectural Press.

Mellado, Nicolas, Peng Song, Xiaoqi Yan, Chi-Wing Fu and Niloy Mitra. 2014. “Computational Design and Construction of Notch-Free Reciprocal Frame Structures.” In Advances in Architectural Geometry 2014, Sep 2014, London, United Kingdom. pp.181 - 197, ff10.1007/978-3-319-11418-7_12ff.

Menges, Achim, Tobias Schwinn, and Oliver Krieg. 2017. Advancing Wood Architecture: a Computational Approach. Oxon: Routledge.

Mesnil Romain, Cyril Douthe, Olivier Baverel, and Tristan Gobin. 2018. “Form finding of nexorades using the translations method.” Automation in Construction 95 (2018): 142-154. https://doi.org/10.1016/j.autcon.2018.08.010.

Mostafavi, Sina and Matthew Tanti. 2014. “Design to fabrication integration and material craftsmanship.” In Thompson, Emine Mine (ed.), Fusion - Proceedings of the 32nd eCAADe Conference, Newcastle, UK, 10-12 September 2014, vol.1, pp. 445-454.

Mostafavi, Sina, and Ana Anton. 2018. “Materially informed robotic fabrication, architectural robotics and multiscalar material architecture.” In: D. Mahesh & A. J. Wit (Eds.), Towards a Robotic Architecture, (pp. 88–99). Novato, CA: ORO Editions.

Mostafavi, Sina, and Henriette Bier. 2016. “Materially Informed Design to Robotic Production: A Robotic 3D Printing System for Informed Material Deposition.” In: Reinhardt D., Saunders R., Burry J. (eds) Robotic Fabrication in Architecture, Art and Design 2016. Springer, Cham. https://doi.org/10.1007/978-3-319-26378-6_27.

Mostafavi, Sina, Benjamin Kemper and Adib Khaeez at 2020. “HI-Cy (Hybrid Intelligence Cy-Matters) workshop” at DigitalFUTURES world 2020 conference. June 27 to July 3, 2020, (More information available on URLs [12] & [13]).

Mostafavi, Sina, Benjamin N. Kemper, and Chong Du. 2019. “Materializing Hybridity in Architecture: Design to Robotic Production of Multi-Materiality in Multiple Scales.” Architectural Science Review 62(2019: 424-437, Issue on Means, Methods and Machines in Architecture, Taylor & Francis. https://doi.org/10.1080/00038628.2019.1653819.

Mostafavi, Sina, Benjamin N. Kemper, and Daniel L. Fischer. 2018. “Multimode Robotic Materialization.” In J. Willmann & P. Block & M. Hutter & K. Byrne & T. Schork(Eds.), Robotic Fabrication in Architecture, Art and Design 2018 (pp. 349-362). New York, NY: Springer International Publishing. https://doi.org/10.1007/978-3-319-92294-2_27.

Mostafavi, Sina, Henriette Bier, Serban Bodea, and Ana Anton. 2015. “Informed Design to Robotic Production Systems - Developing Robotic 3D Printing System for Informed Material Deposition.” In B. Martens & G. Wurzer & T. Grasl & WE. Lorenzand & R. Schaffranek (Eds.), Real Time - Proceedings of the 33rd eCAADe Conference - Volume 2, (pp. 287-296), Vienna University of Technology.

Mostafavi, Sina, M.G. Morales Beltran, and N.M. Biloria, 2013. “Performance Driven Design and Design Information Exchange.” In Stouffs, R and Sariyildiz, S (eds), Proceedings of the Education and Research in Computer Aided Architectural Design in Europe (eCAADe) 2013 conference, Delft, The Netherlands, vol. 2, pp. 117-126.

Mostafavi, Sina, Valmir Kastrati, Hossam Badr, and Shazwan Mazlan. 2020. “Design Computation to Robotic Production Methods for Reciprocal Tessellation of Free-form Timber Structures.” In Werner, L., Koring, D (eds.), Anthropologic – Architecture and Fabrication in the cognitive age - Proceedings of the 38th eCAADe Conference – Technical University of Berlin, Berlin, Germany.

Naboni, Roberto, and Ingrid Paoletti. 2015. Advanced Customization in Architectural Design and Construction. Springer.

Negroponte, Nicholas. 1970. The Architecture Machine; MIT Press.

Oosterhuis, Kas and Henriette Bier. 2013. IA#5: Robotics in Architecture. Heijningen: Jap Sam Books, pp.6-8.

Oosterhuis, Kas, and Ilona Lénárd. 2002. Kas Oosterhuis: programmable architecture ; mission statement, hyperarchitecture. Milano: L’Arca Ed.

