Oliver David Krieg

ARCHITECTURAL POTENTIALS OF ROBOTIC MANUFACTURING IN TIMBER CONSTRUCTION

Strategies for Interdisciplinary Innovation in Manufacturing and Design

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Foreword

Oliver David Krieg's dissertation investigates an integrative, feedback-based approach to computational design and robotic fabrication in timber construction, from which new possibilities for differentiated and locally adapted timber construction methods emerge. Thus, also new potentials for structural performance, material efficiency and resource conservation, as well as architectural design can be explored. In addition to the technical and methodological depth, the work also makes a scientific contribution due to its multifaceted approach. It shows how interdisciplinary research at the interface of architecture and engineering science leads to original findings. The dissertation convinces with its intellectual profoundness and technical competence as well as with its architectural sensitivity!

Professor, AA Dipl.(Hons.) RIBA II, Architect BDA, AKH, Achim Menges

Vorwort

Die Dissertation von Oliver David Krieg erforscht einen integrativen, rückkopplungsbasierten Ansatz zur digitalen Planung und robotischen Fertigung im Holzbau, aus dem neue Möglichkeiten für ausdifferenzierte und lokal angepasste Holzbauweisen hervorgehen und somit auch neuartige Potentiale für die konstruktive Leistungsfähigkeit, Materialeffizienz und Ressourcenschonung, wie auch die architektonische Gestaltung erschlossen werden können. Neben der technischen und methodischen Tiefe leistet die Arbeit gerade auch einen wissenschaftlichen Beitrag durch ihre Vielschichtigkeit. Sie zeigt auf, wie an der Schnittstelle von architektonischen und ingenieurswissenschaftlichen Fragestellungen interdisziplinäre Forschung zu originären Erkenntnissen führt. Dabei überzeugt die Dissertation sowohl durch ihre intellektuelle Durchdringung und technische Kompetenz, als auch durch ihre architektonische Sensibilität!

Professor, AA Dipl.(Hons.) RIBA II, Architect BDA, AKH, Achim Menges

Architectural Potentials of Robotic Manufacturing in Timber Construction

Strategies for interdisciplinary innovation in manufacturing and design

A dissertation approved
by the Faculty for Architecture and Urban Planning of the
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for the conferral of the title of
Doktor-Ingenieur (Dr.-Ing.)

Submitted by
Oliver David Krieg
from Germany

Committee Chair:
Prof. Achim Menges

Committee member:
Associate Prof. AnnaLisa Meyboom

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19.12.2022

Institute for Computational Design and Construction of the University of Stuttgart

2022

Architektonische Potentiale Robotischer Fertigung im Holzbau

Strategien für interdisziplinäre Innovation in Herstellungs- und Entwurfsmethoden

von der Fakultät Architektur und Stadtplanung der Universität Stuttgart
zur Erlangung der Würde eines Doktor-Ingenieurs (Dr.-Ing.)
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Oliver David Krieg

Contents

List of Key Terms

Fabrication refers to singular steps or ways of shaping and processing material. The term is used interchangeably with **fabrication step** and can be automated or executed by hand.

Manufacturing refers to a combination of multiple steps or processes in the making of a building part or element. The term is used interchangeably with **manufacturing process**.

Production refers to a complete manufacturing process that results in a finished product by processing and combining parts from raw materials or other components.

Construction refers to the process of constructing or assembling buildings on-site.

Machine setup refers to the way a single machine is positioned or laid out within a manufacturing setup, and which tools or effectors the machine is using.

Manufacturing setup refers to the entirety of the manufacturing process, how it is laid out, and how many or which kinds of steps are involved.

Human-robot collaboration refers to manufacturing processes where industrial robots and humans work together within the same fabrication step. Safety protocols are in place to protect the human worker.

Building part or element refers to a non-dividable piece made from a single material. In the context of timber construction, the term is used for pieces of plywood or other engineered timber products.

Building component or module refers to an assembly of two or more building elements that were combined in an additive fabrication step.

Building system refers to the systems and sub-systems that make up a building. In this thesis, the term refers to the structural and envelope systems of prototypical buildings. It is interchangeable with the term construction system.

Design surface refers to a three-dimensional surface modeled in a computer-aided design program, which is used to guide the design of a structure in a computational design process.

Design space refers to the possible variation of form and function of building elements, components, or an entire building system, which results in a constrained set of parameters within which designs can be produced.

List of Abbreviations

ABM	agent-based modeling
AEC	architecture, engineering, and construction
API	application programming interface
BIM	building information modeling
BREP	boundary representation
CAD	computer-aided design
CAM	computer-aided manufacturing
CNC	computer-numeric control
DoF	degrees of freedom
EOAT	end-of-arm tooling
FEA	finite element analysis
NURBS	non-uniform rational B-spline
HRC	human–robot collaboration
SDK	software development kit
TCP	tool center point

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Abstract

This thesis investigates the impact of innovation in robotic manufacturing and computational design on the architectural and tectonic possibilities of timber construction. Until recently, the digitalization of manufacturing and design has mostly resulted in increased efficiencies of singular processes without noticeable impacts on the inter-organizational relationships in the architecture, engineering, and construction (AEC) industry. However, recent developments in integrative architectural design research have shown the potential to introduce a paradigm change by bringing manufacturing technology into a reciprocal relationship with the design space of building systems. In a series of case studies, the thesis investigates integrative and inter-disciplinary development processes that resulted in timber building systems that exhibit a high degree of morphological and functional differentiation, and therefore a larger, gradated, and more adaptive design space. The gradual distribution of material and form is akin to biological principles found in natural structures. The goal of the thesis is to develop a methodology that enables the comparison of manufacturing systems for timber building elements with their resulting design space in a qualitative and quantitative manner, thereby re-integrating disciplines of form, material, and materialization. The thesis also discusses the potential of this paradigm shift to introduce much-needed systemic innovation in the industry.

Zusammenfassung

Die heutige Digitalisierung von Fertigungsprozessen im Holzbau dient größtenteils der Automation und höheren Effizienz in der Ausführung standardisierter Bearbeitungsschritte. Die Wechselwirkung zwischen der Maschine, deren Möglichkeitenraum und dem architektonischen Entwurf wurde dabei selten untersucht, und hat sich aufgrund der Fragmentierung in der Industrie als besonders schwierig erwiesen. Neue Entwicklungen in computerbasierten Entwurfs- und Herstellungsprozessen führen gegenwärtig jedoch zu einem Paradigmenwechsel in der Architektur. In diesem Kontext ist in der digitalen Fabrikation derzeit eine Verlagerung von prozess-spezifischen CNC Maschinen zu wesentlich flexibleren und vielfältiger einsetzbaren Maschinen, wie dem Industrieroboter, zu beobachten. Mit dessen Einführung erweitern sich die Möglichkeiten der digitalen Fertigung, sowie deren Einfluss auf den Entwurfsprozess dramatisch. Ziel der Dissertation ist es, die durch Industrieroboter erweiterten Fertigungsmöglichkeiten im Holzbau zu untersuchen und zu systematisieren, um neue und roboterspezifische Möglichkeiten im Vergleich zu den bisher eingesetzten Maschinen zu ermitteln. Durch die Integration des identifizierten Möglichkeitenraums der robotischen Fertigung in eine Rückkopplungsschleife von Entwurf und Herstellung wird erwartet, eine höhere Bauteildifferenzierung, statische Leistungsfähigkeit, material-effizientere Architektur und neue Formensprachen zu ermöglichen.

1

Introduction

Throughout history, technological innovation has changed the role of architecture and its relationship to other disciplines in the construction industry. As one of the oldest building materials known to humankind, wood has had a particular dynamic relationship with its related tools and technologies. Both its use in building construction and its architectural expression have reflected technological progress for centuries [67; 320]. Today, innovation in computational design and robotic manufacturing presents an opportunity to rethink the relationship between form, material, and materialization yet again.

In technological innovation, it is critical to make a distinction between refining and improving an existing design, and introducing a new concept that departs from past practice in a significant way [152]. While incremental innovation builds on improving existing products and therefore reinforces existing connections within a company or an industry, systemic innovation requires a re-conceptualization of established connections or for entirely new networks to emerge [245; 356].

In the past, systemic innovation in construction technology has led to the disruption of disciplines involved in the design and delivery of buildings. Through the development of new construction materials, entire industry sectors emerged, which required their own sets of expertise, building codes, engineering practices, and design methodologies [68; 273]. However, throughout the era of industrialization, a continuous fragmentation of the design and construction process has been observed, leading to today's diverse set of stakeholders with often opposing goals and limited communication [136; 172]. This has led to what is called a mirroring trap in technological innovation: by only accepting incremental innovation that resembles existing components or processes, most disciplines in the construction industry reinforce their own organizational structures and inhibit systemic innovation that would require different organizational and inter-organizational connections [64; 143].

Recent developments in integrative computational design and robotic fabrication in timber construction have led to the disruption of the traditional design and delivery process of buildings, incentivizing the de-fragmentation of disciplines, and converging design and fabrication technology into a reciprocal relation [6; 183; 235; 396]. Manufacturing equipment such as articulated industrial robots can act as an entry point for architectural design research to investigate the relationship between a manufacturing setup, machine tools, and an expanding or newly emerging design space [15; 50; 104; 193]. Contrary to current design and delivery processes in practice, where design and manufacturing are hierarchically and chronologically arranged, an investigation of manufacturing technology, machine setups, controls, and protocols, creates a reciprocal relationship with design research, and therefore enforces the convergence of at least two disciplines that have previously been detached.

Robotic manufacturing in timber construction has proven to be a key technology for this investigation [189; 314]. The integration of manufacturing and design disciplines requires new methods of design exploration, such as computational design, which enable the control of the increased manufacturing complexity caused by the machine's flexibility [239; 241; 336; 392; 396]. The required digital integration and parametric abstraction is more flexible and reciprocal when compared to the typical process of building information modelling (BIM). However, the analysis of this relationship also requires new computational methods to be developed.

This renewed integration of disciplines, and the relationship between design and manufacturing, has been observed in other industries, and has the potential to induce systemic or radical innovation in the construction industry by collapsing or re-organizing previously fragmented disciplines [143; 144].

This thesis presents research that employed a set of computational design and robotic manufacturing methods that enabled the development of building systems, which can geometrically and structurally adapt to different internal and external conditions. This level of differentiation is emblematic for natural systems, where a high degree of morphological variation, and consequently of functionality, is achieved with relatively minimal material input [111; 227; 253; 379]. There is a specific interest in this research to develop building systems with an increasing similarity to natural systems. These so-called *gradient building systems* require innovative manufacturing and design methods but enable previously inconceivable geometric and functional adaptation, structural fine-tuning, and high material efficiency.

In this thesis, it is theorized that the resulting design space of gradient building systems is in reciprocal relation to the manufacturing technology that was developed with them: the parameter space of the machine setup directly relates to the parameter space of a building element that is manufactured by the machine setup. As such, both the building system development and the manufacturing process development influence each other. By drawing further parallels to natural systems, the interrelated design space can be called a *machinic morphospace*. The term "morphospace" describes all possible morphological variants of a building component that can be manufactured given the parameters of a specific machine configuration [233; 237; 240]. Instead of standardized building components that are typically used today, gradient building systems are defined by parameters and their domains.

The thesis contributes to three highly interdependent research areas at their intersection: (1) biomimetic principles in architectural design research; (2) manufacturing systems for gradient building systems in timber construction; and (3) computational design for the control and analysis of such gradient building systems.

In a series of case studies, the development process of computational design and digital manufacturing systems for gradient building systems made from timber will be analyzed. Their resulting workflows and data flows will be described, which necessitated and enabled the integration of disciplines such as materials science, structural engineering, and manufacturing. While the first case studies were developed only within an academic team, later case studies eventually connected to industry collaborators for large-scale applications. By analyzing the machinic morphospace for each case study, the thesis will establish a first quantitative understanding of the relation between machine setup parameters and the resulting design space of gradient building systems. Each case study shows a different attempt at developing geometrically or functionally adaptable building systems that can be more finely tuned for structural and architectural applications, showcasing more intricate and performative connection details, and saving material and weight. The case studies each follow an integrative development process that considers material, materialization, and architectural design in parallel. In contrast to traditional and more fragmented design and delivery processes, this approach results in a seamless data flow from design to manufacturing.

In the discussion and conclusion chapter, the contribution to the research areas of biomimetics, manufacturing systems, and computational design systems is discussed, summarizing the individual contributions of each case study. It is argued that the case studies act not only as prototypical physical results that exhibit new structural and constructional possibilities in timber through the convergence of computational design and digital manufacturing, but they also act as process prototypes for integrated and manufacturing-aware design workflows, opposing traditional design and delivery processes. It is argued that while modern building information modelling promotes early know-how exchange in traditional industry processes, it still reinforces compartmentalized building component knowledge and inhibits innovation diffusion from one discipline to another [116; 351; 358; 397]. In contrast, the case studies in this thesis demonstrate an “industrialized platform development”, in which all stakeholders from design, manufacturing, engineering, and construction share and gather their know-how within the development of a parametric building system platform. From this development, highly customized embodiments can be produced [143; 199]. The machinic morphospace method introduced in this thesis can be considered a key development to collapse interdisciplinary boundaries and enable systemic innovation by enforcing a reciprocal relationship between design and manufacturing.

While integrated development processes have been proven to work on an academic scale, with know-how and expertise shared among a small team, part of the discussion in this thesis will focus on the problem of scaling this methodology up and organizing a large amount of highly specific knowledge. For the effort of such a platform-based development process to make economic sense within the construction industry, it will be further argued that contrary to typical industrialized manufacturing processes in other fields, architecture requires a much higher degree of mass-customization, a so-called *hyper-customization*, as each iteration of the platform will need to be context- and client-specific and therefore requires more adaptability [199].

In the outlook chapter of the thesis, it is argued that the potential complexity of gradient building systems has not yet been accessed by the building industry because such systems require a much closer collaboration or integration of design and manufacturing. This integration is now being incentivized by a technology unfamiliar to both disciplines. In this sense, robotic fabrication technology is an incentive for collaboration because it is a technology previously extrinsic to either architecture or construction. The seamless data flow from design to manufacturing enabled by this development can be considered a catalyst for disruption in the architecture, engineering, and construction (AEC) industry [40; 145; 387]. While in the case studies the machinic morphospace method is documentational, it will need to become operationalized in order to be fully adopted and, in turn, transform the industry. The thesis concludes with a discussion about the challenges of establishing a large platform-based development to focus on one product or product line. However, the potential for this paradigm change lies not only in more material-efficient building systems, but also in enabling highly adaptive architectural products.

1.1 Research aims and areas

The aim of this thesis is to propose, evaluate, and establish a method for providing systemized feedback between computational design and manufacturing innovation in timber construction that results in gradient building systems, which are characterized by a higher degree of functional integration, material performance, and morphological complexity than what could be achieved with hierarchical and standardized building systems in traditional design and delivery processes. This method will be established through the analysis of case studies in which manufacturing systems and computational design systems for gradient building systems in timber construction have been developed. The premise is that both manufacturing development and the design space of building systems are dependent on decisions, and ultimately, parameters that can be analyzed for their reciprocal impact. As the complexity of building systems increases, traditional methods for analyzing and controlling geometric and functional information become progressively insufficient in their processing capacity and flexibility. As such, this thesis contributes to three highly interdependent research areas:

1. The thesis contributes to the research field of biomimetics in architectural design research in two ways: (1) the development of more performative and functionally gradated building systems that exhibit a higher level of geometric complexity and differentiation; and (2) to identify and transfer a method for the comparison of the solution spaces of building systems with their manufacturing process, and the impact both have on each other.
2. The thesis contributes to the research field of manufacturing systems by developing and evaluating innovative manufacturing processes that allow the fabrication of gradient building systems in timber construction using industrial robots and other numerically controlled manufacturing equipment.
3. The thesis contributes to the research field of computational design systems by developing and evaluating computational design processes that allow (1) to engage with and analyze the design space that is enabled by the above-mentioned development of new manufacturing systems for gradient building systems; and (2) to analyze the relationship between the design space of gradient building systems with the parameter space of the above-mentioned manufacturing systems, and their impact on each other.

As part of the main research aim, the development of computational design processes and manufacturing processes will also be evaluated in the context of how innovation in the AEC industry is applied within an academic setting and within industry collaboration.

1.2 Research objectives

This thesis investigates three hypotheses that intersect with, and contribute to the three research areas introduced in the previous chapter:

1. Gradient building systems: Innovation in robotic manufacturing systems in conjunction with computational design systems enables architectural design innovation such as the development of gradient building systems, which exhibit high levels of morphological and functional variation akin to biological systems. This method of an integrated development process collapses interdisciplinary boundaries between form, material, and materialization, which have traditionally been separated in the AEC industry.
2. Information density in design and manufacturing: The development of gradient building systems with a high level of morphological and functional differentiation results in a much higher level of information density and information flow within the digital model. To have enough control over the design and subsequent manufacturing process, new computational design strategies need to be developed for generating, processing, visualizing, and storing information.
3. Machinic morphospace analysis: While biomimetics is used as a driver and inspiration for the development of more functionally and geometrically gradated building systems, other methods from biology used to analyze natural morphologies can also be translated into the fields of computational design and robotic manufacturing to analyze the resulting design possibilities of such building systems and systematically relate the two parameter spaces of design and manufacturing setup.

In each case study, contributions to these three research objectives will be outlined, and an overall conclusion will be provided in Chapter 8.

1.3 Scope and contribution

The research presented in this thesis is situated within the field of technology-enabled architectural design research. The thesis aims to investigate architectural implications that are enabled by the convergence of robotic manufacturing with the development of timber building systems, which are controlled by computational design systems. As such, the computational design systems as well as the manufacturing technologies employed in the case studies are both methods and research areas. Their exploration regarding design control and design freedom is guided by a parallel development and analysis.

The case studies presented in this thesis are research and design work investigated at the Institute for Computational Design and Construction at the University of Stuttgart. Because of the interdisciplinary nature and the scale of the projects, the work usually involved multiple researchers and students. Many of the projects were not purely academic, but also included either an educational part or industry collaboration.

In each case study, the author's involvement and contribution is explained in relation to the project team. Usually, the author contributed to the case studies through the development of the manufacturing process, robot controls, building systems, computational design system, the design process of the architectural prototypes, and the analysis of the machinic morphospace.

1.4 Thesis structure and approach

This thesis is structured into nine chapters. After the introductory chapter, Chapters 2 to 5 contextualize the research of this thesis, Chapter 6 introduces the methods applied in the case studies, Chapter 7 presents a total of six case studies, and Chapters 8 and 9 present conclusions, discussions, and an outlook for future work.

Chapter 2 introduces an overview of innovation research in general, and innovation in the AEC industry in particular. The chapter aims to establish a broad context of the history of innovation in our industry, to which this thesis connects. This context is also of importance because the thesis argues that some of the methods employed in the case studies could be considered a recipe to introduce systemic innovation in the industry.

Chapter 3 introduces biomimetics in architecture. It establishes principles of formation and structure that are important to the conceptualization of gradient building systems that are presented in all case studies. It also introduces the concept of morphospaces in biology and how they were previously translated into machinic morphospaces.

Chapters 4 and 5 contextualize the thesis within the history of timber construction and its relationship with, and dependency on, technological innovation. As the research in this thesis is dedicated to wood and its application in architectural design and construction, it is important to understand this relationship in a historical context. Chapter 5 further introduces the state of the art in what the author calls *computational wood architecture*, which is described as the field of research at the intersection of robotic manufacturing, computational design, and wood design or timber construction.

Chapter 6 introduces the tools and methods critical for the development and analysis of integrative architectural design research. Development methods and strategies in computational design and manufacturing technology are described both independently and in combination with each other. Further, the method for analyzing machinic morphospaces is introduced, which allows to relate the manufacturing setup and resulting design space in each case study.

In Chapter 7, the methods are applied, evaluated, and discussed in six case studies that were developed between 2011 and 2018. Each case study features previously introduced methods of developing highly versatile, adaptive, and material-efficient timber building systems. However, they differ in that each case study follows different, or different combinations of, investigative motivations, and they therefore result in diverse development processes and building systems.

The case studies are introduced through their investigative motivation. Then, the development of the case study's manufacturing system is discussed. While some aspects of these processes have previously been published in scientific papers, this chapter describes and analyzes the development process regarding the manufacturing technology in its entirety. The discussion results in a description of the gradient building system that was developed in each case study. Afterwards, the development of computational design tools required to explore and design with the gradient building system is discussed. In the last part, the development process and computational design process of the case study is discussed, and contributions to the objectives of this thesis are outlined. The relationship and interaction between disciplines, and the methods used to implement innovation, are explored in relation to other case studies and industry practice. Last, the relationship between the manufacturing system and the design space of the resulting gradient building system is analyzed both on a qualitative and quantitative level through the method of machinic morphospace analysis.

In the last chapter of the thesis, the findings from the case studies are summarized and conclusions are drawn regarding both the methods of integrative development processes and the methods for relating manufacturing setups and design spaces for gradient building systems. Further, the impact of these technologies on timber construction and architectural design are discussed. Last, the challenges and next steps for employing these methods at a larger scale in the architecture, engineering, and construction industry are discussed.

In accordance with §2.4 of the University of Stuttgart dissertation regulations, some of the findings of this dissertation have been selectively pre-published by the author and referenced in this thesis.

1.4 Thesis structure and approach

2

Context: Innovation in Architecture and Construction

"Why can we succeed now, given a century-long legacy of failure and disappointment? What has changed today? In a word: Everything. Nothing is the same." Stephen Kieran and James Timberlake [172]

Today, the manufacturing, construction, and operation of buildings are responsible for 36% of global energy use and 39% of carbon-dioxide emissions [2; 371]. At the same time, the sector is expanding at an unprecedented rate. With a growing population and accelerating urbanization [22], the need for new buildings will only become more pressing in the future. This expected growth will not be without consequences, making meaningful innovation in the value chain of architecture, engineering, and construction (AEC) an ever-increasing need.

While many industries have embraced product and process innovation in the last few decades, showcasing the potentials of "Industry 4.0" and the "Internet of Things", the AEC industry has been remarkably disinterested about adopting the opportunities that come with technological innovation. As such, the AEC industry has been the only one where labor productivity has stagnated or even declined since the 1990s [22; 352].

With the onset of digital technologies, there are now many opportunities for meaningful innovation in the industry [292; 305; 352]. While incremental innovation has offered point solutions that increase efficiencies of single process steps within the traditional value chain, the AEC industry remains heavily fragmented, making vertical integration and systemic innovation one of the biggest challenges and opportunities at the same time [27; 148; 172; 237; 395].

Computational design and digital fabrication have the potential to revolutionize how buildings will be designed and manufactured in the future. Today, some of the fastest-growing technological applications include 3D printing, modularization, and robotics [27; 235; 395]. This thesis is positioned in the context of innovation and integration of digital technologies in the design and manufacturing of timber building systems. Therefore, it is important to understand how innovation takes place and diffuses in the AEC industry. This chapter will look at technological innovation, the history of innovation in architecture, and how recent developments in computational design and digital fabrication have the potential to introduce a fundamentally new paradigm in the design and materialization of architecture.

2.1 Systemic innovation and inter-organizational networks

The term "innovation" has been defined by many scholars and industries of our time. Joseph Schumpeter, an influential economist of the early twentieth century, defined innovation in his 1911 book *The Theory of Economic Development* as the process of introducing new goods, new methods of production, new sources of supply, or a new organization of any industry [326]. In their effort to find a broadly applicable definition of the term, Baregheh *et al.* describe innovation as "the multi-stage process whereby organizations transform ideas into new [or] improved products, services or processes in order to advance, compete and differentiate themselves successfully in their marketplace" [23]. Innovation does not require the invention of an entirely new process or product and can happen only through the combination of existing or known processes or products [325].

Innovation is the consequence of the industry from which it emerges, and it exerts influence on that industry at the same time. Clayton Christensen, and others before him, have defined two types of innovation: those that sustain an existing product or industry and improve on their performance, and those that depart from known practices in a significant way and offer a different value proposition [61; 113]. In a paper published in 1990, Rebecca Henderson famously defined four categories of innovation which shed more light on the relationship between the organizational framework and the product that results from it (Figure 2.1). In other terms, her definition describes both the impact of innovation on the components of a product or process as well as on the linkages between them. As such, "incremental innovation" neither changes the components nor the linkages between them but only improves on them, whereas "radical innovation" changes both the components and their linkages. Further, "modular innovation" changes the components but not the linkages, and "architectural innovation" retains the core components but changes the linkages between them [152]. Henderson notes that while the boundaries between these four categories are not always clear, the categorization of "architectural innovation" draws attention to the difficulty of changing the linkages within established networks because they usually require communication channels or typical workflows within a firm or multiple firms to change [152].

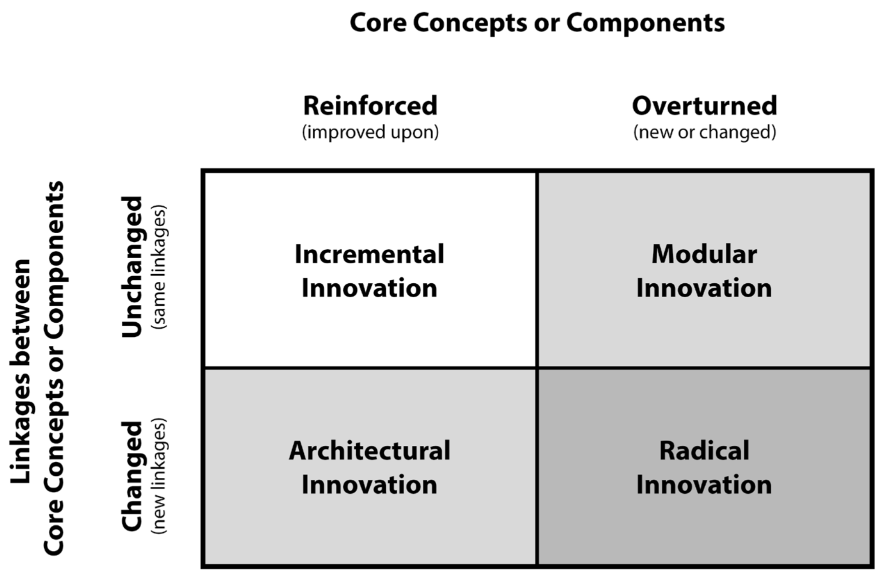

Figure 2.1: A framework of defining innovation. Adapted from Henderson & Clark [152].

The term “systemic innovation” is related to this definition but points to an additional challenge in inter-organizational networks. Takey and Carvalho define the term as innovation “that only generates value if accompanied by complementary innovations. It opposes autonomous innovation, which can be developed independently of other innovations” [356]. Midgley and Lindhult further describe the term as innovation that changes the “thinking, relationships, interactions, and actions” of innovators and stakeholders [245].

The AEC industry is a project-based industry and an inter-organizational network [143; 358; 359]. Research on innovation and its diffusion has shown that while the AEC industry usually adopts incremental innovation as quickly as other industries, it is a laggard adopter when it comes to radical or systemic innovation, which requires multiple firms to change their internal and external processes in a coordinated manner [358]. Walter W. Powell notes on systemic innovation in inter-organizational networks that “a critical task for participants enmeshed in a web of many relationships is to take the problems learned from one project and make them systematic” so that they can be applied system-wide [280]. Even more so, the inter-organizational setup of the construction industry has led to fragmentation in three dimensions: the vertical fragmentation between different disciplines; the horizontal fragmentation between competing firms; and the longitudinal fragmentation of temporarily formed, loose collaborations between firms for each building project [99; 142; 221; 339].

2.2 Systemic innovation in the AEC industry

Since industrialization, the architecture, engineering, and construction industry has become ever more fragmented [136; 172]. The re-integration of specialties and tasks into a single firm for the sake of innovation diffusion has proven to be difficult due to the project-dependent variability of workflows, seasonal fluctuations in business volume, geographic limitations, and the context-specific nature of construction [351; 358]. Until recently, it has seemed as if efforts of re-integration would lead to a level of standardization too rigid for architecture and construction, thereby outweighing the advantages that would come from the ability to quickly adopt systemic innovation [172]. Such a re-integration would already be considered a systemic change.

However, in the past, innovation in technology did cause systemic or radical change. Looking at historical examples can shed light on how innovation diffuses through and changes the network that it emerges from. Its effects on design processes, form, and tectonics in architecture are equally important for this thesis. By looking at patterns of innovation, it is possible to formulate the argument that innovation in timber construction, computational design, and digital fabrication has the potential to create an equally disruptive change in architectural design.

The invention of wrought iron changed the view of materiality and materialization, and how they were conceived within the design process [68]. The first effects of this new material can be observed in the articulation of joints. Instead of heavy timber joints, iron joints were built using bolting and riveting techniques on cast lugs and flanges [273]. Compared to wood, building elements made from iron had to be produced in a factory. It was a "process of assembling prefabricated components with prefabricated connectors" [273]. Design and construction were further defined by engineering pioneers such as Richard Turner and Gustave Eiffel, who learned to work with the material by separating complex challenges of construction and functionality into individual solutions and then recombining them within joints or building elements. The Kew Palm House and the Eiffel Tower, for example, were the result of this new way of designing [273].

The subsequent invention of steel further revolutionized building construction in the nineteenth century. It allowed for high-rise buildings and freed the walls from being load-bearing [68]. In the twentieth century, the invention of reinforced concrete resulted in a similar process of discovery and yet another architectural and tectonic language. Still, between the invention of the material and the innovation in construction that came with it, decades passed [94]. Only when designers and engineers took advantage of its material properties and understood its manufacturing process, they were able to fully embrace a new architectural language. In a paper published in 1998, E. Sarah Slaughter states that structural steel can be considered a radical innovation because "a whole new industry of steel manufacturing and fabrication emerged, as well as new components and systems linked to the new structural forms and systems" [341].

New materials and construction methods required specialized knowledge. In the context of industrialization, each step in the design, engineering and manufacturing of components was further compartmentalized into specialized but also disconnected disciplinary domains [68; 172]. Tom Peters notes that "The development of separate and specialized design professions helped to bring about divergent interests between engineers and architects and the organization of design had no built-in mechanism to bring about innovation in the absence of external stimuli from clients or materials' producers" [273].

Added complexities in the various products and systems involved in the construction process have resulted in the industry's fragmentation to become "institutionalized over the past few centuries by means of separate educational programs, separate licensing and insurance requirements, and separate professional organizations" [172]. On an overarching level, the role of the "systems integrator" is now shared between the architect and the contractor, resulting in a loss of control over the complete process by either [397]. Further, Winch notes that "the fragmentation of the professional bodies in construction has weakened their ability to act as honest brokers of innovations as they typically threaten the interests of one or other amongst them" [397]. The specialization of the professions also led to the emergence of divergent interests between them. As David Gann observes, "The organization of design had no built-in mechanism to bring about innovation in the absence of external stimuli from clients or materials' producers" [116].

For innovation to have the most significant impact on productivity in an inter-organizational network, multiple companies must adopt significant change simultaneously [210; 358]. However, as a result of the AEC industry's fragmentation, companies strongly prefer localized product innovations that increase efficiencies of single processes without disrupting the larger network between them [143]. As Hall notes, this paradigm "traps firms into the prevailing product architecture and resists attempts to innovate at the system level" [143].

Building information modelling (BIM) can be seen as an example of improving efficiencies in the exchange between fragmented disciplines within the same inter-organizational network. Originally conceived by Charles Eastman and Adrian Baer in the 1970s as a digital database for design processes, it took decades for BIM to become an established workflow [84; 85; 86]. Although the digitalization of previously manual or analog processes is only a small step, even today, only few countries have adopted BIM as a government-mandated format for building permits [370].

However, the onset of digital technologies has brought many new strategies that could disrupt and re-integrate the industry, thereby not only changing the inter-organizational network but also heavily impacting architectural design and the tectonics of building systems. In her editorial for *Architectural Design* magazine's special edition on "Material Computation", Helen Castle writes: "By the late 1990s, the onset of CAD-CAM and CNC milling, personified by the high-profile employment of CATIA at the Guggenheim Museum Bilbao (1997) by Frank Gehry, fueled a whole new pipeline of architectural visions" [54]. Although such promises have not yet been fulfilled in large-scale applications, the author suggests that through the reciprocal relation of manufacturing technology and computational design methods, the institutionalized fragmentation of the industry may be reversed in an effort to develop more adaptable and material-efficient building systems.

2.3 Innovation in computational design and robotics in architecture

2.3.1 A brief history of computational design

With the onset of digital fabrication and computational design at the end of the twentieth century, the generation of form could be based on algorithmic processes, which shifted the focus of design from form as an artifact toward form as a generative system [6; 183]. While digitalization only allowed for a faster processing of information, computational design allowed for the conceptualization of how information was generated. For the first time, the generation of form was not only free of geometric restrictions but could also be informed by constraints, requirements, or possibilities of structure, material, and materialization.

However, early explorations in computational design and digital fabrication were not characterized by such an integrative approach. Many building projects at the beginning of what can be described as "Parametricism" in the 1990s and early 2000s were purely formal, ignoring function or materiality [265; 266; 323; 324]. In fact, parametric design did not require architecture to depart from the traditional linear and hierarchical workflow from form to structure and materialization through a process of post-rationalization [266]. As such, parametric design did not elevate itself from the representational nature of typical computer-aided design (CAD) processes [181]. Many iconic buildings designed in the early 2000s pushed the boundaries of parametric design, manufacturing technology, and the data flow from one to the other, but with little concern about material-oriented construction (see, for example [315]). The sometimes overly evident disconnect between design, material and materialization even led to criticism of parametric design. Branko Kolaveric points out that "Their successful application requires careful articulation of a clear strategy of tectonic resolution, such that a sufficiently clear description of interdependences can be achieved; in other words, a well-defined design strategy is essential for the effective application of parametrics" [182].

Around the same time, however, the rise of the technological empowerment of architecture, engineering, materials science, and manufacturing led to the reciprocal integration of these disciplines, reversing the traditional and hierarchical design process. Rivka and Robert Oxman describe this paradigm shift as the "new structuralism" where the "design engineer" can "prioritize materialization over form" [266]. Patrik Schumacher describes it as a transition toward "Parametricism 2.0", where the style "matured from an avant-garde and research focused movement" toward an integration of the structural and tectonic differentiations that are the result of computation in engineering [324]. Achim Menges defined the term "integrative design computation" to describe a computational design process that integrates material behavior, fabrication, and production [232]. Menges emphasizes that the convergence of computational design and its materialization need to form a reciprocal relationship in order for material and materialization to "become the starting points of an exploratory, open-ended design process" [235].

The understanding of form as a result of the interaction of system-internal parameters and system-external data can be seen as the origin of computational design [232]. Before this interaction was executed by algorithms in the digital realm [182; 360], the foundations for this paradigm were laid by architecture and engineering pioneers such as Frei Otto and his work on tensile structures in the 1950s [203] and on grid shells in the 1960s and 1970s together with Carlfried Mutschler and Ove Arup [52; 153; 213], or Jørn Utzon, Ove Arup and Jack Zunz in the development of the Sydney Opera House between 1957 and 1973 [293]. In both examples, a reciprocal form-finding process is established by relating material properties, structural performance, and architectural design, albeit on paper or through physical scale models. Clearly, integrative computational design preceded early explorations in parametric architecture. However, it did not receive the same attention and, ultimately, remained on the sidelines of architecture and construction [324]. Until today, its potential has been explored and observed mostly in academia.

2.3.2 A brief history of robotics in architecture

Although other industries have used industrial robots since the second half of the twentieth century, architecture and construction have been slow to adopt the technology. The first mentions of an articulated industrial robot date back to 1938 with the Pollard painting arm and the first applications in manufacturing starting in 1961 with the Unimate robot arm [242; 249; 256]. While the automobile industry adopted industrial robots in the following decades, building construction only started exploring robotics through large-scale and task-specific, on-site technologies in the 1980s in Japan [41; 69]. Driven by a labor shortage, on-site robotic factories were developed that would construct high-rise buildings with a high degree of automation. However, their development costs, complexity, and lack of adaptability outweighed the value they created [32]. Since then, industrial robots have gained renewed attention in the construction industry. Compared to early construction automation equipment, industrial robots are standardized, mass-produced, and cost-effective tools for customized tasks [237].

For industrial robots, universality has become an inherent part of the machine, while the specialization becomes a smaller and more focused physical aspect, and even more so a digital aspect of programming [237]. The same tendency could also be observed in the development of the smart phone in the early twenty-first century, where more physical aspects of the phone became a universal platform, while the specialization (the apps or programs) became less focused on physical characteristics until, ultimately, the phone became a relatively standardized physical platform and specialization was fully digital [233].

It can be argued that digital fabrication in general is nothing more than an analog fabrication technique that is digitally controlled [406]. The crucial difference, however, is the variability and programmability of the control protocols, and the integrative potential that is enabled by this method. Compared to early digital fabrication tools that were only implemented within the hierarchical process from design to manufacturing, the integration of form generation with fabrication data generation allows for manufacturing to become part of the design process, and ultimately enables a rethinking of the assumptions of traditional manufacturing [121].

2.4 A path toward re-integration

Today, the design and delivery of buildings is typically characterized by a top-down process where questions of material and materialization, or producibility, are only answered at a late stage [197]. While digital interfaces, such as BIM, have allowed for increased efficiencies, they have not re-integrated disciplines.

Only the integration of manufacturing and material aspects at an early stage of the design process would allow for reciprocal feedback during the phase where the most cost-relevant choices are usually made [174]. This concept is called *production-immanent planning* [46], reducing the systemic friction to innovation.

Innovation research in the AEC industry has described many new paradigms that recently emerged in an effort to re-integrate. For example, “collaborative modular clusters” utilize supply-chain integration practices [143; 144], and “core-periphery platform structures” use a platform-based approach to link design and fabrication [143; 199]. Companies like Design-to-Production, Blumer-Lehmann, and SJB Kempter Fitze have worked to realize complex projects by collaborating with architecture firms such as Shigeru Ban [316; 349]. These projects have shown a close collaboration between the design and manufacturing of buildings, albeit within a relatively traditional framework.

In many academic projects the integrative development of design and manufacturing has proven to foster reciprocities between manufacturing, materiality, and the design process [15; 50; 104; 193]. Here, production-immanent planning concepts and the re-integration of disciplines have begun to form a cross-sectionally informed design language. Computational design and digital fabrication have shown the potential to induce systemic innovation and change how architecture is perceived, designed, and delivered. The re-integration of design, engineering, and manufacturing has been described as an "extended digital chain" [259; 357], and the integration of feedback loops into a completely digital optimization cycle as "integrated co-design" [387].

This thesis is part of the recent shift from a purely technological focus on the digital production of architecture to a seamless integration of material and materialization, resulting in a gradation of form and function. Instead of constraining architectural design through the adoption of nineteenth-century mass-production principles, the integration of innovation in computational design and robotic fabrication extends the architectural design space while implementing a higher efficiency in material usage and higher structural and functional performance.

As such, systemic innovation is both necessary for, and a result of, the proposed methods and processes. Their implementation could both disrupt the industry and encourage actors to re-integrate to gain access to highly adaptive, material-efficient, and cost-effective solutions.

3

Context: Biomimetics and Principles of Structural Morphology

"If nature is at all economical, we can expect that she will choose to create at least some complex forms not by laborious piece-by-piece construction but by harnessing some of the organizational and pattern-forming phenomena we see in the non-living world." Philip Ball [20]

Nature has undoubtedly played an inspirational role for architects, designers, and engineers for many centuries. While for a long time such inspiration mostly happened on a formal or aesthetic level, some of the first systematic studies to transfer functional principles from nature into engineering and architecture were conducted as early as the Renaissance. Polymaths, philosophers, and architects such as Leonardo da Vinci or Leon Battista Alberti, analyzed structural or constructional principles from animal parts for the design of machines or the construction of buildings [72; 295].

The transfer of biological principles into structural, constructional, or design principles has gained increased attention with the rise of modern biology at the end of the twentieth century [49; 65; 112; 347]. Learning from the geometric complexity of natural structures for engineered materials has led to promising results in the context of computational design and digital fabrication.

The terms "bionics" and "biomimetics" describe the study of biological materials or natural structures to find underlying principles that can be transferred to human-made structures, machines, or processes [110; 309;

379]. The term "bionics" was first introduced by the medical doctor Jack Steele in 1960, followed by the term "biomimetics", which was coined by the polymath Otto Schmitt in 1969 [146; 379]. However, biomimetics is also a field that biologists are actively pursuing, and as such, it is rooted in interdisciplinary research [129; 177].

Much research in biomimetics is concerned with studies of the morphology of biological systems. The term "morphology" describes the form and structure of organisms or biological materials, and the term "morphogenesis" describes the process of formation.

When comparing morphogenesis in nature with architecture, engineering, or construction, similarities and differences can be observed that help understand potentials for new paradigms in design and manufacturing. Architecture and its materialization are similar to biological evolution in that both processes are non-deterministic. Like biological evolution, architectural design is about finding a compromise between sometimes conflicting requirements such as cost, material or energy consumption, structural efficiency, or functionality [346]. Engineering, on the other hand, is a discipline about solving a clearly defined problem or optimizing an already existing solution [177]. However, both architecture and engineering are highly restricted disciplines compared to the seemingly endless possibilities of biological evolution. They are based on a standardized and limited set of tectonic elements and follow pre-defined typologies [66; 192]. Due to the linearity and hierarchy of the traditional architectural design process, form is often decided upon before a material is chosen [235]. This results in the relationship between design and materialization being static: materials are selected based on their projected use during their lifetime and applied to a pre-defined form.

Natural structures, on the other hand, are not fabricated but grow. Here, the concept of materialization is described as a dynamic strategy, where the growth instructions (the DNA) do not define the outcome directly but only lay out a plan that, in its execution, can change how material is arranged and deposited based on external conditions [111; 380; 381]. During growth, the material, its microscopic structure, and the resulting macroscopic form are created in the same process [165]. As a result, the distribution of material on all scales is responsible for an organism's structural performance [111; 227].

Its geometric complexity is free of the restriction in typology, form, or scale, all of which are so emblematic in engineering and architecture.

As Julian Vincent and his co-authors have shown in their 2006 publication, geometric complexity, and therefore information, is one of the main reasons for material efficiency of natural structures, which, in turn, is critical for survival [197; 379]. More importantly, this high degree of morphological and functional variation is achieved with relatively minimal material input [253; 379].

It is no surprise that structures in biological role models lie outside or between established categories in building construction [29]. On many different scales, natural materials are defined by complex geometric articulations and gradients between them. In that sense, nature is the opposite of modern architecture. Instead of dividing construction into layers of materials with singular functions, nature is functionally integrated [197]. However, up until recently, mechanical constraints and control challenges of industrial manufacturing could not afford such a high level of geometric differentiation and component complexity [190].

As this chapter will show, many fundamental biological principles in combination with computational design and digital manufacturing methods have the potential to be applied in architecture, thereby initiating a new paradigm in the materialization of structure and construction: one of integration and gradation instead of fragmentation and segmentation. In addition, biomimetic methods can also serve as a model for evaluating and exploring design spaces within this new paradigm. The last section in this chapter will introduce the concept of morphospaces, which is fundamental for this thesis.

3.1 Biomimetic principles in natural structures

In nature, many morphological principles show how gradual geometric differentiation can lead to functional and structural adaptation toward system-internal constraints and system-external requirements, without changing the amount of material or energy needed to produce this variation [177; 330].

This thesis aims to provide a collection of the most relevant principles employed in the case studies and that form the basis for this thesis. Jan

Knippers and Thomas Speck first summarized four of the most prominent characteristics exhibited by natural structures—characteristics that are repeatedly transferred in the case studies—as (1) heterogeneity, (2) hierarchy, (3) anisotropy, and (4) multifunctionality [177]:

(1) Heterogeneity: Natural structures are characterized by the local adaptation and differentiation of their elements across many levels of scale. Either through variation in their chemistry or their structural makeup, properties and forms can be gradually changed [177; 207].
(2) Hierarchy: Natural structures usually exhibit five to seven levels of hierarchy that can span up to twelve orders of magnitude [83; 89; 177; 346]. From a molecular nano-scale to the visible macro-scale of biological materials and the shape of an entire organism, the arrangement of atoms, molecules, and their aggregation results in specific properties.
(3) Anisotropy: Many natural structures can be described as natural fiber-reinforced composite materials [10]. In situations with a dominant loading direction, the material structure is arranged to allow more strength in this direction while saving as much material as possible [111].
(4) Multifunctionality: Natural structures usually fulfill many different functions at the same time. Functionality and structure cannot be divided: through a diversity of the material structure, a diversity of function is also achieved. [89; 362]

Compared to the many human-made materials in engineering and construction, biological structures are based on only a few substances: polysaccharides such as cellulose and chitin, proteins, and a small selection of minerals [89]. The diversity of properties and functions is usually not achieved by a change in substance but by a change of the structural makeup of these materials. Furthermore, some material properties are distributed across many scales, ranging from molecular arrangement to macroscopic material arrangement or ratios. A distinction between structure and material, or structure and form, is therefore not possible [111; 177].

The multi-layered combination of scales and gradual variation of basic components that fulfill multiple networked functions is a characteristic found in almost all natural structures [111]. In the last decades, research at the intersection of biomimetics, engineering, and architecture has investigated as to how these principles can be applied for the development of more functionally or structurally performative building systems [177; 180; 231; 253; 271].

From the above-mentioned four principles, four conclusions can be drawn that lay the foundation for a biomimetic transfer towards building systems, and that have been employed by many researchers in the field of computational design and digital fabrication (Figure 3.1):

(1) A gradual variation of building elements replaces standardized, and therefore excessive, material use, through subtle variation in form, and therefore information. By varying form across a building system, structures can not only be more adaptive to their specific function in the building but also become more material-efficient [197; 236].
(2) Variation in form should not only be applied to a single scale or hierarchy, such as the building element. Instead, multiple scales from material to building component must be seen as a part of a building system [65; 281].
(3) Similarly, anisotropy is an additional layer of information for form, orientation, and aggregation that can be implemented in building systems to allow for a variation in structure or function depending on the loading direction [193; 373; 388].
(4) Through one or more of the above principles, building systems can become multifunctional. Instead of layering different materials on top of each other, variation and adaptation in form and material distribution allows for multiple functions to be fulfilled by the same material or building element [56; 194; 279].

Figure 3.1: Examples of the transfer of biomimetic principles to architectural design research. From left to right: (1) gradual morphological variation in building elements (Image by ICD/ITKE University of Stuttgart); (2) multi-scalar variation of form through fiber placement in building modules (Image by ICD/ITKE University of Stuttgart); (3) anisotropic arrangement and performance of building elements (Image by ICD/ITKE University of Stuttgart); (4) multifunctional building elements through variation in material for kinetic structures (Image by ICD/ITKE/ITFT University of Stuttgart).

The work presented in this thesis will mostly reference the first two principles. Heterogeneity and hierarchy are fundamental principles of information embedded in building systems with building elements that exhibit gradual changes in their shape. Both principles were applied in all case studies. Anisotropy and multifunctionality are principles that were either actively pursued in only a few of the case studies or were an indirect result of the development process.

3.2 On principles of formation in nature

In order to appreciate the value of biomimetic principles for architectural design research, it is essential to understand the underlying principles of formation in nature and how they achieve material, structural, and functional performance.

Contrary to the simplified understanding of evolution leading to organisms whose shape and function are optimized by a selection process for the right set of genes, the formation of living structures is much more dependent on fundamental laws of physics, which influence the range of possibilities during morphogenesis (the growth and formation of an organism) and homeostasis (the constant balancing of internal conditions within an organism). The idea that the growth of living organisms is not only governed by their genes but also by the laws of physics was first described by George Rainey in 1858. He argued that due to their observable similarity, patterns in living organisms and non-living natural formations would have to adhere to similar laws [285].

D'Arcy Thompson was one of the first to compare the formation of living organisms to mathematical and physical laws in his book "On Growth and Form" [361]. Thompson mentions explicitly that "Cell and tissue, shell and bone, leaf and flower, are so many portions of matter, and it is in obedience to the laws of physics that their particles have been moved, molded and conformed" [361].

In his paper "The chemical basis of morphogenesis", Alan Turin tested these arguments through mathematical simulation. He argued that in homogenous chemical substances such as those observed in embryonic zygotes, random and minute disturbances can trigger instabilities, and subsequently, components to grow and shape the organism in its morphogenesis [365]. Using models of differentiation with two substances, mutually inhibiting each other in their production rates until a threshold is reached, he simulated linear reaction kinetics that roughly resemble the emergence of patterns in molecular biology [365]. His theory of pattern formation was later supported by Gierer & Meinhardt [123] and Keller & Segel [169], building a foundation of reaction-diffusion and activator-inhibitor models [272].

In his trilogy of books, Philip Ball describes the forces of formation in nature as a combination of physical constraints and genetic code [20; 21]. He describes pattern formation as a natural occurrence in both the non-living and living world due to physical or chemical interactions between components [21]. He later goes further, and describes pattern formation as a natural consequence that allows for the most efficient flow of energy from energy-dense environments toward entropy, thereby describing life itself as being inevitable in energy-rich environments [19; 322].

In addition to the forces of formation during morphogenesis, J. Scott Turner added an essential perspective by discussing the role of homeostasis in living organisms for finding the most effective distribution of material and energy [366; 367]. He argues that by constantly balancing agents of material deposition and removal, complex but efficient structures are built within organisms. He posits that it is not the genes that build organisms, but the genes specify the behaviors of these agents in relation to their environment, resulting in the structures we see in biological systems [367; 368].

Whether the result is the mineralized structure of a bone or the arrangement of skeletal plates in a sea urchin, the underlying principles of material hierarchy and gradients are evident. Continuous differentiation in material deposits or makeup allows for gradual changes in structural stiffness or functions such as nutrient transportation. This form-generation and adaptation is the result of the interaction of the organism's capabilities, the environment, and the laws of physics.

The lesson to be learned from the principles of formation in nature is that materialization is not a consequence of direct instructions but a process of balancing internal requirements and external forces. The consideration of material characteristics, structural behavior, and other rules or constraints intrinsic to the materialization of architectural form presents a fundamental departure from the traditional, hierarchical, and linear process of architecture where materialization is merely an industrial afterthought [207; 235; 236]. As the following section will show, computational design can enable the integration of system-internal behavior such as material characteristics or manufacturing boundaries, and system-external constraints such as structural forces.

3.3 Integrative computational design for gradient building systems

While a negotiation between system-internal behavior and system-external constraints can be enabled through computational design methods, the resulting formal variation within building systems can only be achieved with an equally sophisticated manufacturing method. Therefore, form, material, and materialization need to be related within an integrative design development process [178; 180; 195; 244; 259].

Functional and structural gradation can only be designed with computational methods that can recognize, process, and assign information to individual building elements or a high resolution of material composition.

Menges and Hensel have described the ability of an artificial material system to adjust or vary the shape of its building elements to system-external and system-internal conditions as "performative morphology" [155]. Here, the term morphology is borrowed from biology to refer to a building element's shape and structure. As the variation of dimensions or material compositions is intrinsic to the building system, the author more broadly describes it as a "gradient building system". Building elements in a gradient building system are not defined by their dimensions but by their parameters, which, in turn, are developed and defined through their reciprocal relation to materiality and materialization. Computational design methods can integrate the logic of formation and control the resulting gradients within the building system that is applied in a certain design process. Here, the most crucial information to be integrated into and inform the gradient building system is that regarding manufacturing constraints and possibilities. If it is not integrated, a disconnect between design, material, and materialization can easily occur [68].

Biomimetics has been suggested by many architectural design researchers as a methodology to develop building systems that allow for the morphological differentiation, on different hierarchical levels, for performance-based adjustments [179; 190; 235]. In many recent research projects, the combination of computational design and digital fabrication allowed for the integration of biomimetic principles in the development of new building systems. In the ICD/ITKE Research Pavilion 2011, the author developed a "performance catalog" to evaluate and implement biomimetic principles for architectural performance criteria [190]. In later research projects such as the ICD/ITKE Research Pavilion 2012 [288] and ICD/ITKE Research Pavilion 2013–14 [81], as well as the Landesgartenschau Exhibition Hall [331], the research team employed biomimetics as a concept generator for the development of novel material and manufacturing approaches for shell structures [139] (see Figure 3.2). In an exploratory process, the mechanical behavior, construction morphology, and functional properties of load-bearing biological structures were analyzed and transferred to a technological application [332]. Related research showed that the geometric variability in building systems that resulted from this process led to a higher structural performance due to the individual adjustment of building elements to their specific requirements within the structure [207; 332].

Figure 3.2: From left to right: photographs of the ICD/ITKE Research Pavilion 2011, the ICD/ITKE Research Pavilion 2012, and the ICD/ITKE Research Pavilion 2013–14 (Images by ICD/ITKE University of Stuttgart).

In the above-mentioned research projects, the development of a computational design process was a key element to negotiate between system-internal and system-external conditions. Implementing biomimetic principles resulted in the ability to vary the shape [191; 195], and in some cases, the composition of building elements or structures [375], which resulted in the variation of structural performance and function [317].

In the Rosenstein Pavilion, a group of researchers from the Institute of Lightweight Structures and Conceptual Design of the University of Stuttgart developed a computational design method and an accompanying concrete formwork manufacturing method for the design and construction of a lightweight and porous concrete shell [186]. The same group developed a concrete spray process for microscopic gradation of its structural performance in a different research project. Here, the manufacturing information is also based on a computational design model [404].

Outside of architecture, one of the most prominent uses of computational design and digital fabrication for the gradation of material use and properties is topology optimization and 3D printing. By simulating material properties and external forces, material distribution is optimized and later manufactured through additive material deposition [44; 82; 226]. However, the application of computational design methods for gradient building systems is highly dependent on the manufacturing technology used.

In construction, specifically the application of large-scale robotics has allowed for the implementation of biomimetic design principles both on-site and off-site [77; 117; 145; 207; 238; 259]. There is a bidirectional relationship between the manufacturing technology and biomimetics: on the one hand, robotics has made biomimetic design principles feasible, but they are also limited by the manufacturing technology; on the other hand, robotic fabrication has opened up new possibilities that can be filtered through the lens of biomimetics in order to find meaningful solutions [189]. To gain a better understanding of the consequences of manufacturing technology on design possibilities, it is becoming increasingly important to relate machine setup to design space.

3.4 Machinic morphospaces

In every manufacturing process, the setup of machinery and each fabrication step is critical to the possible shape variation, or morphological variation, of building elements. Therefore, fabrication and design are intrinsically linked. Throughout the history of timber construction, this relationship has changed dramatically. In Chapters 4 and 5, the relevance of technology to the design of timber structures will be discussed in more detail.

With ever more complex manufacturing technology emerging in architectural design research (see Figure 3.3), it is imperative to compare the potential morphological differentiation of building elements with the manufacturing setup to understand a building system's design space. In a purely technical description, the design space defines all geometric possibilities of a building element that can theoretically be designed. Within this space lies another, smaller space, of all building elements that can be produced given the parameters of a particular machine setup [66]. To relate design, material, and materialization without any traditional hierarchical relationship such as is so present in the current construction industry, the biological method of morphospaces can be transferred to this context. First introduced by Menges in 2012, it is called the “machinic morphospace” method [237].

Figure 3.3: Different robotic manufacturing setups. Their work envelopes are one of many parameters that are directly related to the shapes and sizes of building elements they can produce. From left to right: manufacturing setup of the ICD/ITKE Research Pavilion 2011, the ICD/ITKE Research Pavilion 2012, and the ICD/ITKE Research Pavilion 2013—14. Images by ICD/ITKE University of Stuttgart.

3.4.1 Morphospaces in biology

Morphological spaces, also called morphospaces or shape spaces, are a mathematical or diagrammatic representation of morphological variation in organisms. Each axis in a morphospace diagram corresponds to a variable that describes a geometric characteristic of the organism, and each point within the diagram corresponds to the measurements of an individual organism or phenotype [88; 118; 228; 247]. Since its most famous inception by David M. Raup in 1966, where the morphospace of coiled shells was analyzed based on three geometric characteristics [286], morphospaces have become an integral part of evolutionary and theoretical biology (Figure 3.4). Although morphospaces can have many dimensions, they are usually visualized with two or three parameters.

In classical morphospace diagrams, each point is represented as Cartesian coordinates, and therefore, close distances between points represent similarities between organisms [247]. Although Raup's iconic morphospace diagram has been criticized for not possessing a Euclidian structure due to the definition of its parameters [118], it demonstrates clearly how certain points within the space relate to each other. Depending on which parameters are selected to be represented by the two or three dimensions of the morphospace, the resulting diagram can have a strong similarity to a Euclidian vector space. For example, this means that equal distances between points represent equal differences between morphological features, or that a translation in one direction represents an equal change in a morphological feature independent from where the starting point was [247].

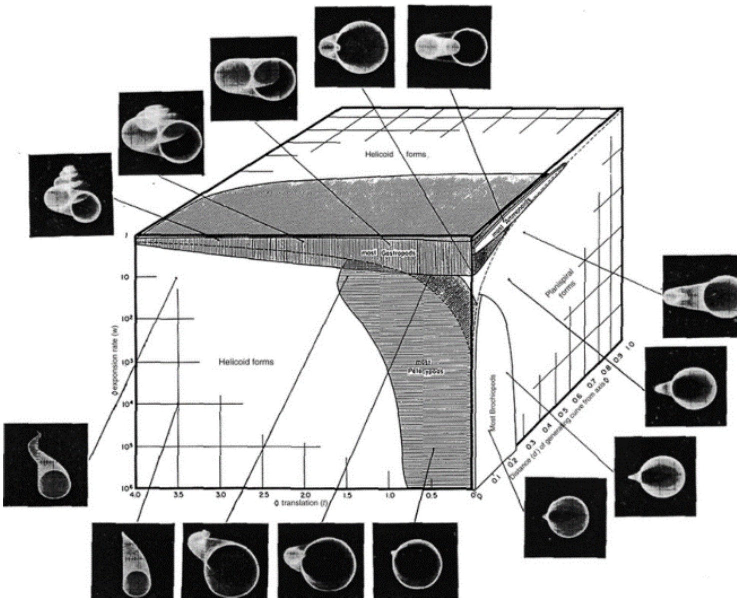

Figure 3.4: The morphospace of coiled shells [286]. The three parameters used in this diagram are (1) the rate of increase in the size of the cross-section per revolution; (2) the distance between the cross-section and the coiling axis; and (3) the rate of translation of the cross-section along the axis per revolution. The gray area shows existing taxa, and the white area shows spaces not occupied by any natural organism.

Figure 3.4 also demonstrates the relationship between theoretical and empirical morphospaces. In Raup's diagram, it is easy to see that only the gray regions are occupied by organisms found in nature. The remaining white regions represent shapes that are theoretically possible but do not exist. Theoretical morphospaces represent morphological features that are theoretically possible, whereas empirical morphospaces result from actually measured morphological occurrences [87; 228]. When using a computational model, theoretical morphospaces become mathematical models and can be used to project certain developments or morphological characteristics outwards in an explorative manner [88; 228].

3.4.2 Machinic morphospaces

Defining morphological features through parameters and their ranges is similar to the definition of form and structure in computational design [329]. When developing algorithms for gradient building systems with variable element shapes, the range of each parameter that defines a morphological feature of an element represents a dimension in its design space [237]. Therefore, the definition, visualization, and exploration of a design space, or morphospace, in computational design can be conducted similarly (Figure 3.5). While empirical morphospaces in biology represent observed morphological features, their boundaries can change for various reasons, such as evolutionary or environmental events [185]. Translated into architecture and computational design, many system-internal and system-external constraints can limit the theoretical morphospace. One of the most fundamental, and for this thesis particularly important, constraints, is the boundary of the producible. The relation between fabrication and design has become a major focus for research, especially in relation to newly developed manufacturing processes that stem from the renewed appreciation for materialization in architecture [193; 402].

The region of form within the morphological range of a building element that is producible with a specific machine setup is called the "machinic morphospace" [233; 237; 240]. The mapping of all theoretically possible shapes in relation to those that can be manufactured with a specific machine setup "lays the foundation for a systemic investigation of non-hierarchical convergence of computational design and digital fabrication" [237]. The computational, and therefore mathematical, description of the machinic morphospace allows for exploration of the producible and non-producible, but also for investigation as to how changes to the manufacturing setup correlate to changes or expansions to the design space of the building system [240]. Figure 3.5 offers an example of the relationship between a machinic morphospace and the machine setup.

In past machinic morphospace studies, affine Q-spaces were used to visualize morphological parameters of building elements in relation to a manufacturing setup [237; 333]. "Q-spaces" describes a multi-dimensional space in which each morphological parameter is represented as a dimension or axis, and each specimen is represented by a point in the resulting space [247]. Figure 3.4 is such a Q-space. "Affinity" refers to the fact that the parameters are not mathematically but qualitatively related because they do not have common units or scales [237]. Such a space is not a Euclidian space but an affine space.

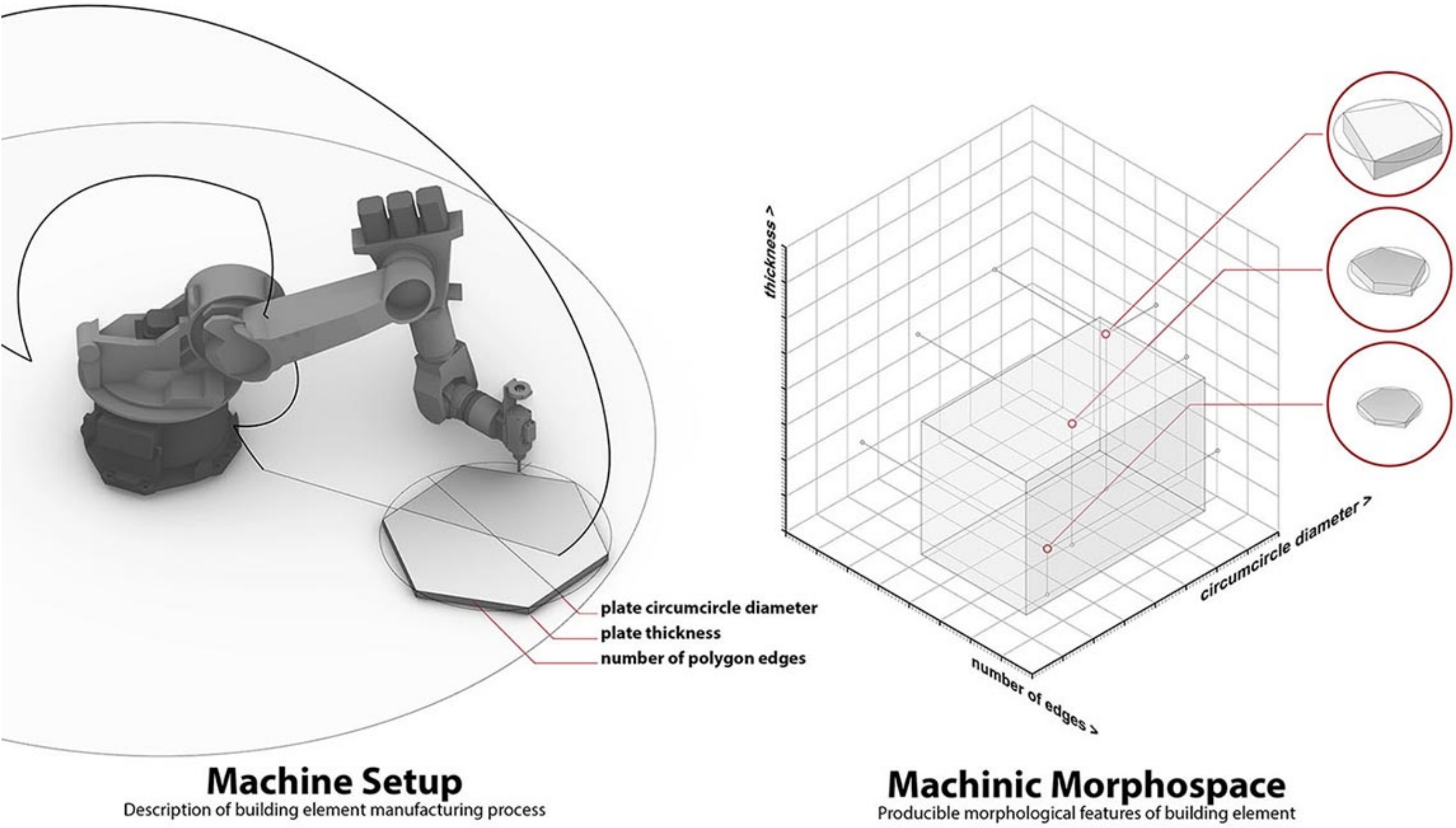

Figure 3.5: An example of a machine configuration and morphospace to cut out the boundaries of a polygonal plate. On the left side is an example of a manufacturing process of a polygonal plate. On the right side, three geometric parameters of the polygonal plate describe a three-dimensional morphological diagram: (1) the circumcircle diameter or size, (2) the number of edges, and (3) the thickness or depth. Although each parameter increases or decreases at the same rate when moving along its axis, the three parameters do not necessarily share the same units or scales. While many configurations of the parameters are theoretically possible, only some are producible with a given machine setup, highlighted by a gray box. Three example configurations are given on the right side.

While the transfer of biomimetic principles to design and engineering enables more adaptive and efficient structures, the method of machinic morphospaces enables the integration of manufacturing technology. In other words, the method enforces an integrative, bottom-up development process that converges material, form, and materialization. It also requires working in multi-disciplinary collaboration, as knowledge about all fields needs to be acquired in parallel.

3.4 Machinic morphospaces

The method of machinic morphospaces is universal and can be applied to a variety of manufacturing technologies and materials. Its use will be exemplified by employing it in the context of robotic fabrication for timber construction systems, with the goal of quantitively and qualitatively relating manufacturing technology to design possibility. In Chapter 6, the method used in the case studies is established and explained in more detail.

3.4 Machinic morphospaces

4

Context: Timber Construction and Manufacturing Technology

"With the emerging technologies of fabrication, the current impact of material upon architectural form has become one of the prominent influences in architectural design. Fabrication is not a modeling technique, but a revolution in the making of architecture."
Rivka and Robert Oxman [266]

Wood has accompanied humanity's cultural, societal, and technological developments for millennia. It is a material with a rich history in architecture, design, and construction as both its shape and makeup were molded and adapted throughout the progress of human civilization.

Used in ornamental fashion [147; 350], in traditional mono-material construction [109; 170], or as engineered construction elements [59; 114], wood has been broken down, processed, rearranged, and used in many ways in the past. Most recently, the material has gained renewed attention within both industry and academia for its potential as a future-proof building material, leaving its antiquated and archaic image behind [59; 197; 296]. This attention can be explained through the general recognition that, as a construction material, wood can lead to carbon-neutral buildings [127; 184; 307], but also through the progress in computational design and digital fabrication that is opening up many new structural and architectural possibilities [35; 241].

As one of the oldest building materials known to humankind, wood has a dynamic relationship with the tools and technologies used to process the material, which can be traced back thousands of years [157; 294]. Because the use of wood in buildings varied greatly before, during, and after the Industrial Revolution, the related construction techniques can easily be traced back to the processing and manufacturing technologies available at the time [320]. As this chapter will show, the material's makeup and shape, as well as its connections and resulting building systems, always depended on the technology of each era. Recent developments in architectural design research, however, have made this dependency even more explicit.

Wood's availability in temperate climate zones and its ease of handling and processing made timber construction a widespread building technique throughout the pre-industrial era [184; 320]. Although it experienced a decline with the innovation of human-made construction materials such as steel and concrete during the Industrial Revolution, the invention of engineered timber products in the second half of the twentieth century slowly led to a renewed interest in the material [59; 184]. Mass timber such as cross-laminated timber (CLT) and other plate-like engineered timber products is a modern example of material innovation in construction and has been recognized as a driver of innovation and integration in the industry [58; 135].

When grown and harvested in a sustainable horticulture system, wood is a renewable resource that maintains a positive carbon footprint even when the entire life cycle of an engineered timber product is taken into account [311; 327; 390]. In addition, a sustainably managed forest adds to the local ecology and economy, offering healthy biodiversity and recreational areas [75; 184; 197].

Changes in building codes, large-scale testing, and new regulations have led to explorations in high-rise construction with mass timber and other innovative building products, which, together, could be described as a renaissance of timber construction [101; 108; 331; 355]. But also, in academia, an unprecedented amount of research dedicated to wood design, timber manufacturing, and construction has recently occurred. The material's ease of use and machinability has made it an ideal building material for exploring the potentials of innovative computational design and robotic manufacturing methods, which has been shown to enable the development of construction techniques beyond standardized and hierarchical building systems [239; 296; 396].

By exhibiting so much versatility and resilience, it is no surprise that wood has been used throughout human history. As such, its application in architecture and construction have reflected technological and cultural progress through centuries [320]. With renewed interest in the material in academia as well as in industry, and with the widespread adoption of digital fabrication, it is essential to discuss the historical relationship between available processing or manufacturing methods or technologies, and the manifestation of construction techniques. In this historical context, it will be easier to understand current developments at the forefront of architectural design research, and how the potential of implementing biomimetic principles can be realized today. This thesis does not intend to establish an overview of the entire history of timber construction in this section. Instead, it intends to provide historical context for current developments in manufacturing technology that allow for a rethinking of building systems and architectural design.

In his doctoral thesis in 2009, Christoph Schindler described the developments in manufacturing technology at the time as part of overlapping "development waves" in timber construction and architectural design that span from the earliest records of human civilization until today [320]. The author argues that the latest developments in manufacturing technology for wood design and timber construction may be even more fundamental to architectural design than the Industrial Revolution that influenced the processing and application of the material in the nineteenth century.

This chapter is divided into three eras in woodworking and manufacturing: the pre-industrial era until 1760, the Industrial Revolution, and the post-industrial era until the early 2000s. The subsequent chapter will discuss developments in computational design and digital fabrication in the last twenty years.

4.1 Locality and differentiation in pre-industrial woodworking

Many historic wooden buildings that still stand today are prime examples of the structural performance and resilience of the material and its construction techniques that were developed over many hundred years. While Japanese and Chinese temples are some of the most impressive structures, many centuries-old buildings can be found throughout Europe and Russia [138; 176; 310; 369]. The origins of the material knowledge and craftsmanship required to build lasting structures from locally sourced and linear wooden elements can be traced back to 8000 BC by looking at the earliest tools for harvesting and processing trees, such as axes and saws [126; 320].

Given that a wide variety of tree species can be found in many different climate zones from tropical to moderate, Mediterranean and desert biomes [71; 284], it is no surprise that wood was the predominant building material for thousands of years. Although it was typically not used for ecclesiastical or representational architecture in Europe, it was still required for the construction of their foundations, roofs, and interiors [106]. Consequently, more than 80% of all buildings were made from timber until the beginning of the eighteenth century [59; 184].

During the long predominance of wood, the tools used to cut, process, and join the material underwent significant development and refinement while also receiving influence from the types of available wood species and the general cultural background of their origin. From the "Great Mosque of Sivrihisar" in Turkey [369], to Central European "timber frame" houses [176] and Asian temples [128], a variety of processing and building techniques emerged. However, all building techniques had in common that the entire chain of processing relied on hand tools and manual labor. Christoph Schindler [320] and Lewis Mumford [251] point out that the energy required for processing, the material being processed, and the geometrical information necessary for processing, were all responsibilities within a single artisan on the construction site. Due to the limited force that could be exerted on the material, only small processing steps could be efficiently executed, resulting in timber components with shapes closely resembling the original shape of a tree trunk or branch [67; 120]. The manual work also resulted in unique and non-replicable connections that could serve specific structural functions within each building [320].

Since processing was strictly related to the available logs or trees, the building system repertoire of the pre-industrial era was restricted to linear elements. Still, a great variety of timber frame building systems with hundreds of different types of connections emerged in many different parts of the world [119; 209; 274]. While there were many different types of connections for each part of a building, every joint within a building was also unique and influenced by the individual craftsman's knowledge, skills, and preferences. Although most building elements were usually processed on-site at the time, wooden elements were typically fabricated in specified areas for "prefabrication" [70].

Non-standardization in the pre-industrial era can be seen as a constraint and a virtue at the same time. The manufacturing of standardized and repetitive connections was almost impossible due to the manual labor leading to slight variations in each joint. However, differentiated connections and unique shapes did not affect the processing time either. Therefore, it was possible to adapt every building element and connection to its specific function in a building or the shape of the tree that it came from (Figure 4.1). The only incentive for standardization came from the logistical challenges in manually handling hundreds or thousands of building elements off-site and on-site during construction [164; 320].

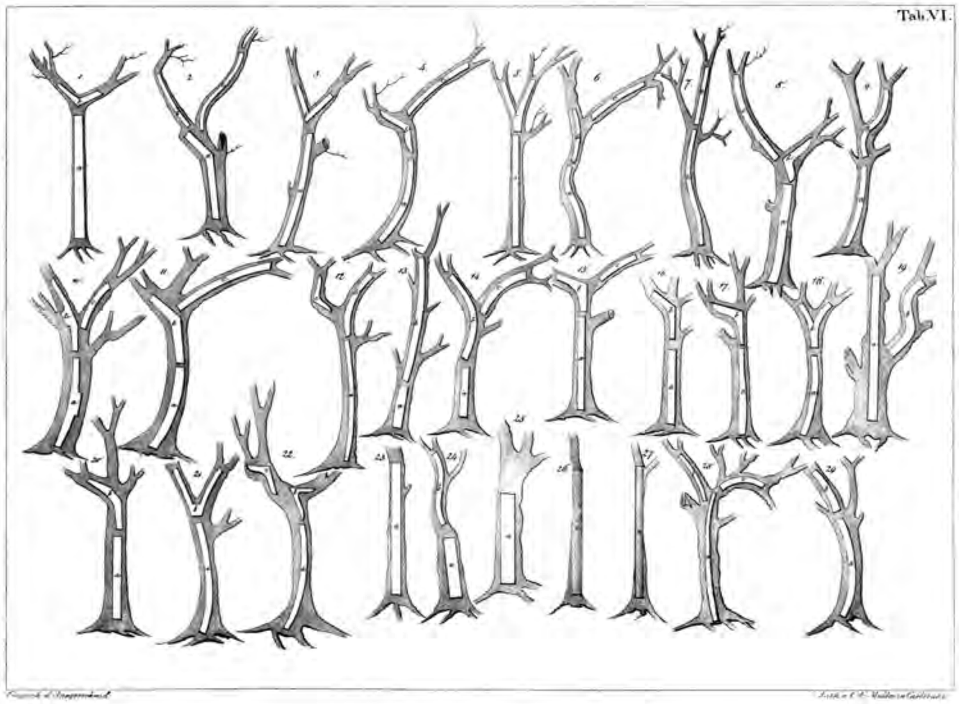

Figure 4.1: Visualization of krummholz for the purpose of different ship building parts that match the growth of trees. From Jägerschmid [163], Table VI (public domain).

The possibility to adapt the shape of every building element to its unique requirements and constraints within a building, independent of the time and energy needed to fabricate said element, can be seen as a processing technique much closer to the natural adaptation of biological systems. Taking the example of connections between elements, a broad range of geometric possibilities similar to that of the biological morphospace can be theorized. The available manufacturing techniques naturally resulted in varying shapes and connections specifically adapted to system-internal constraints and system-external requirements. However, such flexibility and adaptability in each building element's shape were soon lost to a dramatic increase in production rates at the beginning of the Industrial Revolution.

4.2 Impact of industrialization: standardization and globalization

Between 1760 and 1840, the invention of coal as an energy source, the steam engine, and the production of steel brought drastic economic and societal changes that were soon described as the Industrial Revolution [160; 269; 363].

Many wood processing techniques were already mechanized during the pre-industrial era to help manual work processes. Therefore, the focus during the Industrial Revolution was on increasing the amount of energy available to operate machines [320]. Water-powered sawmills with reciprocating saws already occurred in the thirteenth century [115], and wind-powered sawmills with gearboxes and automated feed rates appeared in the Netherlands at the end of the sixteenth century [103]. Finally, the invention of the steam-powered sawmills at the beginning of the eighteenth century led to a fundamental change in cycle times, or throughput of material [103].

During the Industrial Revolution, many machine tools were developed using steam power and later electricity. Although most were derivatives of manual woodworking tools, the general concept of automated machining (the subtraction of material using revolving blades) was actually translated from metalworking machines such as the metal lathe in the early nineteenth century [97].

Using the example of sawmills, it is easy to see that process quality and geometric flexibility were contradicting factors. Throughout the development of sawmills during this period, the accuracy and quality of the cut kept increasing [38]. However, the reciprocating saws could not easily be changed in their spacing, leading to mechanically motivated standards that soon became legal standards [320; 408]. Today, the era of standardization and mass production in the late nineteenth century is generally described as the Second Industrial Revolution [162].

The phenomenon of innovations in machine tools leading to a dramatically increased output but also to the standardization of building elements is commonly observed during the Second Industrial Revolution. Schindler explains this via the fact that powered machine tools transposed material and energy, but they did not allow for the transfer of variable information [320]. In other words, while these machines automated the movement and processing of material, the information of the process was mechanically fixed within the machine. Changing this information (such as the length or width of a building element by changing the machine's guides) required the process to be interrupted if it was at all possible. As a result, the advantages of mass production outweighed the disadvantages of the loss of variability. In his book "Mechanization Takes Command", originally published in 1948, Sigfried Giedion writes about the hand as an organic tool that cannot keep up with the Industrial Revolution: "*For all the complicated tasks to which this organic tool may rise, to one thing it is poorly suited: automatization. In its very way of performing movement, the hand is ill-fitted to work with mathematical precision and without pause.*" [122]

The mass production of identical elements led to the development of standardization and tolerance measurement [220]. This was the beginning of globally interchangeable building elements and components, such as the 2x4 inch plank. In the second half of the nineteenth century in North America, the pre-industrial "timber frame" construction system became the "balloon frame" and later the "platform frame" (Figure 4.2) construction system, both of which were based on the 2x4 inch plank [398]. Both systems were widely adopted for residential buildings and are still used today in up to 90% of all single-family homes in North America [184].

Figure 4.2: Typical North American platform frame house under construction (Image by Jaksmata, distributed under the Creative Commons Attribution-Share Alike 3.0 Unported license).

In addition, the restriction of standardization soon led to various attempts in standardizing their aggregations or combinations as well, leading to standardized components, which are better known under the term "modular construction". Among others, Walter Gropius and Konrad Wachsmann developed the “General Panel System” in 1941 [384], and Rudolph Schindler developed a variation of the wood frame called the “Schindler Frame” from 1945 onwards [168; 340].

Throughout these developments, wood was seen less as a naturally grown and varied tissue, and more as a homogenous building material for the sake of predictability and ease of calculation. A shift can be observed from localized skills and variations in production to a global standardization, ignoring local deviations in materiality, knowledge, or even culture [224; 338]. This shift also led to a disciplinary fragmentation that started with an integrated model of the craftsman in the pre-industrial era and ended with a segmented industry made from highly specialized fields [67; 172].

Despite all these efforts in standardization, wood was not considered a material as suitable for mass production as other human-made building materials when the Industrial Revolution took hold of Europe. Its preeminence was lost within a few decades and has not surpassed a market share of more than 30% in building construction since 1900 [59]. In his book *Holzhausbau* from 1930, Konrad Wachsmann reflects on why the material could not suit the demands of an industrialized world, arguing that the transition from craftsmanship to industrial production was slowed down by the almost romantic image of traditional woodworking [383].

Another reason was that newly developed building materials such as steel and concrete quickly became more economical to manufacture in large quantities [125]. Further, the widespread production and use of steel not only displaced timber construction but also influenced its connection design. The manufacturing of intricate connection details from steel was easier than the manual fabrication of a wooden connection [320], but it also allowed the transfer of higher structural forces while keeping the timber element itself simple in shape [28]. The increase of energy consumption to produce steel connectors compared to the production of wooden mono-material connections was of no concern during the time.

Another attempt to standardize not only the processes and connections in timber construction but also the material itself began with the introduction of plate-like timber products. The process of breaking up the material and recombining it into different shapes—for example, by gluing together sewn veneers into plywood—became feasible on an industrial scale only with the invention of moisture-resistant glues and the appropriate industrial processes in the 1930s and 1940s [34]. By recombining smaller wooden pieces into larger aggregates, their individual discrepancies in material quality and structural performance were homogenized for the sake of calculability [320].

With the introduction of various timber products such as plywood, medium-density fiberboards (MDF), particle boards, or glue-laminated timber beams (glulam), the overall design space of timber construction started to broaden, albeit under the paradigm of standardized building elements. Balloon and platform frame construction was slowly augmented by timber panel construction methods, where plywood sheathing replaced diagonal beams [383]. However, it did not immediately result in any tectonic change in timber construction. Standardized processes produced standardized building elements with little variation and simple connections. Geometric complexity could neither be handled in the design process nor in the manufacturing process. As Schindler [320] argues, the processing information fixed within the machines did not allow for variations, and the standardization systems developed around these constraints still surround us today. In addition, industrialization and globalization led to a fragmentation in architecture, engineering, and construction by further separating building element information and design intent [172; 254].

4.3 Digitalization in the post-industrial era

With the invention of digital electronics and digital information, the Third Industrial Revolution, also called the Digital Revolution, began in the second half of the nineteenth century [43]. A clear division in manufacturing technology between the Second and Third Industrial Revolutions, and a general definition for the beginning of the post-industrial era [33], can be made by analyzing how information is processed within the machine that fabricates a building element.

While the information for how material is processed was mechanically defined and fixed within the machine during the Industrial Revolution, new inventions in the nineteenth and twentieth centuries allowed the information to become detached from the physical realm and move into the digital. The information exchange did not have to be electronic. Schindler [320] notes that even before computers and digital information processing were invented, the punch-card-controlled weaving loom created by Joseph-Marie Jacquard in 1804 could be considered the first machine with variable processing information [320]. The punch card system invented in this machine was later also used in early computers and so-called numerically controlled (NC) milling machines, which were first developed by John T. Parsons in the late 1940s [255; 257].

For the first time in history, the human worker was completely detached from the machining process, and only responsible for the creation of the information that the machine would use to process material [320]. The information for processing a building element was not physically connected to the machine and not created at the moment of processing. Instead, the process was abstracted into codified instructions, and prepared by a human in advance. Punch cards and other early programming solutions that were tedious and expensive during the early days of NC machining were soon developed into a standardized programming language called “G-Code” [342]. It allowed machining data to be more efficiently created and is still being used today because of its universality [171]. Building on this programming language, computer-aided manufacturing (CAM) programs were developed to automate the writing of the machine code [171]. With the transition from punch cards to a standardized electronic programming language, numerically controlled (NC) machines became computer numerically controlled (CNC) machines as we know them today.

This development also represents a typical step in digital information generation that is relevant to this thesis. Instead of writing the machine code directly, a program or algorithm is created to generate the machine code automatically, thereby elevating the required human input to a higher level of information. However, a human is still the author of the algorithm that was used to generate the processing instructions, and the author of the information required as an input for this algorithm. As the next sections will show, this development step in elevating information input and processing was repeated many times throughout history, and this thesis can be considered a part of the latest of these steps.

Although the timber industry was the first to invent mechanical automation in the pre-industrial era, it was slow to adapt to digital automation.

CNC machines were mainly developed for processing metal at first, and most timber construction and carpentry firms only started to purchase wood-specific CNC machines in the 1980s [167; 320]. However, during that time, a unique development can be attributed to timber manufacturing technology: that of *timber processing centers*, also called “automatic joinery machines” [296], which incorporated a variety of tools and functions to trim, cut, and add features to longitudinal timber elements, and later also to plate-like elements as they became more broadly available.

By combining all cutting and milling tools within one machine, these processing centers were developed to make the production of existing timber construction elements more efficient while allowing for more variation at the same time [308; 320]. As such, they reinforced the use of common building element and connection types at first before material-appropriate methods were developed. By comparing this development to historical examples, it is easy to see that innovation in manufacturing technology or materials science did not cause major consequences for construction systems and architecture until decades later [273]. Still, the dissociation of processing information from the machine, and the digital processing of such information, allowed for a renewed variety of building element shapes similar to the formal freedom of the pre-industrial era, but in a formalized, codified, and repeatable manner [102; 301; 320].

As such, building construction made only incremental progress throughout the twentieth century, with new building systems showing obvious similarities to those from the Industrial Revolution. In Europe, modern timber frame construction, timber panel construction, and engineered skeleton construction methods were developed [398]. Although these systems are based on mostly linear elements and dimensions established during the Industrial Revolution, variations within each building element due to dimensional differences in each building project could be efficiently manufactured with modern CNC machines and timber-specific computer-aided design (CAD) plugins or programs [5]. In some instances, this renewed freedom also led to a revival of traditional timber frame methods and the ornamental aesthetics that came with it [320; 399]. In combination with new insulation, waterproofing, and cladding materials, timber construction also adapted the multi-layered composition of exterior walls that we see in most building construction methods today [398].

However, one significant change in construction methods can be attributed to advances in timber processing. While plywood and other plate-like timber products were developed during the Industrial Revolution, only the second half of the twentieth century saw increased use of solid, plate-like timber elements for construction, with the invention of cross-laminated timber (CLT) (Figure 4.3). A surplus of low-graded lumber in 1990's in Europe made the sawmill industry research manufacturing methods to combine, refine, and value-add simple lumber products [98]. In the following decades, timber construction embraced plate-like elements, leading to new building systems such as plate-based construction or space cell construction [58; 135]. Although CLT-based solid wood construction uses much more material than timber frame construction, the material's carbon sequestration and structural performance are advantages that make it especially suitable for multi-story buildings and urban densification [58; 135; 197; 321; 398].

Figure 4.3: Vaulted CLT church in Stroud by Nicolas Pople Architects (Image by Fernando Manoso Borgas).

In parallel with, or because of, these developments, wood started to gain renewed attention at the end of the twentieth century under the premise of being a structurally advantageous construction material and a sustainable and renewable resource [57; 197; 198]. Together with technological progress in the harvesting, processing, and sorting of timber, as well as the development of new timber products and fasteners, it became an attractive building material for multi-storey and high-rise construction in European and North American markets [74; 382]. Today, the possibilities to reconstruct the material on a microscopic as well as macroscopic level, reformulating its shape into beam- or plate-like elements, are almost limitless [39].

5

State of the Art: Computational Wood Architecture

"The next stage in an imaginative leap occurs through establishing adjacency. Two unlike domains are brought close together; the closer they are, the more stimulating seems their twined presence."
Richard Sennett [337]

The author defines "computational wood architecture" as a sub-field of architectural design research that engages with the architectural potentials of computational design and robotic fabrication in timber construction. In this chapter, the reciprocal feedback between technological innovation and timber construction methods is discussed by focusing on the development of, and relationship to, manufacturing technology.

In the context of computational design, wood offers many new architectural opportunities beyond typical constructional applications, many of which have recently been explored in academia and applied research [239; 241; 336; 392; 396; 400]. In a departure from traditional timber construction methods, explorations of the full potential of the digitalization of design and manufacturing technology started at the turn of the millennium [313; 319], and can be described as a more wood-specific construction language [187]. This development was driven by the possibility to re-combine the pre-industrial with the post-industrial, or more specifically, traditional woodworking techniques such as mono-material connections with innovative manufacturing technology [189; 314]. Although motivated by standardization and production efficiency, it can be argued that the digitalization of the timber construction industry has laid the foundations for a renewed appreciation of the material, its characteristics, and its potentials for a gradual variation in form and function as we have seen in the pre-industrial era.

In the following sections, current research in computational wood architecture is categorized as one of two approaches. The first recognizes the material properties of wood and relates research to its specific characteristics and behaviors, most of which were increasingly suppressed in architecture, engineering, and construction during the Industrial Revolution. The second approach recognizes the related processing and manufacturing opportunities because of wood's lightweight and malleable nature. Some research projects combine both approaches, while others have formed nuanced research streams within them. However, all are decidedly specific to the materiality and materialization of wood design and timber construction. They have only become possible through recent developments in computational design methods, engineering computation, and manufacturing technology, and are characterized by a significant increase in information generated with every building element [67; 240]. The following two sections will present current research based on these two approaches, as they both relate to this thesis.

5.1 Integrating material properties

Unlike any other building material, wood cannot be manufactured to meet specific requirements. As a naturally grown biological tissue, the material performance and behavior are the results of its primary function in the support and nutrient transportation within a tree [66]. As such, wood exhibits a broad range of variation as it evolved into a highly efficient biological system in many different regions of our planet and into many different species [79]. The shape, structure, and orientation of wood cells determine the anisotropic material characteristics of wood [157; 385]. Since the Industrial Revolution, these variations have been seen as deficiencies in timber construction, and many efforts have been made to suppress microscopic differences for the sake of standardized engineering calculations [222].

Michaela Eder [90] writes that "Traditional engineering approaches are based on the perception that passive and inert matter needs to be transformed into technology with the aid of motors by the external input of fuel-based and/or electric energy and the input of human or artificial intelligence (information)." The understanding that engineered, human-made materials are homogenous and easy to calculate has lately been challenged by advancements of material-related design and engineering research. While wood's heterogeneous material characteristics have been difficult to control or calculate in the past [66], research from the last decade has shown promising results when engaging with complex material behavior as a generative driver for computational design methods [235; 240; 406]. Computational design can be seen as an enabler for this revival of materiality and of computational wood architecture.

In this regard, many material characteristics of wood have been analyzed and employed in architectural design research in the past decade. While there are many material properties of wood that research groups are engaging with on many different scales, three categories were selected that relate to the research presented in the case studies: irregularity, hygroscopicity, and elasticity.

5.1.1 Irregularity

In a return to the material-oriented design and construction of the pre-industrial era, emerging digital technologies have enabled timber construction with locally sourced and naturally formed building elements. Here, the material's microscopic or macroscopic irregularity can be used as an advantage in the design and fabrication of material-efficient structures under the umbrella of parametric design and digital fabrication.

Hooke Park, owned by the Architectural Association in London, has taught, and researched the potential of locally sourced and naturally grown timber components. The campus's first buildings were conceived as experimental structures either using roundwood sourced from the immediate surroundings for a tent-like structure [78] or spruce thinnings in a series of compression arches for a shell structure [336]. More recently, digital technologies were employed to survey and catalog tree shapes in 3D in order to automatically select the right branch structures suitable for different connection geometries in a large-span truss for the project Wood Chip Barn [336] (Figure 5.1). By employing computational design methods for the branch selection, and robotic fabrication to process the raw material, the forking points of the structure were contained within the naturally grown material. Therefore, a continuous fiber arrangement was kept, and the constructional connections were moved to simple, linear joints, where fiber continuity would not matter as much [76]. Similarly, in the Biomass Boiler House project, curved tree trunks were automatically selected from a 3D scanned library of available trees in the surroundings in order to match the design intent of a curved log cabin wall [389] (Figure 5.1).

Figure 5.1: Left: The Biomass Boiler House project (Image by Design+Make Postgraduate Program). Right: The Wood Chip Barn (Image by Valerie Bennett).

In another research project at the Institute for Advanced Architecture of Catalonia (IAAC), naturally curved wooden logs were scanned and processed by an industrial robot to add connection features [48]. The use of computational design methods to match design intent with available materials was first proposed by Christian Stanton [348] and Monier *et al.* [248] as a variation on form rationalization. Instead of arranging regular building elements to match irregular designs, algorithms were developed to select from a library of irregularly shaped building elements. Similar to the pre-industrial categorization of “krummholz” for the use of curved building elements in shipbuilding or construction, trees or branches usually not considered for the use of standardized building found a new appreciation for creating complex shapes. In the experimental buildings that followed at Hooke Park, the combination of computational design and digital fabrication enabled a new application of irregular growth and a much more energy-efficient and localized use of available material.

5.1.2 Hygroscopicity

One of the most well-known characteristics of wood is its interaction with water, resulting in shrinking and swelling. The cellulose molecules within the fibrils and micro-fibrils of wood are not only responsible for the material's structural but also its hygroscopic behavior [66]. Wood exhibits a fluctuating moisture content in relation to atmospheric humidity, and in return, changes in moisture content result in dimensional changes to the material [79].

Recent research has been motivated by the potential of harnessing the material's swelling and shrinking as a means to actuate movement in wooden components. Steffen Reichert and Achim Menges translated the swelling of thin, triangular veneer elements into a one-directional curl by blocking moisture from entering on one side of the veneer. This results in a reversible and humidity-dependent opening mechanism [230; 287]. This principle was further refined and developed by other research groups into hygroscopic apertures within building skins, which open and close, depending on atmospheric relative humidity [66; 158; 159] (Figure 5.2), or wood bilayers for autonomous shading systems [372]. Hygroscopic actuation was also used for larger self-constructing surfaces based on thicker timber elements [402], and most recently, for the lamination and construction of curved mass timber components as part of the Urbach Tower project [401] (Figure 5.2). In the Urbach Tower project, the combination of computational design methods for the prediction and simulation of the hygroscopic behavior, and industrial manufacturing equipment for the processing of the material, resulted in new free-form construction possibilities for timber shell structures [31; 400].

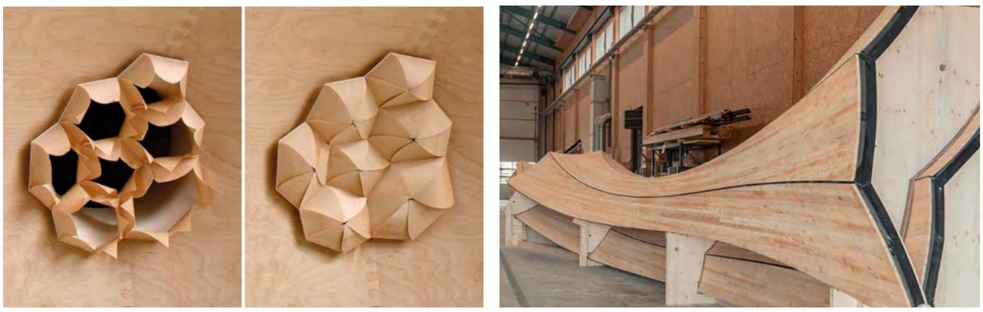

Figure 5.2: Left: hygroscopic apertures of the HygroSkin pavilion (Image by ICD University of Stuttgart). Right: Sections of the hygroscopically formed Urbach Tower construction (Image by ICD/ITKE University of Stuttgart).

5.1.3 Elasticity

Integrating elastic bending in the design of structures requires the consideration of force in relation to form. Without computational methods, this approach has proven difficult, and as such, there are only a few examples from before the onset of computational design [104]. Nevertheless, elastic deformation either during the manufacturing or the assembly process of building elements can be considered one of the most material-efficient and material-aware design approaches. In addition to the resulting geometric stiffness, the elastic deformation in curved beam or surface structures can cause residual stress to act against external forces such as load bearing. In this case, the structure is considered to be bending active [214; 216].

Wood has a particularly suitable bending or flexural behavior for this approach because of its high strength and elasticity, which can be attributed to the tree's primary structural function as a combination of column and cantilever beam that needs to resist dynamic loads [79]. As such, wood can be described as a soft and viscous material with a high suppleness [391]. However, employing elastic bending for form-finding methods is still relatively infrequent as both architects and engineers generally understand large deformations as problematic [230]. The use of computational design methods for the calculation and simulation of such material behavior in combination with innovative manufacturing methods has therefore become a focus for many research groups.

In a series of research projects, the Institute of Computational Design and Construction (ICD) and the Institute for Building Structures and Structural Design (ITKE) at the University of Stuttgart explored the potentials of elastic bending of wood for the construction of complex structures. In the project ICD/ITKE Research Pavilion 2010, initially flat plywood strips were elastically bent and subsequently connected so that one tensioned section would hold one bent section in place, resulting in a self-equilibrating system [104] (Figure 5.3). The Hygroskin project and later the ICD/ITKE Research Pavilion 2015—16 project each employed modular elastic bending for the construction of a large-scale and lightweight segmented timber shell, which are both case studies in this thesis [29; 66; 194; 195]. The author also used elastic bending in combination with robotically fabricated timber joints to explore curved, segmented timber shells [193] (Figure 5.3).

Figure 5.3: Left: the elastically bent plywood strips of the ICD/ITKE Research Pavilion 2010 (Image by ICD/ITKE University of Stuttgart). Right: elastically bent and interconnected plywood strips make up the double-layered structure of a segmented shell prototype (Image by ICD University of Stuttgart).

The IBOIS Laboratory of Timber Constructions at the EPFL in Switzerland has investigated the potentials of elastic bending by combining reciprocal structural methods, interlacing structural elements, and physics-based material simulation, resulting in large-scale timber plate structures [252]. Yves Weinand and Markus Hudert have gone so far as to describe the sequential bending of timber strips as a fabric language, weaving large “textile modules” that can be repeated to form material-efficient structures [391]. Here, the concepts of textile weaving were translated to building scales through the integration of engineering methods.

In other research, the computational simulation of the material’s elasticity was employed in a multi-scalar design approach to design and manufacture branched glulam components [353]. Other research groups combined elastic steam bending with robotic manufacturing to develop methods for the production of free-form timber beams where an industrial robot determines the bending shape of the steamed element [328]. In a different approach, free-form lamination methods were developed for double-curved glulam beams [8]. Here, the industrial robot is used to accurately deform a lamination of timber elements before curing, forming a close relationship between machine, material, fabrication, and design intent.

5.2 Integrating manufacturing possibilities

Recently, advances in manufacturing technology have been more prominently investigated in the context of architectural design research, seemingly closing the feedback loop between the design, structure, and materialization of buildings, and enabling innovative and material-specific approaches that were lost in the effort of standardization during the Industrial Revolution [239]. While 3D printing can be seen as one of the most receptive manufacturing technologies for integrative computational design methods [263; 264], the adoption of industrial robotics allowed architectural design research to engage with wood design and timber construction on a large scale [133; 241].

In comparison to wood processing machines, the main difference to industrial robots lies in their task specificity [198]. Wood processing machines have become versatile by accumulating multiple tools, but at the same time, they are specific to processing tasks for elements of known construction systems. Industrial robots are universal platforms where a specific function needs to be attached to. This is called an “effector” or “end of arm tooling” (EOAT). Industrial robots have been used in off-site prefabrication environments [12; 55; 96; 193] or in mobile in-situ scenarios [145; 150; 206].

Current architectural design research with custom robotic manufacturing strategies questions the traditional design-to-production workflow and instead suggests a “production-immanent design tool” [330]. The resulting digital toolset can automatically generate machine code directly from the design model. The required level of information processing and generation mentioned in section 4.3 might be the highest yet: Researchers have developed algorithms that automatically generate design iterations, which in turn generate manufacturing data, which controls how machines process material. Through the development of these algorithms, the researchers have also become authors of both the design and the manufacturing process. This strategy allows to explore design variations with manufacturing constraints in mind, and thereby short circuits the typical post-processing steps in traditional workflows.

Given the versatility of the industrial robot, several research trajectories have been observed in recent years. For the purpose of contextualizing this thesis, these research trajectories are broadly categorized by the application of industrial robots in either subtractive or additive processes. The next sections will give an overview of the latest research in those two categories, as this thesis is situated within both.

5.2.1 Subtractive: integrated mechanical joints

Wood's success in the pre-industrial era and the renewed attention it is receiving in architectural design research today can be attributed to its workability and machinability [192]. As such, jointing techniques that utilize the geometry of the building elements themselves, also called integral mechanical joints, have always been an important part of woodworking and timber construction [243; 296]. Many traditional integral mechanical joints underwent hundreds of years of development and refinement driven by constraints of material availability and labor input, leading to a variety of techniques that were highly adapted to the structural requirements and the material [134].

Recently, the versatility of multi-axis CNC machines and industrial robots equipped with milling spindles in combination with computational design methods allowed for the resurgence, and even enhancement, of integral mechanical joints. Although automatic joinery machines allowed for the efficient fabrication of traditional timber frame construction joints, the combination of robotic manufacturing and computational design has led to new opportunities in jointing techniques, especially for plate-like elements and structures made from timber plates [198; 296; 302]. Most notably, the difference compared to traditional integral mechanical joints has been the development of joint techniques that are not defined by their dimensions but rather by a range of dimensions in order to be adapted to specific structural or topological situations [192].

One of the first experimental structures made with variable joints was the Swissbau Pavilion in 2005, which used a combination of integral joints and dovetail connectors [313]. Christopher Robeller at the IBOIS, EPFL in Switzerland, and more recently at the Technische Universität Kaiserslautern, investigated integral mechanical connections for folded plate structures, curved-folded shell structures, and double-layered plate structures [296; 297; 299; 302] (Figure 5.4). Recently, researchers at the IBOIS and HS Augsburg also investigated the processing of solid timber components for segmented timber structures [302; 378].

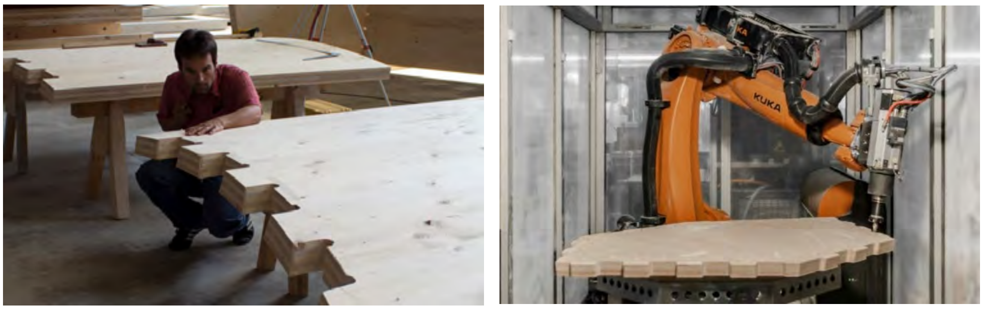

Figure 5.4: Left: Integral joints for a curved folded plate structure (Image by Christopher Robeller, IBOIS EPFL Lausanne). Right: Landesgartenschau Exhibition Hall milling process (Image by ICD/ITKE/IIGS University of Stuttgart).

The research group at the ICD and ITKE at the University of Stuttgart investigated robotic manufacturing for integral mechanical joints first with the ICD/ITKE Research Pavilion 2010 [104; 105], and later in a series of prototype buildings investigating structural and architectural applications of segmented timber shells, starting with the ICD/ITKE Research Pavilion 2011 [189; 330] and continuing with the Landesgartenschau Exhibition Hall [331] (Figure 5.4) in 2014 and the BUGA Wood Pavilion [11] in 2019. The author also investigated integral mechanical joints for elastically bent timber plate structures [68; 193] and for variable connections of insulated mono-material wood walls [50; 51]. Some of these projects will be presented as part of the case studies in this thesis.

Other research has experimented with efficient milling techniques that make use of the kinematic freedom of multi-axis robots. For example, flank milling was used to produce a finished, ruled, surface directly instead of needing the typical rough-cut process beforehand [45; 318].

At the intersection of additive and subtractive methods, recent developments have shown the potential of computational design and robotic fabrication in conjunction. For example, researchers at the Royal Danish Academy of Fine Arts investigated the design and fabrication of complex glulam timber structures [353; 354; 355].

5.2.2 Additive: assembly processes

One common application for industrial robots in other industries is the assembly of components. This can include picking, placing, and fixing, among other tasks. While the previous section presented research in subtractive robotic processes in the context of computational design, the potential for additive processes to assemble building components in timber construction is equally large and has been explored by many research groups.

Additive robotic manufacturing techniques for large-scale timber structures were most prominently investigated by researchers at the Gramazio Kohler Research Group at the ETH Zürich. Using a custom-built effector, several experimental structures were made from small battens stacked either vertically or horizontally. Instead of using building elements with a standardized length, a manufacturing process was developed that included the automatic trimming, placing, and fixing of battens and beams [131; 132; 396]. Later, similar trimming and assembly processes were used for the construction of reciprocal frame structures or multi-layered truss systems, which required metal fasteners or glued connections [151; 396]. For the large-scale roof trusses of the Arch_Tec_Lab building, a similar approach was used to prefabricate the trusses from many small timber slats that are jointed with nail patterns (Figure 5.5). A custom manufacturing process was developed that can handle picking, trimming, nailing, and quality control [12]. Most recently, the research was expanded towards a multi-robot process for the prefabrication of full-scale modular timber frame structures [4].

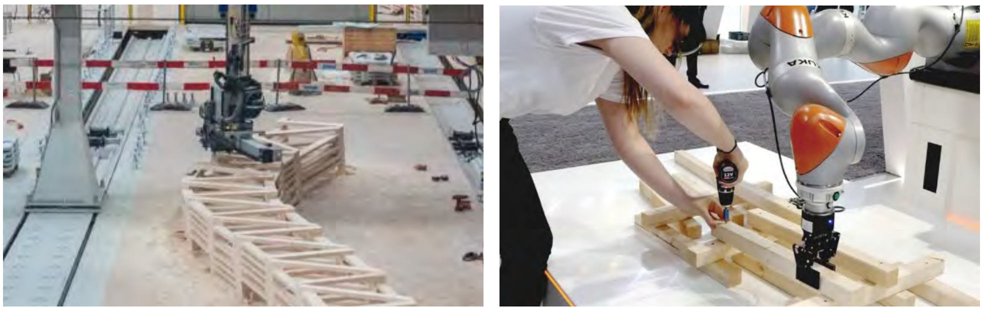

Figure 5.5: Left: The Sequential Roof, Digital assembly of the complex roof structure at ERNE AG Holzbau (Gramazio Kohler Research, ETH Zurich, 2010-2016 © Gramazio Kohler Research, ETH Zurich. Foto: Aleksandra Apolinarska). Right: Manufacturing process of the Collaborative Robotic Workbench (Image by ICD University of Stuttgart).

Other additive manufacturing processes that include fabrication steps such as picking, placing, and fixing have been investigated by many research groups in recent years. Researchers at the RWTH Aachen University explored the robotic trimming and assembly of a space frame structure [77]. Researchers at the ICD of the University of Stuttgart investigated the robotic assembly of a frame structure with a collaborative robot [206], as well as the assembly of a slat-based timber frame structure. The latter is the subject of a case study in this thesis. Both projects required collaboration with human labor to fix elements that were placed by the robot. Most recently, the investigation into robotic assembly processes has also involved automated on-site robotics [145].

Researchers at the EPFL Lausanne and ETH Zurich have investigated robotically assisted assembly processes for timber structures with integrated mechanical joints, combining subtractive and additive processes [300; 306].

Some of the research shown regarding elasticity in section 5.1.3 also involves industrial robots for assembly processes. Here, the categorization is not entirely clear. For example, employing industrial robots for steam bending wooden beams [328] or bending glue-laminated beams [8] can be considered an assembly process, albeit for single building elements that will require another assembly step in a subsequent process.

The research mentioned above shows that the potential of a manufacturing process for timber construction systems lies in the combination and consideration of multiple steps, each tailored to the material, building element, and machine that enables its materialization. The information required to process each building element becomes part of an automated data flow within the computational design data flow, and as such, the data flow becomes part of the development process.

5.3 Segmented timber shell structures: convergence of technological advancements

A focus of the research presented in this thesis, and part of an ongoing effort of the research group at the ICD and ITKE at the University of Stuttgart, is the development of segmented timber shell structures. This research field can be characterized by a convergence of architectural design research with material-oriented and manufacturing-aware design.

5.3.1 Structural and constructional background

The structural typology of thin and continuous shells, such as vaults and domes, was explored in architecture and engineering throughout history by using stone and later concrete [37; 198; 278; 301]. Their structural efficiency and elegant design are due to their curved or double-curved forms that result primarily in in-plane forces and minimize bending moments, thereby reducing the required thickness of the shell [14; 107]. However, the construction of shells has always been their most challenging aspect. For many reinforced concrete shells that were designed and constructed in the twentieth century by architects and engineers such as Heinz Isler, Félix Candela, and Pier Luigi Nervi, their formwork during construction was costly and time-consuming [60].