Oosterhuis, Kas. 2012. Hyperbody: First decade of interactive architecture. Jap Sam Books, Heijningen.

Oxman, Neri, Daniel Dikovsky, Boris Belocon and W. Craig Carter. 2014. “Gemini: Engaging Experiential and Feature Scales Through Multimaterial Digital Design and Hybrid Additive–Subtractive Fabrication.” 3D Printing and Additive Manufacturing, Vol. 1, No. 3 (September). DOI: 10.1089/3DP.2014.1505.

Oxman, Neri, Steven Keating, and Elizabeth Tsai. 2011. “Functionally Graded Rapid Prototyping.” In Proceedings of Innovative Developments in Virtual and Physical Prototyping, The 5th International Conference on Advanced Research in Virtual and Rapid Prototyping, Leiria, Portugal.

Oxman, Rivka. 2008. “Performance-Based Design: Current Practices and Research Issues.” International Journal of Architectural Computing 6, no. 1 (January 2008): 1–17. https://doi.org/10.1260/147807708784640090.

Panagiotis, Michalatos, and Andrew Payne. 2016. “Monolith: The Biomedical Paradigm and the Inner Complexity of Hierarchical Material Design.” In Herneoja, Aulikki; Toni Österlund and Piia Markkanen (eds.), Complexity & Simplicity - Proceedings of the 34th eCAADe Conference - Volume 1, University of Oulu, Oulu, Finland, 22-26 August 2016, pp. 445-454

Pask, Gordon. 1969. “Architectural Relevance of Cybernetics.” Architectural Design 39 (9):494–96.

Pérez, Santiago Rafael. 2017. “Loss of control: error, glitch, and imperfection in architecture” In Borden, GP and Meredith, M (eds). Lineament Material, Representation, and the Physical Figure in Architectural Production. Routledge, New York, pp. 156-174.

Perrella, Stephen, and Bernard Cache. 2015. “Topological Architecture (1998-2003).” In The Digital Turn in Architecture 1992-2012. Edited by Mario Carpo. pp. 146–57, https://doi.org/10.1002/9781118795811.ch10.

Picon, Antoine. 2010. Digital Culture in Architecture: An Introduction for the Design Professions. Basel: Birkhäuser.

Picon, Antoine. 2013. Ornament The Politics of Architecture and Subjectivity. Wiley. https://doi.org/10.1017/CBO9781107415324.004.

Picon, Antoine. 2021. The Materiality of Architecture. Minneapolis, UNITED STATES: University of Minnesota Press.

Pigram, David, and Wes McGee. 2011. “Formation Embedded Design, A methodology for the integration of fabrication constraints into architectural design.” In ACADIA 11: Integration through Computation, pp. 122-131.

Pottmann, Helmut, Andreas Asperl, Michael Hofer and Axel Kilian. 2007. Architectural Geometry. Exton: Bentley University Press.

Price, Cedric. 1978. Letter To John Frazer, Dec 1978, Box 4,Generator document folio, DR1995:0280:65 4/5, CPA.

Ratti, Carlo, and Matthew Claudel. 2015. Open Source Architecture. Architexturez Network. London: Thames & Hudson.

Ratti, Carlo, Matthew Claudel. 2015. “Open Source Gets Physical: How Digital Collaboration Technologies Became Tangible” in Open Source Architecture, 78 - 96. London: Thames & Hudson, 2015.

Retsin, Gilles, Manuel Jimenez García, and Vicente Soler. 2017. “Discrete computation for additive manufacturing,” in Fabricate 2017: Rethinking Design and Construction, eds A. Menges, B. Sheil, R. Glynn, and M. Skavara (London: UCL Press), 178–183.

Rodgers, Paul A., and Joyce Yee. 2018. The Routledge companion to design research. London: Routledge, Taylor & Francis Group.

Schon, Donald A. 1983. The Reflective Practitioner : How Professionals Think in Action. Basic Books.

Senatore, Gennaro, Philippe Duffour, and Pete Winslow. 2018. “Exploring the application domain of adaptive structures.” Engineering Structures 167 (2018): 608-628.

Sennett, Richard. 2009. The craftsman. London: Penguin.

Sobek, Werner, Patrick Teuffel. 2001.”Adaptive systems in architecture and structural engineering,” Proc. SPIE 4330, Smart Structures and Materials 2001: Smart Systems for Bridges, Structures, and Highways, https://doi.org/10.1117/12.434141.

Sigmund, Ole. 2001. “A 99 line topology optimization code written in Matlab.” Structural and Multidisciplinary Optimization, 21, 120-127.

Søndergaard Asbjørn, Oded Amir, Phillip Eversmann, Luka Piskorec, Florin Stan, Fabio Gramazio, and Matthias Kohler. 2016. “Topology Optimization and Robotic Fabrication of Advanced Timber Space-Frame Structures.” In: Reinhardt D., Saunders R., Burry J. (eds) Robotic Fabrication in Architecture, Art and Design 2016, 190–203. https://doi.org/10.1007/978-3-319-26378-6_14.

Steenson, Molly Wright. 2017. Architectural intelligence: how designers and architects created the digital landscape. Cambridge, Massachusetts : The MIT Press.

Sutherland, Ivan E. 1964. “Sketch Pad a Man-Machine Graphical Communication System.” In Proceedings of the SHARE Design Automation Workshop on - DAC ’64, 6.329-6.346. New York, New York, USA: ACM Press. https://doi.org/10.1145/800265.810742.

Tsui, Tanya, David Peck, Bob Geldermans and Arjan van Timmeren. 2021. “The Role of Urban Manufacturing for a Circular Economy in Cities” Sustainability 13, no. 1: 23. https://doi.org/10.3390/su13010023

Wang, Paul S. 2017. From Computing To Computational Thinking. CRC Press.

Willmann, J., M. Knauss, Tobias Bonwetsch, Anna Aleksandra Apolinarska, F. Gramazio and Matthias Kohler. 2016. “Robotic timber construction — Expanding additive fabrication to new dimensions.” Automation in Construction 61 (2016): 16-23. DOI: 10.1016/J.AUTCON.2015.09.011.

Woodbury, Robert Francis. 2010. Elements of Parametric Design. Routledge.

TOC

Yuan, Philip F., Mike Xie, Neil Leach, Jiawei Yao and Xiang Wang. 2019. Architectural intelligence: selected papers from the 1st International Conference on Computational Design and Robotic Fabrication (CDRF 2019). Springer, Singapore. https://doi.org/10.1007/978-981-15-6568-7.

Zomorodian Afra J. and American Mathematical Society. 2012. Advances in applied and computational topology: American Mathematical Society Short Course on Computational Topology. New Orleans, Louisiana. Providence, R.I.: American Mathematical Society.

URLs:

[1] https://ourworldindata.org/emissions-by-sector
[2] https://www.scienceandindustrymuseum.org.uk/objects-and-stories/jacquard-loom
[3] https://architizer.com/projects/softstone-1/
[4] https://dbt.arch.ethz.ch/project/digital-grotesque-at-centre-pompidou/
[5] https://gramaziokohler.arch.ethz.ch/web/e/forschung/223.html
[6] https://vimeo.com/158804655 (Continuous Variation in https://vimeo.com/robotsinarchitecture, presented in Rob|Arch 2018 Sydney)
[7] https://indesem.nl/portfolio-item/indesem-2015-re-craft/
[8] https://platplusforms.com/platform-28/workshop/made-in-tehran-workshops/made-in-tehran-07 (Direct link to the video: https://www.youtube.com/watch?v=ROpjYNz8vzs&t=158s)
[9] http://materiability.com/bioplastic-robotic-materialisation/ (Direct link to the video: https://vimeo.com/316313945)
[10] http://paulino.cee.illinois.edu/
[11] https://robertacucchiaro.wordpress.com/2011/12/22/beijing-linked-hybrid/
[12] https://www.digitalfutures.world/workshops-europe-mideast-africa-blog/mostafavi
[13] https://at.studio/hi-cy-final
[14] https://vimeo.com/287684044 (Concrete Hybridity in https://vimeo.com/robotsinarchitecture, presented in Rob|Arch 2018 Zurich)
[15] https://www.youtube.com/watch?v=BGs5LX_-yqQ (Hybrid Chair, Multi-Mode Robotic Production video, previously presented in Rob|Arch 2018 in Zurich, and The Common Inn Exhibition at NAi Het Nieuwe Instituut in Rotterdam)
[16] https://www.youtube.com/playlist?list=PLFI8PCtYdZQF1e6GZjqtffzQyJ4vlmTTR (A selected video album of Silicone 3D Printing project, Design and demonstration of the extruder)
[17] https://www.youtube.com/watch?v=Gz9sikiZRLA (Robotic Stacking)
[18] https://www.youtube.com/watch?v=44OCQoe--PM&t=421s (conference paper recored presentation in eCAADe 2020, Berlin, title: 100 Years Bauhaus Wood Pavilion)

TOC

Credits

Text and project credits

This dissertation book includes four embedded previously published papers in which the author of this dissertation is the first author in all four peer-reviewed publications. These papers, in total, constitute less than 30% of the text in this book, and the author has originally written the rest of the text for this dissertation. Detailed information on the publications is provided as footnotes in corresponding chapters, and it is also mentioned on the publications list of the author.