For other building materials, achieving a curved and continuous shell surface is equally challenging. Timber products are traditionally available in a straight or planar shape of limited size. Limitations for transportation further influence the size of segments that can be assembled into a shell [332]. Therefore, two main concerns must be addressed in segmented shells. First, the planarity of individual segments requires a geometric approximation of the smoothly curved shell surface that follows material and manufacturing constraints as well as design intent [330; 331]. Second, the joints between the segments need to be resolved so that forces can be effectively transferred without disproportionally disturbing the material continuity [30; 218]. For these reasons, the geometric segmentation, manufacturing, jointing, and assembly all play an essential role in the development of segmented timber plate structures. Advances in computational design and digital fabrication have shown a particular potential to solve these challenges.

When compared to folded structures such as origami patterns, or triangulated lattice structures, the advantage of plate structures lies in their topological rule of no more than three segments meeting at any one point [14; 253]. In graph theory, a vertex that connects to three edges has a valency, or degree, of three. As a result, in-plane forces are transferred through the segments and along the segments' edges, making the vertices of the structure irrelevant [393]. This leads to an emphasis on the segments' material cross-section, which is structurally more comparable to continuous shell structures than the focus on joints in lattice or folded structures [14; 207]. Consequently, the joining detail can be significantly reduced because of the lack of bending moments.

Until recently, the disadvantages in the manufacturing and construction complexity of segmented shells outweighed their structural advantages and architectural opportunities. However, advances in computational design and digital manufacturing technology have led to two distinct developments that played an essential role in the emergence of segmented timber shell structures. First, computational design methods for an integrated, manufacturing-aware design, the segmentation of double-curved surfaces, and the differentiation of segments within a shell [331]. Second, digital manufacturing technologies that enabled the development and fabrication of integral mechanical joints in combination with integrated fasteners to achieve a high connection stiffness even in complex geometrical situations [30; 193; 218; 296]. Structurally, integral mechanical joints are most suitable for plate connections as the interlocking material can transfer forces most effectively [219].

5.3.2 Biological background

Many variations of plate shell structures that clearly exhibit the three-valency of their segments can be found in nature [207; 394]. Here, the non-continuous surface of hard tissue allows growth and adaptation within each segment but also results in losses of structural performance [93; 218]. Therefore, natural systems evolved to balance these opposing requirements.

The sand dollar species, of the taxonomic class of sea urchins (*Echinoidea*), is notable for its morphologically pronounced skeletal plate structure, exhibiting the morphological principles most clearly [190; 218;

335]. The skeleton shell of the sand dollar, also called the “test”, can be described as a modular, polygonal plate system. The plates are composed of calcium carbonate and covered by a thin dermis and epidermis [26; 190]. Each plate is joined by microscopic, interlocking calcite protrusions that allow an integral mechanical connection to adjacent plates. In addition, the sand dollar has mineralized internal tethering underneath the plates, called secondary growth [335], and many other morphological features that lead to high structural performance while allowing flexibility in the joints during growth, such as a shallow double-curved surface, apertures, and column-like connections between the top and bottom shell [219].

Because of these morphological features, the sand dollar has been analyzed for the transfer of structural and constructional principles in plate structures in many research projects led by biologists, engineers, and architects [30; 139; 140; 190; 219; 329; 334]. Macroscopic principles such as the segmentation of shell structures, topological organization of plates, or the transition to morphological features such as columns, as well as microscopic principles such as the finger-jointed connection between plates, have been investigated for their structural performance and architectural potentials [30; 195; 219]. Most importantly, they have proven to be in line with possibilities in computational design and digital timber manufacturing for segmented shell structures [192; 195; 298; 299].

5.3.3 Fabrication and construction methods

With the invention of CNC machines for wood processing in the late twentieth century, integral CNC-fabricated joints have become more commonly used. Especially in modern timber frame constructions, integral mechanical joints allow linear members to be more effectively connected [296; 320], making the revival of traditional joints not a purely aesthetic phenomenon. In the last decades, variations of integral mechanical joints emerged that were the result of a renegotiation between the material, computational design methods, and manufacturing technology. The opportunity to control a large amount of information for the manufacturing of joint geometries, and to develop manufacturing methods that allow this kind of variation, led to innovative applications in the emerging field of segmented timber shells.

A variety of new manufacturing approaches have resulted in different materializations of their structural principles. Notable variations that emerged in recent years are double-layered, box-beam, or other modular construction methods [191; 299; 378], single-plate construction methods made from plywood panels with integral mechanical joints [302; 331], or from large-scale CLT plates with screwed connections [198], as well as more complex construction methods based on modular, hollow and glued cassettes [11; 198]. On a higher level, variations can also be characterized by their level of prefabrication, grouping the research projects in either single plates that get assembled on-site [331], or modular construction where multiple elements get connected before being transported to the site [386]. A general tendency can be observed towards adaptive manufacturing platforms [387] that can be applied to a variety of components and result in composite segmented shells or even slab systems for multi-storey construction [259]. All these research projects have in common that they rely on integrative computational design systems and manufacturing systems with multiple steps, which were developed in reciprocal relationships.

Four case studies in this thesis explored different design and fabrication approaches for segmented timber shell structures. The relation between the development process, the manufacturing, and the design will be explained in more depth as part of the case studies in Chapter 7.

5.3 Segmented timber shell structures: convergence of technological advancements

6

Methods

To answer the research questions described in Chapter 1, different methods in computational design, manufacturing development, and architectural design research are required. This chapter describes and categorizes the methods used in the case studies and the research projects they document.

The first hypothesis states that gradient building systems are the result of an integrative development process in manufacturing and computational design, which further enables the collapse of interdisciplinary boundaries in the development process. To investigate this hypothesis, methods for the development of both manufacturing systems and computational design systems need to be introduced, as well as methods to analyze the integrative nature of such development processes.

The second hypothesis states that the integrative development of gradient building systems requires specific computational design processes that generate, process, visualize, and store a much higher density of geometric and functional information than what is typically seen in traditional design and delivery processes in the AEC industry. To investigate this hypothesis, different computational design methods are necessary, as well as the analysis of the development, design, and manufacturing process of the case studies.

The third hypothesis states that methods from biology used to measure and compare morphological differentiation can be translated into architectural design research to systematically analyze the relationship between manufacturing setups and their impact on the geometrical and functional parameter space of gradient building systems that are being manufactured. To investigate this hypothesis, computational design methods need to be introduced that can analyze and visualize this relationship, ultimately leading to the method of “machinic morphospaces”. The author notes that the higher-level goal of this quantification is to achieve measurable feedback between, and argue for the necessity of, the reciprocal relationship between manufacturing development and design development.

The methods for evaluating each case study can therefore be categorized as follows. In combination, they are utilized to analyze and describe the overarching steps that form a feedback loop in the development process:

(1) Methods for an integrative development process of a gradient building system and the analysis of such development processes.
(2) Methods for the development of manufacturing systems in relation to the development of a building system.
(3) Methods for the development of computational design systems for the exploration of the design space that emerges through (1) and (2).
(4) Methods for analyzing the relationship between the design space and the manufacturing setup for the gradient building system.

While (4) can be seen as part of (3) since both methods mainly employ computational toolsets, (4) is explicitly mentioned as a separate category because it results from the two preceding methods, and it emphasizes the importance of forming a quantifiable and reciprocal relationship between manufacturing innovation and design innovation.

The four categories of methods also form the general structure of each case study. In the following five sections, these methods are further described in detail.

In this thesis, the term “design space” describes the range of possible geometric and functional articulations of a building element and its aggregation into a building system. The term “machine setup” describes the kinematic and functional characteristics of one or multiple machines that manipulate building elements during the manufacturing process.

6.1 Reciprocal manufacturing and design innovation

Each of the research projects presented as case studies in this thesis aimed to develop gradient building systems through combined innovation in computational design and manufacturing technology in timber construction. The case studies explain this parallel and reciprocal development process in detail and analyze key elements of the interdisciplinary nature of it.

6.1.1 Integrative development processes

The research projects followed an integrative development process, which is a development process that integrates multiple disciplines in parallel and enforces a constant, iterative feedback loop from the onset of a project. Manufacturing technology, material research, construction detailing, and design intent are all part of the development process and are either represented by a single researcher or by a research team working on the project together. The constant exchange of ideas and feedback leads to a multi-disciplinary decision process that is guided by experience in each field and identifies open questions that can be explored through digital or physical prototyping. At the same time, the integrative development process is bottom-up and explorative.

In the field of architectural design research, this development process is often referred to as “integrative design” [330], and computational design methods resulting from this process as “integrative design computation” [232; 241]. Menges describes the term as integrating material characteristics, fabrication, behavior, and performance within a computational process [241]. Comparing this development process to methods in software development, it can be described as a multi-disciplinary and bottom-up variant of the “spiral model”, which was first introduced by Barry Boehm [42] as a risk-driven software development process model [258]. In the spiral model, the four main activities are (1) identify, (2) design, (3) construct, and (4) evaluate and plan the next iteration [42; 283].

For its application in this context, the spiral model has been adapted in two ways. First, instead of determining macro-scale architectural objectives upfront, the development process is bottom-up and objectives are only defined regarding either micro-scale construction details, material usage, or (new) principles of manufacturing. This leaves the applicability in architectural design to be determined by the result of the development process. These objectives can also be called the investigative motivation of a project, as described in the next section. However, a top-down design is introduced once the development process moves into the macro scale and its applicability in architectural design can be explored. Second, the spiral model is applied not only for software development but also for the development of the building system, which requires the reciprocal combination of the fields of materials science, structural engineering, manufacturing technology, and computational design, among others. Through several iterations (spirals) of the above-mentioned activities in the above-mentioned fields of research in parallel, reciprocal feedback between those fields is provided many times throughout the development process.

Figure 6.1 visualizes a typical integrative development process of a typical building system. Here, the reciprocal development of the building system, manufacturing system, and computational design system is shown as three horizontal and parallel yet interconnected processes. Each vertical column represents a scale and a process step of significance. By dividing all three systems into scales and steps, it can be visualized at which point in the resulting manufacturing system the investigative motivation started.

In this exemplary diagram, the starting point and investigative motivation of a speculative development process is on the meso-scale of a single fabrication step. From here on, the development process branches out to both the building system and the computational design system (dark gray arrows). Within each scale or step of the process, development spirals and feedback loops are formed. Depending on the case study, more or fewer steps are possible in each development process. Once complete, however, the design tool forms the starting point for the design process of a demonstrator building (red arrows). This also shows how the design process inverts the development process while still making use of its interconnected workflow and data flow.

This diagram will be used in each case study to visualize the starting point of the development process, as well as the location of manufacturing innovation within the overall manufacturing system.

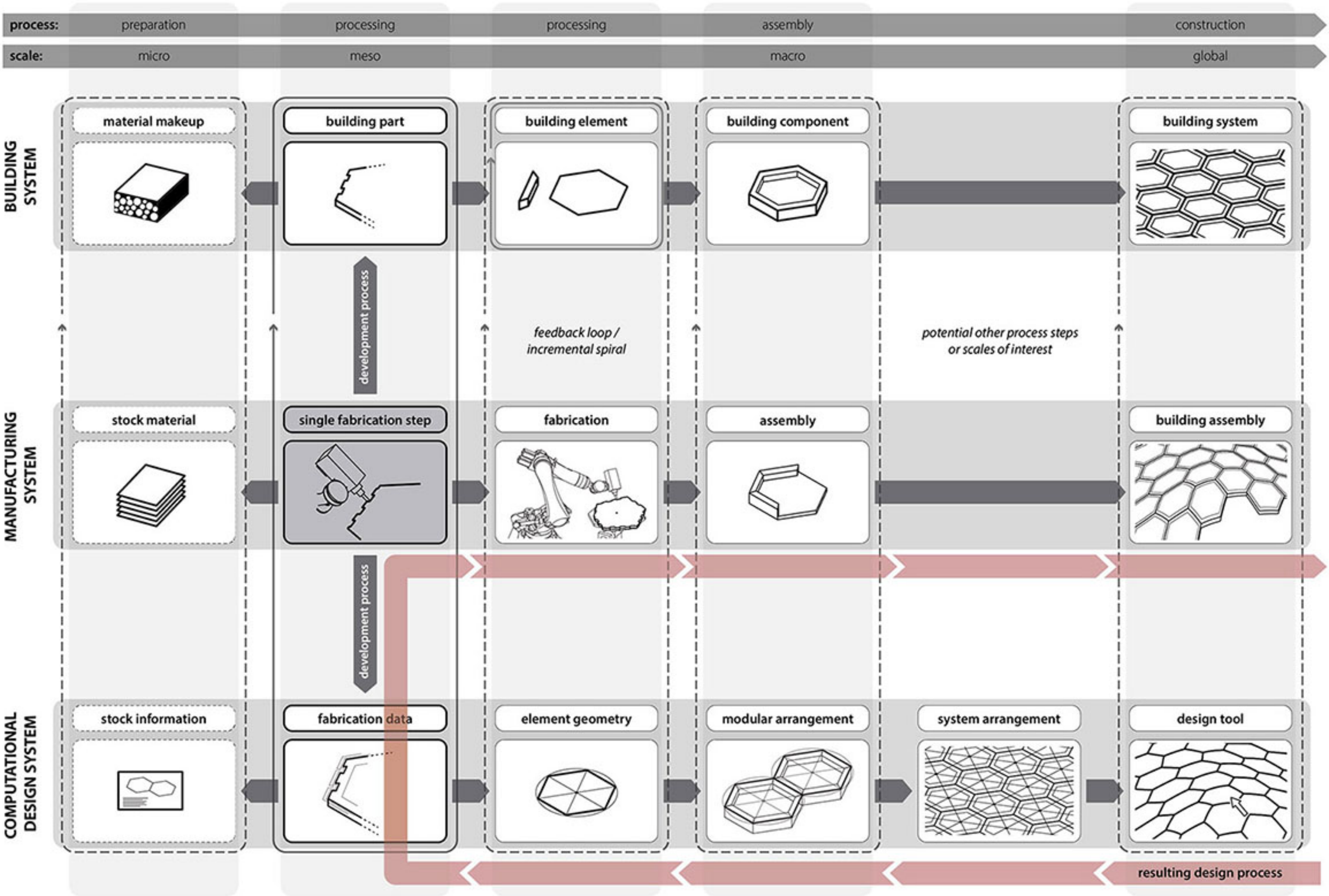

Figure 6.1: Methods for integrative, reciprocal, and parallel development in manufacturing and design. From left to right, the scale of the system increases. The number of columns occupied by each system depends on the number of steps required in the design or manufacturing system. The development process is shown with dark gray arrows, and the resulting design process of the demonstrator building is shown with a red arrow.

Iterative prototyping and testing are the most important characteristics of this form of development process. Because of its bottom-up and open-ended nature, iterative physical and digital prototyping are used to inform the development process until a level of refinement is met that allows the building system to be applied at a large scale, such as in a demonstrator building.

In many case studies, this integrative development process is also applied incrementally. In software development, the "incremental build model" is a method where features and functions of a product are implemented and tested incrementally [282]. A variation and extension of this method is used in the case studies when certain aspects of a building system are implemented or added at later points of the development process. Each incremental development cycle can be considered one spiral of the spiral model.

Both the spiral model and the incremental build model, in their variants applied in the case studies, are methods used to work with the unpredictable nature of bottom-up and multi-disciplinary architectural design research. This allows the development team to react to new findings or implement new ideas that were not originally considered. Within a development process, one turn of the spiral model can take anywhere between a few hours and a few weeks.

While the research aim of all case studies is to develop a gradient building system, the nature of the development process is that of bottom-up architectural design research. Fundamental ideas of construction, material or manufacturing innovation are investigated for their impact on architectural design. Here, architectural design research refers to possibilities and constraints of the design process but also of the tectonics and construction of a design system.

The following sections will appear in every case study, describing the investigative motivation and the development process of the manufacturing system and the computational design system for the specific research project of the case study.

6.1.2 Investigative motivation

In the first part of each case study, the investigative motivation that initiated the research project related to the case study is discussed. The starting point of the research presented in each case study relates to parts or combinations of the context presented in this thesis with the goal of developing a gradient building system that employs wood as the main structural material, robotic fabrication as the main manufacturing method, and computational design tools as the main design generation and data management method.

Topics of investigative motivation can be described as one of four different categories, each relating to a different aspect of innovation within the development process of gradient building systems. In the case studies, one or more of these four topics have been identified as the starting point of the development process.

(1) Material characteristics: Innovation related to the characteristics of wood or timber products, such as the elasticity or hygroscopicity of the material. The motivation primarily stems from the understanding that wood's inherent material characteristics have usually been ignored or actively suppressed. The goal of research projects with investigations into material characteristics is to uncover their advantage in the design, manufacturing, or construction of a resulting building system, and to reconceptualize wood as a heterogenous, flexible, and reactive material—one that requires careful computational analysis and integration of material behavior into the computational design system.

(2) Integrated joinery: Innovation related to geometrically complex joinery between timber elements that is derived from traditional wood connections and does not require additional fasteners to achieve a force and form fit connection. As manufacturing technology advances, these types of traditional connections can re-emerge in gradient building systems as structurally performative and architecturally functional joints between building elements. Even further, they can indicate and guide building element orientation, and as such, incorporate assembly information.

(3) Transfer of biomimetic principles: Innovation related to the transfer of biomimetic principles for the development of gradient building systems. While the concept of gradient building systems is in itself a biomimetic principle, many projects presented in this thesis start with an investigative motivation in biomimetics as a bottom-up process. This can include—but is not limited to—structural principles, material distribution principles, or principles of growth, which can be translated into design or fabrication methods. While some projects were started solely from biomimetic principles, other projects used biomimetics as a filter to determine or clarify certain structural concepts during the development process.

(4) Assembly information and agency: Innovation related to the location of information for the execution of assembly processes during the manufacturing and construction process. Here, “agency” refers to where the assembly information is stored and in which direction the information will flow. Due to a combination of material characteristics, joint geometries, and computationally controlled machines such as industrial robots, the information about assembly processes can be stored either within the machine code or the geometry of the building element, and either inform the machine executing the assembly, or the human collaborating in the assembly. An important aspect of this investigative motivation category is the negotiation between where the information is stored and whether the information is translated and transferred toward a human collaborator or only processed within a machine.

More details on how these topics were applied and in which context they were developed will be discussed in a project-specific manner in each case study in Chapter 7.

The investigative motivation always relates to architectural design and functionality. All research projects presented in this thesis originate from the desire to investigate architectural design potential through inventions in the fields of materials science, manufacturing technology, and computational design. The formulation of, and gradation between, tectonic elements in architecture, such as roofs, walls, columns, or openings, are investigated as a result of the development process, but also as a driver of it. While some research projects were structured specifically bottom-up with a subsequent architectural design investigation within the developed building system’s design space, other research projects exhibit a mix of bottom-up development and top-down architectural motivation since they were meant to result in a specific architectural demonstrator. This relationship between the development of a building system and the resulting design space will be discussed in a project-specific manner in each case study, as well.

6.1.3 Development process analysis

In each case study's result sections, the development process is analyzed in relation to knowledge creation and transfer. By explaining the development steps and their inter-connectivity, the author identifies points within the development process that were crucial for the success of the project and for innovation to take place. More specifically, the author analyzes where innovation started and how it was translated through reciprocal feedback into a gradient building system, using the development process analysis described in Figure 6.1 above.

This section also picks up on state-of-the-art innovation research in the AEC industry. In each case study, the individual researchers and research fields involved are analyzed, as well as the intersection with industry application, if applicable. In the last two case studies, it is recognized that the translation of this type of research into industry application requires a rethinking of collaboration methods, knowledge exchange, and interfaces between the involved parties.

6.2 Development of manufacturing systems

The case studies presented in this thesis are mainly driven by innovation in manufacturing technology. The development process is in close reciprocal relationship to that of computational design systems, and together, both enable and lead to the development of gradient building systems.

6.2.1 Manufacturing systems

In the case studies, the development process of a manufacturing system in relation to the investigative motivation is described in detail. Here, "system" refers to the entirety of the manufacturing process from raw material to finished building element. As a set of parametrically defined procedures according to which building elements or components are manufactured, the technology developed in the case study can be described as a system with internal and external connections or interfaces. Internally, the system requires hand-off points between different fabrication processes or between different entities involved in the process, such as humans and machines. Externally, the system requires hand-off points between the digital data flow and the physical manufacturing process, or between the finished product and the assembly on site. Additionally, several physical and digital parameters of the system influence its capabilities and constraints, and therefore describe design possibilities. The relationship between some of those parameters and their influence on the manufacturing system, and therefore the building system's design space, will be discussed in section 6.4.

6.2.2 Manufacturing methods

During the development of the manufacturing system, two types of manufacturing methods are typically investigated: Subtractive methods and additive methods. Subtractive methods describe machining and cutting material into a dimensionally accurate shape or adding geometrical features to it. Additive methods describe picking, placing, and joining multiple building elements into an assembly or building component. In the case studies, and in timber construction in general, joining can be achieved mechanically or chemically.

6.2.3 Development methods

In this thesis, two methods of manufacturing development can be identified, with many case studies employing a combination of both. In one method, manufacturing development is at the core of the investigative motivation, and new manufacturing technologies are investigated as drivers for the development of a gradient building system. This open-ended, bottom-up development process usually combines new technologies or re-evaluates existing technologies in a new context, without a specific goal of functionality in mind. In a second method, manufacturing processes are developed to accommodate or enable the investigative motivation. In this second method, the manufacturing development process is top-down and goal-oriented, usually because the technology is already known but has not been applied to the specific context yet.

The manufacturing development process is iterative and loosely follows the spiral model introduced above, while integrating into the larger development process of the building system and computational design system. Starting with theoretical discussions and digital prototyping, the development process moves into the physical realm through several iterations, often adding more features or details along the way. With every iteration, feedback from the other development processes is integrated to determine its feasibility. To judge the development process's success, criteria such as speed or tact time, number of required tools, ease of automation or parametrization, and/or number of special cases in programming the automation, are applied.

Physical and digital prototyping are essential for this process. While the digital tool set is explained in the next section, physical prototyping is generally related to the equipment available to the research group. It involves industrial robots of different sizes and articulations, as well as other numerically controlled machines and hand-held equipment for human labor and human-robot collaboration. A prototype is usually built or generated based on objectives and evaluated to confirm the assumptions and to continue the development process in an informed manner.

In each case study, every step in the manufacturing system is analyzed and related to the machine setup, with the goal of establishing a qualitative and quantitative relationship between the machine setup and the design space.

6.3 Development of computational design systems

Each case study will analyze how the computational design workflow was set up for its relative research project. The computational tool set is used to reflect on and provide feedback for the general development process while the tools themselves are under development. At the end of each case study, the flow of information within the computational design system is discussed.

This section describes methods that were used in the development of the computational design system, but also methods of computational design that are part of the resulting tool set of most case studies. Generally, two main computational tool sets can be described: those related to the generation and exploration of the design space, and those related to the simulation and exploration of the manufacturing setup. Separately, the method for establishing the machinic morphospace as a tool to relate the machine setup and the design space is discussed in the next section.

6.3.1 Design systems and computational design systems

In order to explore the underlying methods used in the case studies, it is important to distinguish between a “computational design system” and a “design system”.

In the case studies, the development process and the resulting computational design system are described. Here, “computational design system” refers to the entire, parametric, data flow from early design exploration to manufacturing simulation and the generation of manufacturing instructions. As a set of computationally defined procedures according to which the design is generated, the technology developed in each case study can be described as a system with internal and external connections or interfaces.

The term “design system” refers to a set of rules according to which a design can be generated. The rules of a design system can originate in constraints of material, structure, manufacturing, or construction. Therefore, the design system is also part of the development process in the case studies. During the development, the computational design system integrates the rules of the design system and allows for a certain degree of design automation while also providing enough user interactivity to explore the resulting design space. Different computational methods can be used for this, as described in the next section.

6.3.2 Computational methods for design systems

In the research projects, computational methods were developed that allow the most interactivity and design freedom while ensuring that the design system’s boundaries are not surpassed. User control, interactivity, and direct feedback were crucial in the development and usage of computational design methods for this purpose.

This thesis does not aim to give an overview of all computational design methods available, but rather to summarize those that have been used predominantly during the development and design of the case studies, for the understanding of the overall process, and how the case studies ultimately enable the feedback between the machine setup and the design space. In all research projects, primarily two computational methods were used as the foundation of the computational design system: physical simulation or dynamic relaxation, and agent-based modeling. Both methods allow for the automation of form generation while adhering to user input. As the focus of this thesis is not on computational methods, they will only be briefly summarized.

6.3.2.1 Relaxation and form-finding for discrete networks

Generally, relaxation methods are mathematical, iterative methods for solving systems of equations [260]. Form-finding refers to the method of finding an optimal shape that is close to or in a state of equilibrium [211; 377]. In computational design, physical relaxation is commonly used to form-find complex geometric configurations based on a global rule set that mimics physical properties and laws of nature [212]. Coenders & Bosia go as far as to say that the method is about “finding an appropriate architectural and structural shape” [63]. In the past, form-finding methods have most prominently been used in the simulation of tensile structures, meshes or pneus [7; 149; 154; 215; 377]. In all cases, the material is being discretized so that small interconnected units represent the continuum of a building system, such as representing a textile through a line mesh [212]. Form-finding software such as Daniel Piker’s Kangaroo [277] uses the dynamic relaxation method. In dynamic relaxation, it is assumed that each node in a discretized system contains a portion of the mass, and forces acting on the system will be solved iteratively in each note until all out-of-balance forces are relaxed [212; 377].

Dynamic relaxation can also be used in a more abstract way in order to generate smooth surfaces or mesh networks following user-defined forces. This method has been developed and used in architectural and structural projects since the late 1970s [24; 25; 173]. In the case studies in this thesis, dynamic relaxation is often used for a mesh or other mesh-like surface to follow a design intent while distributing its nodes in an even or smooth manner. The design intent can be controlled through point-like or surface-like attractors, external forces simulating gravity or pressure, or internal forces widening or shrinking the mesh. Usually, a node in the system represents the location of a building element, thereby hardwiring the number and topology of the arrangement of building elements. While these methods have been originally used to explore the design space, applying forces on the system during the relaxation process can also be used to negotiate between structural requirements and architectural intent.

6.3.2.2 Agent-based modeling

The research projects in case studies 5 and 6 employed agent-based modeling strategies as part of the computational design tool set. Agent-based modeling (ABM) describes a system consisting of lower-level elements, or agents, that exhibit a simple set of behaviors, which, in interaction with each other and their environment, generate higher-level orders [95; 124; 312]. This provides a framework for emergent behavior on a higher level without having to understand higher-level rules of a complex system [16]. ABM can be seen as a form of artificial intelligence [47] and can often exhibit emergent behaviors or patterns [18]. In the application of the case studies, it is the expectation that ABM can solve complex, multi-variable problems through interacting agents with their local set of rules. Ehsan Baharlou further explains that interactions among agents need to be based on explicit behaviors each individual agent is exhibiting while being situated within an environment [16]. These behaviors can be fixed rule sets applied to all agents within an environment or adaptive behaviors that can change when confronted with new information [53].

In the case studies presented in this thesis, agents represent building elements with their design parameter sets as well as rules that govern their behaviors in a given environment. Here, the environment is usually a given design area or surface on which agents can move and interact with each other. Behaviors generally govern the agents' movements depending on certain geometric aspects such as closeness to each other, to the design surface's boundaries, or other attractors. The advantage of employing ABM in these case studies is that complex, emergent patterns through the aggregation of many building elements can be achieved through relatively simple behaviors each building element is following. ABM has previously been identified as a method to integrate fabrication constraints as well as design intent [16; 331].

6.3.2.3 System boundaries and exploration

The above methods are often used to allow for dynamic and interactive design exploration. However, in the case studies, they are only underlying methods for the computational design system as they are used to generate a specific aggregation of building elements in the building system. In a combination of design process and geometric representation, the geometrical information of the building elements is either encoded or added onto these modeling methods. By implementing the geometric representation of building elements, information of the actual design space of the building system becomes possible. In other words, the addition of geometric constraints to the building system that relate to manufacturing, material, or constructional constraints will inform the boundaries of the computational design system and allow the designer to work within them.

It also works the other way around: by engaging with the computational design tool, the design space is explored, which can lead to the discovery of invalid areas that have not yet been constrained. This back-and-forth feedback is an important aspect in the development of the computational design tool and the exploration of the design space while the manufacturing and building systems are still being developed.

Therefore, the computational design system has a much larger design space at the early stages of development, much of which is geometrically invalid or not producible. This is due to both a lack of implementation and as well as the fact that the building system is still in development and its boundaries are unknown. With further sophistication comes a closer approximation of the real boundaries of the design system, but the parallel exploration of it also helps define which areas are especially relevant. It can therefore often result in the need for certain manufacturing constraints to be revisited due to the importance of a certain region in the design space. This development process therefore requires a constant feedback loop.

An intuitive tool allows for the exploration of the design space and lets the user find its boundaries quickly. This goal can be achieved with a live 3D simulation of the system, which is an intuitive and quick method for designing with the system, and generally direct visual feedback. Simulation, user interactivity, and visual feedback are design methods that are implemented in the computational design systems and adapted for the specific development process and building system of most case studies. When they are important to the feedback loop from the manufacturing development they will be discussed in more detail.

6.3.2.4 Iterative and incremental software development methods

The development process of the computational design system can be considered a sub-process of the overall integrative development process. As such, similarities to traditional software development methods are even more prevalent.

The computational design system's development process can best be described by the iterative and incremental development method. This method is a combination of iterative design and incremental build models and has been in use since the late 1950s [208]. It provides particular benefits for inter-organizational development processes, as it allows for multiple iterations, or development cycles, that can even happen in parallel [80; 267]. By allowing for multiple cycles, feedback and newly gained knowledge from other fields can be integrated. By incrementally adding more functionality, the algorithm can become more sophisticated over time while the development can focus on the most crucial functionality in the beginning.

In the case studies, usually only the core function of the computational design system is planned out in the beginning. While it is being developed iteratively—revisiting the functionality and adapting it based on experimental results and developments in the building and manufacturing systems—it is also developed incrementally by adding more functions as it progresses.

For the development of computational design tools, visual programming is used as well as small scripts in Python or C#. Programming of any kind was done within McNeel's Rhinoceros and Grasshopper [303] environment. Robot code was generated according to KUKA's KRL language [201].

6.3.3 Robot and manufacturing simulation

The parallel development of manufacturing technology and computational design systems requires a thorough understanding of the manufacturing system's possibilities and constraints. This includes the work envelope of every machine involved in the manufacturing process, overlaid by their relative position to each other, additional tools, and the end-of-arm tooling (EOAT, or end effectors) attached to them.

The case studies will mainly focus on the use of articulated robots, also called "industrial robots", with six joints and six degrees of freedom. The majority of modern industrial robots are serial robots with a chain of three revolute joints, called the "arm", and a spherical wrist attached the end of the arm [261]. Robots are also referred to as "manipulators." Understanding the robot motion in its surroundings is an important aspect of the development process, and later, the manufacturing process. Simulation of robot motion serves to understand the constraints of the manufacturing system, and how it influences the design space of the building system. In computational design and architectural design research, the pre-simulation of robot motion toward a given Cartesian position is a critical element for confirming if a design is producible [376]

6.3.3.1 Robot simulation components

Industrial robot manufacturers have traditionally supplied programmers with their proprietary robot simulation software. For example, KUKA has developed KUKA.Sim [202], and ABB has developed RobotStudio [1]. Although these software packages are versatile and precise when simulating robot movements, they are difficult to connect with a computational design workflow as they require an offline file transfer and are unable to send motion data back into the computational design system without considerable custom programming efforts. These software packages are rather for late-stage manufacturing simulation when the manufacturing system is already developed and fully defined.

To connect manufacturing simulation more closely with computational design processes, independent developers have released third-party plugins for McNeel Rhinoceros or stand-alone software that can simulate robot motion. Although the exact kinematic interpolation by the robot suppliers is usually not publicly accessible, these tools are precise enough for most simulation requirements and can also be integrated into a computational design environment. Commonly used plugins are KUKA|prc [13], HAL [141], and Scorpion [91], for example. Common stand-alone software or programming libraries include Robots.IO [304] and COMPAS Framework [130].

For the projects presented in the case studies, a custom robotics simulation tool was used, which was developed within the ICD for use in McNeel Rhinoceros and Grasshopper. Due to the specific robot types, the unique EOAT, and special configurations of multiple robots or additional axes, it was easier for the research team to develop a custom plugin during many of the research projects. To define a robot within this plugin, a 3D model of its individual components as well as all axis locations and values was required. The plugin was then able to simulate each robot's position based on a standard forward and inverse kinematics calculation.

Forward kinematics is the process of calculating the position and orientation of the tool-tip, also called tool center point (TCP), when all values of the robot's linkages and axes are known [200; 270; 403]. Inverse kinematics is the process of calculating the solution(s) of all joint positions and angles within the kinematic chain of a robot for a given position and orientation of the TCP [9]. The need for inverse kinematics occurs most of the time in manufacturing development since the position, orientation, and motion of the TCP is given [200; 275; 403]. Typical industrial robots like the ones used in the case study are six-axis spherical wrist articulated robots. Their inverse kinematics solutions can be calculated analytically or numerically [200].

As part of the inverse kinematics calculations, the TCP is represented by a three-dimensional frame. To achieve continuous and smooth movement between frames, the simulation interpolates between each frame given by the manufacturing instructions. Because of the added complexity of the physical implications for moving a robot arm, the interpolation algorithms that are part of the robot's internal controls are not known, and the simulation uses linear interpolation between frames only to approximate the motion. Without access to the robot's internal control algorithms or using the robot manufacturer's specific simulation software, this approximation of movement is usually considered enough to simulate and analyze the robots' movements quickly and effectively.

When necessary for visualization and analysis of the manufacturing system development, the material that is manipulated by the robot is simulated as well. While the motion of the robot is usually considered the "master" list of frames to be simulated, the materials or building elements follow the robot's motion only for a specified sequence. For example, the material is stationary until the robot picks it up and moves it to its final position where it is fixed. Between picking and placing the material, it computationally follows the robot's motion.

In robotic configurations that have more than 6 kinematic axes, or in configurations where only 5 degrees of freedom are required (such as in CNC milling) the system becomes kinematically redundant, and an infinite number of solutions are available. This is called a “robot singularity”. For example, in milling, the rotation of the wrist around the CNC spindle’s axis does not result in different milling outcomes. In another example, the robot might travel on a linear track, increasing the number of degrees of freedom. In these cases, user controls are needed during the simulation to determine a solution or to implement an algorithm that decides on a preferred logic. Taking the example of the linear track, in some case studies an algorithm was developed that would control where the base of the robot would be best positioned on the track for the TCP to reach the target frame.

6.3.3.2 Robot simulation analysis

Robotic manufacturing and kinematic simulation are mostly defined by their constraints. Discontinuous axes, work envelope boundaries, and collision detection are typical constraints when developing a manufacturing system. Implementing or testing against these constraints can be considered a method for the development process.

Discontinuous axes, as described above, need to be implemented in the inverse kinematics calculation and the post-processing and file generation. Work envelope boundaries are an essential part of the machinic morphospace analysis discussed in section 6.4. In early stages of the development process, the boundaries are usually discovered through experimentation either in the digital or real-world environment. Lastly, collision detection can be part of the simulation algorithm but is computationally very expensive. Because of the experimental nature of the manufacturing process, collision is usually detected manually by simulating and observing the entire process before execution.

6.3.3.3 Post-processing and file transfer

Many industrial robots have axes with limited rotation and can therefore not rotate in the same direction infinitely. For example, the base of an industrial robot can usually only rotate between -180 and +180 degrees. In most spherical wrist robots, such as the ones used in the case studies, the two opposing axes around the wrist (axis 4 and 6) can rotate infinitely if they are not constrained by cables. This means that these limitations will have to be implemented in the kinematic solver as well as the post-processing of the values to generate a robot control file. In the development of the simulation, it is assumed that the robot's internal control algorithm will rotate the wrist axes only between -180 and +180 degrees, thereby only ever turning the wrist in one direction.

The post-processor translates a list of target frames for the TCP in the computational design process into vectors and position values in the format of the robot control language. It also includes custom inputs for triggering digital input and output values to control EOATs, such as opening and closing a gripper. In all research projects presented in the case studies, KUKA industrial robots and the "KUKA robot language" (KRL) was used.

In all research projects, offline programming was used to transfer the robot control files onto the robot system and execute them. Using a shared network location, the post-processor saves each continuous manufacturing process as a single file that can be executed by the robot operator. Although this is a disconnected and slow process, it has the advantage that manufacturing files can be prepared in advance and loaded into the robot system when needed [376].

6.3.4 Feedback loops

Although the development processes of the computational design system and manufacturing system are explained and analyzed in a linear fashion in the case studies, it is important to understand that they were executed in parallel and usually with multiple researchers or students involved at the same time.

The robot simulation is usually developed at the same time as the computational design system. In some case studies, the manufacturing technology and the simulation of the manufacturing process is the main investigative motivation and therefore developed earlier than the computational design system during the research project.

In many research projects, the feedback between the machine setup's work envelope and the building system's design space was only implemented in an iterative way, with a number of tests for boundary conditions usually satisfying the research team's need to understand the limitations of the system. However, direct, and computationally driven feedback between the machine setup's work envelope and the design system was not fully developed. To quantify and analyze the relationship between the machine setup and the design system, the machinic morphospace will be evaluated in all case studies.

6.4 Evaluation of the machinic morphospace

In order to understand the potential of new manufacturing technology for the development of gradient building systems in timber construction, a numerical and analytical method is presented to form a reciprocal relationship between two parameter spaces: that of the machine setup and that of the building element. Both the machine setup and the building element are part of an integrative development process, meaning that the design space of the building system heavily relies on the capabilities of the manufacturing system, while the development of the manufacturing system informs the building system at the same time. This section will clarify how these parameter spaces are defined and compared at the end of each case study.

The analysis and relation of parameter spaces takes place on the level of the building element or the building component, depending on which is directly manipulated by the aspect of the manufacturing system that is being investigated. In the examples herein, the building element's parameter space is directly related to the *design space* of the building system, which is made from an aggregation of gradated building elements. Therefore, the building element can be considered to represent a "local design space" whereas the building system has a "global design space" as a result of the accumulation of all design spaces of all types of building elements or components. Further, not all parameters of the manufacturing system directly or indirectly influence the design space of a building element or a building system. As shown in Figure 6.2, the evaluation of the machinic morphospace will focus on aspects of the manufacturing system that directly influence the design or parameter space of the building element or component.

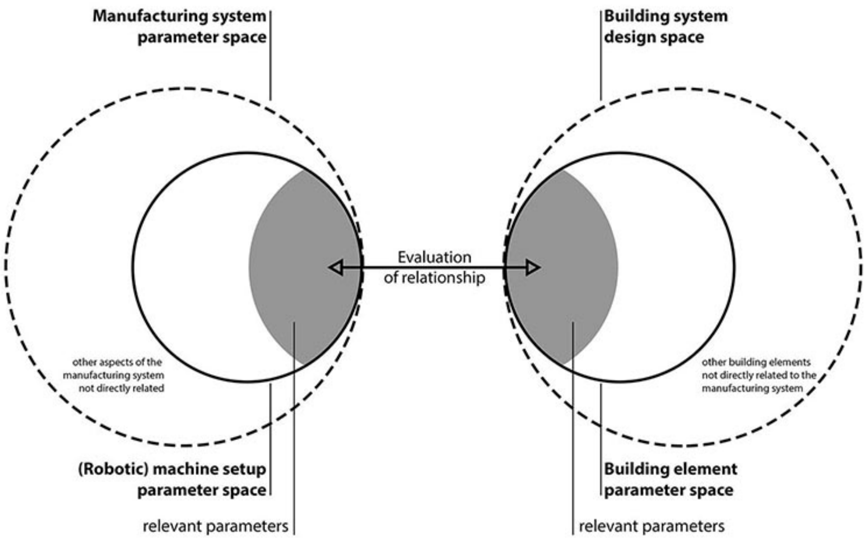

Figure 6.2: Relationship between the manufacturing system's and building system's parameter spaces. The parameters that are relevant to this analysis are defined by their direct influence on each other. While it can be argued that all parameters of both systems have an influence, the work in this thesis explicitly looks at aspects of the robotic setup that have a direct influence on the possibilities of form variation of the building element that is being manufactured by said setup.

6.4.1 Morphological parameters and parameter selection

A parameter is a characteristic that helps to describe a system. As such, building elements, and building components comprised of elements, can have an infinite number of parameters describing any characteristic. For example, material type, density, product name, and geometric dimensions are all parameters that describe a building element. Geometric information can also refer to different scales, such as micro-scale geometric properties referring to the porosity of the cellular or atomic material makeup, or macro-scale properties referring to total length, width, and height of a building element. However, many of these parameters are not directly related to the manufacturing process. In most case studies, for example, the material is a pre-defined parameter and not considered to be changed.

To evaluate the relationship between design and manufacturing, it is therefore important to find and describe parameters that define characteristics with a direct influence on the design space of the building system, and that have a direct relationship with the manufacturing setup (Figure 6.3). More specifically, in each case study, parameters are chosen that describe a morphological feature of the building element that has an important influence on the design space of the building system but is also highly dependent on the manufacturing setup. In many case studies, it is also then shown that a change in the machine setup can lead to significant increases in the parameter's range, and therefore the design space.

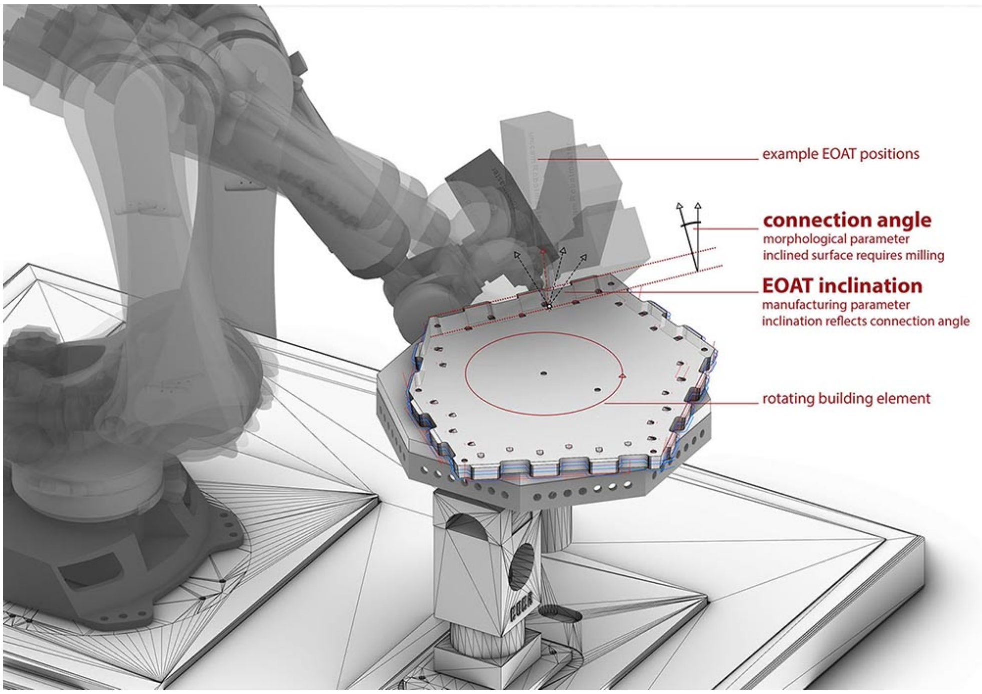

Figure 6.3: An exemplary relationship between a morphological parameter and the manufacturing setup. In order to fabricate the finger joints of the polygonal plate shown in this figure, the milling spindle (EOAT) has to incline in accordance with the angle of connection that the finger joints are produced for. At certain boundary conditions, the milling spindle cannot incline any further, thereby restricting the connection angle as well.

To evaluate possible parameters and find those with the most direct impact, a list is created in each case study. In this list, parameters with any reference to geometric and therefore morphological features is collected. Then, parameters are sorted in three scales: a micro scale referring to the material makeup, a meso scale referring to a part of the building element, and a macro scale referring to either the full building element or a building component. In a final step, all parameters are evaluated based on their impact:

(1) their impact on the design space of the building element and building system, and (2) the impact of the manufacturing system on the range of the parameters. Lastly, three parameters with the highest ranking are chosen for the subsequent machinic morphospace analysis. By restricting the analysis to three parameters, their relationship to the manufacturing system can more easily be visualized in a single diagram.

This evaluation can only be done with existing knowledge about the building system and manufacturing system, and only through experimentation in causation. For example, a morphological parameter can be evaluated by exploring how a smaller or larger range will influence the design space. In the same way, it can be evaluated whether a change in the manufacturing setup, such as the EOAT or the robot arm kinematics, will have a direct influence on the range of a parameter. In all case studies, aspects of the manufacturing setup that can be changed or adapted are of interest, such as the EOAT, the relative position of manipulators to each other, or enclosures of manufacturing cells.

Once three parameters are selected, the building element's morphological parameter range is visualized. Further, the implications of the machine setup on the parameters are visualized by showing snapshots of the robotic simulation in boundary situations, such collision scenarios or transgression of the reach envelope.

By understanding and evaluating the relationship between a design parameter and the manufacturing setup, it is possible to analyze how directly the parameter is influenced by machine setup parameters. In some instances, the design parameter can be directly extracted from a programming parameter, such as the connection angle between adjacent plate structure elements in Case Studies 1, 5, and 6. In another example, the parameter is more abstract, such as the minimal circumcircle of a polygonal plate, which is also used in the same three case studies. In both examples, the parameters have a significant influence on the design space, and at the same time are dependent on aspects of the manufacturing setup over which the researcher team has influence.

6.4.2 Hyperdimensional parameter spaces and their boundaries

A building element can be described with many more morphological parameters that may be interconnected or hierarchical in nature. It would therefore be possible to construct a hyperdimensional morphospace of possible morphologies as suggested by Menges [237]. Although the possibility of visualizing the morphospace in a single diagram is lost when more than three parameters are analyzed, the mathematical relationships, the boundaries of parameters, and their relation and behavior toward changes of the machine setup could be explored mathematically. In biological morphospaces, the collection of all parameters is called the *total hyperspace of form dimensions (U)* [229; 237]. In this thesis, no more than three parameters are visualized because the purpose of this method is to gain visual feedback in the design process.

In the case studies, each parameter has clear boundaries based on the specific machine setup of the analyzed project. In many case studies, small changes to the manufacturing setup are shown to cause large changes to these boundaries. How these boundaries are defined and how they can change is important to understand.

Learning from biological morphospace, similar descriptions of boundaries can be established for machinic morphospaces. The *total hyperspace of form dimensions (U)* can be divided into a *geometrically impossible region of form* (GIF) and a *geometrically possible region of form* (GPF). The latter is further divided into a *non-functional region of possible form* (NPF) and a *functional region of possible form* (FPF) [229; 237]. The boundary between the geometric regions is called the *geometric constraint boundary*, and the boundary between the functional regions is called the *functional constraint boundary*. The regions are visualized in Figure 6.4.

In biology, the FPF is considered the region within which organisms can survive [229]. Although Menges [237] classifies the FPF as the machinic morphospace, it is argued in this thesis that an additional classification has to be introduced, which contains but is not limited to the FPF. As shown in Figure 6.4, the *producible region of possible form* (PPF) is defined as encompassed by the GPF but larger than the FPF. This distinction allows a separate evaluation of the region of form that the manufacturing system can theoretically produce, and the region of form that is functional in an architectural or structural context. However, the thesis follows Menges' argument that further sub-regions can be determined by evaluating the FPF for high structural, architectural, or environmental performance of building elements. The implication of this distinction will be discussed in each case study.

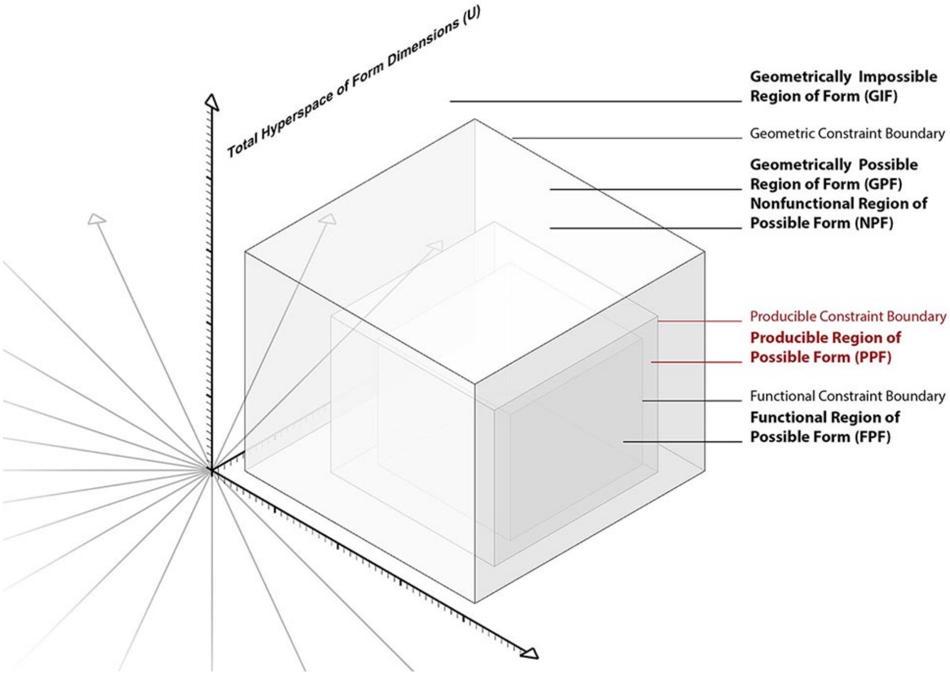

Figure 6.4: Geometric and functional constraints in the hyperspace of form dimensions. While the order of nested regions cannot change, regions can have nested sub-regions within them. For example, a functional region of possible form can have another nonfunctional region of possible form within it due to the reciprocal relationship between parameters. A new classification of region of form is introduced, named the "producible region of possible form" (PPF) to distinguish between what is geometrically possible, producible, and functional. Based on Menges [237] and McGhee [229].

The impact of a building element's parameter on the building system's design space, and its relationship to the machine setup, is explained in each case study. Once these relationships are defined, their boundaries are analyzed in relation to the machine setup, and empirical measurements from the case study are added to analyze which sub-sections of the PPF and FPF have been used and why.

6.4.3 Machine setup: parameter space and constraints

Like the parameter space of the building elements, the machine setup also has a theoretically infinite number of parameters that can be used to describe it in various ways. In the case studies, the parameters that have the most impact on the design space of the building system are usually found through analysis of the building element's parameters, manufacturing simulation, and iterative development.

In the research projects presented in the case studies, important machine setup parameters were found through prototyping and simulation. However, the machine setup's parameters were not adapted significantly once the relationship was established. Rather, it was important to understand the constraints and implement them into the computational design system. Because of the availability of equipment, funding, and laboratory space, significant changes were not feasible in practice. In the case studies, however, occasional changes to the machine setup parameters are introduced to visualize and analyze their effect on the machinic morphospace.

6.4.3.1 Evaluation of the machine workspace

The parameters that have the most influence on a gradient building system's design space relate to the machine setup's work envelope, or reachable workspace. As the relation between workspace and design space is the focus of this thesis, it is important to clarify how workspaces are being defined and calculated.

Alameldin [9] and Kumar [204] describe the *reachable workspace* of a robot, which is more generally called a manipulator, as the volume, space, or area that contains all points the EOAT can reach in at least one orientation. The *dexterous workspace* is described as the workspace in which all points can be reached by the EOAT in all possible orientations [62]. Similarly, the *total orientation workspace* is described as the workspace in which all points can be reached by the EOAT in a defined range of orientation [268] (Figure 6.5).

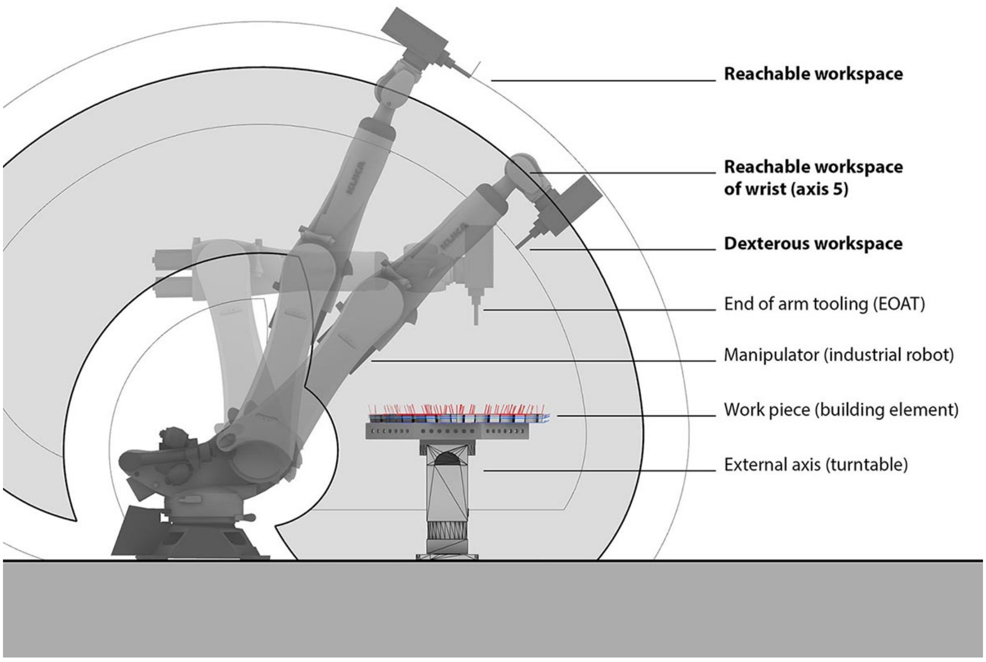

Figure 6.5: Typical robotic manufacturing setup. The end-of-arm tooling (EOAT) extends and constrains the workspace of the robot (manipulator). The dark gray area is defined as the workspace the wrist of the industrial robot can reach, thereby defining a boundary independent of any EOAT or orientation.

The EOAT can reduce or expand the workspace. For example, a tool can reduce the dexterity of one or more joints of the manipulator because of a potential self-collision, or it can be large or long enough so that the manipulator can reach further. In addition, external axes such as a linear track expand the workspace by extruding the cross-section perpendicular to the external axis along its length. Rotating tables, which act as an additional external joint, will allow for the workpiece to rotate while a building element is processed by the manipulator's EOAT, thereby expanding the accessibility of the workspace to the workpiece (Figure 6.5). Examples of the influence of an external axis will be shown in the case studies.

6.4.3.2 Other constraints to be considered

General constraints that were considered in each research project relate to the context of the research institution, the team, and the laboratory spaces. Available equipment, cost effectiveness of the process, as well as available time and budgets are all part of a constraint-based development process.

Because of those constraints, changing the industrial robot or the EOAT to adapt the workspace and therefore the building system's design space was not possible in many case studies.

6.4.4 Analysis and visualization of the theoretical machinic morphospace

During the parameter selection process, a computational tool is developed to analyze those parameters through either selective iterative testing or automated testing. The goal is to find each parameter's boundary conditions to draw the *producible region of possible form* (PPF). First, a preferred range is selected to define an approximate parameter range of preferred design goals. Then, values within that range are evaluated by simulating the manufacturing process with each value. In the early stages of the development process, this can be done manually with only a small number of values. To find the boundary of the machinic morphospace, incremental testing is necessary. In later stages, the resolution of the boundary testing might be increased through automated testing. In the case studies, a combination of incremental testing based on the experience from the time the research project was developed, and automated processes, is employed.

In each case study, the three selected parameters influence each other, and therefore need to be considered in reciprocal relationship. They can be visualized within three 2D, or one 3D diagram, resulting in one or multiple areas or volumes that visualize the range of all parameters in relation to each other. Often, the boundary conditions of one parameter result in other parameters becoming more restricted. These situations are carefully evaluated to find the correct location of the *producible constraint boundary*. Once these boundary conditions are found and described, the theoretical machinic morphospace, or the *producible region of possible form* (PPF), can be visualized (Figure 6.6).

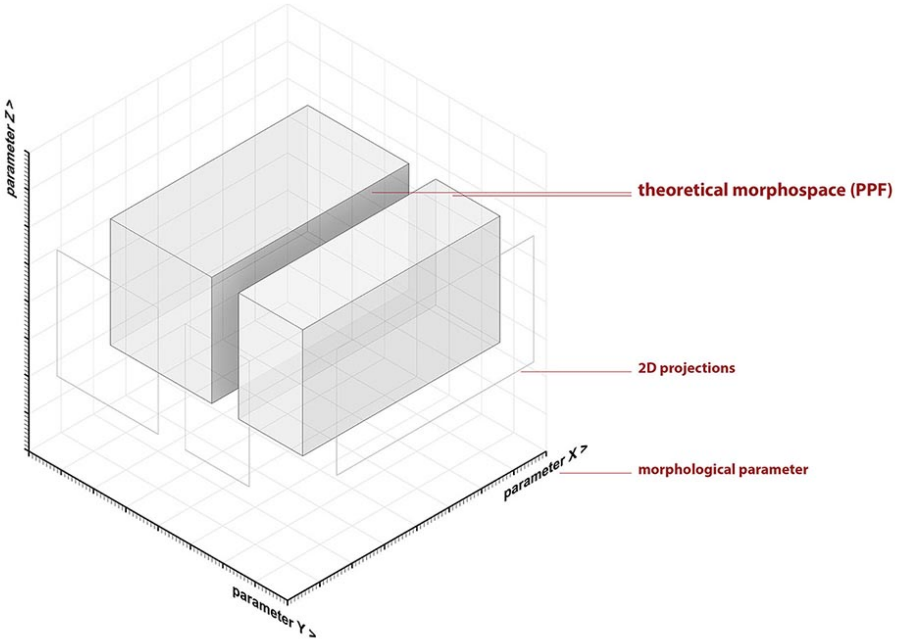

Figure 6.6: Example of a theoretical machinic morphospace. The gray area defines the range of three parameters that can be produced by a specific machine setup. The region can be represented by a single volume or many disconnected volumes. In this example, the theoretical machinic morphospace is represented by two three-dimensional orthotopes.

Once the theoretical machinic morphospace is established and visualized, the impact of certain machine setup parameters can be tested. By changing a single parameter in the machine setup (such as a different EOAT or an additional manipulator joint), the analysis can be redone, and the results compared. This method serves to understand the relationship between the two parameter spaces and to find opportunities to expand the building system's design space with small changes in the machine setup. However, as of the writing of this thesis, this relationship has never been implemented in an automated, computational method.

6.4.5 Analysis and visualization of the empirical machinic morphospace

In the last part of the machinic morphospace analysis, the demonstrator building that is considered the result of each case study's research project is evaluated. Each building element that was produced for the demonstrator building is analyzed for its three morphological parameters, and the resulting values are represented within the morphospace diagram as individual measurement points. All values of all building elements together form a point cloud, which describes the empirical machinic morphospace that was occupied by the demonstrator building, representing a sub-region of the theoretical morphospace (Figure 6.7).

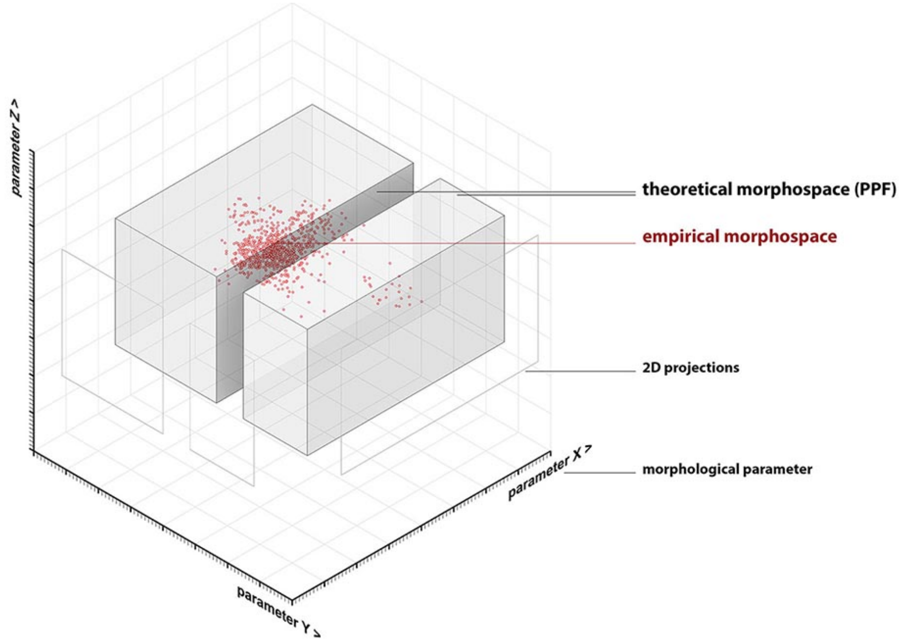

Figure 6.7: Example of an empirical machinic morphospace within the theoretical machinic morphospace. Each point represents a combination of three values measured on a building element. The density and distribution of measurement points indicates the utilization of the producible region of possible form.

By comparing the empirical and theoretical machinic morphospace, observations can be made in each case study. The size of the sub-region of the machinic morphospace determines how much of the theoretically possible design space was utilized for the demonstrator building. Here, a discussion about design intent and design constraints can be introduced. When measurement points are close to the boundaries of the theoretical machinic morphospace, it can be concluded that the design intent collided with the possibilities of the machine setup, and changes could have helped in producing building elements with parameters outside of their producible range. The opposite is also true: When large empty spaces can be observed, it can be concluded that parts of the theoretical machinic morphospace were underutilized because they were either not necessary or functional. Further analysis on the differences between theoretical and empirical morphospaces are discussed in each case study as well as in the conclusion chapter.

6.4.6 Conclusion

Parameters can be defined in various ways and either relate to one single characteristic of a building element (e.g., material thickness) or are a result of many characteristics working together (e.g., the circumcircle of a polygon). The challenge of finding the right parameter in the case studies is in evaluating which ones have the most obvious and direct impact on the design space and can be influenced by changes in the manufacturing system at the same time. Here, a strong impact refers to small changes in the parameter's value having large effects on the design space or other parameters. Parameters can therefore also be called "sensitive" if small variations result in larger changes in the design space, or if small variations in the machine setup result in large changes in the parameter's range.

Further, the number of those sensitive, or impactful, parameters can be larger than three, in which case visualizing the relationship to other parameters is not possible within a single diagram. The visual analysis of multi-dimensional spaces is challenging and would have to be broken down into pairs of two parameters.

In this thesis, a machinic morphospace analysis is used to relate design parameters with manufacturing parameters, and to establish a method to define, develop, and analyze gradient building systems. In each case study, the results can highlight a particular discrepancy or symbiosis between aspects of the manufacturing development and design development. The method allows the relationship to be understood visually and mathematically and helps to identify crucial aspects of an integrative development process for gradient building systems.

6.5 Acknowledgements

Some aspects of the methods presented in this chapter were developed by the author's colleagues. Achim Menges first described the machinic morphospace analysis in 2012 [237]. Lauren Vasey described and developed methods for robotic simulation and control exhaustively during her research projects and in her doctoral thesis [374; 375; 376]. The inverse kinematic solver and post-processing was mainly developed by Long Nguyen and Tobias Schwinn, respectively. Further, Long Nguyen, Tobias Schwinn and Abel Groenewolt are the main authors of the agent-based modeling tools developed at the institute [137]. Lastly, Daniel Piker developed the Rhino Grasshopper plugin Kangaroo [277], which was used for all relaxation methods in this thesis.

7

Case Studies

Between 2011 and 2018, the author participated in research projects that explored different potentials of technological innovation in manufacturing and design in timber construction, many of which resulted in building systems that were evaluated through prototypes, mock-ups, or demonstrator buildings. While they all differ in their approach, investigative motivation, scope, and extent, they share a common bottom-up development method. A rare occurrence in industry and practice, and much more common in open-ended applied research, a bottom-up development method is not goal-oriented or form-motivated. Instead, it sets out to question an underlying concept in the value chain of a design-to-manufacturing process. That underlying concept might be an engagement with a previously ignored material characteristic, the functionality and capacity of a building element or a connection, or potentials of digital or robotic fabrication. The exploration of such concepts requires innovation in manufacturing technology as well as design technology, and such innovation is only possible through an integrative, cross-disciplinary development process where design and manufacturing technology are reciprocal.

The following case studies were selected for their specific contribution to the method of relating manufacturing and design innovation. In each case study, the development process is evaluated for its impact on design possibilities through a comparative analysis of their parameter spaces, as discussed in the previous chapter. All projects share an open-ended methodology of architectural design research, re-evaluating possibilities in shape, aggregation, and space, in relation to technological innovation. The most important contribution of each case study is described in the investigative motivation.

In the first half of each case study, the project is first presented for its contribution to the research areas of biomimetics (if applicable), manufacturing systems, and computational design systems. In the second half of each case study, the author investigates the three research objectives as stated in Chapter 1.

All projects presented in this thesis have been highly collaborative and inter-disciplinary, involving many researchers from different institutes, many students or student assistants and sometimes several professors. Many projects were executed across countries and continents, involving universities such as the University of British Columbia in Vancouver, Canada, or Tongji University in Shanghai, China. All projects were led by the Institute for Computational Design and Construction at the University of Stuttgart, with Professor Achim Menges as the principal investigator.

Generally, the author's main contribution to each research project was to the development of the manufacturing processes and the material systems and their connections. The author also participated in the development of the computational design systems for design exploration and manufacturing control. The author's specific contributions are stated at the end of each project introduction, and the involvement of other researchers and students are explained at the end of each case study. The author's main contribution in each case study in this thesis is the analysis of the integrative development process, the computational data flow, and the development and analysis of the machinic morphospace.

Figure 7.1: The ICD/ITKE Research Pavilion 2011 (Image by ICD/ITKE University of Stuttgart).

7.1 Case Study 1: ICD/ITKE Research Pavilion, 2011

7.1.1 Project introduction

In 2010 and 2011 the Institute for Computational Design and Construction (ICD) and the Institute of Building Structures and Structural Design (ITKE) engaged in a design-and-build seminar and studio project with a group of students. The goal was to develop, design and build a temporary research pavilion made of timber, at the intersection of teaching and research (Figure 7.1).

The project was organized as a year-long seminar and studio. In the first term, students were engaging with classical wood connections, evaluating their origin, structural functionality and relationship to the materials used, and typical dimensions. In their research, students were tasked with translating the original, manual manufacturing process to a multi-axis robotic CNC process. It was anticipated that this would result in increased freedom of form, as the kinematics of an industrial robot and the nature of the milling tools allow for a larger workspace for accessing the building element. The development of new manufacturing processes subsequently led to an exploration of design possibilities through an accumulation and variation of building elements.

In the second term, students formed larger teams to continue the development of the most promising concepts into a mono-material building system with the goal of designing and constructing a large-scale demonstrator building. At the same time, the architectural potentials of the material system were investigated and evaluated in a computational design environment. Through the development of computational tools, the boundary conditions of the building system were explored and related to the manufacturing constraints, as well as general constraints such as the size of the demonstrator and available manufacturing and assembly time. The development of the tool was two-fold: to learn about the building system and explore the design space, and to have the functionality available to generate manufacturing data necessary to fabricate each building element.

The project's main motivation was the translation of biomimetic principles and the renewal and modernization of traditional timber joints.

Through the evaluation of biological precedents for a transfer of structural and constructional principles into a material system or manufacturing system, a sophisticated range of possible shapes in both the building element and the design system became possible, leading to a much higher material efficiency. This premise ties back to the research group's motivation to find new ways of using material properties and manufacturing technology for the development of gradient building systems.

The author participated in this research project as a student and student assistant at ICD, supervised by a team of six researchers and two professors. The author was primarily involved in the development of the timber connections, the manufacturing process, and the computational design process. The author also participated in the fabrication and assembly process and provided his expertise in the first evaluation of a machinic morphospace. Further acknowledgements are at in sections 7.1.5 and 7.1.9.

Some of the project details of this case study were published in the papers "Performative Architectural Morphology" by Krieg *et al.* [190] and "Machinic Morphospaces" by Schwinn *et al.* [329]. Some results presented in this case study are unpublished, particularly details on the manufacturing development in section 7.1.3 and the machinic morphospace analysis in section 7.1.8. The case study will be discussed in depth regarding the analysis of the machinic morphospace and its relationship to the development of design and manufacturing processes. The structure of the development process and the subsequent discussion about the interdependencies between the machine setup, material properties, and design space formed the beginning of the research field of machinic morphospaces and the foundation for this thesis.

7.1.2 Investigative motivation: biomimetic principles for plate structures

Similar to many of the following case studies, this project investigated biological role models in order to transfer constructional, structural, or process principles to either manufacturing or design processes, with the goal of finding innovative ways to reduce material consumption and increase structural capacity through a morphological adaption of building elements in response to system-internal and system-external parameters [190]. As described in Chapter 3, biomimetics can be used as either a top-down process or bottom-up process – to either find biological principles that resemble an already-known process or structure, or to find new principles that might inform a subsequent development process.

This case study was the first of its kind to investigate biological principles for the design and fabrication of timber plate structures. More specifically, a top-down biomimetic process was employed to inform, or filter, the topological arrangement of plate structures that can connect adjacent plates in any angle or form [190]. The high potential for differentiation within plate structures raises the question as to how the geometric freedom can be used to find plate structure topologies, or patterns, with a particular performance capacity [190]. In this case study, performance was defined by a material system's structural capacity as well as its ability to materialize different architectural articulations.

The biomimetic top-down process was initiated in this case study after the first steps of the fabrication development started to reveal such an extended design space. However, it can also be seen as an initial investigation into the potentials of biological examples of plate structures. Looking at these examples, they also reveal high-level principles of hybridized structural methods as well as gradient adaptation of building element morphology [189].

In this project, multiple species of the sea urchin (Echinoidea), and more specifically, the sand dollar, were used as biological examples. As a result of this study, multiple local and global principles were described, such as principles for the global plate topology, the global and local constructional and functional morphology, as well as local connection principles [191]. Each principle was described as the function it holds within the biological role model, and how it could be transferred into an architectural or structural principle. By analyzing its potentials when translated into a building system, its performance, or impact, was evaluated qualitatively. This was later called a "biomimetic performance catalogue" [190].

7.1.2.1 Establishing a performance catalogue

Architectural and structural principles of a plate structure system include load bearing on a local and global level, plate arrangements and patterns on a local and global level, multi-layered structures with higher structural performance, perforation and light modulation, as well as drainage and flow regulation [190; 191]. The catalogue was established to investigate morphological principles of sea urchins and sand dollars for these criteria, and to form basic constructional principles for the development of the building system subsequently. The biomimetic principles were established by Adolf Seilacher [335], Krauss *et al.* [188], and Nachtigall & Pohl [253].

- *Local plate shape:* Skeletal plates of sand dollars develop polygonal outlines and form a rigid shell. The shape of each plate is determined by its location within the body, and global patterns of the skeleton (Figure 7.2) [190].
- *Local plate arrangement:* The echinoid's skeletal plates are arranged in such a way that no more than three plates meet in one point. This basic principle can be found in many plate structures in nature and ensures that forces are mostly transferred as in-plane shear [190].
- *Local load transfer:* Because of the appearance of high in-plane shear forces, the plate-to-plate connections exhibit small finger-joint-like shapes, which prove to be especially strong against shear. Their specific shape also provides a certain tolerance to absorb movements of the structure [188; 190].
- *Global plate arrangement:* The echinoid's skeletal pattern exhibits a five-fold rotational symmetry, which is achieved by both a gradual and abrupt change in plate size. Differentiation in plate size has structural as well as functional reasons (Figure 7.2) [190].
- *Hierarchical build-up:* Each skeletal plate is made of a three-dimensional calcite meshwork, called stereom, which varies in density and therefore stiffness. Material distribution is an important principle for structural performance and material efficiency (Figure 7.3) [190].
- *Voluminous mechanical structure:* The sand dollar's upper and lower skeletal layer is connected by columns, which connect to the plate center. A double-layered structure can be seen as a higher level of material efficiency by forming large cavities and connecting two surfaces (Figure 7.3) [190].

- *Edge formulation:* The echinoid's skeletal plates are smaller around sharp edges because of the low curvature but also because a higher density of joints can absorb dynamic impact forces. Changing plate size depending on curvature or structural forces is a common biomimetic principle (Figure 7.3) [190].
- *Permeability:* The sand dollar's test is perforated by lunules, which are formed by inverting the upper and lower layers onto themselves. Such perforations are structurally performative but also facilitate light modulation or water flow [190].

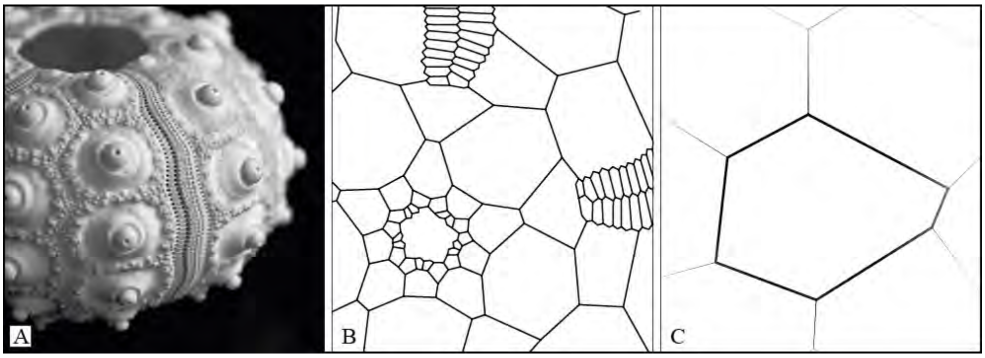

Figure 7.2: Local and global plate arrangement in a sea urchin. Left: Close-up photograph of a sea urchin test. Middle: Schematic view of the plate pattern around the top opening of a sea urchin. Right: Close-up diagram of a polygonal network where only three plates meet at one point (Image by Schwinn et al. [329]).

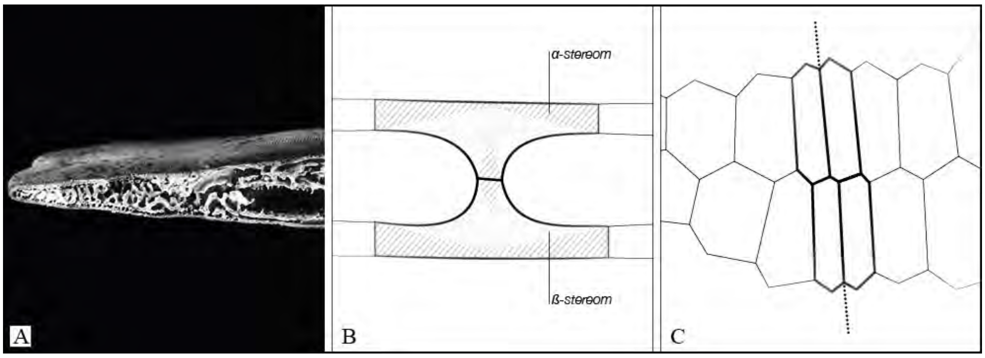

Figure 7.3: Structural principles of a sand dollar. Left: Close-up photograph of a section of a sand dollar [335] (Permission is granted at no cost for use of content in a Doctoral Dissertation according to Cambridge University Press). Middle: Schematic sectional drawing showing the column-like connection between the top and bottom layer. Right: Close-up diagram of the polygonal network around the sand dollar's margin (Image by Schwinn et al. [329]).

7.1.3 Development of the manufacturing system

The starting point of this project was the motivation to rethink traditional timber joints with newly available manufacturing technology such as multi-axis CNC milling with an industrial robot. During the initial studies of timber joints, the finger joint—more accurately called the box joint—became a connection of interest due to its structural performance and geometric complexity. The resulting joint development formed the basis not only for this case study but for many others as well [189].

Finger joints connect force- and form-fitting elements through multiple interlocking teeth with a straight or tapered shape [134]. Each finger, or tooth, protrudes from a plate-like building element and fits into a gap, or groove, in the neighboring, connecting plate-like building element. Multiple such teeth form a row of finger joints, and their width is generally dependent on the tools used, balancing the effort required to produce them, and the resulting structural performance of the connection. The finger joint is further described by Graubner [134] as a connection that does not require any additional fasteners and avoids warping effects during dimensional changes such as swelling or shrinking of the wooden elements. This method of connecting wooden elements is an ancient corner joint first developed over 3500 years ago [175] that most likely emerged for the construction of building log cabins, where each log is connected to its neighbor over a corner. While each log individually formed one finger joint or dovetail joint for the corner of a log cabin, the same principle of joining was later introduced for plate-like building elements on a smaller scale. In carpentry and furniture making, these types of joints are made with standardized and automated machines, mostly for 180- or 90-degree connections. For the manual fabrication of a finger joint, each finger must be cut using a saw and chisel. Industrialization rendered this laborious method impractical, and other methods of joining plates around corners were introduced, such as tongue-and-groove connections, biscuit connections, or metal fasteners [189]. However, a mono-material connection has many advantages that do not have to be sacrificed due to the connection's geometric complexity. Different materials react differently under temperature and relative humidity changes, making mono-material connections longer lasting. It was the premise of this case study that this kind of geometric complexity can be easily handled with new manufacturing technology such as multi-axis milling [330].

The kinematic freedom of an industrial robot equipped with a milling spindle and connected to a stationary turntable on which a building element would be placed, allows for a fabrication process during which finger joints can easily be cut in many different directions and at many different angles (Figure 7.4). When using a cylindrical milling bit for side milling or face milling, the possibilities and constraints of a subtractive process need to be considered. In this case, the tip of the milling bit was used to cut through the plate at an angle, thereby producing rectangular and straight fingers and grooves that connect to a neighboring plate at the same angle as the milling bit's tool path. The finger joint geometry is generated simply by intersecting the cross sections of adjacent plates. Following this logic, a 90-degree connection would produce the smallest intersection profile, and a 0-degree or 180-degree intersection would produce an infinite intersection profile, thereby rendering low angles of connections useless. The advantage of the manufacturing method outweighed the disadvantage of reducing the usable range of connection angles, and the subsequent development process incorporated these constraints [330].

In order to fabricate a row of finger joints along an edge of a plate, three consecutive milling steps were developed (Figure 7.5): (1) the edge is being milled to match the angle of the adjacent plate, using the shaft of a straight milling bit; (2) because finger joints cannot run all the way into a corner, the corners of each edge are milled to form an angled miter with the neighbor, using the tip of the same milling bit; and (3) the remaining edges between each of the mitered corners are filled with finger joints, milled using the tip of the same milling bit oriented to align with the adjacent plate's normal vector, with an up-and-down movement through each finger in order to control the width for tolerances or dimensions larger than the milling bit diameter [330].

Figure 7.4: Robotic setup for milling finger joints on a turntable (Image by ICD/ITKE University of Stuttgart).

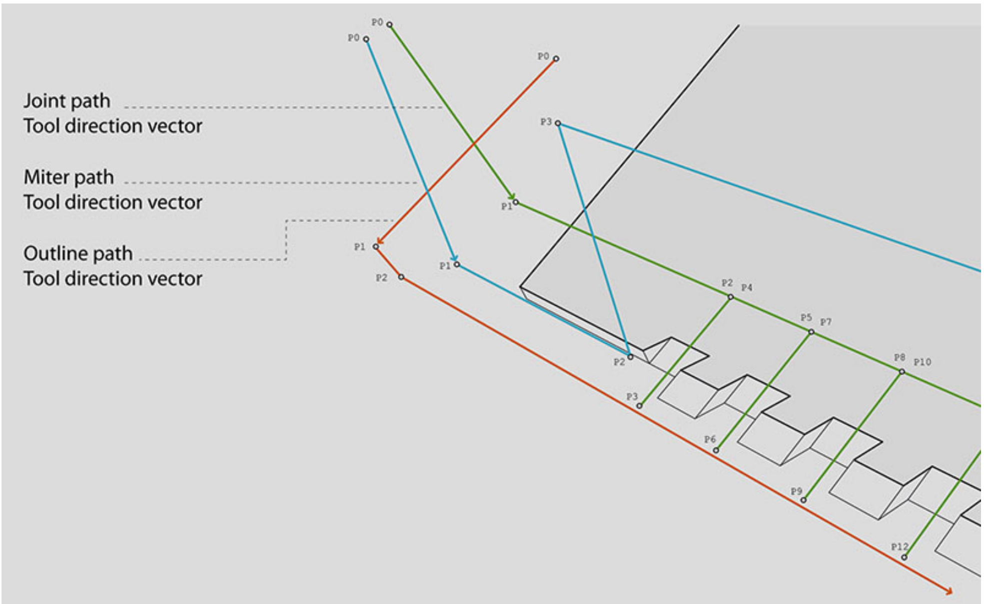

Figure 7.5: Three CNC fabrication steps are necessary to cut a single edge and its finger joints (Image by ICD/ITKE University of Stuttgart).

This fabrication method enables the production of finger joints of varying angles along each edge of a polygonal plate. This bottom-up development process used manufacturing equipment (industrial robot, milling spindle, turntable), materials (plywood plates), and the translation of traditional wood connections as a starting point. In subsequent steps, this approach was parametrized and translated into a manufacturing system and explored for its design opportunities in parallel.

The initial development of this fabrication process was executed by manually programming the robot's movement using HyperMill, a commonly used CAD/CAM program in the industry [73]. While this kind of software allows the user to select surfaces and edges for specific milling jobs, it does not provide pre-defined functions for finger joints. Instead, multiple surfaces and edges must be selected for each finger joint in the user interface. The research team therefore developed a more abstract approach, which provided a direct connection to the design model. Because the joint geometry and the fabrication instructions are in a definitive geometric relation to each edge's connection angle and material thickness, they can be derived from a simple set of topological information [189; 330]. The 3D solid geometry of the building element is not necessary, and the finger joints do not need to be modeled in 3D. Instead, geometry is defined by abstraction, and the tool paths are directly coupled to the abstracted geometry.

Therefore, a simple boundary representation (BREP) or boundary curve of each plate, representing one of the faces of the material, combined with information about the plate topology, connection angles, and material thickness, is enough to generate a set of fabrication instructions for each plate. Other variables that informed the machine-specific tool path generation are milling bit length, milling bit diameter, as well as the robot's kinematics.

From the beginning of the development process, the relationship between the machine setup, the constraints in fabrication, and the resulting design space, was carefully analyzed. In initial milling tests the robot processed only one edge of a plate. Here, the constraints of connection angles became evident: the lower the connection angle, the lower the milling spindle would have to be tilted, which would eventually lead to a collision [189; 237; 330]. It was therefore determined that a connection angle of less than 20 degrees would not be possible with the given machine setup. Subsequent milling tests would make use of the turntable and the robot would be programmed to process all edges of a polygonal plate. Here, the kinematics of the machine setup moved into focus: instead of a single parameter, the industrial robot's kinematics influence a range of geometric parameters of the building element. For example, if the turntable center point is further away from the robot than the robot's reach, very small plates cannot be fabricated. On the other hand, a turntable closer to the robot base constrains the maximum size of a plate [237]. Because the general machine setup and the laboratory layout could not be changed in this case study, the plate size, connection angles, and other parameters were constrained to a range that was explored through iterative testing and simulation.

The development of a workflow from a surface-based 3D model to the fabrication of plates, assembly of modular components, and construction on site can be summarized as a "manufacturing system." The manufacturing system is defined by a sequence of fabrication steps. While information parameters of each step are the same for each building element, their values can differ. In some manufacturing systems, even the parameters can change or adapt depending on certain triggers in the geometry of the building elements. The development of such a manufacturing system is ultimately dependent on a computational design system and data transfers. In this case study, a computational design process produces abstract geometry such as the surface-based 3D model representing the overall design of the demonstrator. This level of information is enough for the subsequent process of manufacturing data generation. Here, the interface between design model and manufacturing model is the geometry itself: although it does not represent the material thickness or the joint geometry, it is enough to visualize the pavilion's design and spatial impressions, and at the same time to generate the manufacturing data. If necessary, an additional sub-routine could be developed in order to generate the real, solid, 3D geometry of each plate with all its finger joints for visualization purposes [330].

This interface can also be seen as a breaking point in the computational design process. It allows for manual intervention and correction, as well as for the permanent storage of information for later retrieval. After the design freeze, the geometry is used as the input for the subsequent fabrication data generation. Here, every plate is read as part of a module, and the data is sorted as such. While the “design model” is defined as the surface-based 3D model, the “fabrication model” uses this as an input and outputs the tool paths for the robotic milling process.

Then, a third computational process reads the individual plate and the associated tool paths in order to generate the machine instructions for the robotic fabrication. Here, the tool paths are visualized as robotic movements in a digital simulation. This last step allows for minor adjustments in the robot’s movements and acts as a collision check before the hand-off to the manufacturing team.

The workflow can be applied to any 3D model with polygonal plate surfaces. Because no structural system or any topological logic for how plates would be combined to form a larger structure was set up at this point, the process was developed to receive such a variety of plate shapes. This is fundamentally different to typical industrial processes, where either the shape or several shapes are pre-defined. Here, the geometric flexibility is inherent in the manufacturing system [330].

Throughout the development process of this case study, the design space of the building system was gradually informed, and constrained, by added information about the material, fabrication process, structural performance, and architectural articulation. Most importantly, the transfer of biomimetic principles was a key method to guide and inform this process. This led to a specific topological arrangement of plates and their assembly strategy, as follows. Multiple plates are connected to form a double-layered module (Figure 7.6). Within a module the biomimetic principle of connecting only three plates in one point is adhered to, while on a higher hierarchy, the same rule is applied to the assembly of modules [190]. This strategy allowed for the joining of plates into modules using adhesive inside the workshop, and the assembly of the modules on site using bolted connections. Before the robotic fabrication workflow begins, plates with an offset of their final shape are cut out with a CNC machine from sheets of plywood. During this process, two holes are cut indicating the polygon vertex-weighed center point and the direction of the X-axis of the plate’s local plane. These two holes are used to orient the plate correctly on the turntable positioner. Here, the robotic fabrication is at the beginning of the process, and manual work is necessary afterwards to correct milling mistakes and assemble the modules.

Figure 7.6: The building system exhibits two hierarchies of building elements (individual plates) and building components (modules made from 12 to 21 plates) (Image by ICD/ITKE University of Stuttgart).

7.1.4 Development of the computational design system

From the beginning of the development process, computational design tools were used to assist both prototyping and design exploration. Those tools would become more sophisticated with time and eventually form what can be called a computational design system that enabled a seamless process from a design interface to manufacturing data generation. For example, small algorithms were developed early on to assist in generating manufacturing data for a single plate-to-plate connection. The data flow required for this tool was later implemented in a computational design workflow explained in the previous section. In another example, small geometric algorithms explored the aggregation of different plate patterns, one of which was later selected for the design process.

The computational design system also introduced a turning point in the case study. As it became more sophisticated, the development process switched from a bottom-up and solely explorative approach to a top-down approach with design intent [330]. At this point, exploration of the design space and the intent to design and build a demonstrator converged, steering the remaining development process toward a required functionality for the execution of the project.

The development process of the computational design tool is also an exploration in the design space of the building system even while it is undergoing development. Because they are uninformed by constraints, early computational tools have a much larger design space and can generate geometry that might later turn out not to be fabricable. Therefore, the development process of the manufacturing system informs the design tools about possibilities and constraints of the building system [237; 330]. However, exploration in design might also lead to a desire to expand fabrication possibilities due to desired architectural articulations. Further, the development of this computational design system had to include biomimetic design principles as well as fabrication constraints. While it is not required to be restricted to the space of the producible, its purpose is to explore, reflect, and indicate on what is producible or functionally viable. As such, the dialogue between biomimetic principles, design intent, and manufacturing development are crucial for the computational design system to evolve and mature. In the final stages of development, design and manufacturing data generation were connected into one computational process.

In this case study, the purpose of the computational design tool was to provide a design method that allows the user to explore the design space given by the building system without the need to manually control all parameters of all building elements. Further, the tool needs to adhere to the analyzed biomimetic principles and their related critical characteristics such as the topological rule of three plates meeting in any one point [190].

The study of topological arrangements of plates marked the beginning of the computational design system's development. In this early stage, aggregations of plates following geometric rules were explored using small algorithms that would produce variations of each pattern or topology. At the same time, methods for the overall design process were explored in order to easily aggregate a large number of plates populating a pre-defined design. Both methods were explored individually and later in combination. This development resulted in a computational form-finding method that was combined with a parametrically defined arrangement of modules, which in turn were divided into individual plates (Figure 7.7).

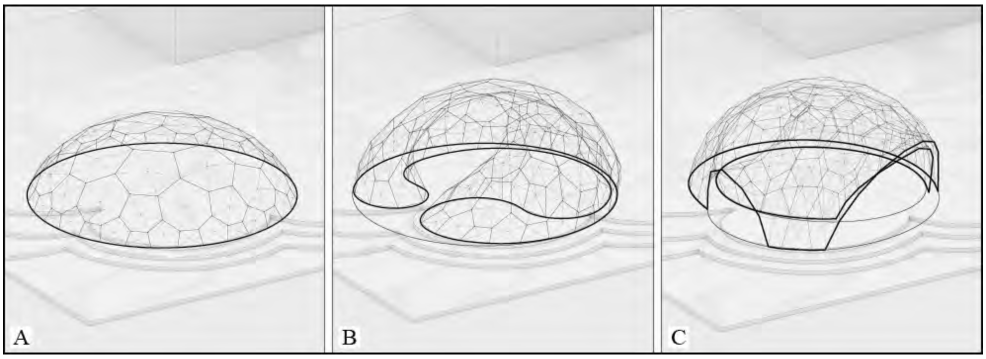

Figure 7.7: The computational design system provides a high-level control of a design surface, which represents a modular arrangement of plates with a modular mesh (Image by ICD/ITKE University of Stuttgart). From Schwinn et al. [329].

On a local level, the development was focused on a modular system of plates, which not only allowed for prefabrication processes during the execution phase of the demonstrator but also allowed for a high degree of adaptability and performance due to the morphological differentiation of each plate element [191]. The biomimetic principle of three plates meeting in one point was translated on both the modular and the plate level: only three modules would meet in one point, while within each module only three plates would meet in one point as well. In addition, a module consists of two layers connected by an interstitial connection. Aside from advantages during prefabrication and transport, this method also added to the structural performance of the shell [330].

Each module can be based on non-planar polygonal outlines with four to eight edges. The outline serves as the lower base of a frustum, which will be topped off with a truncated pyramid (Figure 7.8). The height of the frustum and the height of the pyramid are separate parameters that can be adapted individually. The truncated pyramid is generated by extruding the center point upwards and cutting the tip off with a plane. Lastly, the same process is repeated for the second layer, and both layers are connected by vertical plates around the frustum. This method has an important advantage: it allows for the underlying global design to result in non-planar outlines and therefore does not need to be as constrained, while the resulting modules are ensured to always produce planar plates.

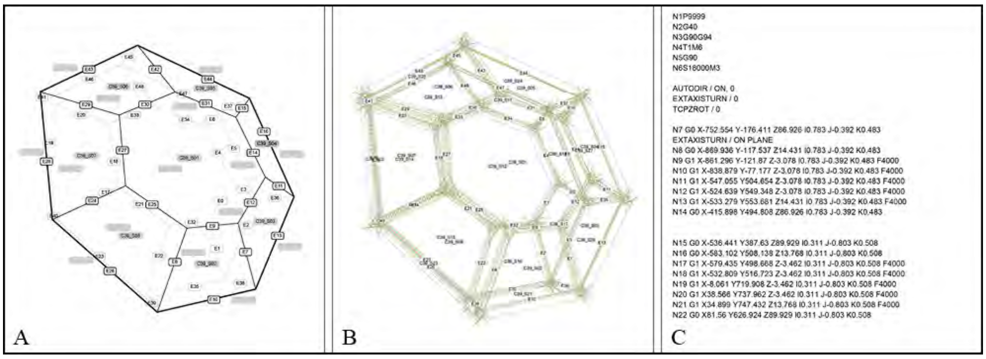

Figure 7.8: The manufacturing data generation process of a modular plate-cell from a polygonal outline. On the top left, the topological analysis identifies neighboring plates, which is used to generate machine code (Image by ICD/ITKE University of Stuttgart).

The resulting modular "plate-cell" integrates biomimetic principles with fabrication and material constraints. The module's morphology can be adapted for direction-oriented load bearing, curvature in the global design, or structural performance.

On a global level, a form-finding process was developed that combines design intent, distribution and arrangement of modules, and incorporation of global biomimetic principles such as curvature-dependent plate arrangement. The design tool was based on a two-dimensional Voronoi diagram as a topological map for the modules, with each Voronoi cell serving as the polygonal outline of a module [191]. This method loosely followed a previous research project that implemented a growth model to represent plates of a sea urchin [407]. Each Voronoi cell is then further represented by mesh triangles by connecting the polygon's vertices with their centroid.

Using this method, an arrangement of Voronoi cells is generated on a flat plane, which results in a flat mesh. Then, using a form-finding process, the mesh experiences several simulated forces that sometimes oppose each other. The most important ones are an attraction force to a design intent represented by simple surface geometries, an inverted gravity force that acts on the mesh to force it into a structurally optimized shell shape, and a spring force that acts on every edge of the mesh to equalize their lengths [329; 330].

The more edges a Voronoi cell has, the more triangles are created. The topology of such a mesh structure can have a direct impact on the form-finding process. When mesh edges relax to approximate equal lengths, a six-sided cell would remain flat, while a five-sided cell would form a spherical shape, and a seven-sided cell would form a hyperbolical shape [191]. The topological manipulation of the cells therefore pre-programs form-defining effects on the global form. Depending on the design intent, the local curvature might require spherical or hyperbolical configurations, which inform the topology of the initially flat mesh.

The computational design system in this case study was developed to allow for manual intervention at the early stage of this mesh configuration. Iterative testing led to an optimized mesh topology that would fit best with the intended design of the demonstrator. In the resulting form-finding process, other tectonic elements were also included, which manipulated the relaxation. First, the mesh was forced apart in one area to open up the double-layered module configuration and create a secondary room in the demonstrator. Second, the mesh was closed back in on itself to form a large circular opening within the main enclosure. Both tectonically distinct situations could be achieved with the same local method of generating individual plates within each modular cell, which followed the mesh relaxation process.

Once the relaxation process was completed, each module's pyramid center was extruded and truncated as described above. Depending on the curvature and structural requirements, the extrusion varied accordingly. The resulting three-dimensional model grouped each plate within each module, and only represented each plate by a single boundary curve or BREP surface. This geometry was then saved and could further be refined manually before it was handed off to the second part of the computational design system that was responsible for generating manufacturing data.

7.1.5 Project result

The result of this project was a pavilion with a radius of around 10m (Figure 7.9). The larger space of the pavilion has a large vault-shaped roof with gradually changing building components adapting in size in terms of their interior openings. These openings facilitated assembly and disassembly of the building components. From an architectural standpoint, the openings of the inner layer visualize the effective depths of the structural system, and serve as indirect lighting elements that create distinct spatial experiences depending on the time of day [191; 330].

The digital model contained the fabrication information for each of the demonstrator's 855 plates, and all tool paths for the more than 100,000 finger joints. Following the robotic production, the 6.5mm plywood plates were joined to form modules. The assembly of the prefabricated modules was carried out at the city campus of the University of Stuttgart. All design, research, fabrication, and construction were carried out jointly by students and faculty researchers.

The structural potential of the building system is demonstrated by the fact that the demonstrator could be built exclusively out of 6.5mm thin sheets of plywood [329] while spanning almost 10m, and with an average weight of 6kg/m^2.

Figure 7.9: The ICD/ITKE Research Pavilion 2011 (Image by ICD/ITKE University of Stuttgart).

7.1.6 Research result: Development process analysis

To evaluate how the integrative development process was enabled in this project, the relationship between the gradient building system, manufacturing system, and computational design system is analyzed in this section.

This case study shows a biologically inspired development process for novel timber joints and a timber construction system. Here, biological principles have been transferred for structural and constructional principles of the building system but also for the underlying understanding that building components, much like the morphology of biological entities, can be gradually adapted in their shape within a certain range. In this case study, the close interrelation of computational form generation and manufacturing results in the ability to produce plate connections at varying angles, and plates in varying shapes.

The development of the manufacturing system in this case study is initiated by what could be considered a single, subtractive fabrication step (Figure 7.10). While it can be argued that the industrial robot itself would not be necessary for this process as almost all the milling routines and tool motions developed in this case study could also be executed by sophisticated multi-axis milling centers, the robot can be seen as a vehicle to engage with manufacturing technology in the first place. As a relatively unknown technology to both architects and engineers in the construction industry, the industrial robot was an entry point for the reciprocal development of a manufacturing system and a building system. Since this case study was one of the first instances in which the research group engaged with such a machine setup, selecting a single process to engage with was considered a reasonable approach toward unknown technology while simultaneously ensuring that a demonstrator could be produced within a given time frame.

In the initial, small-scale, experiments of this case study, constraints of the machine were identified that would translate into constraints in the geometry of the joint. For example, the spindle would collide with the work piece if the angle of a finger joint were lower than 15 degrees or higher than 165 degrees [189]. The relationship between an identified range of the machine's kinematics and the building element's geometry translated directly to a design constraint. Namely, that plates could not be connected at angles outside of those identified above.

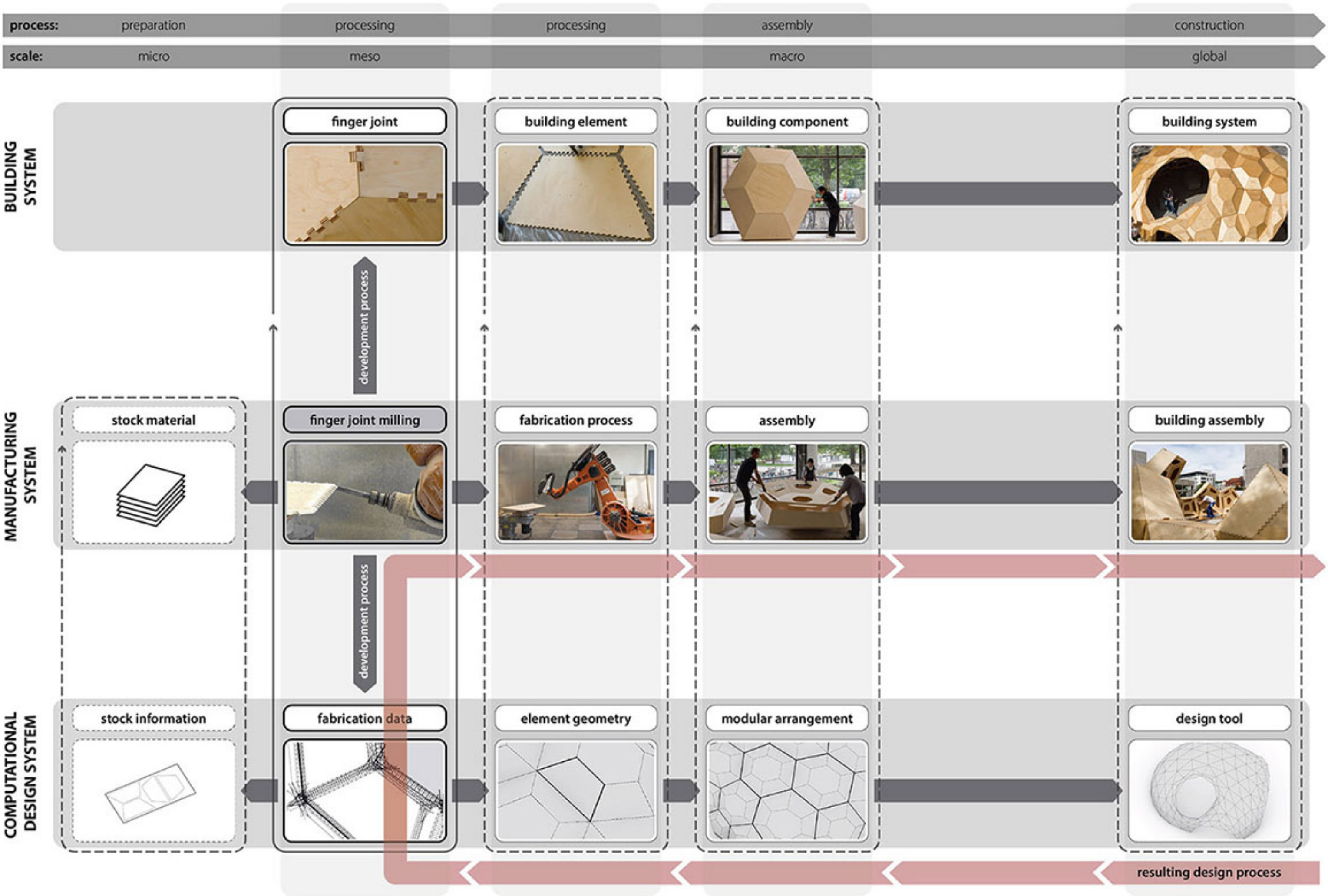

Figure 7.10: Development process overview of Case Study 1. The development process is highlighted with dark gray arrows, and the resulting design process of the demonstrator with red arrows. The process was initiated by the development of a fabrication step and branched out towards a building system and a computational design system. Although stock material was part of the manufacturing process it was not necessarily part of the development process. Four process or building system hierarchies can be identified, which were developed bottom up. The diagram contains images by ICD/ITKE University of Stuttgart.

This relationship was observed in later development steps as well. In subsequent experiments with polygonal plates on the turntable positioner (which acts as a seventh axis to the kinematics of the industrial robot) it was observed that smaller plates would inhibit the robot from milling from below the plate as the spindle or the robot wrist would collide with the turntable.

Similarly, it was observed that if the turntable was positioned further away from the robot, it would not be able to reach certain points of elongated polygons, or polygons that were too small.

Through iterative testing, the constraints of the robot's kinematics in relationship to each specific fabrication step, and later, the entire manufacturing process, were discovered. Although it was recognized that these constraints were directly related to the specific machine setup such as the robot type and its position and distance to the turntable positioner, this relationship was not further investigated until after the project was finished. Instead, the constraints were considered non-negotiable limits in the computational design tool. For example, when it was discovered that no connection angles of less than 15 degrees could be milled due to the spindle geometry and tool length, this limit was internalized in the development process. The limits were also programmed into the computational design tool as post-processing analyses. After a design was generated, polygon sizes and connection angles would be analyzed, and highlighted if they were outside those limits.

The development steps for this project relied on iterative prototyping and learning. Starting from a single line of finger joints to the development of the manufacturing system, each step had its own set of challenges in programming, fabrication controls, material constraints, and engineering. At the same time, the possibilities of aggregating the resulting building elements into a building system were investigated in every step. By engaging with all these questions in every step, the increasing complexity could be handled while ensuring constant feedback between these disciplines. It can be argued that during this iterative development process, the relationship between design space and machine setup was explored as well.

The building system development also received constant feedback from the design process. Here, design intent, manufacturing constraints and computational design tool development are reciprocal. For example, the size of the openings on the inside of the components was evaluated from an aesthetical point of view but also required for the assembly of components on site. Another example is the division of the double-layered structure into two single layers: an interstitial space was formed in one part of the pavilion to visualize the tectonic logic of the system [191]. While the division of the double-layered structure does not affect the manufacturing system or the fabrication of a single plate, it does require special conditions in the design tool as well as a more detailed structural analysis.

7.1.7 Research result: Information flow analysis

To evaluate how the morphological differentiation of the building system was digitally generated, processed, visualized, and stored, the computational design process is analyzed in this section.

Two main contributions to this hypothesis can be identified. The first is in reference to the generation and representation of geometric information. As described in the previous sections, each building part was automatically generated as a result of the mesh relaxation process that was developed to control the overall design intent. However, only a minimal amount of geometric information was generated at this point. Each building part was generated as a simple polyline representing the topological information of the plate structure. Both material thickness and joint geometries were not generated, neither for the design process nor for the manufacturing process.

The second contribution is in reference to the information flow from design to manufacturing. In this project, the design process could be interrupted at any time while using the mesh relaxation method. This allowed for manual intervention or adaptation of vertices that would otherwise lead to invalid solutions. The mesh relaxation method could then either be continued or stopped completely, upon which the mesh would be translated into the polyline representation of the plate structure and saved as an individual file. Afterwards, an independent computational design process would pick up each plate individually and generate the manufacturing code. This would result in one CAD file and files with manufacturing code for each individual building part.

In conclusion, the simplification of geometric information as well as the division of the design and manufacturing data process allowed for both manual intervention when necessary, and for lightweight data models that contained enough visual information for design decisions, and enough intrinsic geometric information for the subsequent manufacturing process.

7.1.8 Research result: Machinic morphospace analysis

To evaluate how the morphospace analysis can be effectively used to analyze the relationship between the machine setup and the gradient building system's design space, the author applied this method to the project in this section.

The machine setup is critical to the morphospace of the building element and therefore, fabrication and design development are intrinsically linked. In this case study as well as in the following ones, the machine setup has a direct impact on the range of geometric, or morphological, adaptation of the building element that it produces. For example, the finger joint geometry, the size of the building elements, or the connection angles, are directly related to the kinematics of the machine setup and its shape or size. More specifically, the morphological parameter that describes the angle of a finger joint has a direct impact on the overall building system and therefore its overall design space. By limiting the connection angle to a range of 20 to 160 degrees, co-planar connections cannot be produced. Therefore, no matter the global design of a building or structure, each plate will always have to be connected to its neighboring plate in a non-planar angle. Although this is the most visual impact on the design space, many geometric parameters for the building element have an impact on the design space. It is therefore the goal of this analysis to evaluate the relationship between the machine setup and domains of morphological adaptation for a building element.

When evaluating the machinic morphospace, many parameters define the building element's geometry, its impact on the building system's design space, or the machine setup. However, for the purpose of visualizing the relationship between machine setup parameters and building element parameters, only those parameters with a high impact or very close relationship should be considered.

7.1.8.1 Parameters of the machine setup

The machine setup in this case study consisted of a KUKA KR125-2 industrial robot. The robot's kinematic information can be seen in Figure 7.11. The industrial robot was equipped with a 6.5 kW HSD milling spindle. In addition, the industrial robot was connected to a one-axis positioner, or turntable, KPV-1 500. For all fabrication steps, the same milling bit with cylindrical geometry was used: 120mm in length and 20mm in diameter.

During closer examination of the machine setup in the manufacturing development process, the position of the turntable relative to the industrial robot was determined to be the most crucial parameter. The distance was selected to allow for the biggest range of objects to be processed. As the machinic morphospace analysis will show, the added rotational axis of the turntable was crucial for the design space of finger-jointed plate structures.