The projects presented and discussed in this dissertation result from collaborative and interdisciplinary research and education with different groups of researchers and students at the faculty of Architecture and the Built Environment of the Delft University of Technology (BK City TU Delft) and Dessau Institute of Architecture on the Bauhaus Campus (DIA Bauhaus). In this context, the author has played a co-leading role as studio master in designing and coordinating studios and research projects and colleagues, students, and collaborators to establish synergies between educational curriculum and research objectives.

The methods, workflows, and prototypes are developed as a part of design-to-production studios and workshops. The developed theoretical frameworks, methodologies, and technologies are then further extended and explored throughout the academic semesters and/or as a part of research projects at Hyperbody Research Group and Robotic Building Lab at BK City, and DARS [Design, Architectural Robotics, & Systems] design-to-production unit at DIA, at both TU Delft and Anhalt University of Applied Sciences.

Further author's contribution to the presented projects includes the design and development of the methods and workflows, both on software and hardware levels, and the leading and supervision of the M.Arch and M.Sc. design to production courses and studios in Delft and Dessau.

In addition to the internal support by the Architectural Engineering and Technology department at BK City TU Delft and DIA Bauhaus, external funding and supports were provided for some of the projects. In several phases and on various levels, this involved grants and contributions from 4TU - Bouw Center of Excellence for the Built Environment, Delft Robotic Institute, 100% Research, Bächer Bergmann GmbH, ABB automation company, and KUKA Robotics of Benelux.

Figure credits

Except for the following figures, all the other figures and photos are original and taken or produced by the author or team members of the projects in the research groups, labs, and institutions, as mentioned in the project credits section.

FIG. 2.1: Top: Carpet weaving craft example from city of Kashan, Photography by Julia Maudlin; Middle: Jacquard's Loom Machine for textile weaving, Photos from National Museum of Scotland; Bottom: 80 Column Computer Punch Cards for IBM computers, photo from Ken Sheriff's Blog on Computers History (www.righto.com).

FIG. 2.7: Left: Kandovan Village, Photo from Tourism on The Edge (https://www.surfingpersia.com/city-guide/Tabriz/), Wave UP Travel; Right: Stonehenge, Photo by Gareth Wiscombe.

FIG. 2.8: Top: Dom-Ino House, Drawing by architect Le Corbusier; Middle: The Oblique Function, Sketches by architects Claude Parent and Paul Virilio; Bottom: Endless House, the model by architect Friedrich Kiesler, Photo from MOMA archive (Museum of Modern Art, New York) .

FIG. 2.10: Sculpture City, team: Ilona Lénárd [genepool], Kas Oosterhuis, Menno Rubbens | RAM Gallery Rotterdam 1994.

FIG. 2.12: SEEK, Installation by MIT Architecture Machine Group, Nicholas Negroponte. Photo from e-flux architecture platform.

FIG. 2.15: Ali-Qapu, The Music Hall, Isfahan. Photo from Wikipedia Creative Commons.

FIG. 2.18: Left: Undulating Cantilevered Brick Wall in Estación Atlántida, 1960, Uruguay by Eladio Dieste, Photo from The Architectural Review originally published in AR September 1961 Pg. 173-175; Right: Inside Out by Richard Serra/Artists Rights Society (ARS), New York. Photo: Lorenz Kienzle, from Gogosian Gallery.

FIG. 2.20: Monumental building designed by Amanat Architects 1966, Structural Calculation, and construction rationalization by Arup; Left: Drawings by Arup and partners, from Arup Journal 1970, Redrawn by author in vector format; Right: Photo taken by Blondinrikard Fröberg.

FIG. 2.21: Soft Stone office building designed by SETUParchitecture studio (Sina Mostafavi et. al.), Left: Photography by Parham Taghioff; Right: Diagram courtesy of SETUP architecture studio.

FIG. 2.22: Resolution and production technology, Top: Photos courtesy of Nader Khalili Architects, Cal Earth Institute, Middle: Photos by Contour Crafting Corporation, Behrokh Khoshnevis; Bottom: Photos by D-Shape, Enrico Dini.

Curriculum Vitae

Sina Mostafavi

Sina Mostafavi is a practicing architect, researcher, and educator with expertise in computational design and architectural robotics. Born and raised in Tehran, he is from Iran and the Netherlands. He has received his Ph.D. in Architecture from TU Delft, M.Arch from University Tehran, and B.Sc. in Architectural Engineering from Tehran University of Art. He is the founder of SETUParchitecture, an award-winning studio that aims at providing innovative design solutions by adapting digital design and production technologies to geocultural specificities. He has taught and led design studios at Delft University of Technology and Dessau International Graduate School of Architecture (DIA) at Bauhaus, where he has been the initiator and director of DARS hub, a unit that focuses on Design Systems and Architectural Robotics to deliver interdisciplinary design research projects.