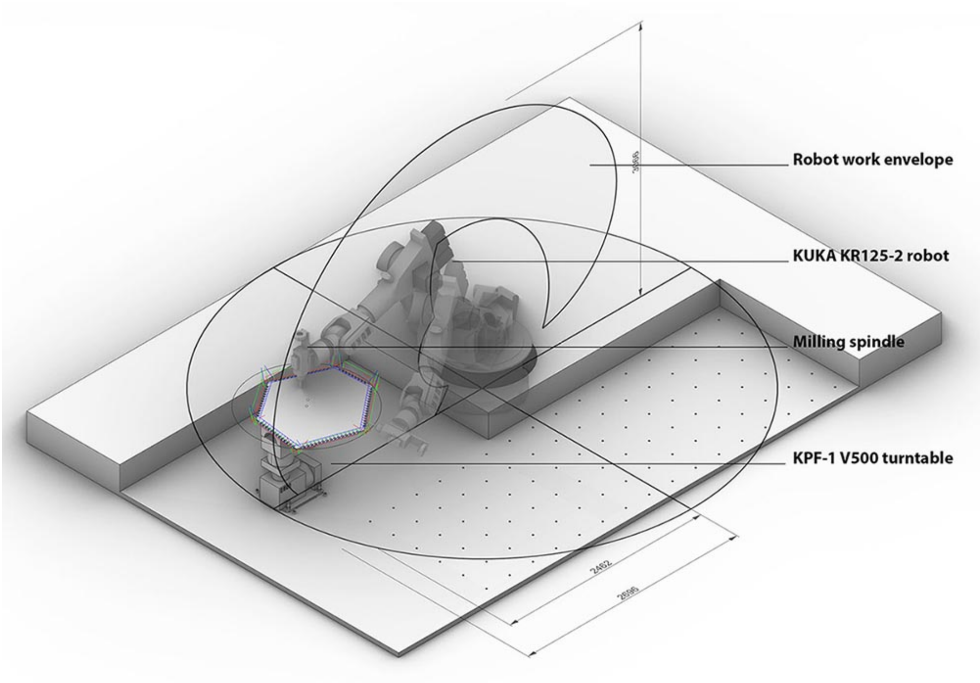

Figure 7.11: Machine setup of Case Study 1. The industrial robot's controls are directly connected to the turntable, extending its kinematic model to seven axes. The robot's work envelope is highlighted in a cross-sectional curve to visualize the distance between the turntable and the robot center.

7.1.8.2 Morphological parameters of the building element

Parameter selection is a critical step for the analysis of the building element's morphospace and its relation to the manufacturing process. Generally, the building element can be described as a polygonal plate with finger joints around all or some edges, made from 6.5mm birch plywood. In order to define morphological parameters that have the most influence on the building system's design space while at the same time being directly influenced by the machine setup or through an interdependence of parameters, Table 7.1 below is used.

	Morphological parameter	Influence on design space	Influence of machine setup
scale increases	**Micro scale (from molecular to cellular makeup)**		
	Material density	medium	medium
	Average or individual wood cell length/width ratio	medium	low
	Average or individual veneer layer thickness	medium	low
	Average or individual grain direction	high	low
	Meso scale (part of a building element)		
	Material thickness	high	medium
	Plywood veneer lay-up	medium	medium
	Single finger joint dimensions	medium	high
	Plate individual edge length	high	medium
	Number of finger joints along single edge	medium	medium
	(P) Polygon-internal angle	high	high
	(A) Finger joint connection angle on single edge	high	high
	Macro scale (building element or component)		
	Number of polygon vertices	medium	low
	Number of polygon edges	medium	low
	Number of finger joints	low	medium
	(D) Plate circumcircle diameter	high	high
	Plate surface area	medium	medium
	Plate directionality (ratio of min to max width)	high	medium
	Module circumcircle diameter	high	medium
	Connection angle at module boundary	high	medium
	Gaussian curvature at plate location	high	medium

Table 7.1: Analysis of morphological parameters in Case Study 1. The higher the rating, the more direct the impact toward the building system's design space or the impact from the machine setup. Based on the rating, the highlighted parameters are selected to evaluate the relationship between the machine setup and the design space of the building system.

In this case study, some of the highest-rated morphological features appear multiple times within a single building element, such as the connection angle along a single edge, or the polygon-internal angle. Because these features can have significantly differentiated values within a building element, it is not possible to evaluate the building element with a single value, but instead with a collection of values.

Based on the above analysis, three morphological parameters are selected that are most indicative of both the resulting design space of the building system, and the influence of the machine setup. Because of the relationship between the scale and the parameters, two out of the three selected parameters refer to a part of the building element, while one parameter refers to the whole building element. This relationship is further explained below:

- *(D) Diameter of the smallest circumcircle of a plate (in mm)*
  The smallest circumcircle is calculated for every plate to define the center point that results in the least space required for its rotation on the turntable. This is beneficial for the machine setup because the turntable will rotate every plate many times during manufacturing. At the same time, the minimum circumcircle is the closest numerical description of the building element's overall size. Here, a single value is used to characterize the size of the building element.
- *(A) Finger joint connection angle (in degrees)*
  This parameter directly relates to the angle between two neighboring plates and has a direct impact on the machine movement as different connection angles are milled by tilting the milling spindle. It is measured by evaluating the angle between the normal vectors of adjacent plates that share an edge. 0 degrees is a coplanar connection, positive values refer to a convex connection, and negative values refer to a concave connection. Here, a single value refers to a single edge of a building element. A building element can have several edges with different connection angles.
- *(P) Interior polygon angle (in degrees)*
  This parameter describes the angle between two adjacent edges within the plate and it affects the overall plate outline. Values below 180 degrees are convex polygon angles, and values above 180 result in concave polygon angles. In the demonstrator of this case study, no plates had a concave polygon angle.

All three parameters are visualized in Figure 7.12. While parameter (D) is a single value for each building element, parameters (A) and (P) occur multiple times within a plate because each plate has multiple edges. Therefore, the viewpoint for measuring is at the meso-scale, focused on a single edge within a plate. A single edge has one connection angle (A) and two polygon-internal angles (P). All edges share the same value for the circumcircle diameter (D). To accurately portray a combination of all three parameters, individual measurement points are used for each plate in the below morphospace visualization.

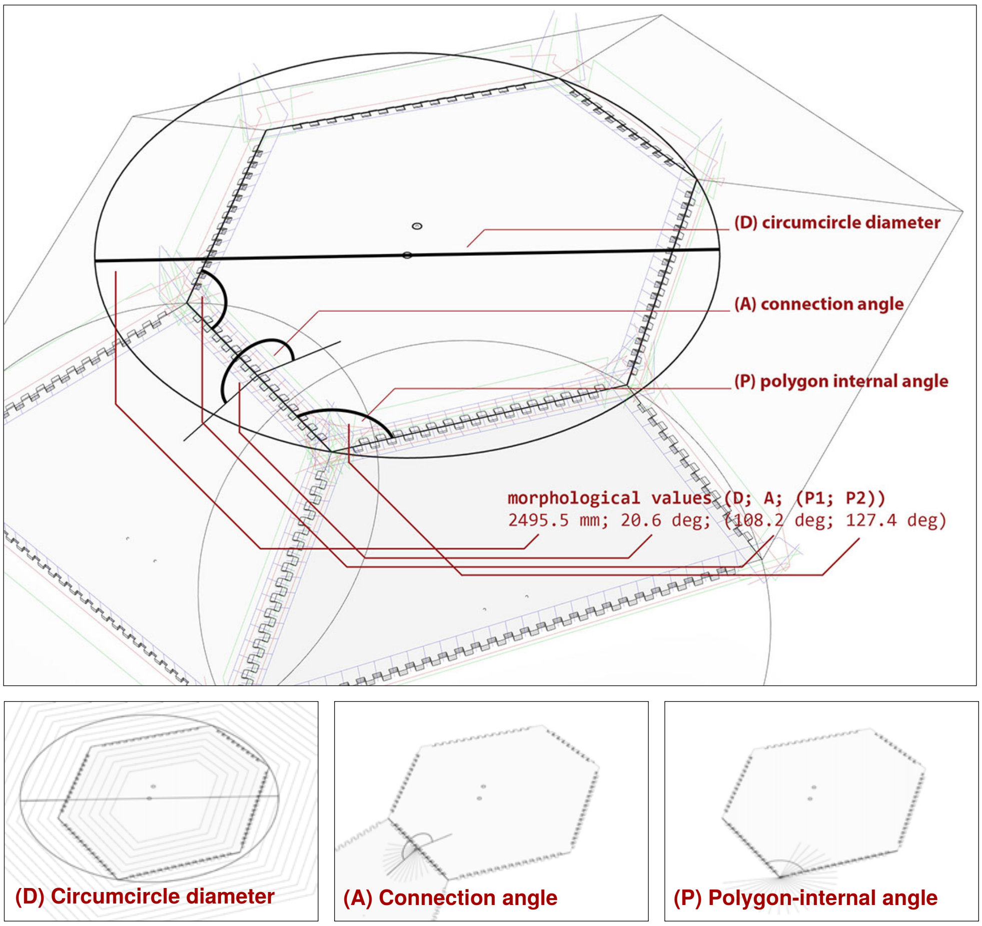

Figure 7.12: Top: Overview of the three morphological parameters of the building element surrounded by other building elements within the building system. The resulting morphological values of a building element's edge are shown within the image to explain the relationship between the three parameters. Bottom left: (D) as the diameter of the minimal circumcircle. Bottom middle: (A) as the connection angle between two plates at one edge. Bottom right: (P) as the interior polygon angle between two edges.

Typical boundary situations of these morphological parameters are described in more detail in the below series of images (Figure 7.13). In these images, the variation of the parameters and example situations for their boundary constraints are shown. There are many other instances during the fabrication steps in which constraints are met; however, they are not all visualized. The min/max constraints of the parameters due to the machine setup, and their interdependencies, can be described as follows:

- The minimal circumcircle, or plate, diameter (D) is constrained by the industrial robot's work envelope. Although the plate can rotate on the turntable, the maximum size is constrained by the robot's reach as well as the rotating plate colliding with the robot arm. The minimal size of plates is given by the size of the turntable but also by geometrical requirements of having at least one set of finger joints on every edge. Plates smaller than the turntable result in the milling spindle intersecting with the milling bed.
- The connection angle (A) is constrained by the inclination of the milling spindle at higher angles. While the milling angle for producing the individual finger joint is linearly related to the connection angle, its depth and spatial requirements grow exponentially towards coplanar connections. Therefore, connections close to 0 and 180 degrees are not possible.
- The internal polygon angle (P) is constrained by the geometrical self-intersection of finger joints at higher angles, which would lead to the milling spindle cutting off parts of the plate. The extreme values of this parameter can also cause reach problems, which is why (P) influences the maximum value of (D).

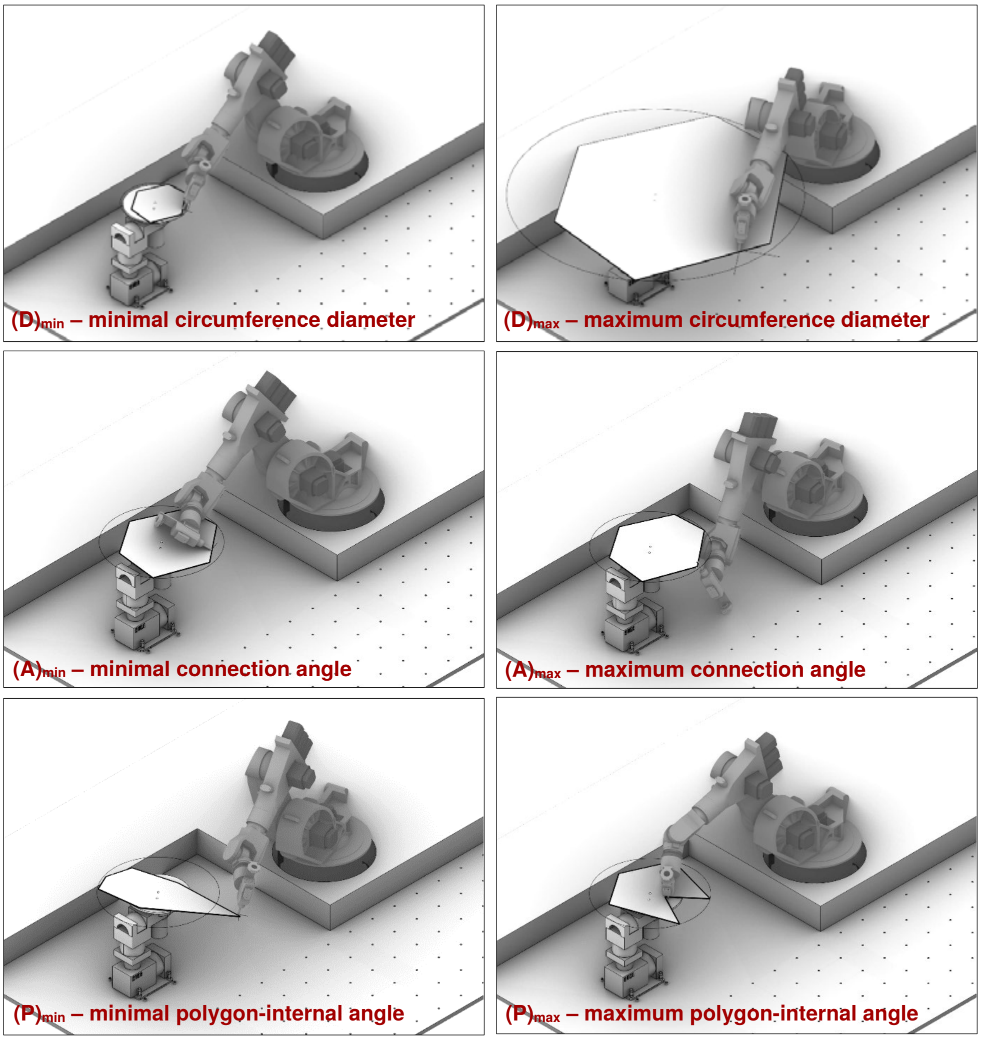

Figure 7.13: Exemplary boundary conditions of all three parameters. Top row: minimal and maximum plate diameter (D). Middle row: Minimal and maximum connection angle (A). Bottom row: Minimal and maximum polygon-internal angle (P).

7.1.8.3 Result: theoretical and empirical machinic morphospace of Case Study 1

In Figure 7.14, the resulting theoretical machinic morphospace is represented by a light gray volume within the three-dimensional parameter space described by (A), (D), and (P). The theoretical morphospace is further divided into two regions, where the smaller volumes in the front represent the *producible region of possible form* (PPF) for the machine setup without a turntable. The larger, lighter volumes represent the PPF with a turntable included in the machine setup, which allows for the fabrication of much larger plates because they can be rotated so that the robot arm can more easily reach the area that is being processed. The larger PPF includes the smaller PPF. At the time of the project, the necessity to install a turntable for the machine setup was a crucial decision, although the boundaries between the two regions of form were not analyzed to such a degree until after the project finished.

The theoretical machinic morphospace is made from two distinct regions, which are divided by a non-producible region at connection angles (A) between -15 and +15 degrees. The two regions are further limited by connection angle (A) values below -165 and above +165 degrees. Because of the interrelation of the three parameters, the regions are further constrained at very low and high polygonal angles (P). Especially high concave polygonal angles constrain the manufacturing process because of collisions, as seen in Figure 7.13.

It needs to be noted that a similar analysis for this project had previously been performed by Achim Menges [237]. In the machinic morphospace analysis of this case study, two deviations occurred. First, a closer examination of the producible constraint boundary resulted in slight adaptations of the theoretical machinic morphospace. Second, the parameter for polygon angle (P) was mapped differently, which also changes how the machinic morphospace is visualized in the three-dimensional diagram.

In Figure 7.15, the empirical machinic morphospace of all 855 building elements of the demonstrator building ICD/ITKE Research Pavilion 2011 is visualized in red. Each building element is represented by a collection of measuring points representing individual connection angles and polygon angles, and a faint polygonal area indicating that they belong together. This polygonal area is in a single plane on the axis of (D) because each plate only has one value for its circumcircle diameter. The parameters (A) and (P) are related in that every edge represents one connection angle and the adjacent polygon angle. Further, the diagram shows 2D and 1D projections of the measurement points for better readability.

Only about 20% of the theoretical morphospace was populated by building elements in the demonstrator building. All plates had a convex outline with no polygon angles (P) above 180 degrees. Connection angles (A) were mainly distributed in the convex region, while concave connection angles remained mostly at low values. The circumference diameter was on average 1290 mm, although the plates ranged from 500 mm to 2475 mm, almost completely filling up the theoretical morphospace.

The analysis of the empirical machinic morphospace shows two situations where boundaries were surpassed. There are two regions where the empirical machinic morphospace is outside the theoretical machinic morphospace, as can be seen in the 2D projection diagrams (D)-(A) and (P)-(A). In the first, it becomes evident that some plates have a connection angle (A) too low for a small plate diameter (D). During the fabrication phase of the demonstrator, this was a problem that was resolved with a special milling bed that was smaller and lifted higher from the turntable so that the milling spindle would not collide with the turntable. In effect, the machinic morphospace was changed with this adaptation of the machine setup. In the latter, it can be observed that some plates exhibit a combination of very low connection angles (a) and very low convex polygon angles (P). As discussed earlier, this would lead to an intersection of finger joints between neighboring edges of a plate. During the fabrication phase of the demonstrator, this problem was simply ignored, resulting in the milling spindle cutting into neighboring edges, and on rare occasions, cutting off the corners of these plates.

The analysis shows that upfront design decisions can heavily influence the region that will be occupied by a building design. For example, the geometric and topological logic of the building system does not result in plates with concave polygon angles although they could be produced by the manufacturing system. It can further be argued that sub-regions of design intent or design performance could be defined upfront or analyzed after a design was generated.

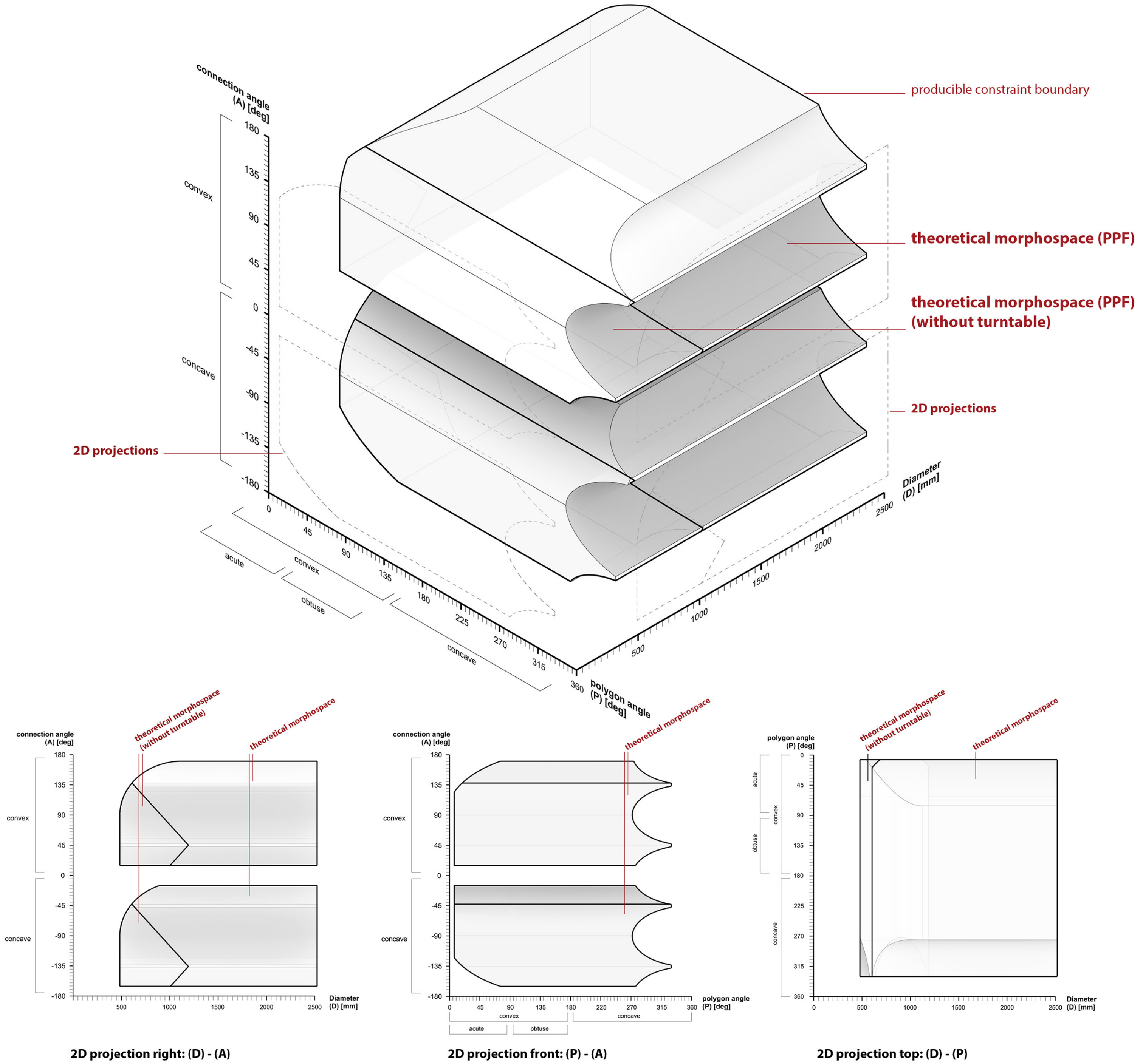

Figure 7.14: The theoretical machinic morphospace of Case Study 1 is visualized as a gray volume with thick outlines, which is further divided into a front part to visualize how small the region of form would be without a turntable as part of the machine setup. 2D projections of the theoretical morphospace are overlaid on the planes of each pair of axes and plotted at the bottom of the diagram as parallel projections.

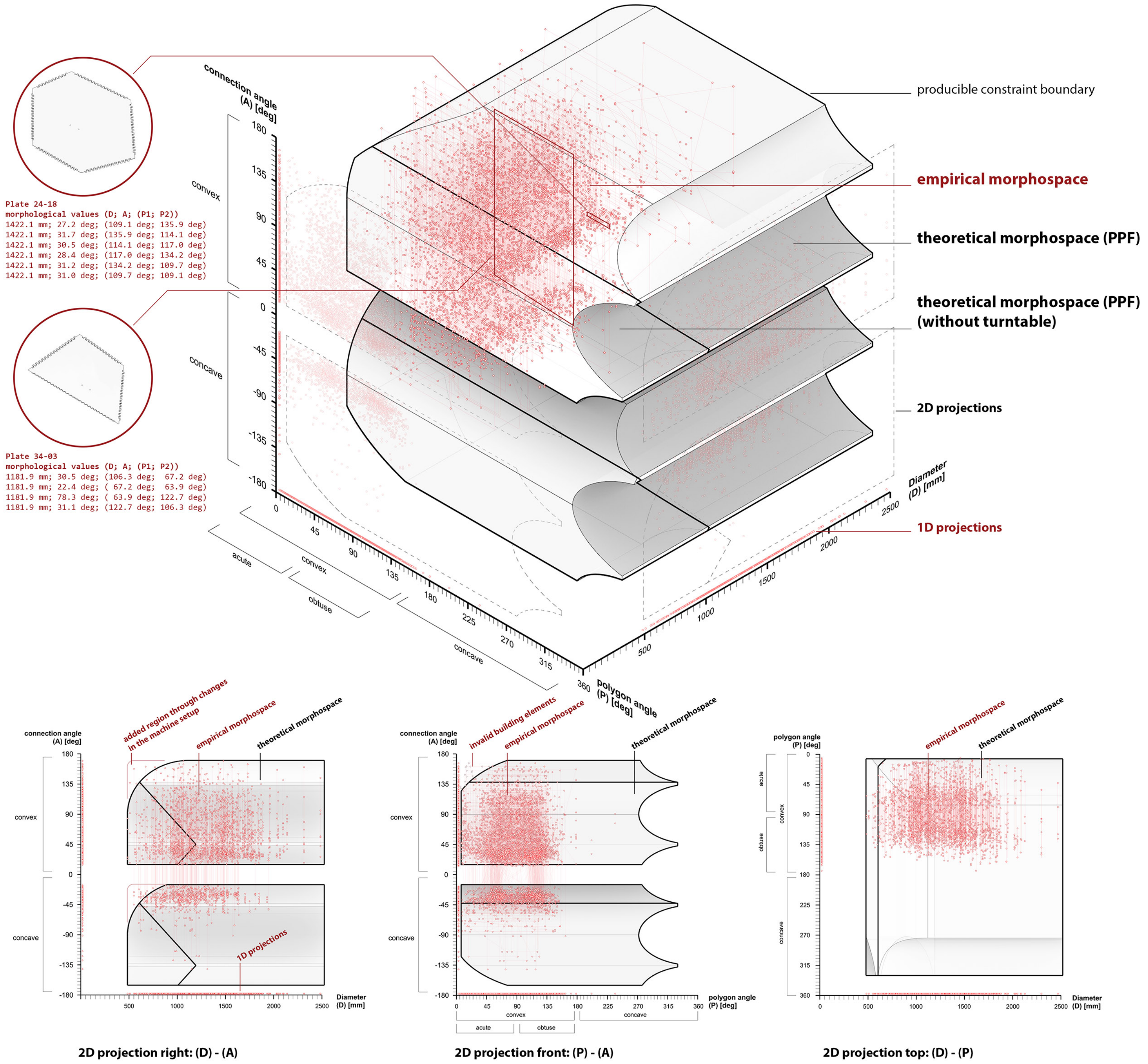

Figure 7.15: The empirical machinic morphospace of Case Study 1 is visualized by red measurement points that represent each parameter value of each plate of the demonstrator building ICD/ITKE Research Pavilion 2011. Two example plates are shown on the top left. Plate 24-18 has very similar values for both (A) and (P), while plate 34-03 has a larger range of variation for (A) and (P), therefore spreading out the measurement points further.

7.1.9 Acknowledgements

This project was a collaboration between several researchers and students.

Institute for Computational Design – Prof. Achim Menges
Institute of Building Structures and Structural Design – Prof. Jan Knippers

Concept & System Development
Oliver David Krieg, Boyan Mihaylov

Detail Design & Fabrication & Construction
Peter Brachat, Benjamin Busch, Solmaz Fahimian, Christin Gegenheimer, Nicola Haberbosch, Elias Kästle, Oliver David Krieg, Yong Sung Kwon, Boyan Mihaylov, Hongmei Zhai

Scientific Development
Markus Gabler (project management), Riccardo La Magna (structural design), Steffen Reichert (detail design), Tobias Schwinn (project management), Frédéric Waimer (structural design)

Other contributors to the aspects covered in this dissertation are listed below.

7.1.9.1 Finger joint connection

The original development of the finger joint connections was done by the author and his colleague Markus Burger as part of the seminar “Robotically Manufactured Material Systems” taught by Christopher Robeller at the ICD in 2010. The finger joint was further developed by the author and his colleague Boyan Mihaylov during the first half of the above-mentioned studio.

7.1.9.2 Manufacturing system

Under the supervision of the above-mentioned research associates, the author developed the manufacturing system together with his colleagues Boyan Mihaylov and Nicola Haberbosch.

7.1.9.3 Global design

Under the supervision of the above-mentioned research associates, the author developed the global design and the required tools together with the above-mentioned student team.

7.1.9.4 Structural design

Structural analysis of the connections and the global design of the demonstrator was supervised by Markus Gabler, Riccardo La Magna and Frederic Waimer. The student team assisted with data transfer and small-scale testing.

Figure 7.16: The HygroSkin Pavilion (Image by ICD University of Stuttgart).

7.2 Case Study 2: HygroSkin - Meteorosensitive Pavilion, 2013

7.2.1 Project introduction

Between 2012 and 2013 the Institute for Computational Design and Construction (ICD) engaged in a research project that explored a combined approach of novel manufacturing technology and an innovative use of material properties. The project HygroSkin – Meteorosensitive Pavilion was initiated from a commission by the FRAC Centre Orleans for its renowned permanent collection and was first shown in the exhibition “ArchiLab 2013 - Naturalizing Architecture” in September 2013 (Figure 7.16).

While modern material science in building construction has a history of suppressing wood’s material behavior that could lead to a dimensional change or dynamic deformation, this project was motivated by the inherent qualities of wood that can lead to such changes. The initial research objective was to highlight the responsive capacity of the material through dimensional instability of wood in relation to moisture content for the development of meteorosensitive apertures that can open and close autonomously. By embedding the humidity-responsive behavior in the material of the apertures, the feedback from and interaction with the surrounding environment became part of the material system and the architecture. The aperture’s wood-composite skin can adjust its shape in direct response to changes in ambient relative humidity. While the development of meteorosensitive apertures using wood veneer was a research topic conducted by Steffen Reichert and David Correa at the time [289], the means of exhibiting and housing these apertures became an area of interest for the development of the demonstrator building.

For this research project, a building system was developed based on the potential form-finding capacity of the material. It was developed as a modular wooden skin employing the self-forming capacity of initially planar plywood sheets for the formation of conical surfaces, within which a humidity-responsive aperture was placed. As described in Chapter 5, employing the capacity of elastic bending for the development of complex but structurally performative material systems has the potential to change structural engineering approaches toward wood, and to find more material-efficient solutions and larger design spaces for timber structures. After first investigating the properties of the material and potentials of elastically formed shapes, a material system was developed in parallel to a manufacturing system. Lastly, a computational design process was developed integrating the material's capacity to physically compute form through elastic bending, the design and structure of the building components, the detailing of the joints, as well as the generation of manufacturing data such as robotic machine code.

The project was initially designed by Achim Menges and Steffen Reichert in an earlier competition phase. For the main execution phase of the project, the author participated as a research associate at ICD in a team of seven researchers and one professor. The author's role was to lead the execution of the project, which included the material system and manufacturing system development, as well as planning and executing the fabrication and assembly processes with the help of student assistants. Further acknowledgements are in sections 7.2.5 and 7.2.9.

Some of the project details of this case study were published in papers by Correa *et al.* [66] and Krieg *et al.* [194]. Some results presented in this case study are unpublished, particularly details on the manufacturing development in section 7.2.3 and the machinic morphospace analysis in section 7.2.8. In the following sections, only the elastic bending of thin plywood components and the integrated manufacturing system and computational design development will be discussed. The meteorosensitive apertures that are placed within these components are not part of this case study.

7.2.2 Investigative motivation: rethinking material characteristics

This case study investigates incorporating material characteristics in the development of a material system. As described in more detail in Chapter 5, wood's elasticity and structural performance have been combined in several research and built projects in the last decades. Usually, however, bending or deformation of building components is seen as a deficiency in the structural design. The motivation for this case study came from the structural potentials of double-curved surfaces that would otherwise have to be constructed in much less efficient ways. Instead, using surface curvature as a means to achieve geometric and therefore structural stiffness, and the material's potential for elastic bending, could be combined [66]. However, this combination requires a more complex manufacturing process. Computational design and robotic manufacturing methods promised to enable this combination.

While this approach towards the development of a material system poses a challenge due to the interrelation of force, form, and fabrication, it promises a much more effective use of the material. In a series of previous projects, most notably the ICD/ITKE Research Pavilion 2010, the research group explored how the elastic bending of wood enables the generation of complex geometries from initially flat sheets of plywood, demonstrating both considerable structural capacity and a novel tectonic repertoire for architectural articulation [104]. While the ICD/ITKE Research Pavilion 2010 uses local elastic bending within continuous strips, all strips connect to form the global structure, the HygroSkin project builds on the formal and performative transfer of material behavior into material systems on a modular level. However, both projects result in a global design influenced by the elastic bending of each individual building element.

This case study is of interested because it extends the line of research by exploring the architectural potentials of "local" elastic bending of individual components in the context of modular construction. From the outset, the research group was focused on developing a building system based on a single-curved bending geometry that could be used for generating morphologically differentiated building components through a repetitive yet parametrically adaptable manufacturing process. From all the possible surfaces plywood can be elastically bent into, different options were tested beforehand for their functionality and efficiency in the context of a modular construction system. The method chosen was to start out with initially flat, polygonal sheets of plywood that could be elastically bent and subsequently locked into a conical shape. A key performance indicator for the case study is the ability of the component to connect in all directions with its own plane to become part of a larger segmented shell structure. This would be enabled by the development of a highly adaptable and repeatable manufacturing system.

7.2.3 Development of the manufacturing system

During the early development, the geometric analysis of cone shapes became an area of particular interest, providing the basic morphological principles for further development. A cone shape can be unrolled into a flat sheet by introducing at least one seam from the cone base to its center. Its geometry makes it possible for the initially flat surface to find a force equilibrium in a regular, circular cone, by connecting the seam [194]. Although a circular cone exhibits a circular symmetry around its revolution axis, intersecting multiple cones of the same kind within the same place results in unique intersection curves, when placed in randomized locations. Architectural and structural implications of cone intersections were first explored by Frei Otto when he used sand boxes with holes underneath them, which resulted in multiple cones intersecting within the same plane [262]. When cones of the same base geometry are intersected in the same plane, their intersection curves are all single-curved and within a plane perpendicular to the cone's base plane (Figure 7.17).

While this geometric relationship can have architectural and spatial potentials, intersecting cones can also exhibit structural advantages. First, a single-curved connection between intersecting cones would be easier to manufacture and more stable than a straight connection: A curved connection allows bending forces between cone components to be distributed into tension and compression between the ends and the center of the connection curve. Second, the curvature of the cone component itself increases its dimensional stability in comparison to a flat component. In addition, the intersecting geometry of each cone module operates similarly: while a random distribution of cones on a plane result in different connection curves, they all follow the same geometric rules and can be easily parametrized. All cone modules will therefore connect to their neighbors with the same set of rules but with varying geometry. A modular arrangement with the same type of connection is therefore feasible. Using a set of rules instead of fixed geometric values is fundamental to the development of a parametric building system [194]. However, if each cone component is based on the same base cone geometry, the component curvature is the same and therefore the cone itself can be manufactured using a single formwork mold while only its outline changes (Figure 7.17).

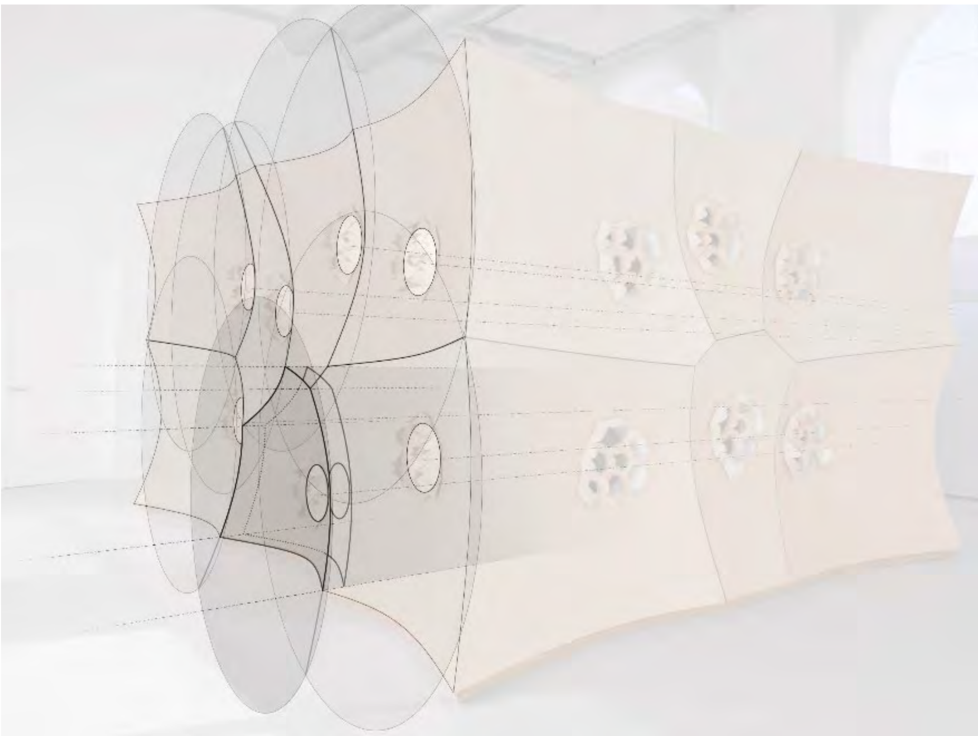

Figure 7.17: Intersecting cones with the same base geometry result in a variation of their outlines. The intersection between two cones remains single-curved, making its fabrication process more feasible.

On a larger scale, an arrangement of intersecting cones can be seen as a plate structure. Instead of planar plates, each component is made from a cone shape. Similar to other research projects in this thesis where plate structures were developed taking natural systems into account [66; 330], the main characteristics of this plate structure lies in the topological rule of joining not more than three plates at one point. This results in very low bending forces along the connection [253]. However, this structural characteristic of plate structures is only applicable when the global structure also exhibits a double curvature [219]. In situations where all plates are arranged in the same plane such as in a flat wall or ceiling, the connections experience unfavorable forces. It was of interest for this project to explore these situations but with locally double-curved components such as cones. To cope with potentially higher forces in component connections, the components themselves were required to have a structural depth large enough to accommodate a bending-stiff connection around their boundaries (Figure 7.18) [194].

For this project, 4mm thin birch plywood was chosen because it was available in the large stock sizes and could be easily bent into the cone's curvature. The tip of the cone was cut out as a circular hole in order to avoid regions of higher curvature and to include the meteorosensitive openings later in the process.

Since cones are bent in only one direction, a line drawn from the center of the cone to its outer edge is straight, and as such, lightweight Styrofoam strips can easily be integrated between two layers of the same cone-shaped plywood piece. This sandwich-like construction provides geometrical and structural stiffness and increases the connection area between two adjacent cone modules. 100 mm thick Styrofoam strips were chosen as infill material because they can provide a high stiffness while being extremely lightweight (Figure 7.18) [194]. In a series of manufacturing steps, strips of Styrofoam are glued between two layers of plywood that was previously elastically bent into a cone, creating a composite structure. After lamination is complete, the component becomes a structural entity capable of acting as a plate structure element. To achieve a strong lamination between the layers, it was decided to use vacuum forming (Figure 7.19).

The development of these manufacturing steps raised the question of how to ensure dimensional accuracy. Both the 4mm thin plywood sheets and the Styrofoam cores are flexible until laminated into a rigid component, and they can easily deform while the glue is still curing.

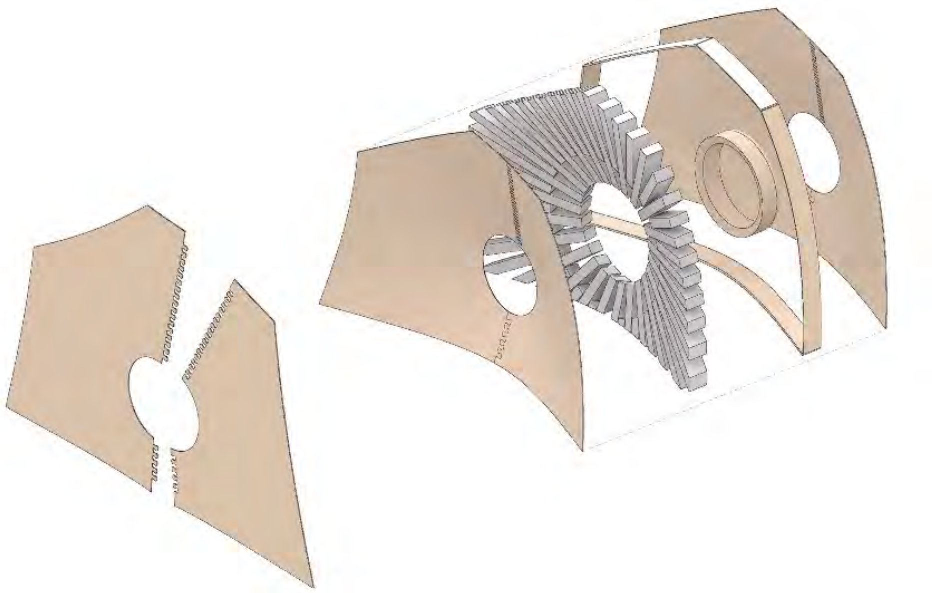

Figure 7.18: Exploded view of a HygroSkin cone component. It is made from two outer 4mm plywood layers and a Styrofoam core. The plywood is cut out as a flat sheet and elastically bent into its cone shape. The edges are cut from flat plywood as well and form connection areas to neighboring modules (Image by ICD University of Stuttgart).

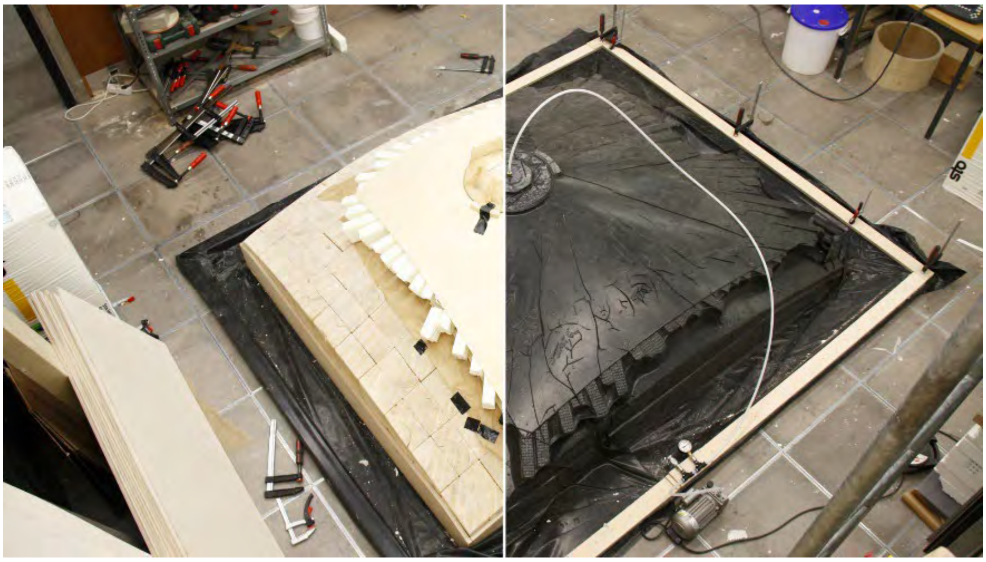

Figure 7.19: A building component during and after vacuum forming on the custom-built formwork (Image by ICD University of Stuttgart).

Additionally, the three-dimensional nature of a cone-shaped building component with differentiated outlines poses a challenge for typical quality assurance techniques in comparison to planar plate components [194]. This required a rethinking of manufacturing steps, and a strategic implementation of manual work and digital fabrication techniques. For ensuring a precise geometry of the cone curvature, a mold was built that would be big enough to receive all components for vacuum pressing. The plywood and Styrofoam cores were manually glued and assembled on the formwork, and then wrapped with a vacuum bag. In the vacuum forming process, the self-formed plywood provides consistency in the geometric definition while the Styrofoam core provides dimensional stability. As a result, the cone surface exhibits high accuracy in all three dimensions [194]. The formwork itself was also created using a CNC milling process.

In summary, the first and manual steps to produce what is called a raw module, are as follows:

(1) The geometric information for the plywood layers is retrieved from the digital 3D design model, where the cones can be unrolled and mapped on a flat plywood sheet.
(2) Each cone surface is made from two initially flat sheets of 4mm plywood that are cut out on a on a 3-axis CNC machine. They have a puzzle-shaped joint along their edges to connect to each other.
(3) In a combined bending and gluing process, the two strips are connected along their puzzle-joints and therefore elastically bent into their cone geometry.
(4) After two plywood cones are ready, they are glued together with Styrofoam strips on top of the formwork, and then wrapped in a vacuum bag.
(5) The vacuum pressure pushes the component onto the formwork and ensures a high and repeatable surface accuracy shared by all components.

In order to evaluate the fabrication precision up to this point, a three-dimensional laser scanning process was employed on a subset of the cone modules. By scanning the modules, it was possible to evaluate the location of 25,000 3D points on the surface of the vacuum-formed cone surface and compare them to the surface geometry of their respective 3D model. The comparison showed an average deviation from the digital target geometry of less than 0.6 mm [194]. This measurement verified that the initial manual fabrication steps ensured a high enough accuracy for the subsequent process. However, while the vacuum forming ensures surface accuracy, this process cannot ensure the accuracy of the component's edges or corners because of rotational slip between the plywood layers and the Styrofoam core during curing [66; 194].

Therefore, a robotic fabrication process was developed to be implemented after these initial manual steps. The vacuum forming process results in an approximate module outline, and the plywood layers are fabricated with an additional offset to provide enough material that can be trimmed off afterwards. Here, the robotic fabrication process is meant to provide the accuracy for the outline of each cone module. In another set of manufacturing steps, robotic fabrication is implemented as an adaptable process to measure first and then trim each cone module into its precise outline:

(6) The raw sandwich component is mounted onto a turntable positioner in the robot cell.
(7) The robot's tool center point (TCP) is used to measure the position of the module's corners. It is not important to meet the exact coordinates on the horizontal plane, but rather to measure the location of each point in the vertical direction. That way the plane in which the module is positioned can be determined (Figure 7.20).
(8) The measured points are read by the fabrication script, and the 3D position of the module is approximated through a simulated annealing process, which is a probabilistic technique for approximating the position (Figure 7.20).
(9) After the module's position in the virtual model space is adjusted, the machine code for the robotic fabrication process is adjusted and exported.
(10) The robot trims the module edges with a circular saw, and the foam core with a foam cutter (Figure 7.21).
(11) The trimmed module is taken off the turntable positioner and pre-cut plywood strips are inserted into the now precisely trimmed edges, which will act as connection interfaces to adjacent modules.

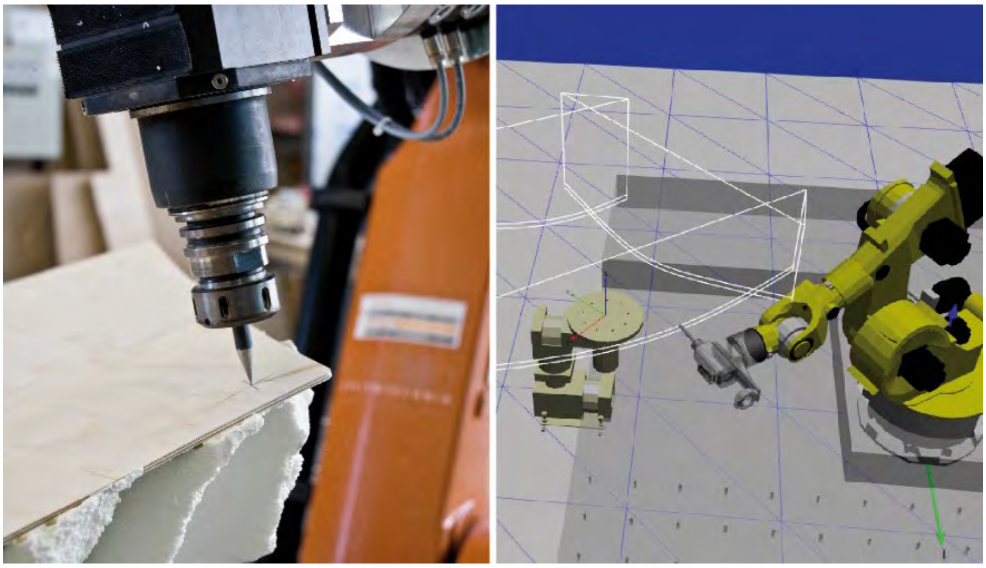

Figure 7.20: Adaptive robotic manufacturing. Left: a measuring tool is used on the robot to scan the cone module within the robotic manufacturing setup. Right: the robot code is adapted to the actual location of the cone module (Image by ICD University of Stuttgart).

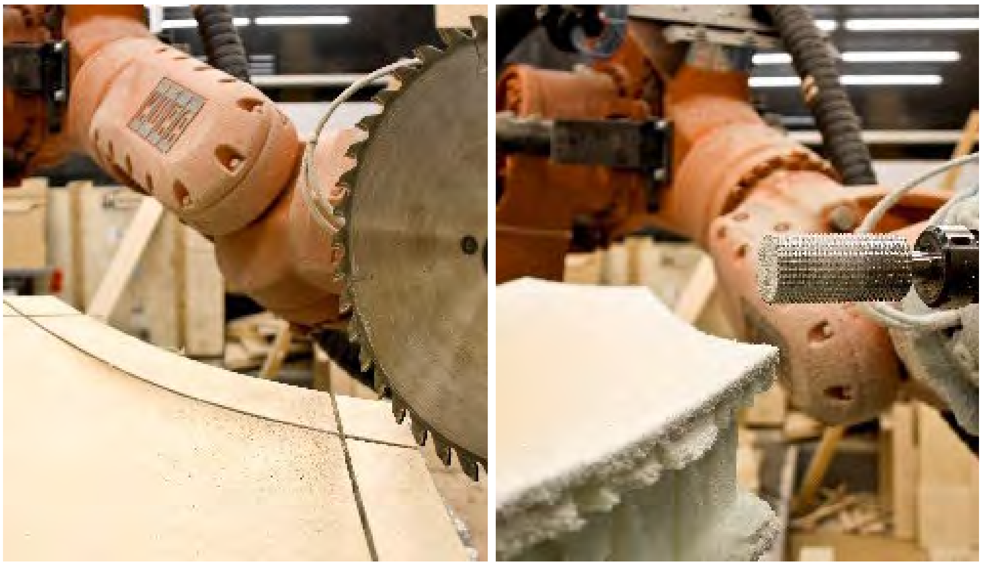

Figure 7.21: The subsequent robotic trimming process is divided into two steps. First, the outline of the cone module is trimmed using a saw blade (left), then, the foam core is cut with a foam milling bit (right) (Image by ICD University of Stuttgart).

The strategic integration of robotic fabrication makes this case study unique. Here, the robotic process becomes one of many steps within a manufacturing system. While the production of the sandwich modules is possible through common manufacturing techniques of low complexity, the module's required level of high geometrical precision can only be realized efficiently through the integration of robotic fabrication methods [66; 194]. This ensures the possibility to manufacture differentiated module geometries using a single base geometry, while at the same time ensuring the high precision that is necessary for the subsequent on-site assembly and general fit of the building system.

In this manufacturing system development, the manufacturing data is generated directly from the design model, and the design model is developed in conjunction with the manufacturing process. The next section will explain how the development of a computational design tool is necessary for this manufacturing system to work seamlessly and allow for the differentiation of each sandwich module outline.

7.2.4 Development of the computational design system

The development of a computational design process to allow for the exploration of the design space was established in parallel to the manufacturing development and resulted in a computational design system that facilitates the design and manufacturing of the building system. The goal of the computational design system is to integrate the material's capacity to physically compute its form in the elastic bending process [194], the global arrangement of the modular cone components, the parametric detailing of the connections between components, and the generation of machine code and fabrication data. The system was used to reflect on and integrate feedback of manufacturing constraints throughout its development process.

As such, the computational design process starts with the automated population of cones on a design surface. The user can then decide whether to allow for an equalized distribution of these modules through a circle-packing algorithm, simulating forces to achieve equal distance between each cone, or to use manual intervention to move each cone module into a pre-defined position (Figure 7.22). This interactivity allows for minor design changes or different methods for the distribution of the cone modules depending on external or context-specific factors. In this project, the cone modules were placed to achieve an equal distribution but also ensure a visible difference in their shape. As another constraint in the design process, it can be assumed that each edge of a cone module should have a minimum edge length for structural reasons. Other manufacturing constraints such as the size of the module were implemented, but only once the manufacturing system neared the end of its development.

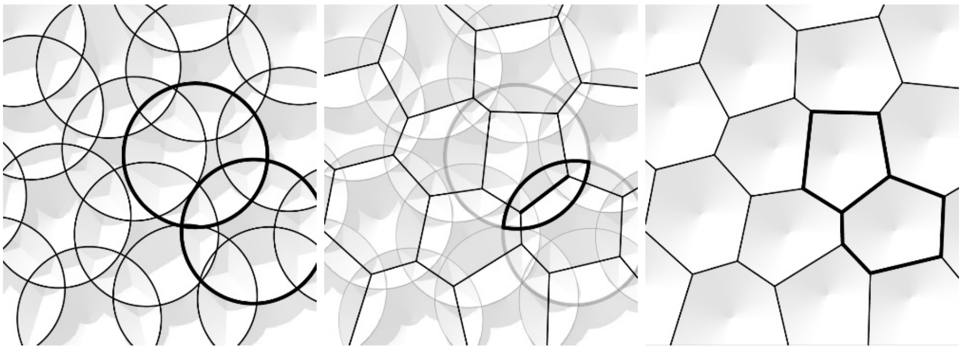

Figure 7.22: From left to right: distribution of cones on a flat surface viewed from top, their intersection, and resulting module geometry.

While the cone modules are placed, they are represented as a point on the design surface. Multiple design surfaces can be used in parallel, as was the case in this case study to design the four walls of the demonstrator. At the same time, values for the cone angle and depth can be chosen, and cones are generated and intersected with their neighbors at the same time (Figure 7.22). This allows for direct visual feedback of the geometric representation of the intersection and the resulting cone module outline. The depth of the module is given by the added values of plywood material thickness and Styrofoam thickness. While the parametric design process can be stored as 3D BREPs at any time, a real break between the design and the manufacturing workflow only happens at the early stage of this process, where a single cone surface exists as a representation for each module. The thickness of the cone module is considered a parameter of the manufacturing system. However, the material thickness itself is not generated in the computational design tool, as each plywood cone shape is represented only as a surface and not as a volume. For every subsequent step, it is not necessary to generate the geometry but rather keep the plywood's material thickness as an internal parameter.

Once the design is finalized, the second part of the computational design system generates all manufacturing necessary for the execution and assembly. Each module can be selected by the design tool, and a bill of materials is generated. This includes the front and back plywood sheets, the foam core, the edge conditions, connection elements, and the meteorosensitive inset that is produced in a separate process. All connection strips along the cone modules' boundaries are also produced separately on a CNC machine, although their tool paths are generated by the computational design system [194]. They are calculated by intersecting the connection plane of an edge with the cone's surface and subtracting the material thickness of the plywood. Each piece is subsequently reoriented in 3D space onto the CAD world's XY-plane. The flat plywood sheets for the cone modules are generated similarly: The cone surface is unrolled onto the world's XY-plane and then divided into two parts to be cut out on a CNC machine. Puzzle-joints are added along the seams to ensure a precise connection between the two pieces. 3D and 2D drawings are automatically generated to assist and guide the manual assembly of the cone module [66; 194].

For the robotic fabrication process, an interactive simulation of the robot's and turntable's motion, as well as the generation of machine code, was developed. In a first step, the outer edges of both plywood layers of a cone module are used to calculate the tool paths for the trimming and foam cutting process. The tool paths are generated through offsets from the cone module's edges. For both the circular saw trimming and the foam cutting process, the spindle orientation is perpendicular to each edge's connection plane, which in turn is defined by the top and bottom plywood edge of the cone module. Because the robotic machine setup has in total seven axes of rotation, two of those axes can be adjusted without changing the physical outcome. The two adjustable axes are the turntable rotation and the orientation of the robot wrist, or the spindle. In this case study, G-Code was generated from the computational design tool and then loaded into a robot simulation software the robot cell was using. Here, these two values can be adjusted to allow the robot to avoid out-of-reach or collision events. The manual adjustment of the robot's position allowed to analyze the machine setup's constraints in detail, albeit in a non-automated and iterative method.

Before the G-Code is loaded into the robot simulation software, the laminated module is loaded onto the turntable positioner. A measuring tool mounted to the spindle chuck is used to measure each corner of the top surface of the module. The coordinates of the resulting four to seven points are loaded into the computational design system, and the 3D position of the module is then approximated through a simulated annealing process as described above [194]. Once the revised position of the cone module is found, the G-Code of the robotic manufacturing process is adjusted, exported, and loaded into the simulation software. This adaptive code generation was developed because of the sensitivity of the manufacturing setup towards the placement of the cone module. When the module is fixed on the turntable positioner, any minor inaccuracy can result in large deviations in the module's edge locations. Additionally, the module could be slightly misplaced and in a different orientation than assumed, which would result in a distorted shape after trimming.

Instead of enforcing accuracy, the robotic setup was used to adapt to deviations. The adaptive generation of robot code and the interactive simulation of the robot and turntable kinematics is possible because of the integration of manufacturing data generation in the parametric modeling environment.

7.2.5 Project results

Following the development process, the demonstrator was manufactured at the faculty's robotic fabrication laboratory. In total, 28 wall modules and three ceiling modules were manufactured for the 4m by 5m demonstrator with a rectangular footprint. In addition, 28 apertures were manufactured by injection molding using a 3D printed mold. The responsive apertures adjust the porosity of the pavilion's walls in direct response to changes in ambient relative humidity. Everyday climatic changes trigger a silent movement of the wooden skin. This subtle yet constant modulation of porosity and light between the pavilion's exterior and interior provides for a unique experience (Figure 7.23). The pavilion was transported by grouping cone modules of similar size in transportation boxes that could be stacked within a typical container truck (Figure 7.24).

Figure 7.23: The HygroSkin pavilion was set up on the university's campus before being shipped to the FRAC center (Image by ICD University of Stuttgart).

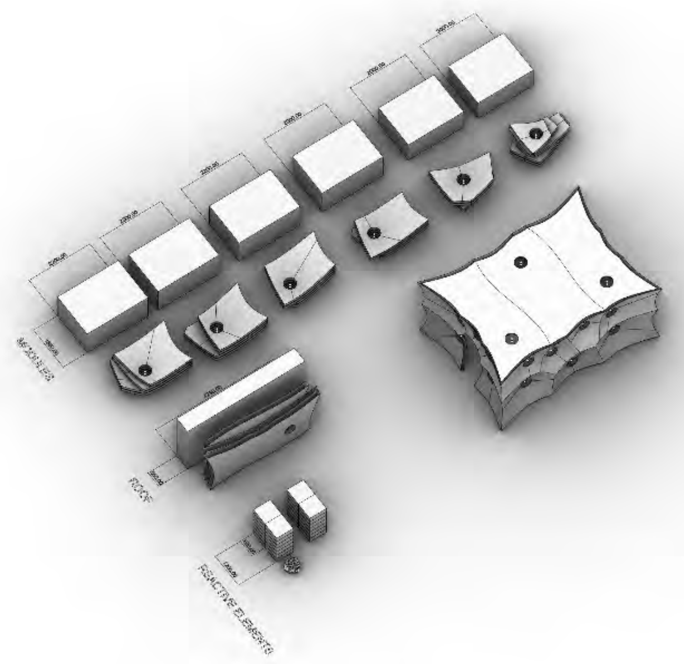

Figure 7.24: Overview of the transportation arrangement for the pavilion. Groups of three to four cone modules were stacked and placed into custom-built transportation boxes.

7.2.6 Research result: Process analysis

To evaluate how the integrative development process was enabled in this project, the relationship between the gradient building system, manufacturing system, and computational design system is analyzed in this section.

The process in this case study can be described as a directed search for complex shapes of structural efficiency incorporating material properties that have previously been ignored. The case study is an example of negotiating availability: material performance availability, stock material availability, technology availability, and access to technology due to budgetary constraints. Employing material characteristics such as elastic bending poses many challenges. First, it requires access to stock material large enough to meet the requirements of a building component or module. Second, connections between elastically bent sheets of plywood that provide a continuous material stiffness are difficult to fabricate and assemble. However, using standard stock material to manufacture highly complex and differentiated building components can be considered a key strategy of integrating innovation within an existing industry framework.

When investigating the architectural potentials of material characteristics such as elastic bending, developing a manufacturing process that can either control or react to the material's behavior becomes a necessity. The relationship between material behavior and manufacturing complexity resulted in an integrative development process where manufacturing and design are intertwined. Compared to the previous case study where a singular robotic fabrication step for milling finger joints was developed, this manufacturing process had multiple manual and automated steps that benefitted from each other. The strategic placement of manual and automated fabrication allows for the resourceful distribution of labor and quality control. For example, the robotic process is used to measure the cone modules' three-dimensional location also reveals the average and maximum deviation between the measured points and the digital geometry.

The research project presented in this case study started as a top-down design process that guided the subsequent development of manufacturing technology and computational design tools (Figure 7.25). The switch from a top-down design process to a bottom-up development process happened at an early stage of the project.

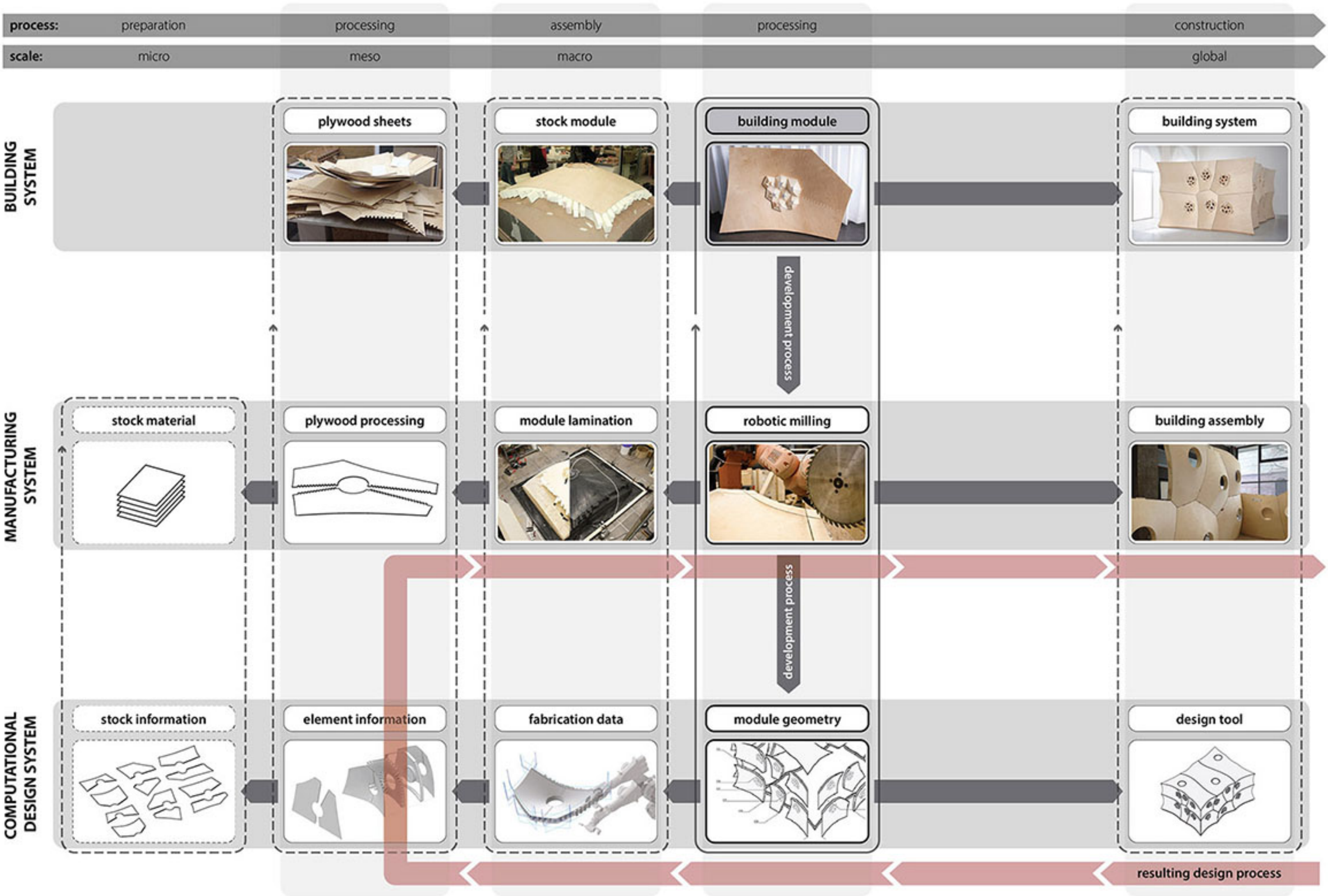

Figure 7.25: Development process overview of Case Study 2. The development process is highlighted with dark gray arrows, and the resulting design process of the demonstrator with red arrows. Case Study 2 is the only project where the development process originated in a building system or material characteristic. It progressed towards the manufacturing system and computational design system from there. Within the manufacturing system it can also be observed that robotic processing is the last in a sequence of manufacturing steps.

This bottom-up development process resulted in design explorations used to verify the initial design. However, the goal of developing a gradient building system was set from the outset of the project, and a known characteristic of cone intersections. It can be argued that in this project, instead of discovering the potential design space during the development process, it was expected because of the known geometric relationship of intersecting cones. However, this theoretical knowledge had to be translated into physical building components through the integration of manufacturing technology and material characteristics.

7.2.7 Research result: Information flow analysis

To evaluate how the morphological differentiation of the building system was digitally generated, processed, visualized, and stored, the computational design process is analyzed in this section.

When compared to the previous case study, similar contributions can be identified. First, the generation and representation of geometry was limited to the least amount of required information to oversee the design process and to generate the subsequent manufacturing information. In this case study, the modules were represented only by three-dimensional surfaces indicating the center of the plywood cones without any material thickness. This was enough information to visually represent the design of the demonstrator and to generate manufacturing information. Second, the computational process was again interrupted to allow for manual intervention and small adjustments before the manufacturing data was generated. For the subsequent manufacturing process, the design model was loaded, and manufacturing data was only generated per module, thereby allowing an individual analysis for each module before moving on to the next.

An additional contribution to this discourse that can be identified in this case study, is how the geometric information was processed during the robotic manufacturing setup. As described previously, the position of each raw module on the turntable was measured using the robot and adjusted in the digital model. Represented and referenced by the top (outer) plywood layer of the cone, the CAD file for each module is updated based on the measured position in the real world. As a result, individual CAD files are created for each module's manufacturing process, documenting not only their position on the turntable but also their dimensional accuracy in relation to the ideal cone shape from the design model.

In conclusion, the simplification of geometric information and feedback from the manufacturing setup showed the value of a detached computational process with real world accuracy tracking and updates.

7.2.8 Research result: Machinic morphospace analysis

To evaluate how the morphospace analysis can be effectively used to analyze the relationship between the machine setup and the gradient building system's design space, the author applied this method to the project in this section.

In this case study, robotic fabrication steps are strategically placed in the manufacturing process due to a combination of challenging accuracy requirements and large-scale processes where precision is difficult to control. While the manual vacuum lamination process results in an accurate shape of the module, it also results in an inaccurate module outline. This outline is then precisely trimmed by subsequent robotic manufacturing steps that measure the workpiece and adapt the trimming instructions before execution.

The design space and complexity of the cone module's shape is closely interconnected with the robot's kinematic range as well as the material performance of the plywood and Styrofoam. To be able to reach all edges of the cone modules with trimming and foam cutting tools, a machine setup with at least seven degrees of freedom is required. It becomes evident that the design space for the developed material system therefore directly relates to the parameters of the machine setup. During the manufacturing process, the robot's tool center point (TCP) and the turntable's rotational position can be adjusted to accommodate large cone modules. Therefore, the location of the TCP in relation to the module is crucial in finding the module's dimensional constraints.

7.2.8.1 Parameters of the machine setup

The machine setup in this case study consisted of a KUKA KR125-2 industrial robot. The robot's kinematic information can be seen in Figure 7.26. The industrial robot was equipped with a 6.5 kW HSD milling spindle. Further, the industrial robot was connected to a one-axis positioner, or turntable, KPV-1 500. The fabrication steps that involved the industrial robot used a measuring tip, a 250mm saw blade, and a 50mm foam milling bit. The position of the turntable in relation to the robot center could not be adjusted for this project.

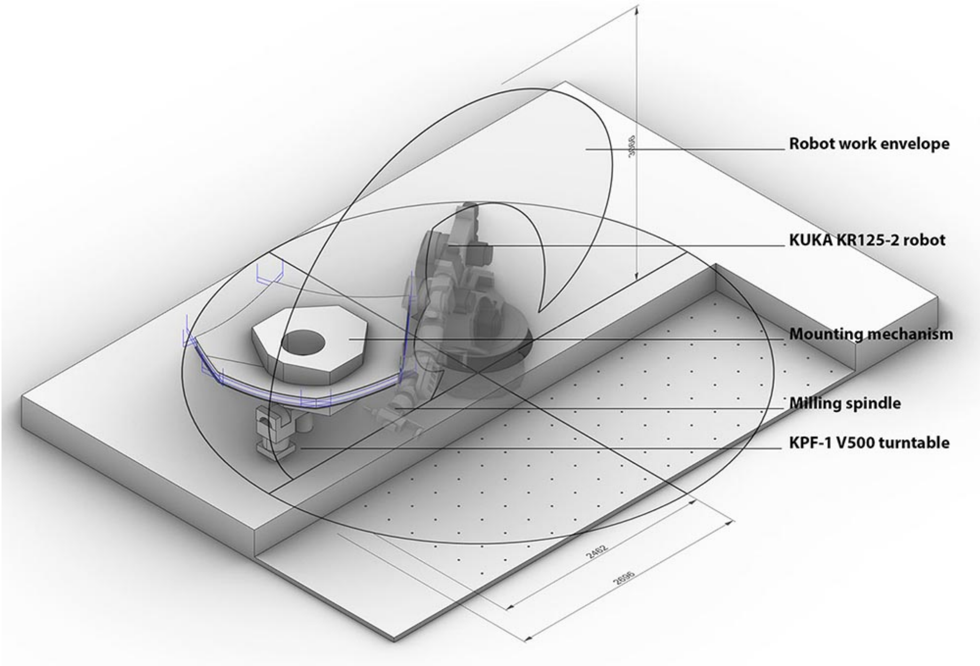

Figure 7.26: Machine setup of Case Study 2. The industrial robot's controls are directly connected to the turntable, extending its kinematic model to seven axes. The robot's work envelope is highlighted in a cross-sectional curve to visualize the distance between the turntable and the robot center.

7.2.8.2 Morphological parameters of the building component

The building element can be described as a cone-shaped sandwich module with a polygonal outline when viewed from the top. The edges of the polygonal outline are single curved in a plane orthogonal to the cone's base plane. To define morphological parameters that have the most influence on the building system's design space while at the same time being directly influenced by the machine setup or through an interdependence of parameters, Table 7.2 below is used.

	Morphological parameter	Influence on design space	Influence of machine setup
	Micro scale (from molecular to cellular makeup)		
	Plywood material density	medium	medium
	Average or individual wood cell length/width ratio	medium	low
	Average or individual veneer layer thickness	medium	low
	Average or individual grain direction	high	low
	Meso scale (part of a building element)		
	Material thickness of plywood	medium	medium
	Plywood veneer lay-up	medium	medium
	Styrofoam core depth	high	medium
scale increases	Individual polygon edge length	high	medium
	Curvature of single module edge	medium	medium
	Polygon-internal angle	high	high
	(A) Connection angle on single edge	high	high
	Aperture opening radius	medium	medium
	Macro scale (building element or component)		
	Number of polygon vertices	medium	low
	Number of polygon edges	medium	low
	Average curvature of all module edges	low	medium
	(D) Module circumcircle diameter	high	high
	Cone surface area	medium	medium
	Module directionality (ratio of min to max width)	high	medium
	(C) Cone inclination angle (depth of module)	high	high
	Gaussian curvature of design surface	high	medium

Table 7.2: Analysis of morphological parameters in Case Study 2. The higher the rating, the more direct the impact toward the building system's design space or the impact from the machine setup. Based on the rating, the highlighted parameters are selected to evaluate the relationship between the machine setup and the design space of the building system.

In this case study, some of the highest-rated morphological features appear multiple times within a single building component, such as the connection angle along a single edge. Because these features can have significantly differentiated values within a building component, it is not possible to evaluate it with a single value, but instead with a collection of values.

Based on the above analysis, three morphological parameters are selected that are most indicative of both the resulting design space of the building system, and the influence of the machine setup. Because of the relationship between the scale and the parameters, one of the three selected parameters refers to a part of the building component. This relationship is further explained below:

- *(D) Diameter of the cone module circumcircle (in mm)*
  Based on the center point of the cone module, a circumcircle is described that encompasses all corner points of the polygonal outline. Because the turntable will rotate the module during the robotic processing steps, this value is the best measure to determine the building element's overall size. Here, a single value is used to characterize the size of the building component.
- *(A) Connection angle of a module edge (in degrees)*
  This parameter directly relates to the angle between two neighboring modules and directly impacts the machine movement as different angles are milled by tilting the milling spindle. 0 degrees is a coplanar connection, positive values refer to a convex connection, and negative values refer to a concave connection. Here, a single value refers to a single edge of a building element. A building element can have several edges with different connection angles. If neighboring cone modules have the same cone inclination angle, the connecting edge is single curved.
- *(C) Cone inclination angle (in degrees)*
  This parameter describes the angle of inclination between the cone axis or normal vector and a line from the center of the cone to its boundary. Values between 0 and 90 indicate a concave cone like the one used for the HygroSkin demonstrator building. Values above 90 degrees indicate an inverted or convex cone. Here, a single value refers to a single morphological feature of the building component.

All three parameters are visualized in Figure 7.27. While parameters (D) and (C) are single values for each building module, parameter (A) occurs multiple times within a module because each polygon has multiple edges. Therefore, a single building component is represented by multiple measurements of the connection angle (A) that share the same measurements for the other two parameters as they only occur once within the component. Depending on the number of edges a building component has, the number of measurement points analyzed and visualized varies.

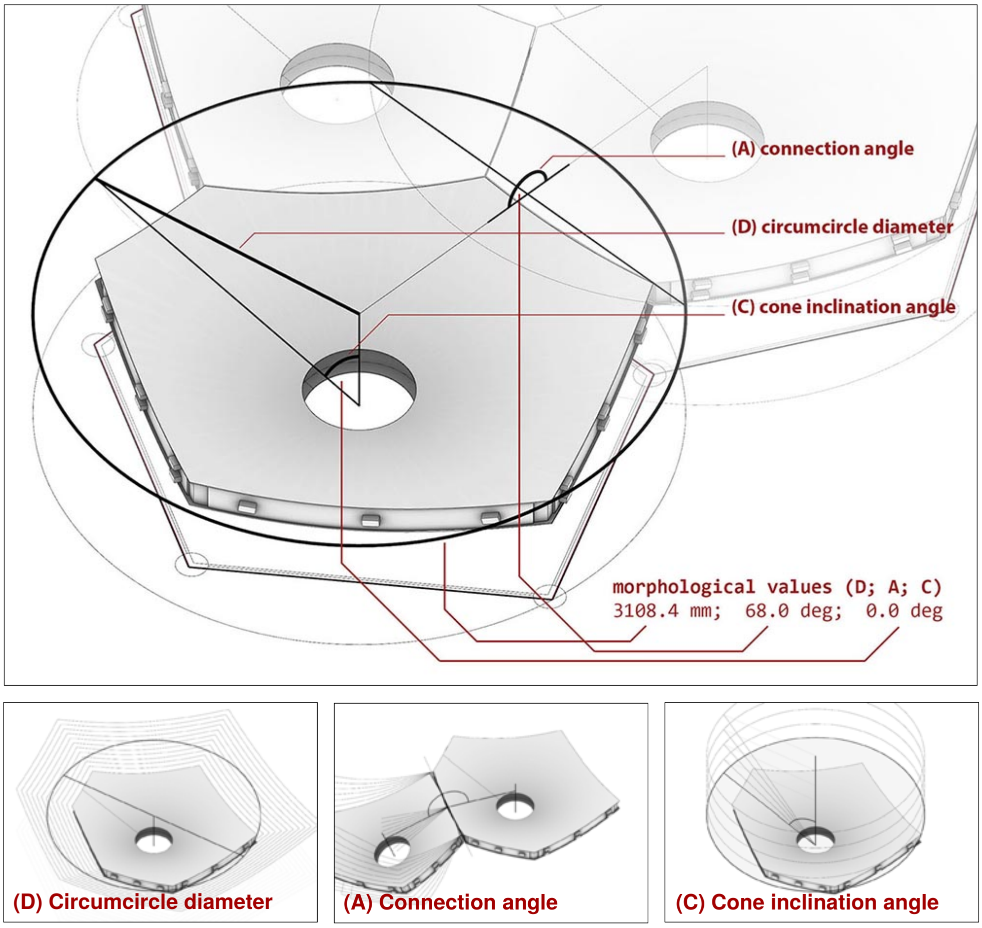

Figure 7.27: Top left: Overview of the three morphological parameters of the building element surrounded by other building elements within the building system. The resulting morphological values of a building element's edge are shown within the image to explain the relationship between the three parameters. Bottom left: (D) as the diameter of the module's circumcircle. Bottom middle: (A) as the connection angle between two modules at one edge. Bottom right: (C) as the cone inclination angle within the module.

Typical boundary situations of these morphological parameters are described in more detail in the below series of images (Figure 7.28). In these images, the variation of the parameters and example situations for their boundary constraints are shown. There are many other instances during the fabrication steps in which constraints are met; however, they are not all visualized. The min/max constraints of the parameters due to the machine setup, and their interdependencies, can be described as follows:

- The circumcircle diameter (D) is constrained by the industrial robot's work envelope. When rotating the module on the turntable, the maximum size is constrained by the robot's reach as well as the rotating module colliding with the robot arm. The minimal size of plates is given by the size of the fixture on the turntable. Modules smaller than the fixture would result in the EOAT colliding with it.
- The connection angle (A) is constrained by the inclination of the milling spindle at higher angles. While the milling angle is linearly related to the connection angle, its depth and spatial requirements grow exponentially towards acute connection angles. Additionally, acute angles result in shallow cuts that are difficult or impossible to mill. Therefore, connections closer to 0 degrees are not possible.
- The cone inclination angle (C) is constrained by the height required to accommodate the location of the resulting boundary. If the angle is above 90 degrees, the cone inclination is downwards and will collide with the floor. If the angle is too high in either direction, the resulting boundary cuts will also become too shallow, further restriction parameter (A).

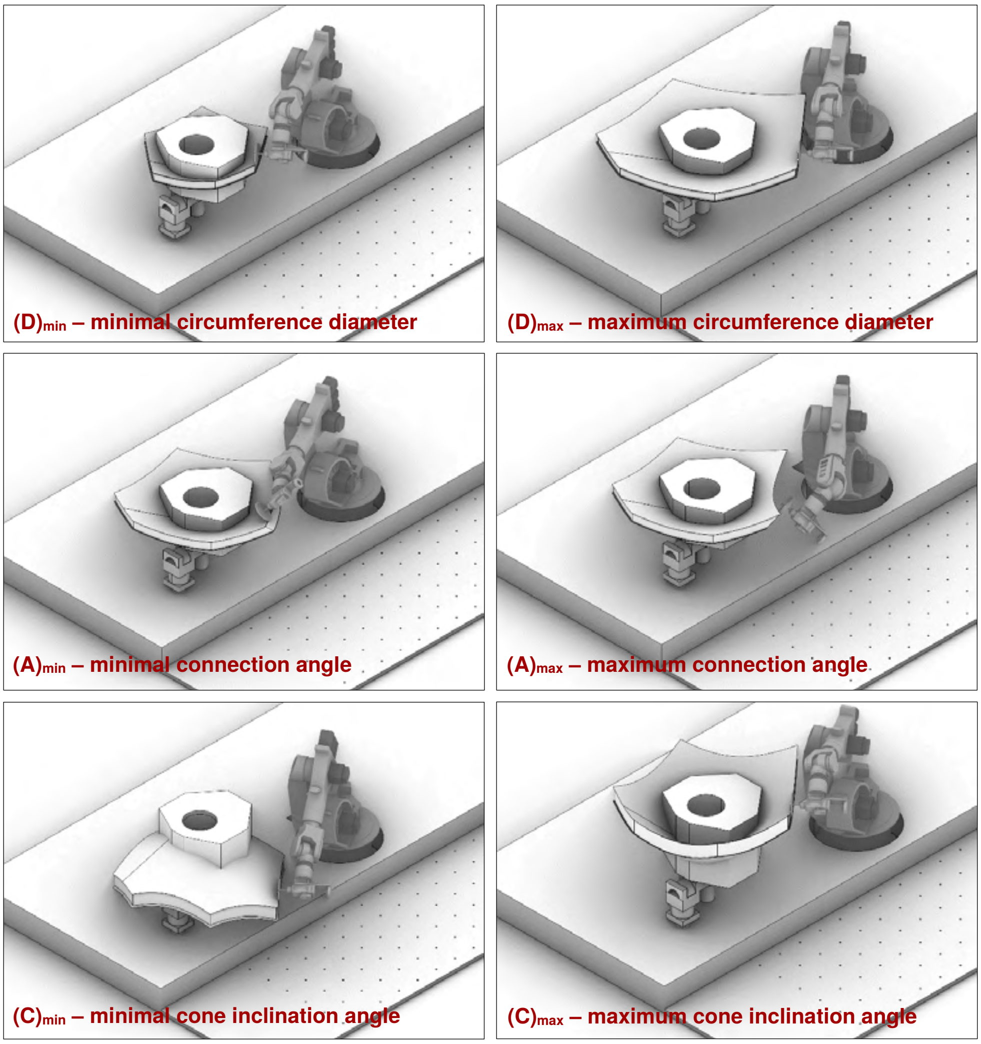

Figure 7.28: Exemplary boundary conditions of all three parameters. Top row: minimal and maximum plate diameter (D). Middle row: Minimal and maximum connection angle (A). Bottom row: Minimal and maximum cone inclination angle (C).

7.2.8.3 Result: theoretical and empirical machinic morphospace of Case Study 2

In Figure 7.29, the resulting theoretical machinic morphospace is represented by a light gray volume within the three-dimensional parameter space described by (A), (D), and (C). The theoretical morphospace is the *producible region of possible form* (PPF) for the machine setup with the turntable. Unlike in Case Study 1, the machine setup was not changed for this project.

The theoretical machinic morphospace is a single distinct region with strong features in relation to the connection angle (A) and cone inclination angle (C). The size of modules, represented by the circumcircle diameter (D), is almost completely independent from the other two morphological parameters. It is mostly constrained by the fixture mechanism on the turntable on the lower end, and by collisions with the robot arm on the higher end of the range. Because of the nature of the robotic milling process, the connection angle (A) does not directly influence the size of the modules. Changes in the connection angle can easily be handled by the robot because the wrist is always oriented in a similar way. However, the spindle restricts the size of convex modules because it would collide with the floor. Therefore, higher convex connection angles at convex cone inclination angles restrict the circumcircle diameter (D).

The connection angle (A) and cone inclination angle (C) have a strong linear interdependence. This is because both parameters have an influence on the geometry of the connection areas of each module edge. Generally, higher cone inclination angles (C) result in a shallower connection geometry at the same connection angle (A). Once the connection geometry is too shallow, the milling tools will not be able to cut the material anymore. More specifically, higher *concave* cone inclination angles restrict the *convex* connection angle, while higher *convex* cone inclination angles restrict higher *concave* connection angles. This inverse relationship results in the characteristic diagonal boundaries of the theoretical morphospace.

In Figure 7.30, the empirical machinic morphospace of the HygroSkin pavilion's 25 cone modules is visualized in red. Although a single point represents an edge of a module, it can be observed that most points share the same location and therefore appear only once. This is because of the strict design guidelines of the pavilion and the manufacturing system's practicality constraints.

First, all cones share the same cone inclination angle. As described in the previous sections, the manufacturing system was developed so that a single mold could be used to produce each cone module. A cone inclination value was chosen that would be within range of the elastic bending capacity of the plywood while showcasing the aesthetic and functional features of the cone geometry. Therefore, all cone modules share a cone inclination angle (C) of 68 degrees. It could be argued that for this project, only a plane with this particular value for (C) is the producible region of possible form (PPF). The plane is highlighted in dark red in the figure. If a different mold or multiple molds were built, the morphospace would be expanded beyond this plane. Since this constraint is not in relation to the robotic setup, the research interest is for all theoretically possible cone inclination planes. Second, the pavilion was designed with a rectangular floor plan. Therefore, only two values for the connection angle (A) exist: 0 degrees and 90 degrees. The figure shows a thin red line that connects the point measurements of those cone modules that have contain one edge with a 90-degree connection angle. Because of the large size of those modules with a 90-degree connection angle, they are close to the producible constraint boundary. Last, the pavilion was designed to be easily transportable. Many of the cone modules were shaped to be similar or equal in their circumference diameter (D) so that they could be grouped in custom-built transportation boxes. Therefore, many cone modules share the same diameter and their measurement points in the empirical morphospace overlap.

The analysis shows that upfront design decisions and other constraints can heavily impact the region of what could be called the design intent. While the plane of (C) where all modules lie is one of the largest planes within the theoretical morphospace, different upfront decisions could have led to different cone inclination angles or connection angles.

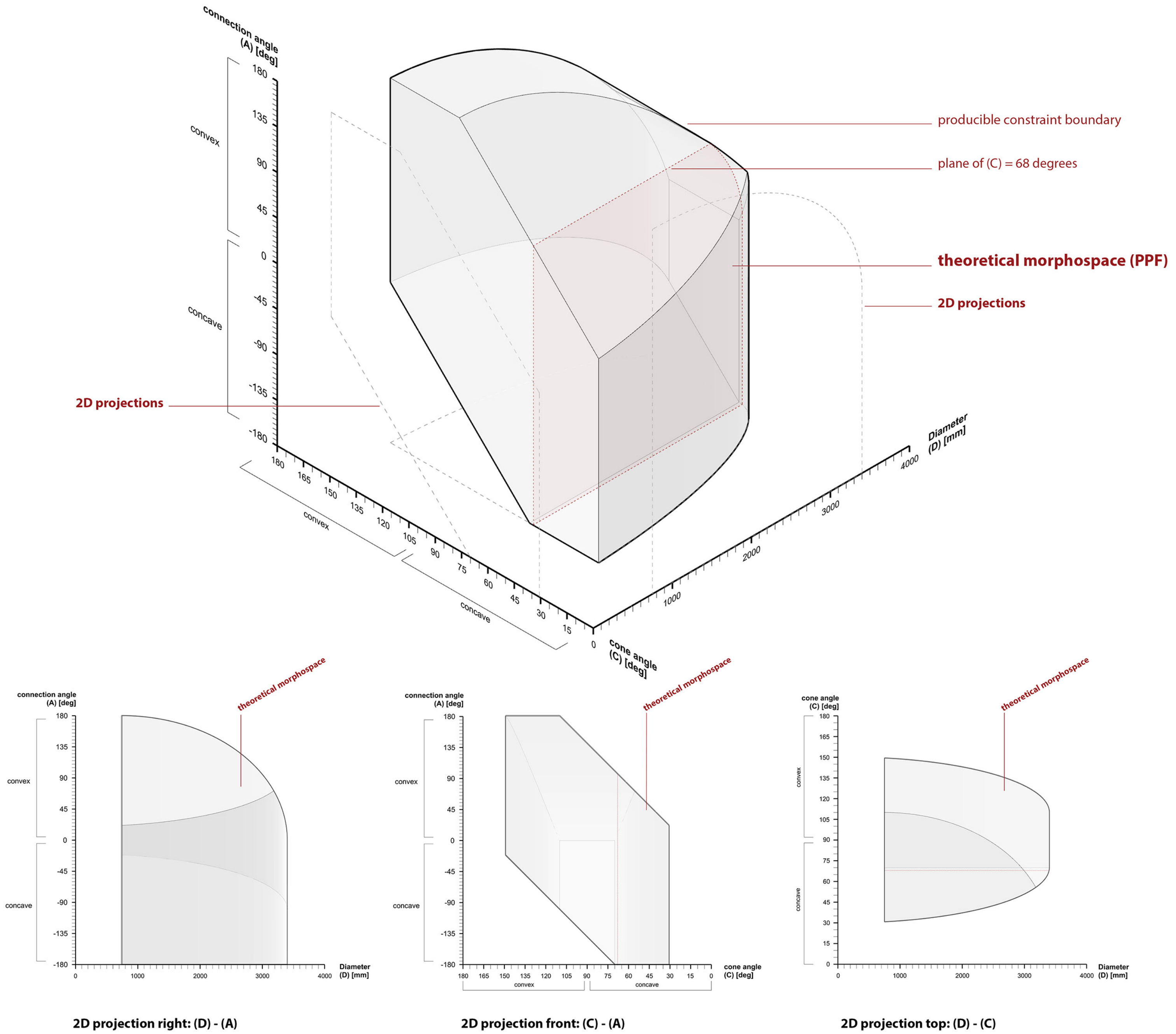

Figure 7.29: The theoretical machinic morphospace of Case Study 2 is visualized as a gray volume with thick outlines. 2D projections of the theoretical morphospace are overlaid on the planes of each pair of axes and plotted at the bottom of the diagram as parallel projections. The cone inclination plane of (C) = 68 degrees is shown as a dark red and dotted line.

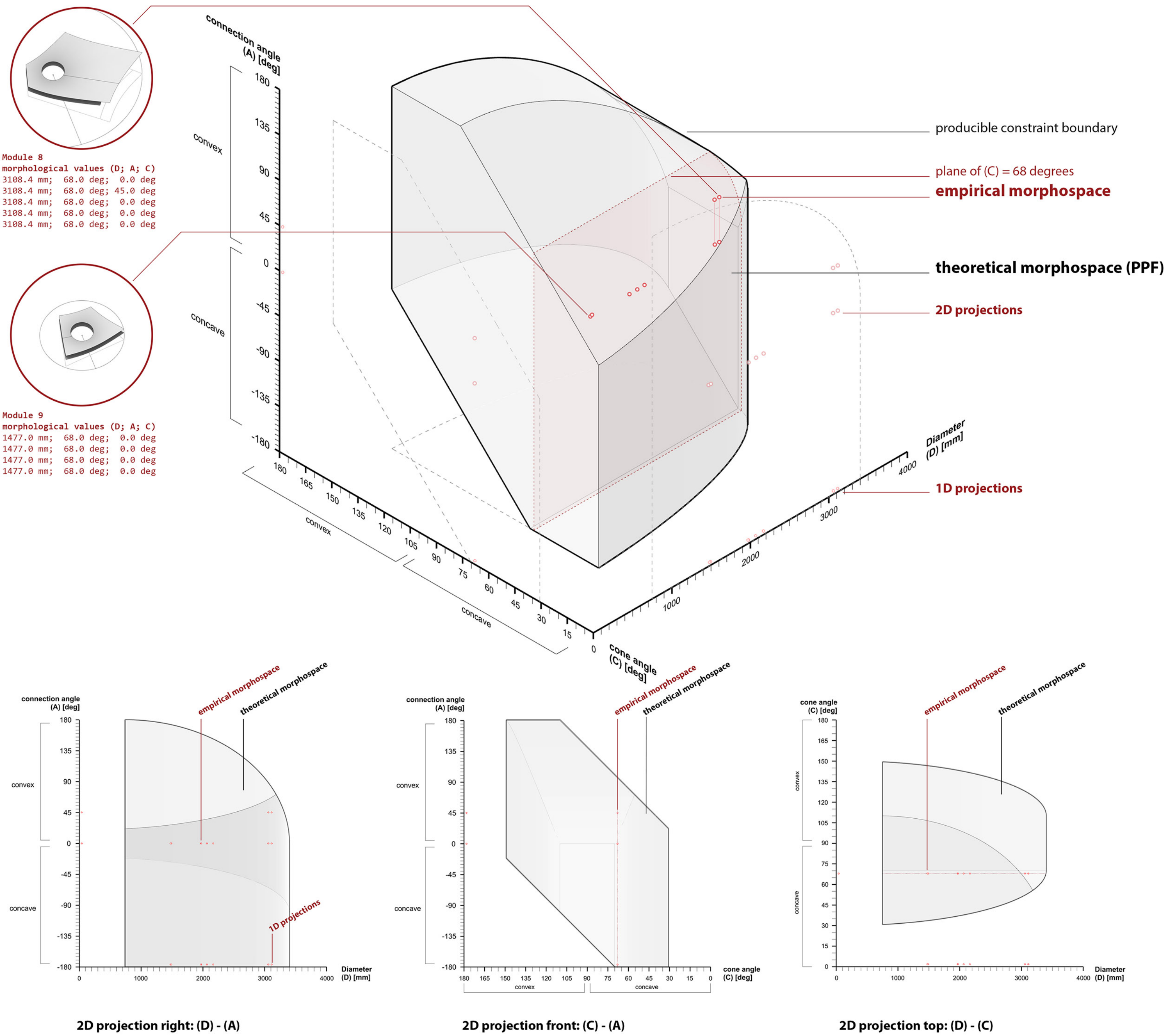

Figure 7.30: The empirical machinic morphospace of Case Study 2 is visualized by red measurement points that represent each parameter value of the 25 cone modules of the HygroSkin pavilion. Two example modules are shown on the top left to exemplify the variety of morphology within the building system. Modules 8 and 9 are the smallest and largest modules, with module 8 also exhibiting a 90-degree connection.

7.2.9 Acknowledgements

This project was a collaboration between several researchers and students.

Achim Menges Architect, Frankfurt
Achim Menges, Steffen Reichert, Boyan Mihaylov
(Project Development, Design Development)

Institute for Computational Design, University of Stuttgart
Prof. Achim Menges, Oliver David Krieg, Steffen Reichert, Nicola Burggraf, Zachary Christian, David Correa, Katja Rinderspacher, Tobias Schwinn with Yordan Domuzov, Tobias Finkh, Gergana Hadzhimladenova, Michael Herrick, Vanessa Mayer, Henning Otte, Ivaylo Perianov, Sara Petrova, Philipp Siedler, Xenia Tiefensee, Sascha Vallon, Leyla Yunis
(Scientific Development, Detail Development, Robotic Fabrication, Assembly)

Other contributors to the aspects covered in this dissertation are listed below.

7.2.9.1 Meteorosensitive apertures

Steffen Reichert was responsible for the development of the meteorosensitive apertures, which were an essential part of this project. His research into hygroscopically activated mechanisms led to the development of these apertures. David Correa was responsible for the production of the apertures and continued the research afterwards.

7.2.9.2 Global design and building system

The case study is based on an initial design competition that was developed by Achim Menges, Steffen Reichert and Boyan Mihaylov. The global design and system idea were part of the competition and did not change when the project in this case study started.

7.2.9.3 Manufacturing system

The manufacturing system described in this case study was developed by the author within the team of research associates. Tobias Schwinn developed the

computational process to approximate the location of the component on the turntable with a simulated annealing algorithm. The entire team of researchers and students assisted in the manufacturing process of the demonstrator.

7.2.9.4 Structural analysis

The finite element analysis of a single component and the completed demonstrator was developed by Zachary Christian.

7.2.9.5 Geodesic analysis

The geodesic measurements of the vacuum form and of a finished component were executed by Annette Schmitt of the Institute of Engineering Geodesy at the University of Stuttgart. The data was analyzed by her as well as by Tobias Schwinn.

Figure 7.31: The Robot-Assisted Assembly demonstrator structure constructed at the DADA Digital Factory conference at Tongji University in 2015 (Image by ICD University of Stuttgart).

7.3 Case Study 3: Robot-Assisted Assembly in Wood Construction, 2015

7.3.1 Project Introduction

The project “Robot-Assisted Assembly in Wood Construction” is the result of a nine-day long workshop hosted by the DADA Digital Factory conference at Tongji University in Shanghai, China, in 2015 (Figure 7.31). The workshop was prepared by Abel Groenewolt and the author at the Institute for Computational Design and Construction during the months leading up to the event. The manufacturing as well as the computational design system were developed during the preparation phase and finalized during the first three days of the workshop. After that, the workshop participants and assistants worked together with the ICD team to design and build the installation for six days.

This project explored a digital fabrication technique that allows for the production of double-curved and uniquely shaped building components without relying on elaborate measuring techniques or complex CNC-milling methods. The research team was interested in the possibilities of using an industrial robot as an assembly assistant in a collaborative manufacturing process where standardized building elements can be accurately placed at any desired location.

The building system developed in this research project consists of a double-curved timber frame construction with a CNC-cut cladding. While the timber frame structure is assembled with this newly developed robotic fabrication method, the cladding is added later in a manual step. It functions as both a confirmation of the accuracy of the frame structure as well as for lateral stiffening.

By encoding the geometric specificity in the assembly *process* instead of the building *elements*, complex structures can be produced out of standard and widely available building materials. As a result, the geometric specificity of a gradient building system is encoded not in the building elements themselves but in the assembly process.

During the workshop, the computational tools were used to design a double-curved structure made from several sub-segments, building components. Each building component consisted of several smaller, standardized building elements. A simulation of the robotic assembly process was used to verify the size and shape of the components for the specific machine setup of the workshop. With a group of over 15 participants, six modules with a surface area of around 5m² each were produced within five days and shipped on-site for the assembly into a larger structure.

The author participated in this research project as a research associate at ICD in a team of two researchers, several students, and professional workshop participants. The author was primarily involved in the development of the manufacturing system and building system, as well as in the supervision of the participants during the workshop. Further acknowledgements are in sections 7.3.5 and 7.3.9.

Most of the results presented in this case study are unpublished, particularly details on the manufacturing development in section 7.3.3 and the machinic morphospace analysis in section 7.3.8. No academic papers about this project have been published as of the writing of this thesis. In the following sections, the case study is analyzed from the perspective of the manufacturing system development in reciprocal relationship with the design process and exploration of the design space. As one of the first projects of the research group motivated by the possibilities of robotic assembly and human-robot collaboration, this case study will analyze the strategic use of robotic fabrication steps within a manufacturing process, and the relationship between the robotic machine setup and the potential geometric variation of building components.

7.3.2 Investigative motivation: assembly instructions

While the investigative motivation of most case studies in this thesis is situated within the material properties or the connection of building elements, this case study stands out as the research is not in direct relation to physical characteristics but rather to the process of assembly itself. In an effort to investigate manufacturing methods that would enable geometrically differentiated building pars for gradient building systems, the investigation is usually focused on the geometry of the building element itself. The reasoning behind this method is that if manufacturing processes can be developed that allow for differentiated building elements, then the material system or building system can become differentiated enough to specifically react to local structural requirements or context-specific situations. However, this reasoning is based on the understanding of a traditional assembly process where instructions are externalized such as in a plan drawing or shop drawing. If the assembly of building elements into components or modules is standardized, then the building element needs to be non-standard to result in a uniquely shaped structure.

In this project, it was instead considered that the building elements can be standardized if the assembly process is unique or parametrized and differentiated for every assembly or connection step. For this method to work, the building element cannot have specific connection locators such as holes or notches that are individualized, but instead it requires a connection area that allows standard building elements to be connected in many different orientations and positions. Connections that do not require the building element to be machined and can be easily executed are nailed connections, for example. When using nails to connect two co-planar board-like building elements, their orientation to each other can be infinitely variable (Figure 7.32). However, since no other physical guidance is given by the connection or the building element, measuring the position of a building element is challenging for a human worker. This is an opportunity to internalize the placement of the building elements within a machine such as the industrial robot. Using robotic motion to indicate the position of the next building element to be connected transfers instruction from the building element or an external plan drawing to the manufacturing process.

Figure 7.32: A nailed connection between two standardized building elements in a unique position (Image by ICD University of Stuttgart).

By internalizing instructions within the machine, off-the-shelf building elements can be used independently from the location of the project or the qualification of labor. Instead, the machine encompasses the specificity of the building structure and the assembly instructions, while human collaborators only need to follow the instructions and use standard tools such as a nail gun.

This case study investigates this manufacturing strategy based on a robotic pick-and-place assembly process with human collaboration for connecting building elements. Human-robot collaboration was chosen for this process as connecting building elements usually requires a high degree of flexibility and dexterity, which are both characteristics that humans have, while accuracy and repeatability are characteristics inherent to industrial robots. Splitting the tasks between human labor and robotic machines depending on the required capacity is a manufacturing method that was part of this research project.

The main manufacturing principle used for the development of the subsequent manufacturing system can therefore be described as a robotically guided assembly process of standardized wooden boards that are jointed in a lapped, co-planar but rotated orientation using a nailed connection. Multiple boards of standardized width and length can be assembled at their respective ends in a vertical orientation, and while they share the same plane of orientation they can be connected at different angles (Figure 7.33). When multiple vertically oriented assemblies are arranged next to each other, they form a lattice structure, resembling sections of a lofted surface. Between each of those assemblies, smaller horizontal plates can be placed to connect all building elements into a structure resembling a ladder frame construction.

Figure 7.33: Human-robot collaboration: The manufacturing steps that require precision and repeatability are executed by an industrial robot, while humans execute tasks of jointing building elements (Image by ICD University of Stuttgart).

7.3.3 Development of the manufacturing system

With the main manufacturing process described above, a manufacturing system was developed that would exemplify the design potentials of standard building elements in a non-standard assembly process. The ladder frame structure described above was developed to be built out of only a limited number of standardized elements. Certain dimensions of plywood strips were used to represent standard board sizes such as five inches or seven inches in North American markets, or 120 mm or 180 mm in European markets. Generally, these boards were meant to represent universally available building elements, and their exact dimensions were considered parameters in this system that could be changed.

With the goal in mind to develop a building system with a high degree of design flexibility, the boards would be connected to each other at their ends, sharing the same plane of orientation, but in different angles within this plane and in different positions (Figure 7.34). While the center point of the connection is defined by the overall computational design process and can vary gradually, the length of the board chosen to accommodate the connection and position would only vary in a limited number of steps. Ultimately, the goal was to connect multiple boards with a limited length, in vertical orientation, to form a wall structure. The different angles between the individual boards would result in kinks and shape variations (Figure 7.34). Through a sequence of these arrangements the overall impression of the wall structure would be that of a lofted surface. By varying the connection angles and lengths of the boards, this wall structure could change between convex or concave situations, between short and high sections, and potentially between a vertical and horizontal orientation, eventually forming a roof structure as well.

The smaller horizontal elements described above connect the vertical elements to form a ladder frame structure. They are also placed by the robot but do not differ in size. Instead, the distance between each vertical board assembly is standardized. A third element, which is even smaller than the horizontal elements, was developed to be added on to the side faces of the vertical boars, sticking out of the structure and acting as a receiving connector for a cladding layer, which was added as a last assembly step.

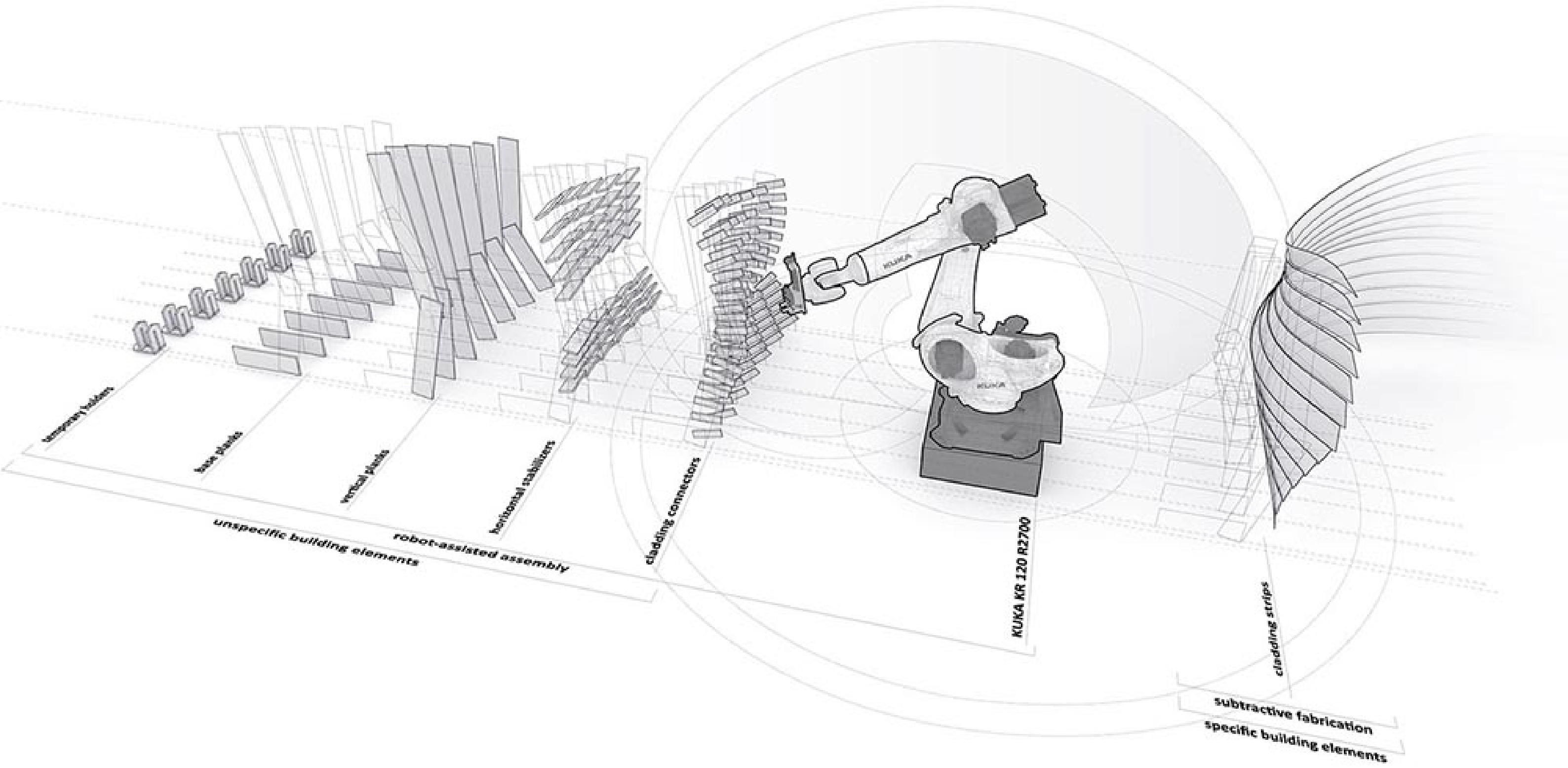

Figure 7.34: Overview of the manufacturing system. On the left side of the industrial robot, all standardized building elements are listed. The main building elements are the large, vertical boards, the smaller horizontal boards, and the small cladding connectors. All of them have standardized sizes. On the right side of the robot, the customized cladding strips are shown (Image by ICD University of Stuttgart).

Contrary to the frame structure made from standardized elements, the cladding layer is made from non-standard CNC cut building elements (Figure 7.34). The goal of the cladding is to cover the surface, and therefore the ladder frame structure, completely, while also granting the structure lateral shear stiffness. The cladding surface is divided into the same number of strips, resulting in the individual strip shape to adapt to the local curvature, and generating a smooth pattern similar to shiplap cladding (Figure 7.35). The cladding layer was chosen to be made of unique and custom-fabricated plywood strips because it was meant to represent an opposing approach to the ladder frame structure. At the same time, it is a reminder that an individual manufacturing concept such as that of the ladder frame structure cannot always be applied to a complete building system with multiple layers and functions. In this project, non-standard building elements are required to fully cover the surface of the structure. Therefore, each cladding strip is unique and requires a custom CNC cutting process, a numbering or naming system, and detailed plan drawings to instruct human workers during the assembly process. In addition, the cladding layer was made from thin plywood to allow the strips to be bent elastically onto the complex, double-curved surface. Each cladding strip overlaps the adjacent strip below by rotating along its length axis.

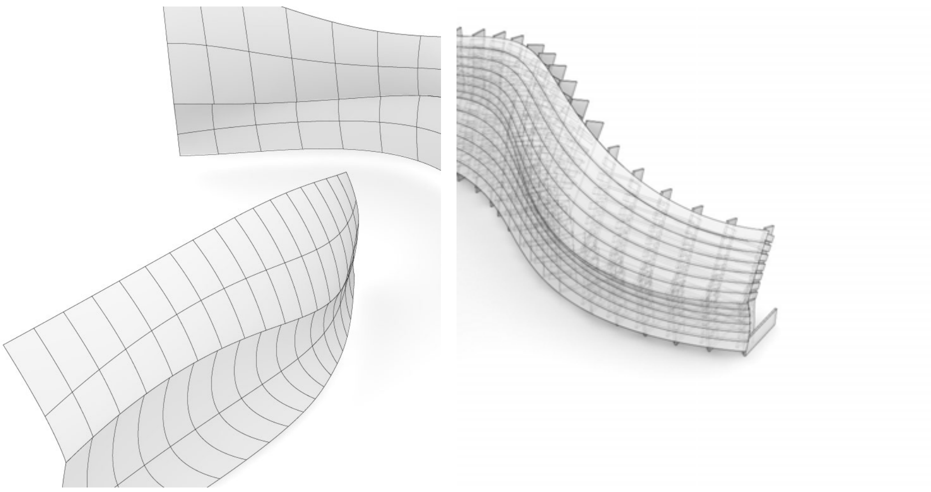

Figure 7.35: The design surface (left) and the resulting construction system (right) of the demonstrator built at the DADA Digital Factory conference. The diagram shows how the kinks in the design surface translate into the ladder frame structure (Image by ICD University of Stuttgart).