At TU Delft's Faculty of Architecture and the Built Environment, he has been involved in several research projects as a senior researcher and tutor, where he has been the manager and co-initiator of the Robotic Building Lab at Hyperbody Research

TOC

Group of TU Delft. He has completed his Ph.D. at TU Delft, with his project titled Hybrid Intelligence in Architectural Robotic Materialization (HI-ARM). In HI-ARM, he has explored and developed methodologies and technologies that incorporate computational, fabrication, and material intelligence in integrated design-to-robotic-production workflows.

At TU Delft and DIA Bauhaus, he has led and taught more than 60 design studios and seminars and has supervised more than 50 M.Arch and M.Sc.graduate students with research-oriented design projects focusing on computational design and robotic production systems. His recently featured interdisciplinary projects in DARS studios in DIA Bauhaus include Cyber Craft 40 architectural design studios, collaborative research on Bioplastic Robotic 3D printing, and Adaptive City Car sponsored by AUDI car manufacturing company together with Materiability Research Group in Dessau Department of Design.

He has led international workshops such as InDeSem 2015 Re.Craft, IASS 2015 in Amsterdam, SimAUD 2018 in Delft, and DigitalFUTUREs 2020 global event. He has lectured internationally and has been a member of the scientific committees of various journals and conferences such as eCAADe, ACADIA and CAAD Futures, and 3D Printing and Additive Manufacturing, among others. He is also an organizing member of DigitalFUTUREs annual and weekly events.

The results of his work are published and presented in books, journals, and conferences, such as eCAADe 2013 in Delft, Algorithms, and Actualization at AA London, eCAADe 2014 in New Castle, ACADIA in Los Angeles, eCAADe 2015 in Vienna, Game Set Match 2015 in Delft, ACADIA in Cincinnati, Rob|Arch 2016 in Sydney, Rob|Arch 2018 in ETH Zurich, eCAADe 2020 in Berlin, KNAW Amsterdam, Digital Knowledge in Paris Malaquais, chapters in Towards a Robotic Architecture book, Mutations-creations of Imprimer-le-Monde in Centre Pompidou, and Dutch Design Week among others.

His Architectural Design projects have received several awards and nominations, such as the first prize in Architizer A+ Awards 2020 and the second prize in 2A Continental Euro Asia Award 2018 in IAAC Barcelona for Softstone office Building. His architectural prototypes and works have been featured at international exhibitions, such as construction week in Utrecht, V2 gallery-institute for unstable media of Rotterdam, synthetic Exhibition in Le Mans Lillie, NAi in Rotterdam, and Print the World Exposition in Centre Pompidou Paris.

Websites: www.setuparchitecture.com | www.sinamostafavi.com
Contact: s.mostafavi@tudelft.nl | info@sinamostafavi.com

TOC

Publications

From the following selected publications, four previously peer-reviewed papers (P01, P09, P20, and P22) are integrated into this dissertation book. P01 and P09 are used in chapter 2 (Porosity), P20 is used in chapter 3 (Hybridity), and P22 is integrated into chapter 5 (Assembly).

Journals, peer-reviewed conferences, and book chapters

P22	**Mostafavi, S.,** Kastrati, V., Badr H., Mazlan S. (2020) Design Computation to Robotic Production Methods for Reciprocal Tessellation of Free-form Timber Structures, In Werner, L., Koring, D (eds.), Anthropologic – Architecture and Fabrication in the cognitive age - Proceedings of the 38th eCAADe Conference – Technical University of Berlin, Berlin, Germany, 16-17 September 2020.	Peer-Reviewed eCAADe Proceedings
P21	Kretzer, M., **Mostafavi, S**. (2020) Robotic Fabrication with Bioplastic Materials: Digital design and robotic production of biodegradable objects, In Werner, L., Koring, D (eds.), Anthropologic – Architecture and Fabrication in the cognitive age - Proceedings of the 38th eCAADe Conference – Technical University of Berlin, Berlin, Germany, 16-17 September 2020.	Peer-Reviewed eCAADe Proceedings
P20	**Mostafavi, S.,** Kemper, B., Du, C. (2019). Materializing Hybridity in Architecture: Design to Robotic Production of Multi-Materiality in Multiple Scales, Architectural Science Review, Issue on Means, Methods and Machines in Architecture, Taylor & Francis.	Peer-Reviewed Journal Taylor & Francis
P19	Kretzer, M., **Mostafavi, S.** (2019). Bioplastic Robotic Materialization, Design to Robotic Production of Biodegradable Lamps, in ICS Materials, Interactive, Connected and Smart Materials, Edited by Venere Ferraro and Valentina Rognoli, FrancoAngeli Publisher, Milan	Book Chapter FrancoAngeli
P18	Morales Beltran, M.G., **Mostafavi, S,** (2021- expected). Topology Optimization Techniques for Architectural Design: a method for obtaining discrete truss structures from continuum systems.	Peer-Reviewed Journal