Since all building elements were of a standardized rectangular shape, a simple rig was developed where each part would slide into a corner that was known to the robotic system (seen in Figure 7.33). From there, the robot can pick each building element at a defined location with a pneumatically activated parallel gripper.

In total, the manufacturing process is grouped into the following sets of process steps:

(1) In a first set of steps, the robot picks and places the vertically oriented, larger boards. Only the first row of boards is placed, with the second row being constructed once the following steps are completed. Additional boards are placed by human workers to secure the boards to the ground.
(2) In a second set of steps, the robot picks and places the small, horizontal building elements to connect each vertical board. They are slid in between two vertical boards from the top.
(3) In a third set of steps, the smallest building elements, the cladding connectors, are placed. Because these are too small to be picked by the robot, and too tightly packed for the robot to place them without colliding with previously placed building elements, the robot only indicates the position of these parts, and the human collaborator takes over the capacity to place and connect them.

Steps (1) and (2) have several parametric sub-steps:

(a) The robot picks up the building element from the rig. The picking location is dependent on the length of the part.
(b) The robot activates its parallel gripper to pick the building element up and moves it to the desired location and orientation relative to the final structure.
(c) The robot stops and waits for a human worker to enter the robot workspace and use a manual nail gun to connect the building element held by the robot to its adjacent, previously placed, building element.
(d) After the human worker exits the workspace, the robot continues its programmed motion by opening the parallel gripper and moving back to the rig to pick up the next piece.

In step (3), the robot only indicates the position of the building element but does not pick it up. Instead, it uses a rig at the end of its arm that can indicate the location and orientation of the building element. It can therefore easily be placed by a human collaborator. With this repeating process, the first row of vertical elements, horizontal connectors, and cladding connectors are placed and jointed. Afterwards, the second row is built with the same sequence, and the process will repeat until the last row of building elements is built. Finally, once the structure is completed, it is referred to as a building module or component, being made out of multiple building elements. The size of a building module and the number of building elements within it, depends on the work envelope of the machine setup. This was tested through simulation described in the next section. Once a module is completed, it is detached from the ground plane and transported on site. There, the cladding layer is attached to the frame structure in an on-site, manual assembly process. The strips of the cladding layer are fabricated on a standard 3-axis CNC machine.

During the development of the manufacturing system, the capacity of a human worker and the industrial robot played an important role. For example, the dexterity required to position the nail gun between the vertical boards to connect them to the horizontal boards would have been too high for an automated robotic solution. Given the time and resources, the division between human and robot labor was strategic to be able to develop this kind of manufacturing process and building system.

7.3.4 Development of the computational design system

To better understand the design space resulting from the arrangement of building elements for the frame structure, a computational design tool was developed. Its primary function was to allow the user to explore the design space while manufacturing constraints are being implemented, and export manufacturing data. For that purpose, the computational design system was developed in parallel to the manufacturing system, and both development processes informed each other. Because the fabricability is so fundamental to the building system, the simulation of the robot motion for the assembly process is a key aspect of this development. In this case study, the computational design part and the manufacturing data generation part are ultimately within the same data flow and parametric process. Only for computational efficiency, the latter is deactivated during the design process and only activated once the design is finalized. However, compared to other case studies, there is otherwise no hard break in the data flow.

In the computational design process, the user-defined design input is a BREP made from multiple NURBS surfaces that form elongated strips and are connected to each other in a vertically stacked arrangement (Figure 7.35). Their individual orientation and curvature lead to kinks along their shared edges. This design input can be larger than the maximum size of building modules later produced by the manufacturing system. Then, a section of this BREP is selected manually to represent one module that can be produced by the machine setup. Once the development of the computational design system was completed, the robot simulation could be activated at this point in the design process to evaluate how large a module could fit the work envelope of the machine setup. Once an appropriate module size was selected, the computational design process only requires a small number of input values to complete the generation of all building elements for the ladder frame structure and cladding layer, such as material thickness and dimensions of available building elements. In the case study, only five different sizes for the vertical boards were selected, and one size for the horizontal connectors and cladding connectors.

To populate the building module with these building elements, it is further divided into smaller sections by intersecting it with parallel and evenly spaced planes (Figure 7.36). Their orientation can be defined manually, but their spacing is defined by the dimensions of the horizontal connectors. Along the intersection lines, the points where the individual BREP surfaces are connected become the anchor points that define the end points of each vertical board. From there, the vertical boards are generated with their given dimensions. Their length is selected based on the given choice of intervals. Between the vertical elements, several horizontal connectors are generated. Their spacing is provided by the machine setup again, with minimal distancing depending on the space required by the robot’s parallel gripper.

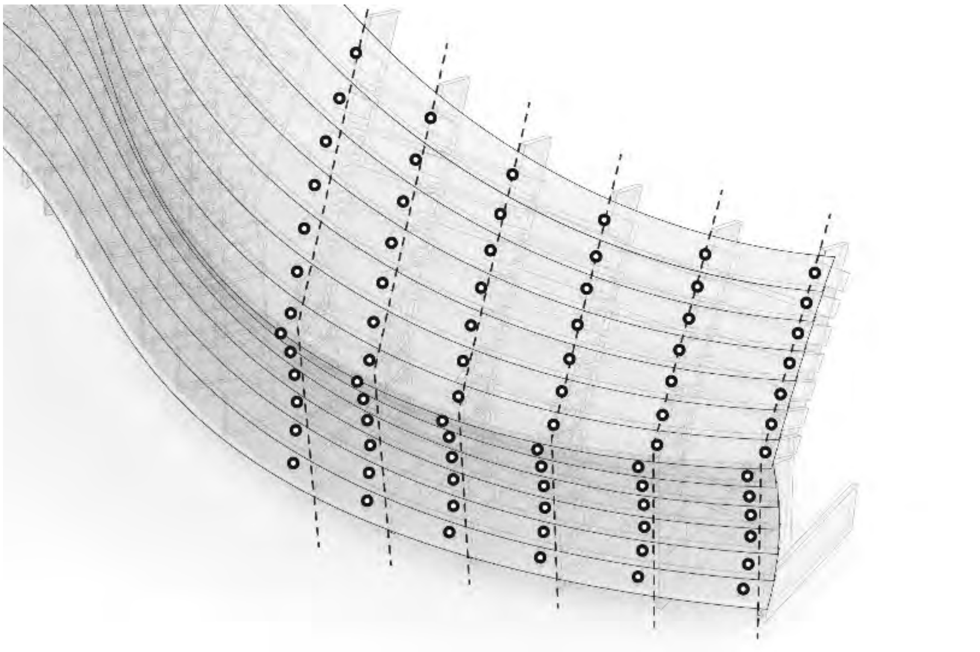

Figure 7.36: The original design surface is divided into vertical sections that guide the placement of the vertical boards. The cladding connectors are shown with black circles (Image by ICD University of Stuttgart).

For the cladding layer, the original design surfaces of the BREP are used to generate the shiplap structure. They are divided into smaller strips and cut into a maximum length, which is in turn defined by available stock material for plywood. Based on the division of the cladding strips, the cladding connectors are placed on the center lines of the strips, in plane with the vertical boards, perpendicular to the design surface (Figure 7.36).

Each of the three standardized building elements has a parametric assembly sequence attached to it that will be accessed once the data flow to the manufacturing data generation is activated. Here, parameters of the robot's motion necessary to complete an assembly sequence of one building element are fed directly from the geometric information of the design process: the location of the building element in relation to the overall structure, the size of the building element, and the position of the robot in relation to the structure (Figure 7.37). Other parameters such as the geometry of the parallel gripper influence the robot kinematics but not the tool path of the robot. With these parameters varying between every building element, the tool path is generated per part and then combined into a list of consecutive instructions for the entire section of the structure that will be manufactured in one single process. Then, the entire robot movement is simulated in this process, and constraints of reach and position, or the size of elements can be checked manually. In an alternative process, the position of the robot is checked automatically for every step of the process, and out-of-reach scenarios are tracked and reported to the user.

During the development of the computational design system, the feedback from the robot simulation was used iteratively to define the best scale of the structure and the dimensions of building components. The immediate simulation of the robot movement informs the design process, and at the same time, design possibilities that might affect the manufacturing system can be explored and evaluated.

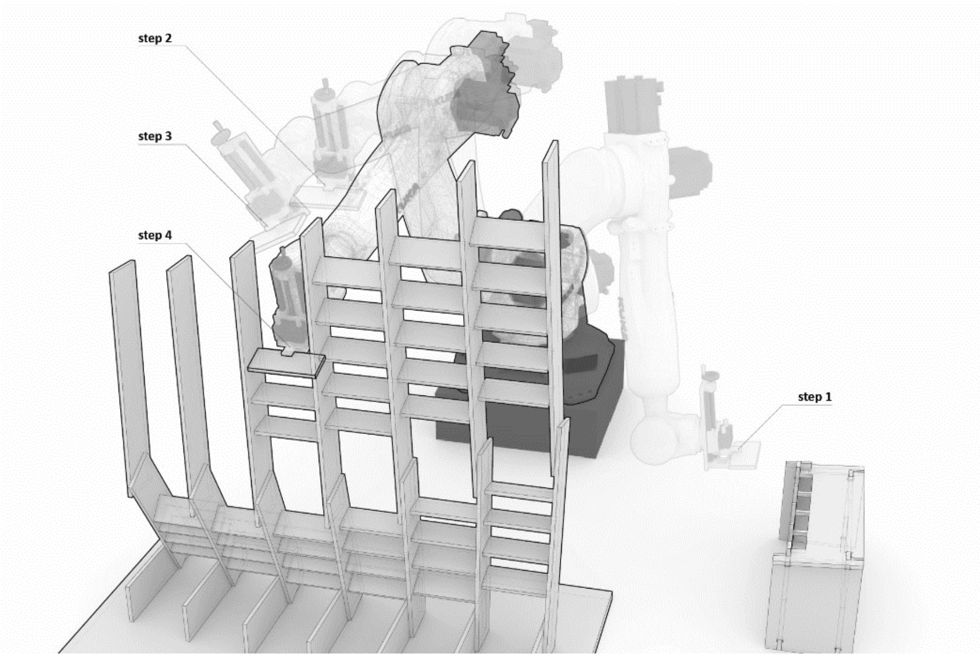

Figure 7.37: Parametric robotic assembly steps. The robot picks up an element from the rack on the right and places them in the appropriate location. In the visualized sequence, the horizontal elements get placed between the already assembled vertical elements. Therefore, the robot must slide the piece in from the top. It then pauses for a human collaborator to fix the element (Image by ICD University of Stuttgart).

The design and simulation tool were also used to determine the best position for the material rig as well as the structure relative to the robot. Because it was not known before the workshop how much space would be available and which geometry the robot's gripper would have, these measurement points were kept variable and only adjusted once the project team was on site. However, the movement steps necessary to pick and place a single building element could be pre-determined. Slight variations in the dimension of the available plywood were possible if the general sequence of movement such as the one shown in Figure 7.37 was possible.

7.3.5 Project results

Following development process, the robotic assembly of off-the-shelf building elements was employed to build seven prefabricated modules for two doubly curved walls (Figure 7.38). These modules fit within the working space of the industrial robot used in the workshop and could easily be transported in a box truck. Once positioned on-site, the modules were combined with a cladding layer previously produced. With the help of eleven participating students, the structure was manufactured and erected in only six days.

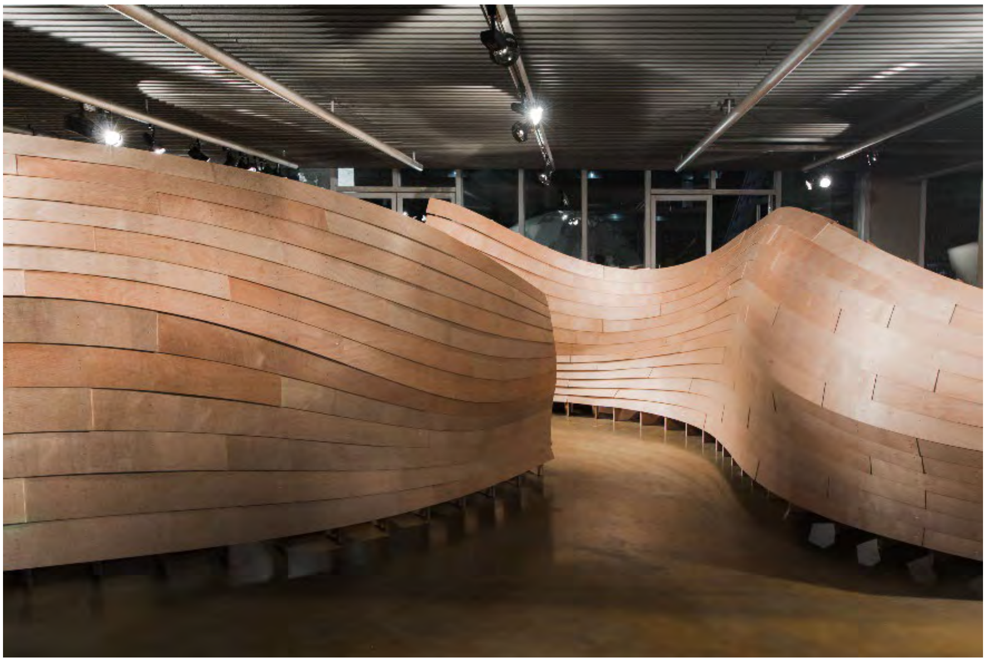

Figure 7.38: The finished demonstrator at the DADA Digital Factory conference at Tongji University in Shanghai, China, in 2015. Image by ICD University of Stuttgart.

7.3.6 Research result: Process analysis

To evaluate how the integrative development process was enabled in this project, the relationship between the gradient building system, manufacturing system, and computational design system is analyzed in this section.

In this case study, a robotic, additive manufacturing process is implemented to investigate three aspects of innovation in relation to each other: the location or embodiment of assembly instructions, the collaboration between human workers and machines, and the method of building specific structures with non-specific building elements. While the development process of this case study was mainly motivated by the embodiment of instructions, all three aspects need to be considered as they became dependent on each other as the development progressed.

Assembly instructions can be implemented through different media. In a traditional workflow, instructions are usually printed on paper as representational drawings, which must be interpreted and translated into human or human-controlled labor. In other cases, assembly instructions can be embodied by the building component itself: Through a highly specific visual or physical characteristic on the building element, the connection to its adjacent parts can only be achieved in the desired location and orientation. In this project, a third possibility was investigated: Through the robotic assembly process, the assembly instructions were embedded in the machine code, and not visible to a human worker upfront. This strategy has the potential to eliminate the need for plan drawings or informed labor.

Starting out from the potential of transferring traditional assembly instructions from a 2D drawing into a machine's motion, and therefore merging the assembly instructions with machine instructions, the project quickly moved to investigate the design implications of using standardizes building elements as well. For a clear evaluation of this novel assembly concept, assembly instructions needed to be embodied in only one medium. Machine-embodied assembly instructions in combination with specific building elements that indicate their assembly position or location would be a redundant manufacturing system. To clearly evaluate the advantages of machine-embodied assembly instructions, building elements were chosen to be generic or non-specific, resulting in a large range of possible assembly positions and orientations. Hence, when using standardized building elements to build a non-standard structure, specific assembly instructions are required.

As a result, the third aspect of investigation became inherent in the process: That with the specific assembly of non-specific elements, complex structures can be manufactured. More specifically, gradient building systems with varying structural performance can be manufactured from standard building elements, which can be more easily and readily available than specific building elements. At this point in the development process, the design envelope of a structure became the focus of attention, and the exploration of the architectural expression of a building system with non-specific building elements became the main purpose of the case study.

The division of roles between a human worker and a machine, or human-robot-collaboration, can be based on the ability to fulfill a task with an expected level of success. In a human-robot collaboration scenario, the manufacturing system can be described though the embodiment of a capacity by an agent. For example, the capacity to produce a building material, or to process a material into building elements, is usually embodied within a human or a machine. In this case study, however, the focus of investigation is within the capacity to precisely place a building element at varying orientations and join it to its adjacent parts with high precision. Independent of the agent, placing a building element always requires a feedback loop between desired position and current position. The capacity of placing building elements has traditionally been embodied by a human worker using measuring tools and plan drawings. Technological innovation can externalize this feedback loop. For example, augmented reality measuring its environment and instructing a worker where to place a building element replaces the need to manually measure and confirm the part's location [206]. This capacity can also be held by the building element itself, either through indications that instruct a human worker where it should be place in relation to other building elements—usually through notches or paint—or by the connection allowing the building element only to be connected to its adjacent part in a pre-determined position—usually through pre-drilled holes for screws or bolts. Lastly, this capacity can be embodied by a machine such as an industrial robot. A robot knows its position within the environment as well as that of previously assembled building elements. When using a gripper as the EOAT, it can indicate where the next building element will be placed with high accuracy. In this case study, the industrial robot is used to indicate where the building element would be placed while it would wait for a human collaborator to connect it. Here, the capacity to connect elements is embodied by the human collaborator.

The development process explored the manufacturing technology in parallel to the building system and design envelope (Figure 7.39). While early robotic assembly simulations were run on an individual building element, the combination of such building elements was explored through the development of the computational design system. Here, the feedback between manufacturing possibilities and the design possibilities is entirely digital: The robot movement is only simulated, not physically experimented, and is directly connected to the computational design system as the development process progressed. As such, the assembly instructions become inherent to the manufacturing process development, and part of the manufacturing system. This closed digital loop from design to fabrication and back not only allows for innovative pre-fabrication methods in timber construction, but also for a re-interpretation of traditional structural techniques in timber architecture.

The prefabrication of modules that maximize the robot's work envelope was a result of the availability of only a single robot for this manufacturing setup. A second robot or an additional linear axis would have expanded the work envelope. It can also be argued that a second robot could have used a nail gun to fix the building elements in a fully automated manufacturing process. Although the machine setup did not allow for the investigation of the potential of a fully automated setup, it can be considered that the machinic morphospace would have been more limited. Due to the space required by a nail gun effector attached to the flange of an industrial robot arm, the high density of building elements in the demonstrator would not have been possible, and the building system would not have achieved its desired structural performance. However, it can also be argued that if this dual-robot manufacturing setup would have been available from the outset of the project, then different decisions regarding building element dimensions and module dimensions would have been taken. The machinic morphospace would have been different, and the difference could be investigated in further studies.

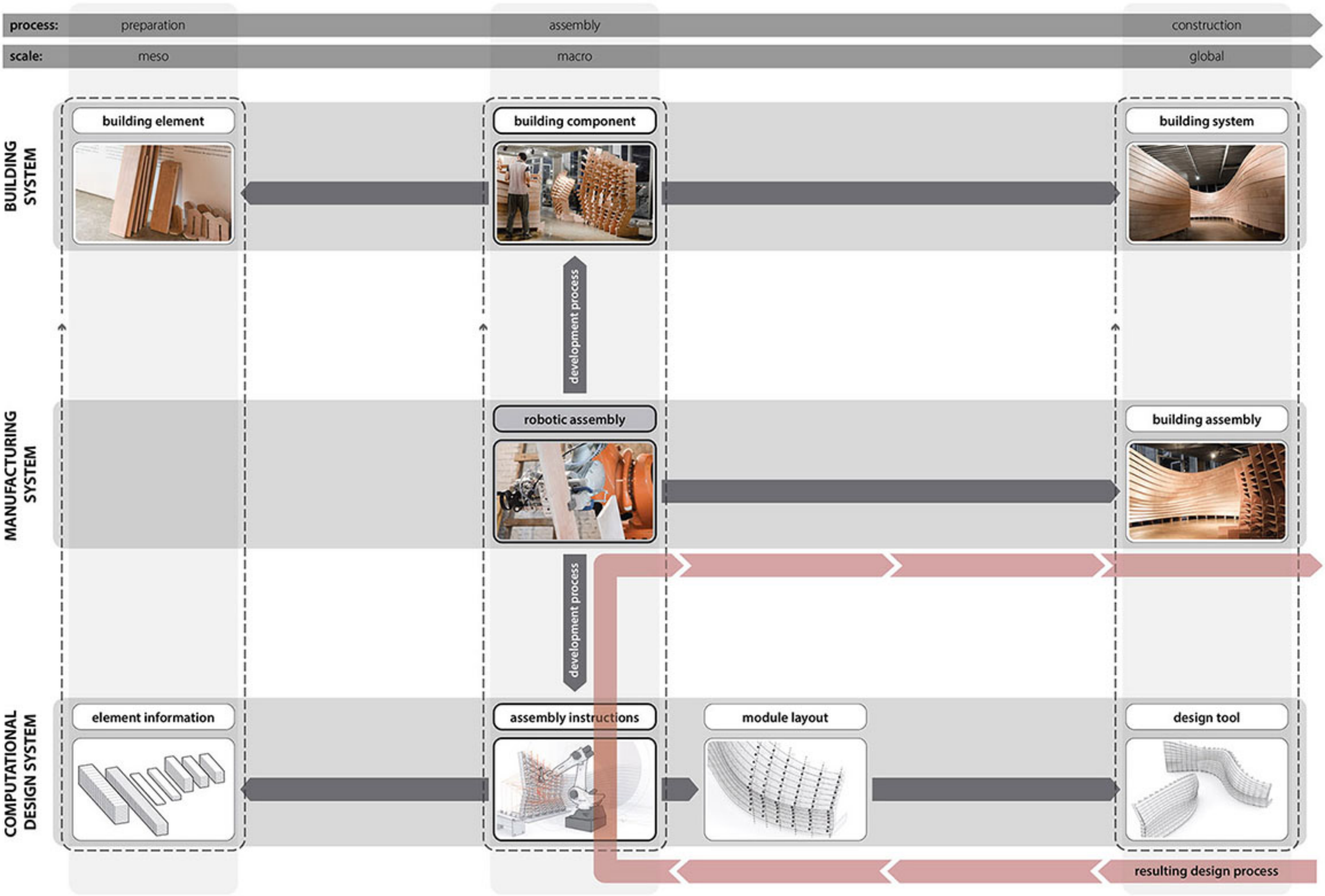

Figure 7.39: Development process overview of Case Study 3. The development process is highlighted with dark gray arrows, and the resulting design process of the demonstrator with red arrows. Starting out from the robotic assembly steps originally developed, the process branches into the building system and computational design system development. It can be observed that because of the use of standard building elements, less manufacturing steps are necessary. The diagram contains images by ICD University of Stuttgart.

By combining two approaches towards assembling complex structures—robotic assembly of unspecific elements and subtractive CNC fabrication of highly specific parts—the strengths of the agents in the process are employed strategically: the industrial robot works in a controlled environment assembling modules that fit within its reach, while human workers embody the task of fixing building elements in their robotically defined positions, thus avoiding the need to measure. This results in a very effective manufacturing and assembly process both off-site and on-site, as well as new tectonic strategies and architectural aesthetics.

7.3.7 Research result: Information flow analysis

To evaluate how the morphological differentiation of the building system was digitally generated, processed, visualized, and stored, the computational design process is analyzed in this section.

As the only case study in this thesis that contains a predefined set of standardized elements, the contribution to the discourse of information generation and handling, is only marginally different when compared to other case studies. Contributions can be identified most prominently in three different steps along the computational design process.

First, the computational design tool developed to explore the design space is automatically dividing up a designed wall into sections in which the sub-structure elements are oriented in a single plane. As such, the constraints of the robotic assembly and its work envelope are an integral part of the design process and have a strong visual influence on the design.

Second, the resulting CAD model of the design chosen for manufacturing and assembly is branched off into two files, one for each subsequent manufacturing process. While one file contains the outer plank layer, the other file contains the geometric information of the support structure. The plank layer is first represented in its bent and assembled state. Computational tools are then applied to unroll the bent surfaces into flat surfaces, nest them on available stock material dimensions, and prepare them for CNC cutting on a typical 3-axis CNC router. The building elements in this file are all unique and named accordingly. An installation plan with all name tags is generated as well.

Third, the file for the supporting structure is split up into one file for each section and its assembly process. Because this file contains several identical elements, they do not have to be individually named but can simply be identified by their type. However, their position in the three-dimensional space is unique and the corner points of each building element will serve as the input for the robot's assembly instructions. Each building part's assembly path is generated parametrically from a set of fixed instructions and relative instructions that change depending on the building part type and its final position in space.

Similar to previous case studies, the representation of the design is limited to simplified surfaces without material thickness. Although the material thickness is not shown in the design model, it is indirectly influencing the position of building elements as they're stacked on each other and therefore influence the distance to each other.

In this case study, the information density of the overall structure is less influenced by the uniqueness of building parts and more by their position relative to each other. While the outer plank layer requires an assembly plan that can be read by a human worker, the supporting structure solely relies on the meta-data of each building part identifying its type and relative position in the assembly sequence. The robotic assembly instructions are therefore generated automatically. However, the quantity and sequence of the different building element types must be exported as a list for human workers so that a building part stack can be prepared for the robotic assembly. This process was not automated and therefore required specific instructions.

In conclusion, the division of the computational design process was necessary to accommodate different means of manufacturing and assembly. Different layers of information were necessary to generate robotic manufacturing data as well as assembly instructions for human workers.

7.3.8 Research result: Machinic morphospace analysis

To evaluate how the morphospace analysis can be effectively used to analyze the relationship between the machine setup and the gradient building system's design space, the author applied this method to the project in this section.

The machine setup in this case study consists of one industrial robot with six degrees of freedom. Therefore, the position and orientation of a building element directly translates into the kinematics of the machine without any additional freedom for the user to control. Limitations of reach played an important role in the development of the manufacturing system and became most visible during the exploration phase of the design tool. Compared to other case studies with more equipment involved in the manufacturing process, the robot's reach and the effector design influenced the machinic morphospace more directly.

Apparent relationships were the overall size of a module, and the resulting structure, angles of connections and the density of the ladder structure. Here, the focus of investigation is not an individual building element but rather the building module. Because the manufacturing system was developed to produce a building module, all the steps considered in its development have a direct effect on the design space of the structure. While some case studies explore the machinic morphospace of one single building element that cannot be further divided, this case study is looking at the higher level of an assembly. The number of parameters influencing its design space can vary independently from this decision.

7.3.8.1 Parameters of the machine setup

The machine setup in this case study consisted of a KUKA KR120 R2700 industrial robot. The robot's kinematic information can be seen in (Figure 7.40). The robot was equipped with custom-built pneumatic parallel gripper. The building module was fixed on the ground to a large plywood plate, which was known in its position to the robot system. Because this base plate was measured and calibrated with the robot system, it was not changed during the manufacturing process. Within the work envelope of the robot, a rig was positioned where building elements would be picked up. The rig is manually refilled by human workers.

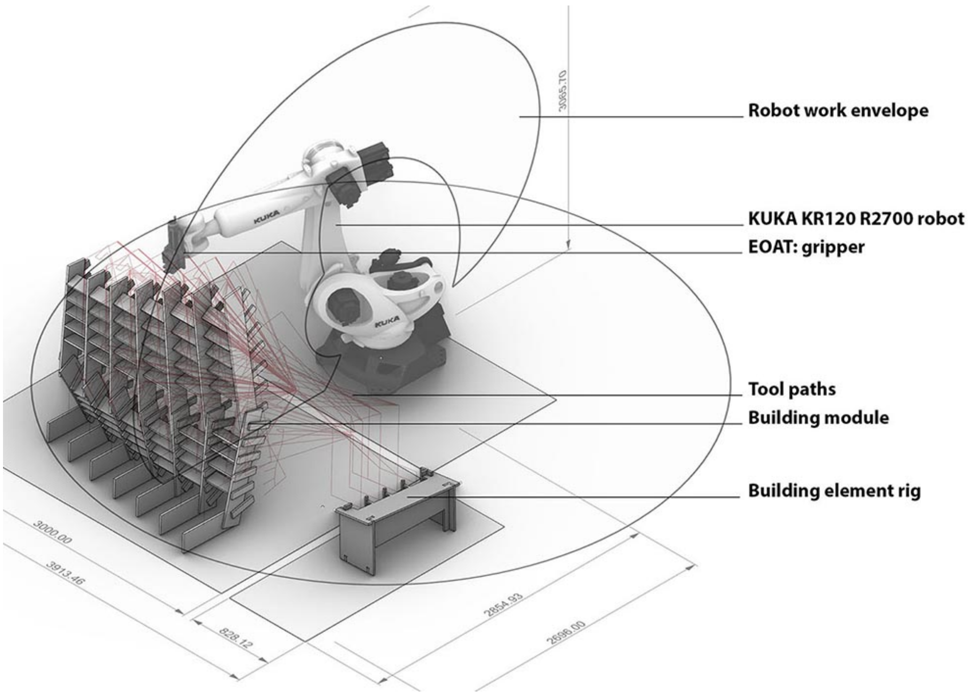

Figure 7.40: Machine setup of Case Study 3. The industrial robot is not constrained by any enclosure as the process is designed to be collaborative. Inside the robot's work envelope is a platform to assemble a building module, as well as a rig for picking up building elements.

7.3.8.2 Morphological parameters of the building element

The building module can be described as a ladder frame structure made from three types of standardized building elements. Its main geometric features are the vertical orientation of the largest building elements, also described as boards in the case study, and the angles, or kinks, where the boards are connected to each other. The two smaller types of building elements fill up the space between the horizontal boards and connect to the cladding layer. While each building element has its own set of geometric parameters that influence the design space of the module, the case study is focused on evaluating higher-level parameters that have a more direct influence on the overall design space of the building system. In order to define morphological parameters that have the most influence on the building system's design space while at the same time being directly influenced by the machine setup or through an interdependence of parameters, Table 7.3 below is used.

	Morphological parameter	Influence on design space	Influence of machine setup
	Micro scale (from molecular to cellular makeup)		
	Material density	medium	medium
	Average or individual wood cell length/width ratio	medium	low
	Average or individual veneer layer thickness	medium	low
	Average or individual grain direction	high	low
	Meso scale (building element or part of component)		
	Material thickness	medium	low
	Plywood veneer lay-up	medium	low
	Individual building element dimensions	medium	medium
	Spacing between vertical boards	medium	medium
	Spacing between horizontal boards	low	medium
	(A1) Inclination of lower vertical boards	high	high
	(A2) Inclination of upper vertical boards	high	high
scale increases	Building element density per area	medium	high
	Number of cladding strips	medium	low
	Gaussian curvature at specific point	medium	medium
	Offset between cladding and vertical boards	high	medium
	Depth difference between adjacent vertical boards	high	medium
	Macro scale (building component)		
	Number of kinks within building component	high	low
	Building component width	medium	high
	(H) Building component height	high	high
	Building component depth	high	medium
	Maximum inclination of vertical boards	medium	high
	Cladding surface area	medium	low
	Design surface average gaussian curvature	medium	medium

Table 7.3: Analysis of morphological parameters in Case Study 3. The higher the rating, the more direct the impact toward the building system's design space or the impact from the machine setup. Based on the rating, the highlighted parameters are selected to evaluate the relationship between the machine setup and the design space of the building system.

In this case study, the focus of the machinic morphospace analysis is on meso- and macro-scale morphological parameters of the building system. More specifically, the investigation relates to morphological features of a vertical section of a building component. Not all high-level parameters—such as the depth of the building component—reveal information about the relationship of the machine setup and the design space. Instead, the inclination of vertical boards more directly reflects a feature of the building system. If it is assumed that a building component is horizontally divided into two halves, then the angle of inclination for the bottom and the top row of vertical boards are morphological parameters with the most impact on the design space. Additionally, it is assumed that the width of a component is not an important morphological feature because a long wall can be divided into smaller components if needed. Therefore, the height of a component is a better indication of the design space.

Based on the above analysis, three morphological parameters are selected that are most indicative of both the resulting design space of the building system, and the influence of the machine setup. Their relationship is further explained below:

- *(H) Building component height (in mm)*
  As a parameter describing the maximum height of a building component in relation to the other two parameters, this morphological feature is a high-level feature, but it also relates to a single building element within the component. It is directly related to the design space in that it describes how high of a structure could be built with a particular machine setup and the required motion to assemble it.
- *(A1) Inclination of bottom row vertical boards (in degrees)*
  This parameter describes the angle between the horizontal plane and the inclination or direction of a vertical board in the first row of the building system. Values below 90 degrees refer to boards leaning forward toward the robot and values above 90 degrees refer to boards leaning away from the robot. Because multiple boards exist within a building component, this value also exists multiple times. It more accurately reflects the design space of the building system compared to a high-level value such as the depth of a building module.
- *(A2) Inclination of top row vertical boards (in degrees)*
  This parameter describes the same morphological features as (A1) except for the upper row of vertical boards. Because of their relation in space and orientation within a module and in reference to the manufacturing setup, this parameter has different implications on the design space.

All three parameters are visualized in Figure 7.41. While parameter (H) has a more high-level impact on the design of the building component, all parameters appear multiple times within a building component. More specifically, each vertical board generates one value for the bottom inclination (A1), top inclination (A2), and overall height (H). Therefore, one vertical section creates one measurement point, while measuring a module will result in as many measurement points as there are vertical sections.

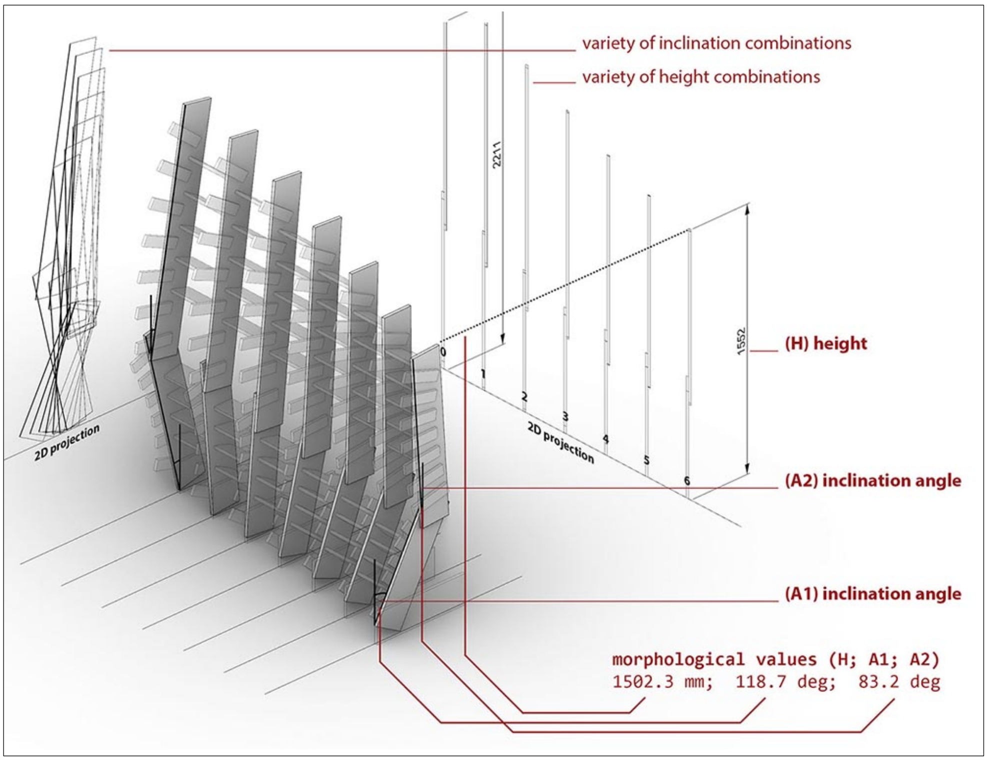

Figure 7.41: Overview of the three morphological parameters of a full building component or module. The vertical boards are shown in full opacity while the other building elements are overlaid with more transparency. Variations of the parameters are also shown either within the component or in a projected view on the left or behind the module. The resulting morphological values of a section are shown within the image to explain the relationship between the three parameters.

Typical boundary situations of these morphological parameters are described in more detail in the below series of images (Figure 7.42). In these images, the variation of the parameters and example situations for their boundary constraints are shown. There are many other instances during the fabrication steps in which constraints are met; however, they are not all visualized. The min/max constraints of the parameters due to the machine setup, and their interdependencies, can be described as follows:

- The height of the building component (H) is directly related to the other two parameters as they determine where the top of the second row of boards will be positioned. Depending on the position and inclination of the boards, the robot can be quickly out of reach. The height of the building component is further constrained by the orientation of the connecting horizontal boards as they sometimes result in an out-of-reach or collision event as well.
- The inclination angle of the bottom row of vertical boards (A1) is constrained mostly by collision events with the robot's effector due to the boards being close to the ground. A high inclination towards the back can quickly result in out-of-reach scenarios for the second row, while a high inclination towards the front will result in a collision with the floor.
- The inclination angle of the top row of vertical boards (A2) is mostly a consequence of the previous parameter (A1) because the top boards are connected to the bottom boards. There are generally out-of-reach scenarios in which the boards will be too far away for the robot arm. However, those scenarios depend on the value of (A1) and therefore a more detailed analysis was done. Further, particularly low inclination angles can also lead to collision events with the built structure.

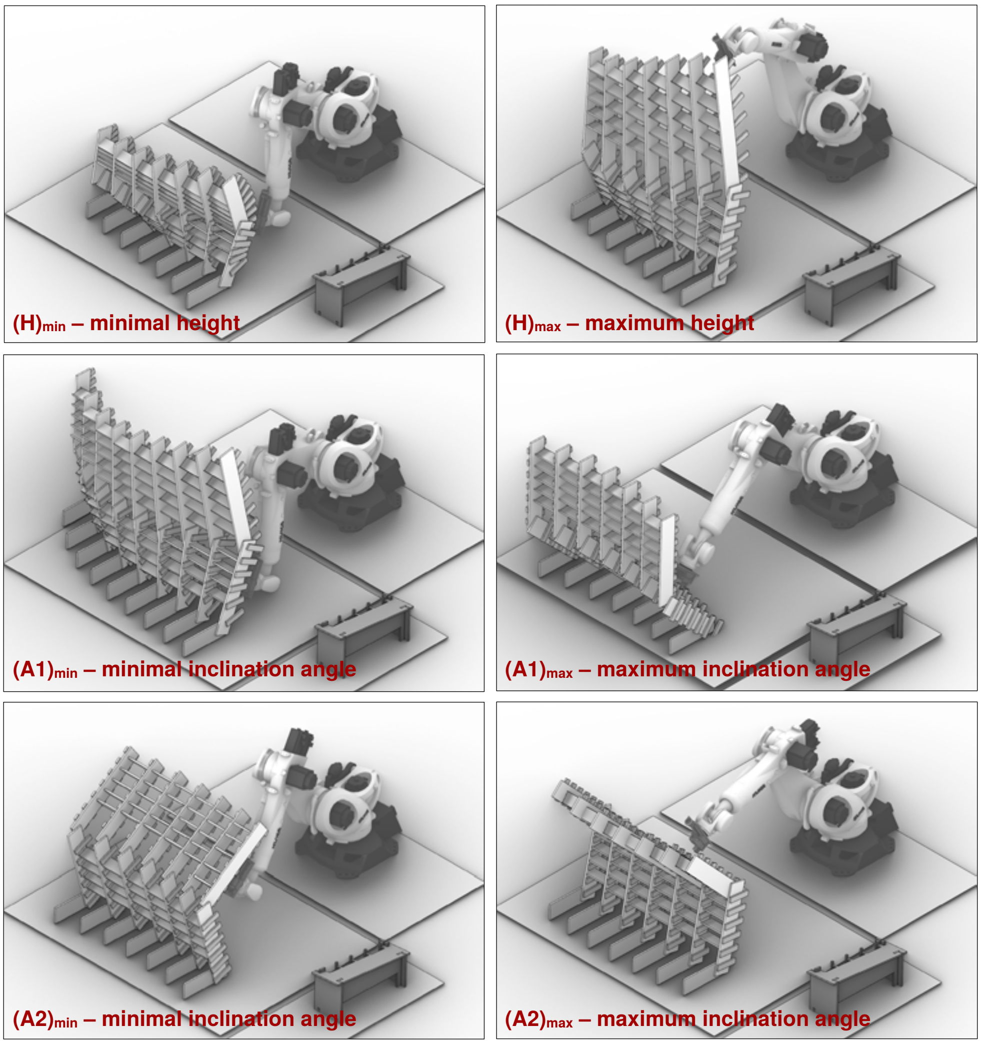

Figure 7.42: Exemplary boundary conditions of all three parameters. Top row: minimal and maximum component height (H). Middle row: Minimal and maximum inclination angle (A1). Bottom row: Minimal and maximum inclination angle (A2).

7.3.8.3 Result: theoretical and empirical machinic morphospace of Case Study 3

In Figure 7.43, the resulting theoretical machinic morphospace is represented by a light gray volume within the three-dimensional parameter space described by (H), (A1), and (A2). The theoretical morphospace represents the *producible region of possible form* (PPF) for the described machine setup and a building component being assembled in the specified location.

The three morphological parameters chosen to visualize the design space are characterized by a strong interdependency. This is because the inclination (A1) of a board on the bottom row directly influences the position of a board on the top row. Therefore, its inclination (A2) depends on (A1). For example, backwards inclined bottom boards will most likely push the top board out of reach of the industrial robot. Therefore, the combination of (A1) and (A2) is cut off in regions with higher (A1) angles.

Both inclination parameters (A1) and (A2) also have individual and combined influence on the possible height (H) of a module's section. A low inclination of the bottom row board (A1) will restrict the minimum height of the structure because the robot's EOAT will collide with the floor. Similarly, a high inclination of the top row board (A2) restricts the maximum height because it will be out of reach for the robot arm. Generally, the minimum height of the structure is 500mm and the maximum height is 2950mm. The highest value can only be reached if the inclination angle of the top row (A2) is such that the robot's wrist is stretched out completely.

In Figure 7.44, the empirical machinic morphospace of all 40 vertical sections of the demonstrator structure built for the DADA Digital Factory conference at Tongji University in Shanghai is visualized in red. Each point represents one vertical section with a bottom and top inclination of its boards and the total height of the building component at that section. The complete demonstrator was built in six sections, which resulted in two continuous walls. Because of their continuity in height and inclination angles, the measurement points trace a continuous, three-dimensional curve within the theoretical morphospace.

In the (A1) – (A2) projection, it is possible to see that (A1) was relatively evenly distributed between forward and backward inclinations, while (A2) has more backward leaning inclinations. This is because of the design intent of the demonstrator. The resulting wall was supposed to generally lean more backward so that visitors would be able to see its features more easily. This is also the reason why very few upper row boards had a forward inclination (A2) below 90 degrees, which results in a cantilever. Those (A2) values that did have a cantilever were also heavily inclined backwards on the bottom row (A1), balancing out the structure. This is also true for the opposite condition, resulting in an inverse relationship between (A1) and (A2).

The height of the sections within the demonstrator (H) ranged from 1323mm to 2215mm. Similar to the distribution of the board inclinations, extreme values were avoided. Although the theoretical morphospace extends further in both height and inclination values, the demonstrator is focused on moderate values for the sake of continuity and subtle gradients in the design. Yet, some values were close to the producible constraint boundary. On occasions, both the bottom and top board had high inclination values, meaning that they were leaning backwards and were therefore at the boundary of the robot's work envelope.

As shown in other case studies as well, the empirical morphospace reveals specific design decisions that result in some regions within the theoretical machinic morphospace to remain empty. There are clear preferences towards some regions, and clear indications of the design intent coming close to the producible constraint boundary. In this case study, the height of the structure was a clear issue. Although the demonstrator had no particular function, it could be argued that if this building system was used as a cladding for buildings, a larger work envelope would be necessary to be able to produce modules as high as a building's floors are.

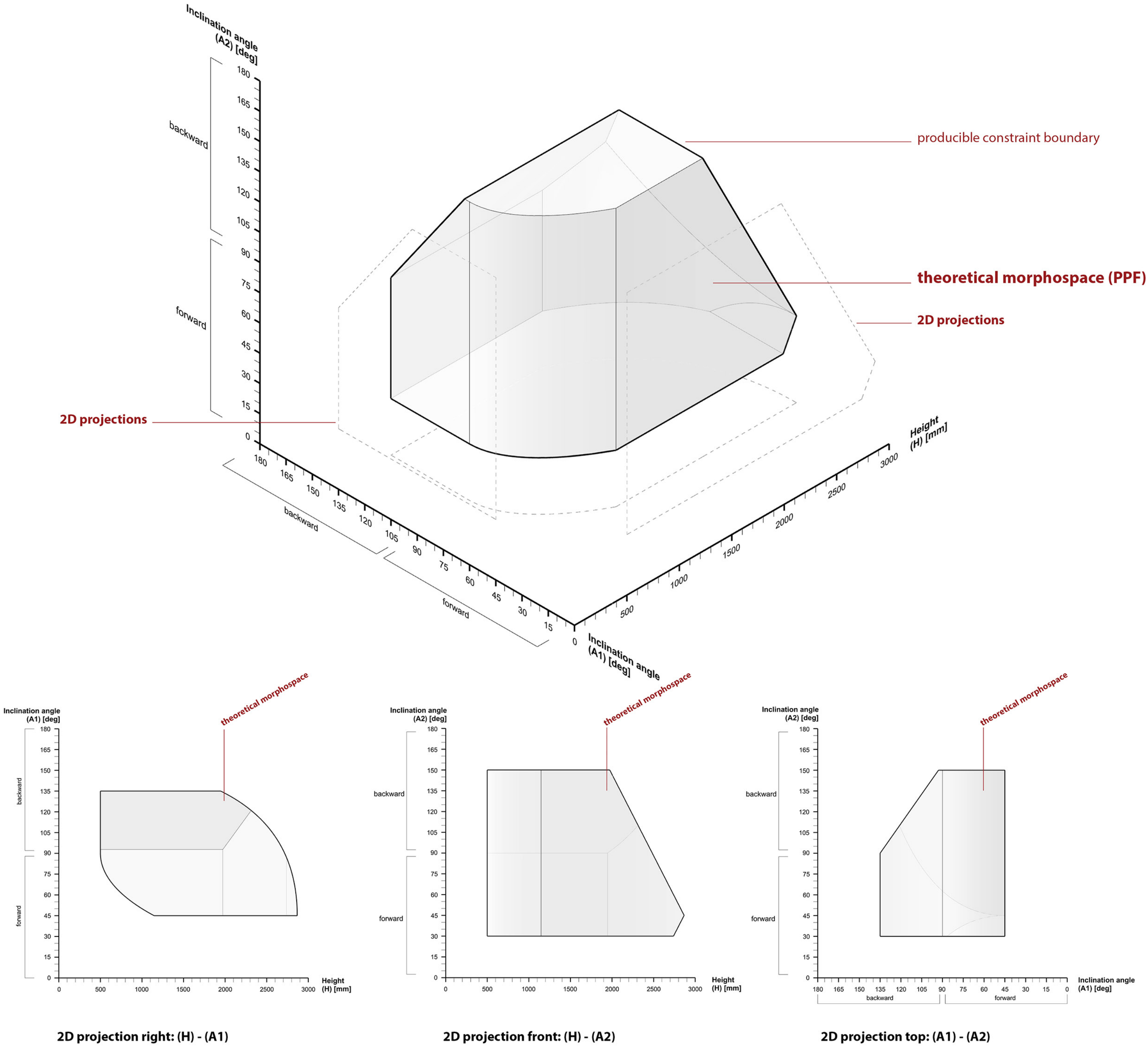

Figure 7.43: The theoretical machinic morphospace of Case Study 3 is visualized as a gray volume with thick outlines. 2D projections of the theoretical morphospace are overlaid on the planes of each pair of axes and plotted at the bottom of the diagram as parallel projections.

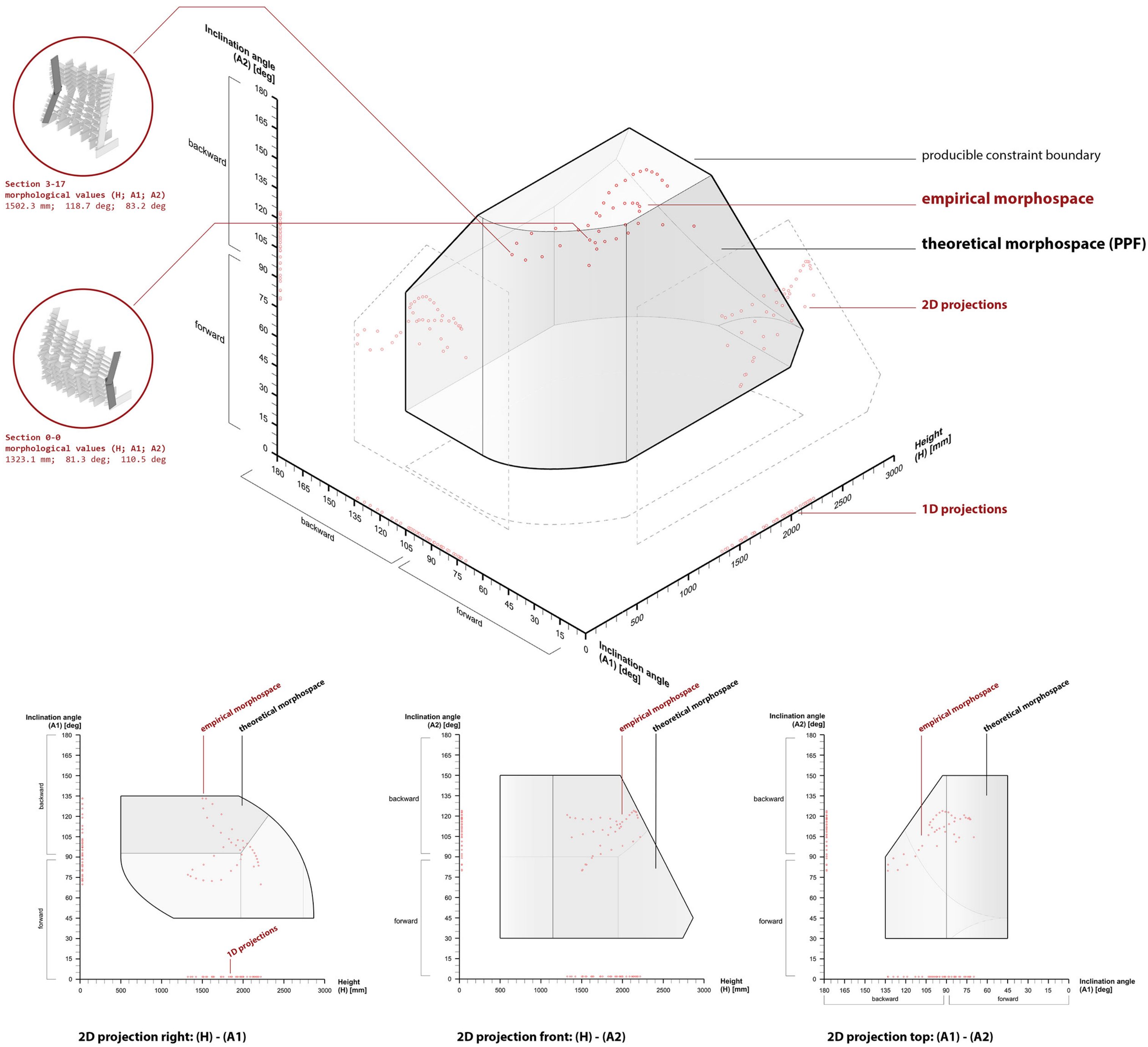

Figure 7.44: The empirical machinic morphospace of Case Study 3 is visualized by red measurement points that represent each parameter value of each vertical section of a building component made for the DADA Digital Factory conference at Tongji University. Two example sections are shown on the top left to exemplify the variety of morphology within the building system.

7.3.9 Acknowledgements

This project was a collaboration between several researchers and students.

ICD Institute for Computational Design – Prof. Achim Menges
Abel Groenewolt, Oliver David Krieg, with Jian Ming Huang

Workshop Participants
Shi Xinyu, Li Yutong, Gu Xiaolin, Hu Jialiang, Zheng Xin, Liu Yang, Zhang Shiqi, He Yiwen, Liu Jingrui, Wu Chaoran, Du Jie

Organized and Supported by
DADA 2015 International Conference and Exhibition
CAUP Tongji University, Shanghai
ArchiUnion, Shanghai – Prof. Philip F. Yuan

Other contributors to the aspects covered in this dissertation are listed below.

7.3.9.1 Manufacturing system

The manufacturing system was developed by the author in collaboration with his colleague Abel Groenewolt.

7.3.9.2 Computational design system

The computational design system was conceptualized by the research team, but it was Abel Groenewolt who developed most of the programming for the generation of the geometry and robot code.

7.3.9.3 Design process

The design was developed during the workshop. The workshop participants developed many different options for the design using the tools that were previously developed. A design was chosen that would showcase the flexibility of the system and maximize the available time for manufacturing.

7.3.9.4 Manufacturing and assembly

The robotic system was set up by Prof. Philip Yuan at ArchiUnion. The gripper effector was supplied by the team, and the exact reach and work envelope was evaluated by the researchers. The author and Abel Groenewolt were assisted by Jian Ming Huang at the site of the workshop, and together with all workshop participants the manufacturing and assembly was executed.

Figure 7.45: The ICD/ITKE Research Pavilion 2015-16 (Image by ICD/ITKE University of Stuttgart).

7.4 Case Study 4: ICD/ITKE Research Pavilion 2015-16, 2016

7.4.1 Project Introduction

In 2015 and 2016 the Institute for Computational Design and Construction (ICD) and the Institute of Building Structures and Structural Design (ITKE) engaged in a design-and-build studio project with a group of students. The goal was to develop, design, and build a temporary research pavilion at the intersection of teaching and research that investigates novel manufacturing techniques in timber construction (Figure 7.45). In this case study, the project's manufacturing system and computational design system development processes will be discussed. The project and resulting demonstrator will be analyzed for their design space in relation to the manufacturing setup, and the relationship of design to the development processes.