TOC

P17	**Mostafavi, S.**, Anton, A. (2018) : Materially informed robotic fabrication, architectural robotics and multiscalar material architecture. Book Chapter In: Daas, M., Wit, A.J. (eds.) Towards a Robotic Architecture, pp. 88–99. ORO Editions, Novato, CA.	Book Chapter ORO Editions
P16	**Mostafavi S.**, Kemper B.N., Fischer D.L. (2018) Multimode Robotic Materialization, Design to Robotic Fabrication Method of Integrating Subtractively Produced Hard Components and Additively Deposited Soft Silicone. In: Robotic Fabrication in Architecture, Art and Design 2018. ROBARCH 2018. Springer.	Peer-Reviewed Chapter- RobArch Springer
P15	**Mostafavi, S.**, Bier, HH., Kemper B.N., Fischer D.L. (2018) Robotic Materialization of Architectural Hybridity - Modelling, Computation and Robotic Production of Multi-materiality, In Kepczynska-Walczak, A, Bialkowski, S (eds.), Computing for a better tomorrow - Proceedings of the 36th eCAADe Conference - Volume 2, Lodz University of Technology, Lodz, Poland, 19-21 September 2018, pp. 301-308.	Peer-Reviewed eCAADe Proceedings
P14	Chiang, Y., **S. Mostafavi,** and H.H. Bier. (2018) Assembly of shells with bi-stable mechanism, Conference proceeding of Advances in Architectural Geometry, AAG 2018 at Gothenburg.	Peer-Reviewed AAG Proceedings
P13	Chiang, Y., H.H. Bier, and **S. Mostafavi.(**2018) Design to Robotic Assembly: An Exploration in Stacking, Frontiers in Digital Humanities 5	Peer-Reviewed Journal Frontiers
P12	**Mostafavi, S.,** Anton, A., Bodea, S. (2017) Design to Robotic Production for Informed Materialization Processes. in Cyber Physical Architecture, SPOOL, [S.l.], v. 4, n. 1, dec. 2017.	Peer-Reviewed Journal Spool
P11	Liu Cheng, A., Bier, H., & **Mostafavi, S.** (2017). Deep Learning Object-Recognition in a Design-to-Robotic Production and -Operation Implementation. In Proceedings of the 2nd IEEE Ecuador Technical Chapters Meeting (ETCM 2017) IEEE.	Peer-Reviewed IEEE Proceedings
P10	**Mostafavi S.,** Bier H. (2016) Materially Informed Design to Robotic Production: A Robotic 3D Printing System for Informed Material Deposition. In: Reinhardt D., Saunders R., Burry J. (eds) Robotic Fabrication in Architecture, Art and Design 2016. Springer.	Peer-Reviewed Chapter- RobArch Springer
P09	Bier H.H., **Mostafavi S.** (2016) Robotic Building as Physically Built Robotic Environments and Robotically Supported Building Processes. In: Dalton N., Schnädelbach H., Wiberg M., Varoudis T. (eds) Architecture and Interaction. Human–Computer Interaction Series. Springer.	Peer-Reviewed Chapter- RobArch Springer

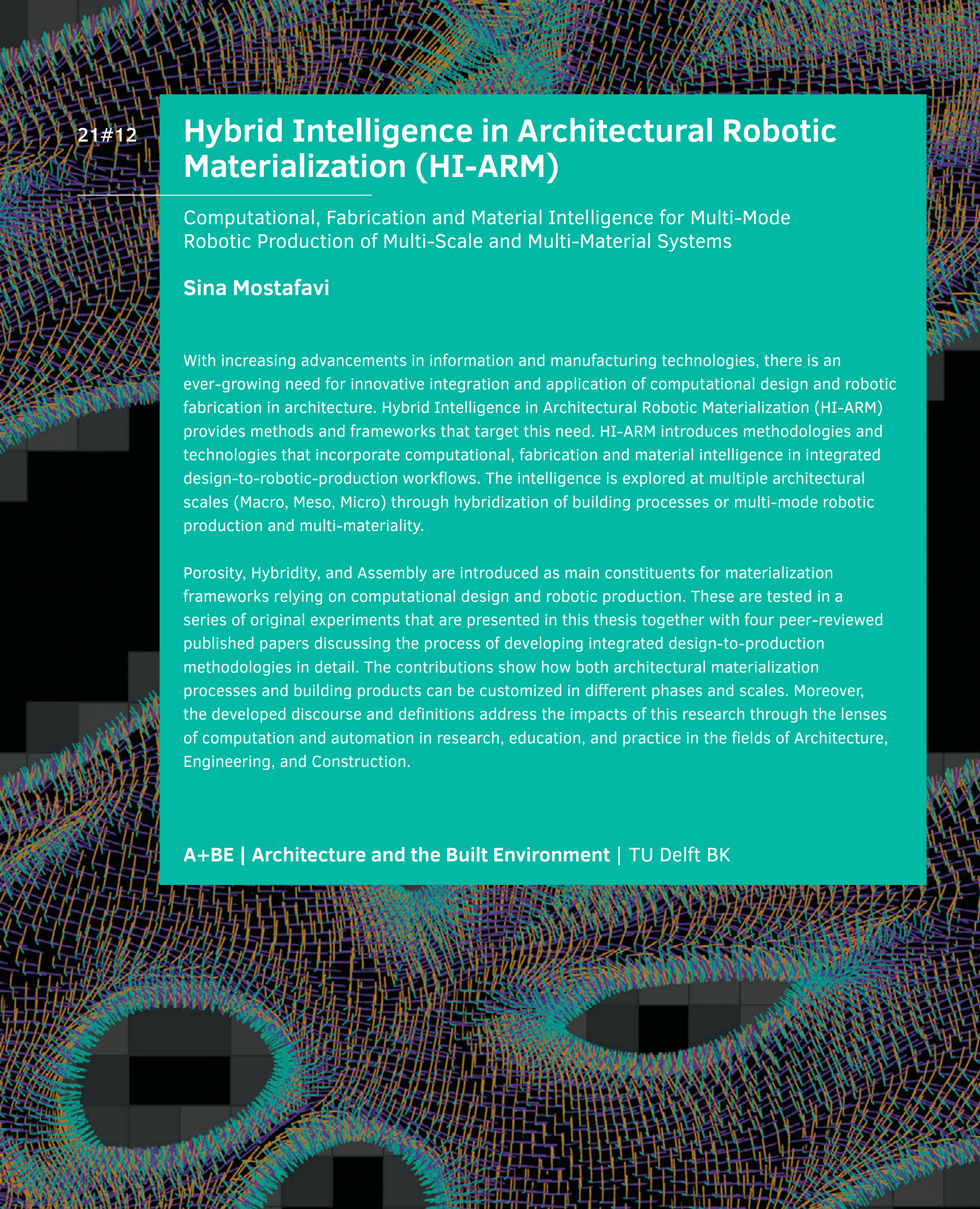
TOC

P08	Bier, HH & **Mostafavi, S** (2015) Data-Driven Architectural Design to Production and Operation in open-access journal Systema: Connecting Matter, Life, Culture and Technology.	Peer-Reviewed Journal Systema
P07	**Mostafavi, S.**, Bier, HH. Anton, A., Bodea, S (2015), Informed Design to Robotic Production Systems - Developing Robotic 3D Printing System for Informed Material Deposition Real-time eCAADe 2015 proceedings, Vienna, Austria.	Peer-Reviewed eCAADe Proceedings
P06	**Mostafavi, S.**, Bier, HH.(2015) Robotic 3D printing in Computational Ecologies, Peer reviewed projects proceeding, ACADIA October 2015, Cincinnati, United States.	Peer-Reviewed ACADIA Proceedings
P05	Bier, HH, **Mostafavi, S.** (2015) Structural optimization for materially informed design to robotic production processes American Journal of Engineering and Applied Sciences 8 (4), 549-555.(2015).	Peer-Reviewed Journal Science Publications
P04	Bier, HH & **Mostafavi, S**. (2014) Data-driven architectural production and operation in J Wilby, S Blachfellner & W Hofkirchner (Eds.), the 22nd European meetings on cybernetics and systems research (pp. 248-255): Bertalanffy Centre for the Study of Systems Science (BCSSS), Vienna, Austria.	Peer-Reviewed EMCSR Proceedings
P03	**Mostafavi, S.** & Tanti, M. (2014) Design to fabrication integration and material craftsmanship in, eCAADe Conference, FUSION, September 2014, New Castle, United Kingdom.	Peer-Reviewed eCAADe Proceedings
P02	**Mostafavi, S.**, Yu. S., Biloria, N. (2014) Agent based complex design systems in multiple scales in Design Agency, ACADIA October 2014, University of Southern California (USC), Los Angeles, United States.	Peer-Reviewed ACADIA Proceedings
P01	**Mostafavi, S.,** Morales Beltran, M.G., & Biloria, N.M. (2013). Performance driven design and design information exchange. In R Stouffs & S Sariyildiz(Eds.), Proceedings eCAADe 2013 conference, (pp. 117-126), Delft, The Netherlands.	Peer-Reviewed eCAADe Proceedings

Featured peer-reviewed videos, and articles

VA08	**Mostafavi, S.**, Kretzer. (2020) " Adaptive City Car, Collaborative Studio Sponsored by AUDI automotive Manufacturing Company, Video submitted and published in ACADIA 2020.	Peer-Reviewed Video and project article ACADIA 2020
VA07	**Mostafavi, S.**, Kretzer. (2020) " Bioplastic Robotics materialization, Design to Robotic Production of Bio-degradable lamps", Collaborative course between Dessau Department of Design and Dessau Institute of Architecture, Video screened by Docu Team, Juried by ACADIA Committee.	Peer-Reviewed Video and project article ACADIA 2020
VA06	**Mostafavi, S**. et al. (2020), Nine selected Architectural Design and Robotic Production DARS studio projects "Next to Bauhaus 2 - Anhalt university of Applied Sciences, Book Edited by Matthias Hohne and Natascha Meuser, Dessauer Schule . Dessau School of Architecture.	Project articles DDD 2018
VA05	**Mostafavi, S.**, Kretzer. (2018) " Bioplastic Robotics materialization, Design to Robotic Production of Bio-degradable lamps", Collaborative course between Dessau Department of Design and Dessau Institute of Architecture, Video screened by Docu Team, Published by Dessau Department of Design.	Project Video DDD 2018
VA04	**Mostafavi, S.**, Bier. H., Moharram, M.S., Hesham, H., El-Meligy, M., Du. C. (2018) "Design to Robotic Production of Intertwined Hybrid of Polystyrene and Fibre Reinforced Concrete" has been accepted and presented at Rob|Arch 2018 (robarch2018.org) through the Robots in Architecture 2018 at ETH Zurich Call for Videos.	Peer-Reviewed Video Rob|Arch 2018
VA03	Bier, S., **Mostafavi, S.,** Anton, A., Bodea, S., Gali, M. (2017). Robotic 3D Printing in Imprimer le Monde, Print The world, Mutations and Creation, Centre Pompidou Exhibition Book.	Book of Abstract HYX
VA02	**Mostafavi S.**, Bier H.H., Anton A.M., Bodea S., et al. (2016) "Informed Porosity" has been accepted and presented at Rob|Arch 2018 (robarch2018.org) through the Robots in Architecture 2018 at University of Sydney Call for Videos.	Peer-Reviewed Video Rob|Arch 2016
VA01	**Mostafavi S.**, Bier H.H., Anton A.M., Bodea S., Oosterhuis, K. et al. (2016) "Continuous Variation – Informed Robotic 3D Printing " has been accepted and presented at Rob|Arch 2018 (robarch2018.org) through the Robots in Architecture 2018 at University of Sydney Call for Videos.	Peer-Reviewed Video 2016

TOC



21#12

Hybrid Intelligence in Architectural Robotic Materialization (HI-ARM)

Computational, Fabrication and Material Intelligence for Multi-Mode Robotic Production of Multi-Scale and Multi-Material Systems

Sina Mostafavi

With increasing advancements in information and manufacturing technologies, there is an ever-growing need for innovative integration and application of computational design and robotic fabrication in architecture. Hybrid Intelligence in Architectural Robotic Materialization (HI-ARM) provides methods and frameworks that target this need. HI-ARM introduces methodologies and technologies that incorporate computational, fabrication and material intelligence in integrated design-to-robotic-production workflows. The intelligence is explored at multiple architectural scales (Macro, Meso, Micro) through hybridization of building processes or multi-mode robotic production and multi-materiality.

Porosity, Hybridity, and Assembly are introduced as main constituents for materialization frameworks relying on computational design and robotic production. These are tested in a series of original experiments that are presented in this thesis together with four peer-reviewed published papers discussing the process of developing integrated design-to-production methodologies in detail. The contributions show how both architectural materialization processes and building products can be customized in different phases and scales. Moreover, the developed discourse and definitions address the impacts of this research through the lenses of computation and automation in research, education, and practice in the fields of Architecture, Engineering, and Construction.

A+BE | Architecture and the Built Environment | TU Delft BK