The premise of this project was the evaluation of biological precedents for a transfer of structural and constructional principles into a building system, which would lead to a wider range of possible shapes in the building element or building component, which, in turn, would lead to a higher adaptability of the building system on a macro scale. This outset ties back to the research group's motivation to find new ways of using material properties and manufacturing technology for the development of gradient building systems as described in Chapter 5. In this project, the translation of biomimetic principles and the transfer of textile manufacturing techniques into timber construction formed the foundation of the development process.

The project was organized as a year-long seminar and studio. In the first term, students engaged with the constructional morphology of sea urchins as biological role models, and derived biomimetic principles by evaluating their material makeup, growth, and structural functionality. The students then transferred those principles into early iterations of material systems made from wooden components. Except for the desire to work with wood as the main structural building material, the development process was open ended. Once a certain combination of principles was confirmed through preliminary material, manufacturing, and design studies, the students engaged with developing the required technology.

In the second term, students formed lager teams to continue the development of the building system, manufacturing technology, design methods, and structural analysis. In parallel, computational design tools were developed to explore the design space of the developing building system. These tools were used to explore design possibilities through the accumulation of building elements and components with a particular set of material and manufacturing principles. Through the development of the computational tool set, the boundary conditions of the building system were explored while the building system was still under development. This feedback loop guided both development processes. Further, the output of fabrication data required to produce each building element was also developed to test the manufacturing process. Considering methods of pre-fabrication and assembly on site, the final version of the building system was a modular structure with double-layered building components made from plywood loops.

The author participated in this research project as a research associate at ICD in a team of four researchers and two professors. The author was primarily involved in supervising and assisting the group of students from early research of biomimetic principles, to manufacturing technology development, building system development, and the final design and fabrication of the demonstrator. Further acknowledgements are in sections 7.4.5 and 7.4.9.

Some of the project details of this case study were published in the papers “Textile Fabrication Techniques for Timber Shells” by Bechert *et al.* [29], “Biomimetic Timber Shells Made of Bending-Active Segments” by Sonntag *et al.* [344], and “Robotic Sewing” by Schwinn et al. [332]. Some results presented in this case study are unpublished, particularly details on the manufacturing development in section 7.4.3 and the machinic morphospace analysis in section 7.4.8.

7.4.2 Investigative motivation: material characteristics and novel manufacturing technologies

The case study's main hypothesis is that the design and construction of very thin, geometrically differentiated timber shells requires alternative and adaptive material, connection, and component manufacturing methods, and that consequently, they can be built without traditional wood joints or metal fasteners [29; 332].

This project combined two research areas in material properties and manufacturing technology, both of which have been identified and investigated individually in other case studies: (1) Employing the specific material characteristics of wood such as elasticity to assist the pre-fabrication of elastically bent building components, which results in a high level of material efficiency and structural performance through geometrically stiffening; and (2) adaptive, or reactive manufacturing methods where live feedback from the manufacturing process results in changes of the machine's motion planning [29; 332].

The first topic of investigative motivation was based on the search for higher material efficiency in timber plate structures and led to a rethinking of how laminations of plywood can be fabricated and processed in subsequent manufacturing steps. Wood's inherent material characteristics such as anisotropy and elasticity are both depending on its grain direction. In engineered timber products, these characteristics are usually suppressed through the cross-lamination of individual veneer layers.

The material's elasticity became a vital characteristic when engaging with thin sheets such as single veneer layers or thin plywood with less than five layers of veneer. However, at this scale the anisotropy of each layer of veneer has a proportionally stronger effect on the elastic bending behavior of the product. At the same time, plywood at this low thickness is usually not available as a building product on the market. Therefore, the custom lamination of veneer layers into a thin sheet of plywood with a specific, and locally differentiated, elastic behavior, became the first topic of investigative motivation [332]. By controlling the grain direction of individual veneer layers at specific locations within the laminate, the bending stiffness can be pre-determined, or embedded within the lay-up. An individualized lamination process would therefore allow for the control of a differentiated bending curvature along a strip of plywood when elastically bent [29; 332].

The second topic of investigative motivation is a consequence of the first. To engage with the potential of elastic bending, the custom-laminated plywood strips were designed to be between 3mm and 6mm in thickness. However, in conventional timber construction, connections rely on thick cross sections and metal fasteners. More specifically, segmented timber shells rely on geometrically complex connections that usually require thicker material cross sections. The design of joints for segmented timber shells is crucial as the stiffness continuity of the material is interrupted between segments [29; 218]. With decreasing materiel thickness, the geometric complexity of integral joints cannot be embedded within a building element's edge. Further, building codes also limit the reduction of a shell thickness beyond approximately 50mm. These constraints led the research team to find alternative joining techniques specifically for thin timber segments.

On a microscopic level, wood, like many biological materials, can be considered a natural fiber composite. Similar to human-made fiber-reinforced polymers (FRP), the fiber direction in the lay-up of the material determines the anisotropic behavior. In the case of FRP manufacturing, the fiber direction is sued to control the resulting material properties [332]. By determining the micro scale properties of a material, its performance can be adapted, and weight can be optimized. Further, the technical textile industry has established methods for manufacturing, processing, and joining thin and flexible sheet materials. These textile methods were investigated for their potential to be transferred and applied to timber construction. In particular, industrial sewing was identified as a promising approach where initially planar sheets were connected along their edges with many small stitches to form complex three-dimensional shapes [29; 332].

The goal of the project was therefore to establish textile techniques such as patterning, sewing, lacing, and lamination, to the manufacturing of lightweight building components made from thin, elastic, and custom-made plywood panels. By combining textile techniques with timber construction, the material's elasticity could be exploited, resulting in structural performative and highly material-efficient building systems.

With a thickness of about 1mm, rotary cut veneer can be manipulated like textile sheets. Furthermore, sewing thin sheets of wood has similar advantages as it has in textiles in that many small connections can transfer forces more easily than few large connectors that can lead to force concentration [156].

The premise of textile techniques in timber construction led to the development of a sewing method for thin sheets of plywood. Using an industrial sewing machine, plywood with a thickness of up to 9mm can be penetrated by a needle and sewn together in a tight bond (Figure 7.46). This technology was developed during the project through iterative testing of materials, laminations, and different needle shapes and types. The most important aspect of this investigation, however, was the development of an adaptive robotic manufacturing technique that engages with the sewing machine [332]. The flexibility of the material that allowed the research team to draw parallels to textile techniques in the first place also requires a high level of dexterity and adaptability of the manufacturing process. Sewing requires highly experienced craftsmen that move the material through a sewing machine while constantly reacting with small adjustments to the material's behavior. The flexibility of the material makes it very sensitive to the forces exerted on it when the needle penetrates. Due to this requirement, textile sewing has historically been difficult to automate with non-adaptive methods [332]. Therefore, the research team developed an online control method where an industrial robot would guide the material through the sewing machine while the instructions would be corrected based on the material's actual behavior. This allowed for adjustments to unpredicted material behavior and movement, and therefore, precise sewing patterns could be achieved.

Through the combination of these developments, a segmented shell building system was developed making use of the elastic bending of thin and custom laminated plywood (Figure 7.47). Each building module is based on three elastically bent plywood strips, which form a tri-loop to connect both ends at the top and the bottom. This results in a six-sided module where three sides are closed and three are open loops. Each strip of a tri-looped module, in turn, consists of laminated patches of varying curvature and thickness.

Figure 7.46: Close-up of a robot sewing process with 6mm thick plywood (Image by ICD/ITKE University of Stuttgart).

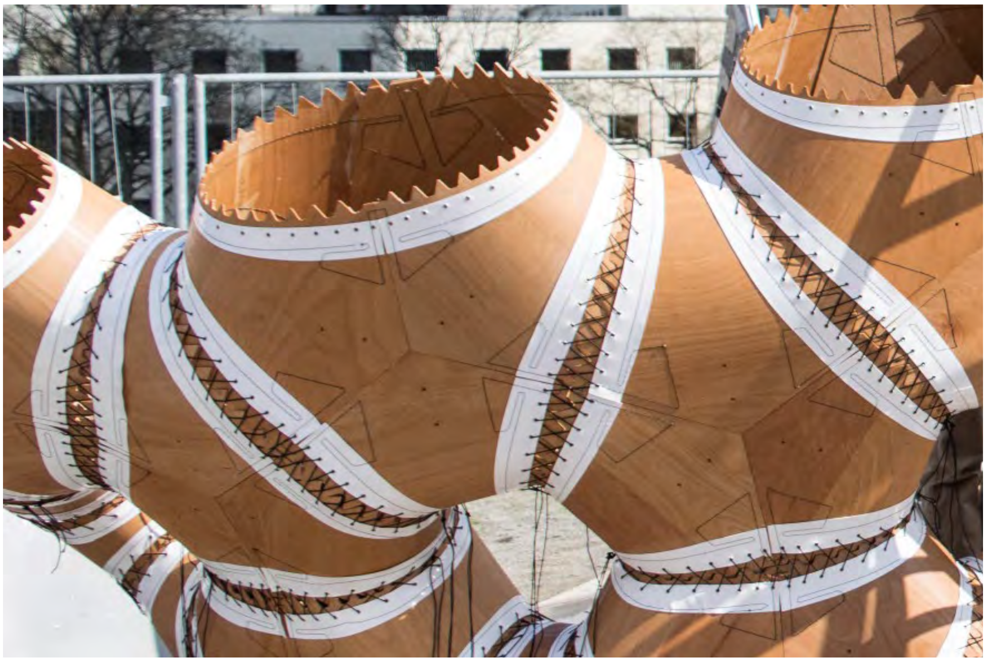

Figure 7.47: Multiple connected tri-loop building modules of the ICD/ITKE Research Pavilion 2015-16 (Image by ICD/ITKE University of Stuttgart).

The open edges of the module would later be used to connect to adjacent components using a combination of intersecting finger joints and membrane lacing techniques.

7.4.3 Development of the manufacturing system

The development of the fabrication steps described in the above section became part of a larger manufacturing system that was established by incorporating material constraints, available stock sizes, design intent, and the kinematic envelope of the machine setup. This led to the development of a material system and building system, with the building components, or modules, in close relation to the manufacturing technology developed at the same time.

The manufacturing system is closely interwoven with the computational design system described in the next section. In this section, only the data flow coming from the computational design system necessary for the manufacturing process is considered. The interface between the computational design system and the manufacturing system is information and geometry that is required for the manufacturing process to function. This data is transferred in different ways depending on the process step. The manufacturing system is divided into four main stages:

(1) Material manufacturing
(2) Building element manufacturing
(3) Building module manufacturing
(4) Assembly on site

Contrary to projects in other case studies, this project investigated the advantages of including the custom manufacturing of the building material instead of using available stock material. Expanding a custom and parametrized manufacturing system towards the early steps of the value chain allows for a higher degree of building component differentiation, and, ultimately, a higher level of material efficiency. However, it also requires a higher level of technological implementation in every stage of the manufacturing process.

In the first step, the building material is manufactured through a combination of custom veneer selection and lamination. As discussed earlier, the lamination of differently oriented veneer layers is in direct relation to the required stiffness and resulting bending radius [29; 345]. The impact of varying grain direction, the number of veneer layers, and the resulting bending stiffness of a plywood strips was evaluated through physical and digital prototyping. To achieve areas of high curvature, the material's stiffness needs to be reduced, which results in low material thickness and most of the grain direction perpendicular to the bending direction. Conversely, areas with low curvature require high material stiffness and therefore more veneer layers as well as the grain direction mostly in parallel to the bending direction. Where a high material cross section is required for structural performance, the material thickness can be high while the grain direction in the laminates can run perpendicular to the bending direction to allow for a higher curvature [29; 345].

Here, the first and second step of the process converge. From the design model, each building element is divided into 100mm wide areas of discretized stiffness, which results in lamination instructions for grain direction and the number of veneer layers. The building element is then unrolled into a flat strip and nested on the available stock material that acts as a minimum base layer for additional veneer lamination. Then, additional sections of 100mm veneer strips are cut and laminated on the base layer in a vacuum press. To ensure a precise and efficient lamination process the instructions are transferred to the stock material using a projector. From here on, the building element is engrained in the stock material sheet, and the building material is no longer a generic stock. In the last part of the second step, the individual strips are cut out from the laminated sheet in a 3-axis CNC process. Special finger joints are cut along the edges of the strips, which will later act as a localization and connection guide for on-site assembly (Figure 7.48).

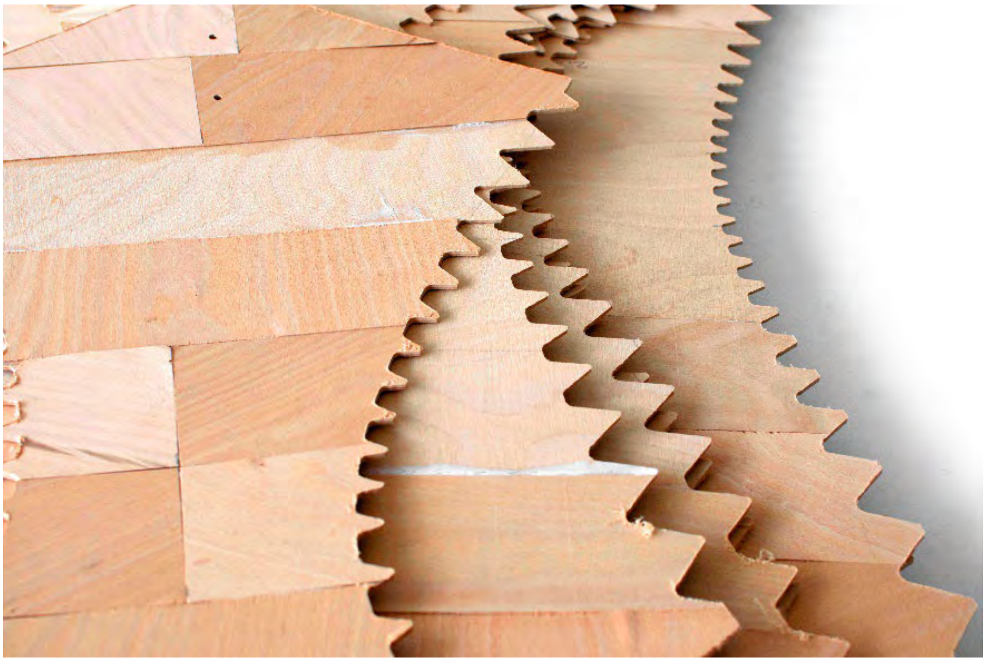

Figure 7.48: Laminated strips after CNC cutting (Image by ICD/ITKE University of Stuttgart).

In the third step, the building module is manufactured from three building elements by means of robotic sewing. Here, the robotic pre-fabrication process was developed for both an assistance process and the automatic and adaptive sewing process. In the first part, the robot is used as a positioning guide in order to assist human workers in pre-assembling the three strips in their correct elastically bent shape to form the module geometry. In a similar process to that of Case Study 3, the robot is used to indicate the relative position of the upper and lower base of the module were all three strips meet [332]. More specifically, the height and inclination of the two opposing planes where the strips are connected, are indicated by the robot's effector position. The robot then pauses for human collaborators to bend and glue all three strips to a lap joint. Then all building elements are connected with the robot's effector, which in turn is then fastened in the defined position in order to stabilize the segment for sewing [332].

After the effector is fastened and the human collaborators exit the work envelope, the robot continues to move with the building module towards a stationary sewing machine. This industrial grade sewing machine is used as an external tool through which the robot then moves the segment and controlled through the robot code. When the sewing machine controller receives a command from the robot control, it initiates a single stitch. During the stitch the robot does not move, which ensures that there is no lateral movement of the segment while the needle is penetrating the material. Instead, the robot only moves the module between stitches. The communication between the sewing machine and the robot control results in two stitches every second [332]. The sewing lines have the purpose to permanently connect all three plywood strips and to attach membrane strips on the outside of the module, which are later used for on-site assembly. The membrane strip is a secondary textile connection that employs a lacing technique to tightly connect each module to its neighbor (Figure 7.49).

Figure 7.49: Robotic sewing of a module of the ICD/ITKE Research Pavilion 2015-16 (Image by ICD/ITKE University of Stuttgart).

The computational design system not only generates the distribution of building modules and their individual morphologies, but also the specific sewing lines needed for the manufacturing process. In this process, the geometry of the 3D model of each module is used to create the sewing lines. They are placed in a pattern around the top and bottom base of the module to form an area of evenly distributed pressure where it is most needed, but also along the edges of each of the three elastically bent strips to attach the additional membrane element. The direct connection between the digital model and the manufacturing system allows for the sewing lines to be translated into machine code for the industrial robot's motion planning. Each stitch is represented by a location point and a codified instruction for the sewing machine to execute a stitch.

To ensure the needle doesn't break, the part of the segment that is currently sewn must be orthogonal to the needle axis. This requirement, along with the required accuracy of the sewing line in general, drove the development of the manufacturing process towards an adaptive, online, robot control method. While the robot's motion is simulated before the initial set of machine code instructions are exported for the robot system, minor differences between the expected module geometry and the physical module in the robot cell require a motion path correction routine incorporated into the sewing process. Through an online control interface, the robot position can be adjusted with each stitch [332]. Adjustments include lateral positioning of the component in relation to the sewing plane, or adjustments along the needle axis. Between a needle stitch, the robot operator can initiate the adjustments and confirm the new position. Small deviations are usually due to the unique material characteristics of the building element, which in turn can be caused by deviations in material density or knots in the individual veneer layers. Because of the low number of veneer layers in the custom plywood laminate, these deviations can have a significant impact on the material behavior. In some cases, the component geometry deviated by over 10mm from the expected location.

The sewn connections ensure that the three strips of each module are tightly connected while the glue is curing even after the component is taken off the robotic setup. This manufacturing method allows for an effective glue lamination process of complex, three-dimensional plywood components without the need for equally complex formwork, which would have to be manufactured for a specific shape, and thus could only be used once. Instead, the manufacturing process was developed to be adaptable enough to temporarily clamp the components for the sewing process, which then takes over the capacity to ensure the material lamination while the glue is curing [29; 332].

In the last step of the manufacturing system, the finished building modules are brought on site and connected through a laced joint using the membrane strips around their edges. This connection, in turn, assures that minor deviations in the shape of the module can be adjusted because of their elasticity. Only once the modules are tightly connected to each other, the overall shape of the building system becomes stable enough to span over several meters.

7.4.4 Development of the computational design system

The development of a computational design tool was guide by multiple aspects of the building system and manufacturing system. In an early stage of the building system development, computational tools were developed together with physical prototyping to evaluate the relationship between the bending radius of a plywood strip and its veneer lay-up [332]. Afterwards, computational tools were developed to calculate the required veneer layers and translate the information into manufacturing instructions to achieve a designed bending radius. Later, more elaborate tools were developed that generated a detailed CAD model of a tri-loop component with all its connection details and sewing patterns. All in all, multiple interconnected tools were developed over the course of the development process of this project that were joined together in what can be called a computational design system, which would connect design intent, manufacturing constraints, and instructions.

There are different computational strategies to control and evaluate interdependent parameters within a form-finding process. In this research project, the procedural biomimetic principle of plate accretion and addition in a sea urchin was transferred as a growth model for the development of a computational design tool. In biology, many studies have previously analyzed the growth process of sea urchins in regard to how discreet plates are added and grow throughout their life span [92; 166]. One of the most distinguishing procedural principles is that plates are added from the apical disc, and as they move towards the equator of the sea urchin calcite material is added around each plate's edge [29]. The principle of adding and growing plate segments can be seen as a form finding process that balances the distribution of plates and the structural integrity of the shell. This principle was transferred into a form finding process through a simulated circle packing algorithm with growing plates that emerge from the two feet of the pavilion [29; 332; 407] (Figure 7.50).

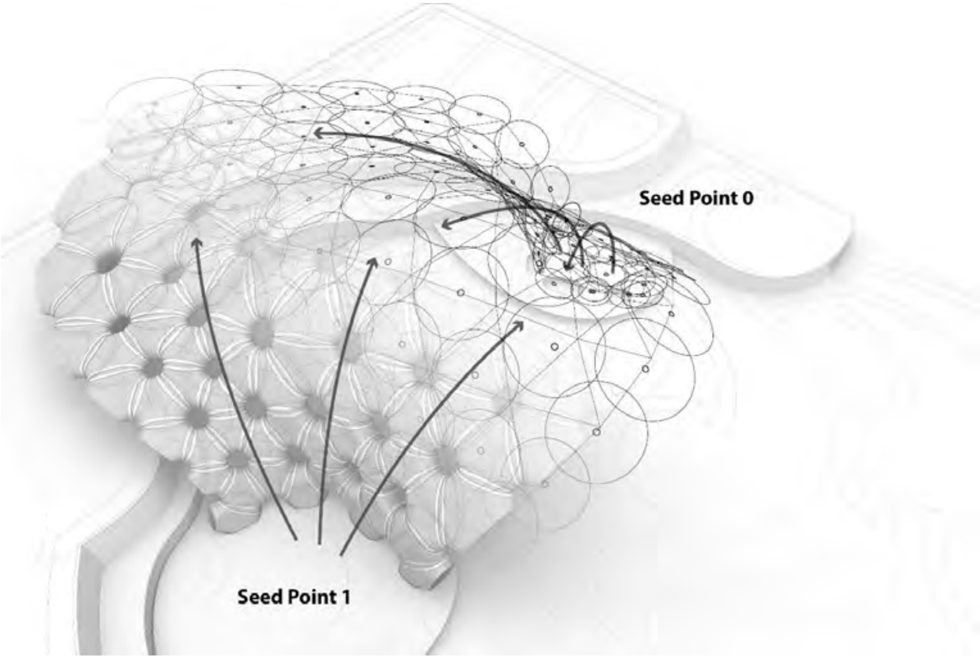

Figure 7.50: The computational design tool adds plates along the feet of the pavilion, which then grow and move into the top center (Image by ICD/ITKE University of Stuttgart).

The team developed a computational design system that can spawn and grow a segmented shell structure following a pre-defined design domain in the form of a NURBS surface. Then, a particle simulation starts to populate the design domain starting out from defined growth locations. In the case of the demonstrator, the growth locations were the two supports where the pavilion would interface with the ground. In this simulation, each particle represents a segment, which would later be transferred into the geometry of a full tri-loop module. At this stage of the simulation, however, the particles are only represented by a point and a circle that simulates its size [332]. Using the radius of the circles, each particle balances repulsion and attraction to its neighbors so that all particles get distributed according to their preferred size. As the simulation is ongoing, each particle expands its radius while new particles spawn at the support points until either a certain number of particles is reached, or the design domain is fully covered. This simulated growth process results in a segmented layout similar to that of the sea urchin's skeletal plates.

The resulting global geometric characteristics are also structurally advantageous because smaller segments at the support locations result in a higher material density and therefore a higher structural stiffness [29]. Further, segments gradually get larger towards the top of the shell structure, which is where the least material and structural performance is required.

Once segments are distributed and the simulation stops, a topological map is generated that establishes the connection between adjacent segment using a Delaunay triangulation [332]. The resulting triangular mesh is the basis for the geometry generation of the tri-loop modules. Here, other user-controlled parameters influence the resulting height and size of the modules. Once their morphology is generated, each plywood strip can be extracted, and its required stiffness deduced from its curvature. As a result, each strip and each module are saved with all information required for material, element, and module fabrication. Additionally, by exporting certain data sets from the digital model, design iterations can be structurally analyzed as well [29].

At this point, the digital model not only contains the architectural design intent, but also the material specifics of the plywood strips and information required to generate manufacturing instructions, such as lamination instructions for individual plywood strips, the CNC code necessary for cutting out each plywood strip, and the robot code for connecting and sewing together the building modules.

During the development of the computational tools, manufacturing constraints were analyzed by simulating the robotic fabrication process. This allowed the team to find constraints such as collisions or out-of-reach scenarios. During this process, both the design space of a module and the machine configuration were analyzed and optimized.

In order to directly connect the design model and its digital geometry with the manufacturing setup simulation, an individual component can be selected by the algorithm, which is then simulated by mapping its movement in relation to the position of the industrial robot and the stationary sewing machine. The component is being moved in three-dimensional space so that each stitch of the sewing machine is executed perpendicular to its surface at that location, while the robot's kinematics need to adjust to hold the moving component's top surface. Together, this kinematic relationship is essential for the exploration of the work envelope of the machine setup and the subsequent deduction of the machinic morphospace.

7.4.5 Project result

In the final months of the project, a large-scale demonstrator building was designed that could exhibit the structural and architectural potentials of such a development process. As a result, the ICD/ITKE Research Pavilion 2015-16 provided a large interior space that combined a dome-like typology with a flat roof resting on columns (Figure 7.51). The feet of the pavilion required smaller, skewed, and stronger modules, whereas the roof structure had larger and more light-weight modules. Smaller modules increased the density of material per volume, and the interconnection between the outer and inner layer increases with the higher density of modules as well.

Following the biological principles derived from sea urchins, the demonstrator's structure not only functions as a pure shell but also allows for higher bending moments through internal connections between the upper and lower layer. Loads are ultimately translated locally into membrane forces even when the shell transitions towards a column and slab scenario. This possibility was shown in the back of the pavilion where columns protruded from the shell by inverting the module geometry, thereby creating a secondary module typology.

The demonstrator consists of 151 modules. Each module is between 0.5 and 1.5 meters in diameter and has a material thickness of 3mm to 6mm. Due to the textile connection techniques, the entire shell structure was constructed without the need for metal timber fasteners. The structure weighs 780 Kg in total while covering an area of 85 square meters and spanning 9.2 meters. As a temporary structure, it was secured to the ground with a base that contained extra weights to keep the pavilion secured during high winds.

Figure 7.51: The ICD/ITKE Research Pavilion 2015-16. Image by ICD/ITKE University of Stuttgart.

7.4.6 Research result: Process analysis

To evaluate how the integrative development process was enabled in this project, the relationship between the gradient building system, manufacturing system, and computational design system is analyzed in this section.

This case study investigated the development process of a robotic sewing method in conjunction with a computational design method for the development of a lightweight gradient building system made from extremely thin and custom-laminated plywood. The project emerged from a combination of many investigate motivations: employing and controlling material elasticity, adaptive and reactive manufacturing technologies, construction techniques for thin timber shells, the transfer of biomimetic principles, and textile techniques for construction.

As one of the most complex case studies, this project also exhibits the most integrated development process and reaches furthest in the value chain of a manufacturing system (Figure 7.52). Building on previous research on the development of gradient building systems that can become more material efficient through the differentiation of their building component morphology, it expands the range of technological innovations toward the fabrication of the material that is used to produce building elements and components. The step towards rethinking building materials is a logical step in the ambition to innovate within the value chain in order to achieve more adaptive building systems.

The project also shows that a much lower structural weight can be achieved with this set of technological advancements. While other case studies have only investigated manufacturing innovation in the processing of stock material to produce building elements, or in the assembly of processed material into building components, this project shows that standardized stock material can be a limiting factor.

Instead, highly material-efficient structures require material characteristics or lay-ups that standardized stock material in the timber industry does not provide. One such requirement can be material thickness or the grain orientation of veneer layers within very thin plywood, as was the case in this project. Without a customized lamination process that was directly connected to the computational design system, the material efficiency and building component geometry could not have been achieved.

More importantly, the material also has a direct impact on the manufacturing technology. While typical engineered timber is thick enough to provide almost homogenous material characteristics, the material thickness also usually provides enough stiffness for the stock material not to deflect or move during machining or other processing steps. With a decreasing material thickness, however, the material becomes less predictable and a higher level of dexterity for handling the material is required. Two innovative manufacturing strategies were implemented to efficiently work with such thin material: (1) A robotically guided pre-assembly process with human-robot collaboration for the lamination of the building component, and (2) a live feedback loop and motion adaption within the robotic sewing process to react to unexpected material deflections or movements.

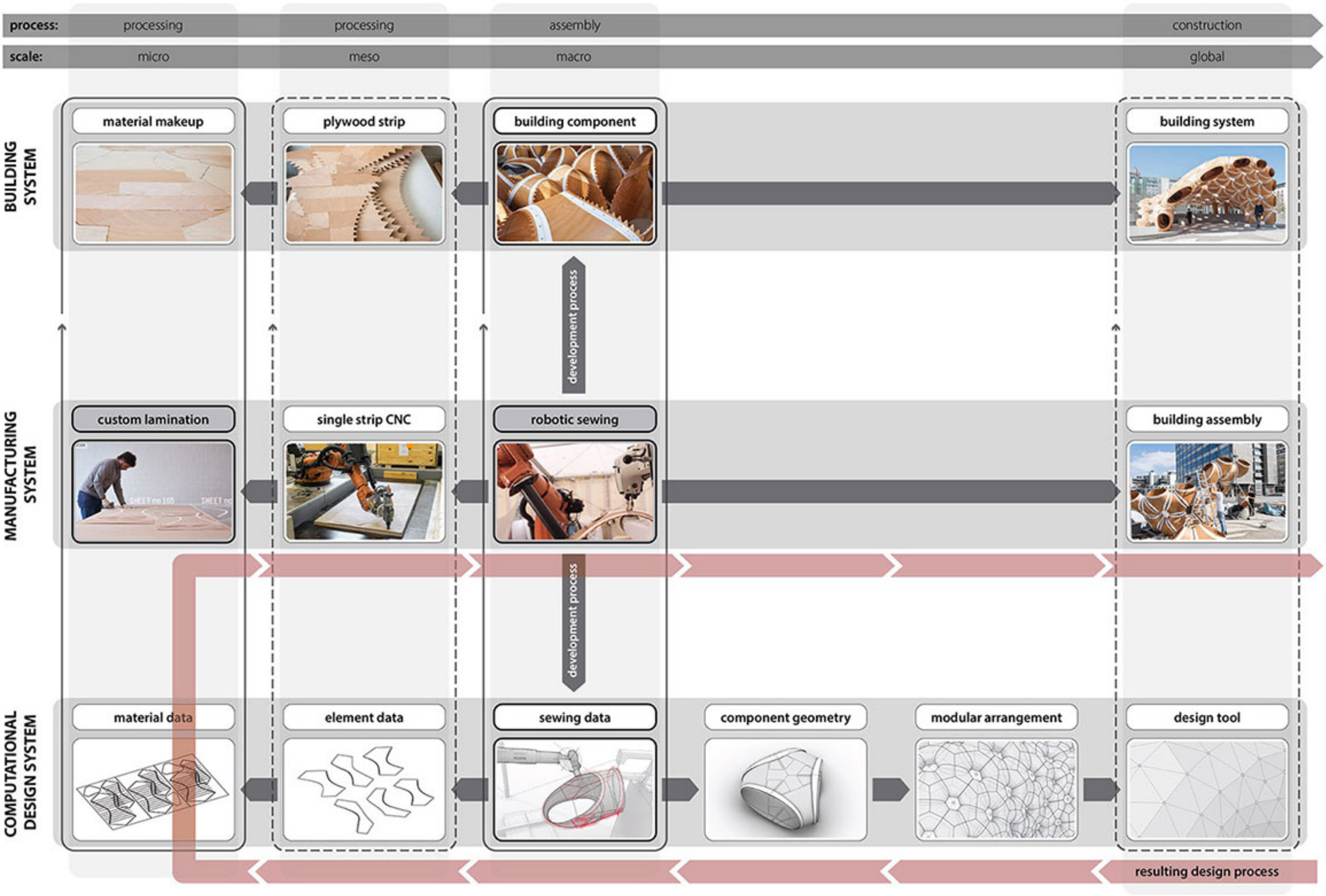

Figure 7.52: Development process overview of Case Study 4. The development process is highlighted with dark gray arrows, and the resulting design process of the demonstrator with red arrows. It can be argued that the development process originated in both the custom lamination process as well as the robotic sewing process. From these points the process branched out into the building system development and the manufacturing system development. This case study stands out as the only one in which the make-up of the material used for the manufacturing process was designed, developed, and fabricated as well. The diagram contains images by ICD/ITKE University of Stuttgart.

Although the complexity of the manufacturing process can be considered higher compared to other case studies, it did not require more time or capital investment to manufacture the components for the case study's demonstrator. After an initial prototyping and startup phase, components were manufactured with a tact time of 60 minutes. The number of building elements, the total manufacturing time, and the size of the demonstrator were all equal to similar projects such as Case Studies 1 and 5. The machine setup consisted of a large-scale industrial robot and a standard industrial sewing machine. The effectors and the machine control were developed cost-effectively in-house.

Interestingly, the development process of this case study started out as a biomimetic bottom-up process. Both the manufacturing technology and the building system development were either inspired or informed by an analysis of biological principles found in nature. Through a combination of a wide range of these biological principles, structural and manufacturing principles were derived and integrated into a building system, manufacturing system, and computational design system. All three systems were developed in parallel and in a reciprocal relation.

7.4.7 Research result: Information flow analysis

To evaluate how the morphological differentiation of the building system was digitally generated, processed, visualized, and stored, the computational design process is analyzed in this section.

Due to the computational complexity of the modules' elastically bent geometry, the final shape of the modules was not immediately generated during the design process. Instead, a representative mesh was used to visualize the number of modules and their approximate size, and which would later be translated into the fully articulated geometry of the modules. As such, the computational design process in this case study is particularly simplified during the early design steps. The level of geometrical and visual abstraction is unique in this case study when compared to others. The division of the design steps and the subsequent preparation of manufacturing information is a strong contribution to the hypothesis that a representational design process with direct connections to the building part and manufacturing information allows for better control of the complexity of gradient building systems.

Further contributions can be identified when analyzing the subsequent computational process of adding geometric information for all building elements and generating manufacturing data afterwards.

Once the overall design is determined in the first step of the design tool, the depth of each module can be controlled in a second step. This second step can be completely divided from the first, allowing the designer to generate a large quantity of design studies upfront, and then analyzing the impact of the modules' shapes afterwards. As part of this second step, the bending radius of individual plywood strips can be analyzed and become part of the information model. Further, the geometry of the membrane strips as well as all sewing patterns can also be generated. While the plywood strips and membrane strips are represented by a single layer of a BREP surface, the sewing patterns are represented by polylines. Once this step is completed, the CAD model can again be saved and used for manual adjustments.

Before the design model is split up into individual files for each module to generate the necessary robotic assembly information, all plywood strips are unrolled at the same time and saved into another CAD file. At this point, the model is split into a file for the plywood lamination and CNC cutting, and individual files for each module's robotic assembly and sewing process. The waved finger joints are only added as outlines to the individual plywood strips once they have been unrolled.

In the individual files that are created for each module, each plywood strip and sewing pattern can be identified by its meta-data. The robotic motion and sewing instructions are derived from geometric identifiers on the plywood strips and the sequence of the sewing pattern polylines.

In conclusion, a careful simplification of the geometric representation was necessary to allow for quick design iterations without slowing the computational model down. Complex and information-intense geometry was only generated after an initial design process concluded. However, even with a very small amount of geometric information in this first design step, the resulting CAD model was still directly linked to the manufacturing process, its constraints, and the subsequent data flow.

7.4.8 Evaluation of the machinic morphospace

To evaluate how the morphospace analysis can be effectively used to analyze the relationship between the machine setup and the gradient building system's design space, the author applied this method to the project in this section.

During the project only approximate constraints of the work envelope were evaluated and used to limit high-level morphological features of the building module. This information was used as feedback in the design model, where components that exceeded these constraints were marked. However, an iterative analysis of the machine setup in relation to the design space was not considered during the time-constrained project. Yet, the relationship between the industrial robot's kinematics and the position and orientation of the stationary sewing machine has a direct impact on the range of certain morphological parameters.

In this case study, the robotic fabrication setup in conjunction with the overall fabrication sequence is analyzed for its possibilities and constraints, which influence the morphospace of possible module shapes. For example, the component size, described by its radius, is limited by the reach of the industrial robot's linkage arm as well as the position of the sewing machine. Likewise, if the module is distorted, as described by the relative position and inclination of its top and bottom plane, collisions between the component and the robot arm, or between the robot arm and the sewing machine are possible. This relationship can be translated back into the computational design tool for design iterations to stay within the solution space set by material characteristics and the machine setup.

7.4.8.1 Parameters of the machine setup

The machine setup in this case study consisted of a KUKA KR120 R3900 K industrial robot with a stationary tool. The robot's kinematic information can be seen in (Figure 7.53). The robot was equipped with custom-built and adjustable fastener that could hold the tri-loop modules in their desired position during the sewing process. The manual assembly of the tri-loop module was assisted by the robot but did not affect the machinic morphospace. The stationary sewing machine is a Hightex 441 with a custom-built electrical motor that could be directly controlled through the robot code.

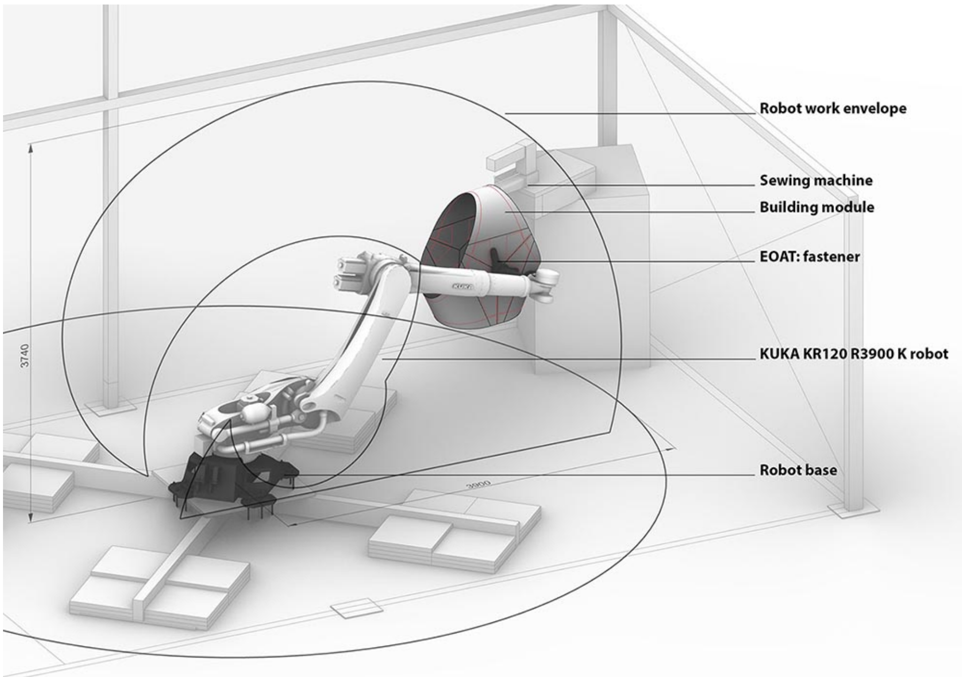

Figure 7.53: Machine setup of Case Study 4. The industrial robot is not directly constrained by the enclosure but has limited motion capabilities because of the effector and the stationary tools surrounding it. Not visible in this image is the manual station where the tri-loop module is being assembled prior to the sewing process.

7.4.8.2 Morphological parameters of the building element

The building module can be described as a tri-loop building component consisting of three elastically bent plywood strips that are bent back in on themselves and sewn together at their meeting points. In addition, a membrane strip is sewn along the module's open edges that will act as a laced connection for on-site assembly. Although the overall shape of the module can change, it is always made from three plywood strips. The resulting shape of the loops and their open edges depends on the plywood lamination and the width of the plywood strips. Many meso scale and macro scale morphological parameters can be used to describe the individual plywood strips, parts of the module, or the entire module. In order to define morphological parameters that have the most influence on the building system's design space while at the same time being directly influenced by the machine setup or through an interdependence of parameters, Table 7.4 below is used.

	Morphological parameter	Influence on design space	Influence of machine setup
	Micro scale (from molecular to cellular makeup)		
	Material density	medium	medium
	Average or individual wood cell length/width ratio	medium	low
	Average or individual veneer layer thickness	medium	high
	Plywood layer grain direction	medium	high
	Meso scale (building element or part of component)		
	Material thickness	medium	high
<<<	Plywood veneer lay-up	medium	high
	Single strip length	medium	medium
scale increases	Minimal bending radius of single strip	high	medium
	Membrane length	medium	low
	Connection angle to neighbor	high	medium
	Loop opening height	high	medium
	I Loop opening width or edge length	high	high
	(I) Module inclination angle at loop opening	high	high
<<<	(T) Triangle angle between two module edges	high	high
	Ratio of length of open and closed edges	medium	low
	Macro scale (building component)		
	Height or depth of module	high	medium
	Circumcircle diameter of module	high	medium
	Opening size between neighboring modules	high	medium
	Gaussian curvature at module location	medium	medium
	Surface area of module	medium	low

Table 7.4: Analysis of morphological parameters in Case Study 4. The higher the rating, the more direct the impact toward the building system's design space or the impact from the machine setup. Based on the rating, the highlighted parameters are selected to evaluate the relationship between the machine setup and the design space of the building system.

The building module can be described by the bending radius, length, and width of each of its three looped strips. While each strip influences the design space of the module, there are also several morphological parameters that describe features that are not directly related to a single strip but by a combination. Further, there are morphological parameters that have a large impact on the design space of the building system but without an evident relation to the machine setup. For example, the height of a single module, while a very important morphological feature of the building system, does not reveal as much about the relationship with the machine setup.

Based on the above analysis, three morphological parameters are selected that are most indicative of both the resulting design space of the building system, and the influence of the machine setup. Their relationship is further explained below:

- *(E) Loop opening width edge length*
  This parameter refers to the projected length of an open loop edge. Although most other case studies use the diameter of a building component's circumcircle, here the edge length was chosen to indicate the size of a module. A preliminary analysis showed that the ratio between the edge length and the overall circumcircle diameter of a module is between 1:1.25 and 1:1.67. However, in this case study, the edge length is more indicative of manufacturing constraints.
- *(I) Module inclination angle*
  The relative orientation of the top and bottom meeting points of the three strips defines how skewed a module is towards one of the three loop openings. This parameter also influences how quickly the building system can change between different heights of its double-layered structure. 0 degrees refers to a parallel top and bottom layer. Positive angles refer to the module opening away from the loop edge, and negative angles refer to the module opening up towards the loop edge—or closing away from the loop.
- *(T) Triangle angle between two module edges*
  The projected angle between a closed and open side describes both proportions of a module and the directionality of the overall building system. A stretched or acute module can have a higher density of neighboring modules in one direction than in another. This parameter is therefore highly indicative of the design space of the building system. It is also directly influenced by the machine setup, and therefore an interesting parameter for this case study.

All three parameters are visualized in Figure 7.54. All parameters have in common that they refer to the meso scale of the building module. The loop opening edge length (E) describe the projected size of one of the module's three sides, and therefore occurs three times. The inclination angle (I) describes the angle between the top and bottom module surface towards a loop opening, and therefore also occurs three times. The triangle interior angle (T) occurs six times within a module, with two values referring to a single loop opening edge.

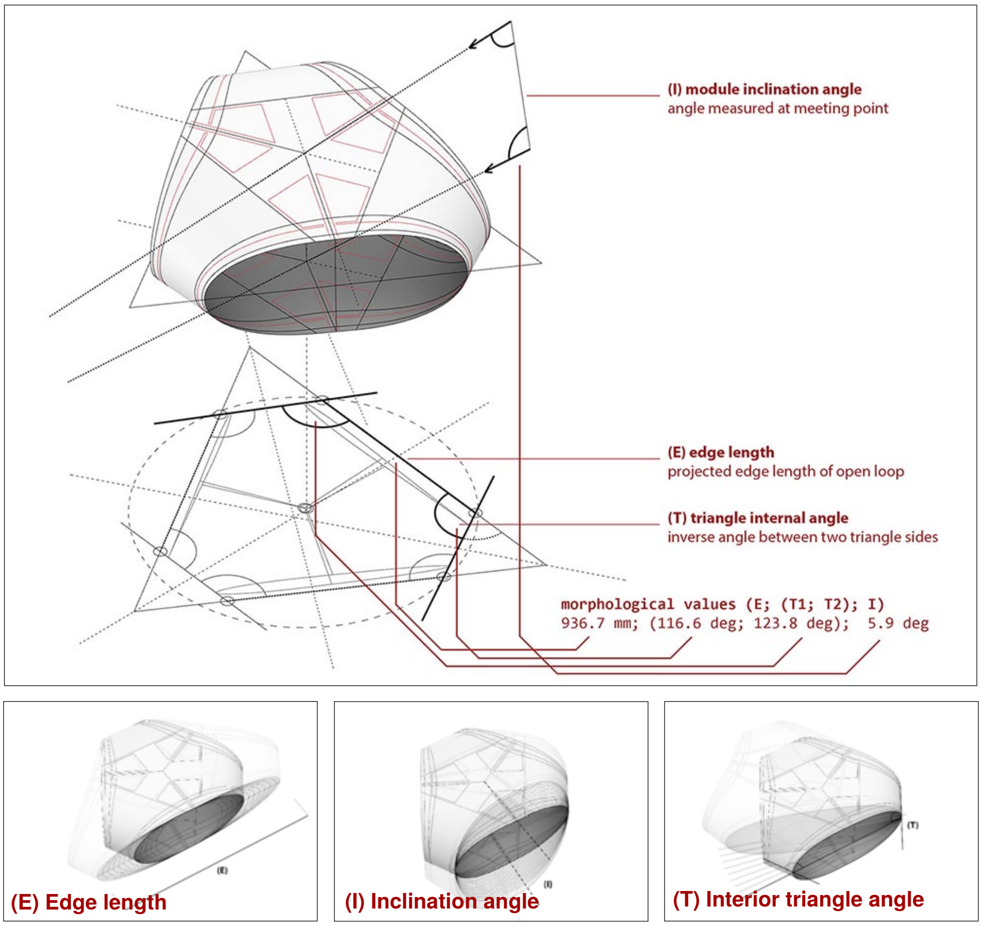

Figure 7.54: Top left: overview of the three morphological parameters of a full building module, explained in a three-dimensional view as well as a projected view below. The resulting morphological values of a module's edge are shown within the image to explain the relationship between the three parameters. Bottom lt: (E) as the edge length of one of three open loop edges of a module. Bottom middle: (I) as the inclination angle of the module towards an opening. Bottom right: (T) as one of six interior angles, with always two shared by the measured edge length.

Typical boundary situations of these morphological parameters are described in more detail in the below series of images (Figure 7.55). In these images, the variation of the parameters and example situations for their boundary constraints are shown. There are many other instances during the fabrication steps in which constraints are met; however, they are not all visualized. The min/max constraints of the parameters due to the machine setup, and their interdependencies, can be described as follows:

- The edge length (H) is directly related to the size of a module. The smallest edge length is constrained by the size of the sewing machine's arm and the robot's effector, which requires enough space to be fixed on the top and bottom surface of the module. It is also constrained by the bending radius of the plywood strips. The largest edge length is constrained by collision events with the robot and the sewing machine.
- The module inclination angle (I) is mostly constrained by the size of the module. The smallest modules can have the largest inclinations and therefore the most extreme changes in the building system's height. However, larger modules quickly restrict the maximum and minimum inclination angle. This can lead to collision events between the robot and the module, or to out-of-reach scenarios.
- The interior triangle angle (T) is only partially constrained by the machine setup. Acute angles are only constrained by the overall resulting geometry of the module. Obtuse angles are constrained by the stationary sewing machine, leading to colliding events during the sewing process. It was also observed that the module inclination angle (I) has no direct effect on this parameter.

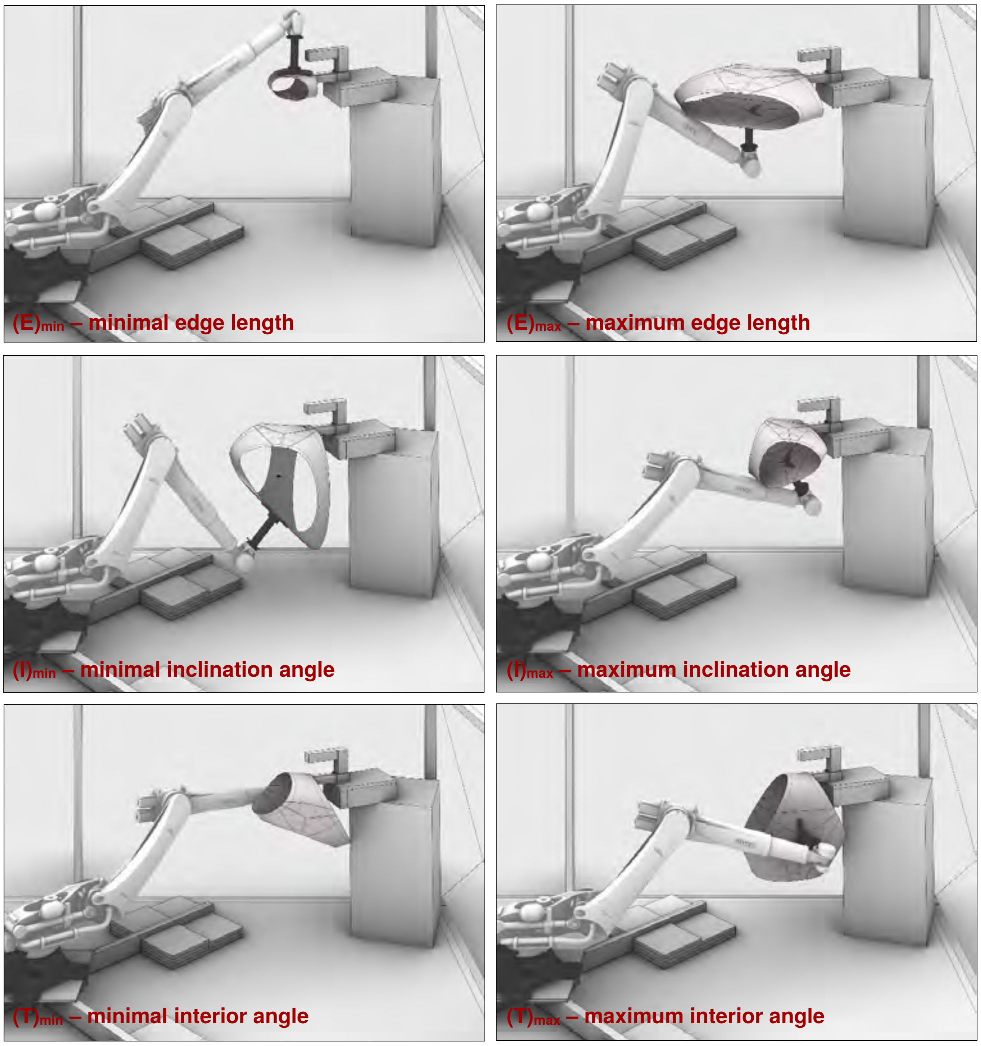

Figure 7.55: Exemplary boundary conditions of all three parameters. Top row: minimal and maximum edge length (E). Middle row: Minimal and maximum module inclination angle (I). Bottom row: Minimal and maximum interior triangle angle (T).

7.4.8.3 Result: theoretical and empirical machinic morphospace of Case Study 4

In Figure 7.56, the resulting theoretical machinic morphospace is represented by a light gray volume within the three-dimensional parameter space described by (E), (T), and (I). The theoretical morphospace represents the *producible region of possible form* (PPF) for the described machine setup in the specified location and orientation.

Some of the morphological parameters chosen to represent the theoretical machinic morphospace have direct influence on each other, while others do not. For example, the module inclination angle (I) was found not to impact the interior triangle angle (T) for the smallest module edge lengths (E). However, for larger edge lengths, both the inclination angle and the triangle angle have smaller parameter ranges.

The module inclination angle (I) is heavily constrained by the edge length (E). This is because of the nature of the sewing process and the setup and location of the sewing machine. Smaller modules can have much higher positive and lower negative inclination angles. The larger the module, the more constrained the inclination angle is. For positive angles, larger modules quickly collide with the robot’s arm. For negative angles, larger inclination leads to the module colliding with the ground or an out-of-reach scenario. The machine setup also results in constraints for the interior triangle angle (T) for larger modules. While the minimal angle is not affected, the maximum angle is constrained by collision scenarios with the sewing machine’s support structure. At higher values of the edge length (E), the maximum triangle angles are more limited.

These findings are interesting for the design space of the building system. If sudden changes in the depth of the structure or the directionality of modules are required, smaller modules would be needed to accommodate these global morphological adaptations.

It needs to be noted that there are many other morphological parameters that would require a thorough analysis in order to represent the design space of the building system. For example, the true circumcircle diameter or the height of the module are two such morphological features that are visually easy to understand. However, both of those examples only have a secondary relationship to the manufacturing process, which is in itself an important finding.

In Figure 7.57, the empirical machinic morphospace of all 151 modules of the ICD/ITKE Research Pavilion 2015-16 is visualized in red. One module is represented by six points, with a pair of points representing one of its three edges. The pairs are visualized with a thin connection line for orientation purposes. The analysis shows a relatively even distribution in the size of modules, represented as the edge length (E), with some modules being close to the minimal or maximal size. The triangle angle (T) shows a symmetrical distribution around 120 degrees, which represents an equilateral triangle. This finding shows that most modules were close to having even sides. However, some outliers exhibit angles close to 140 degrees and 90 degrees, which result in very skewed modules.

As mentioned above, larger module edges (E) constrain the triangle angle (T). This boundary is closely followed by the empirical machinic morphospace. Where the design requires more skewed modules—such as at the base supports of the pavilion where the curvature of the design surface is highest—they also become smaller. Last, it can be observed that all module inclination angles were between -15 degrees and 15 degrees. Although much lower and higher values are possible, the design intent of the demonstrator was such that only shallow variations in the depth of the structure were necessary.

The empirical morphospace reveals clear design preferences towards some regions and avoidance of others. For example, no acute modules were designed, which would have resulted in heavily skewed modules. It could be argued that a different demonstrator in another context might have required such modules. Although the design of the demonstrator was developed in conjunction with the machine setup and the building system, these regions remain empty and could be occupied for a very different pavilion design in the future.

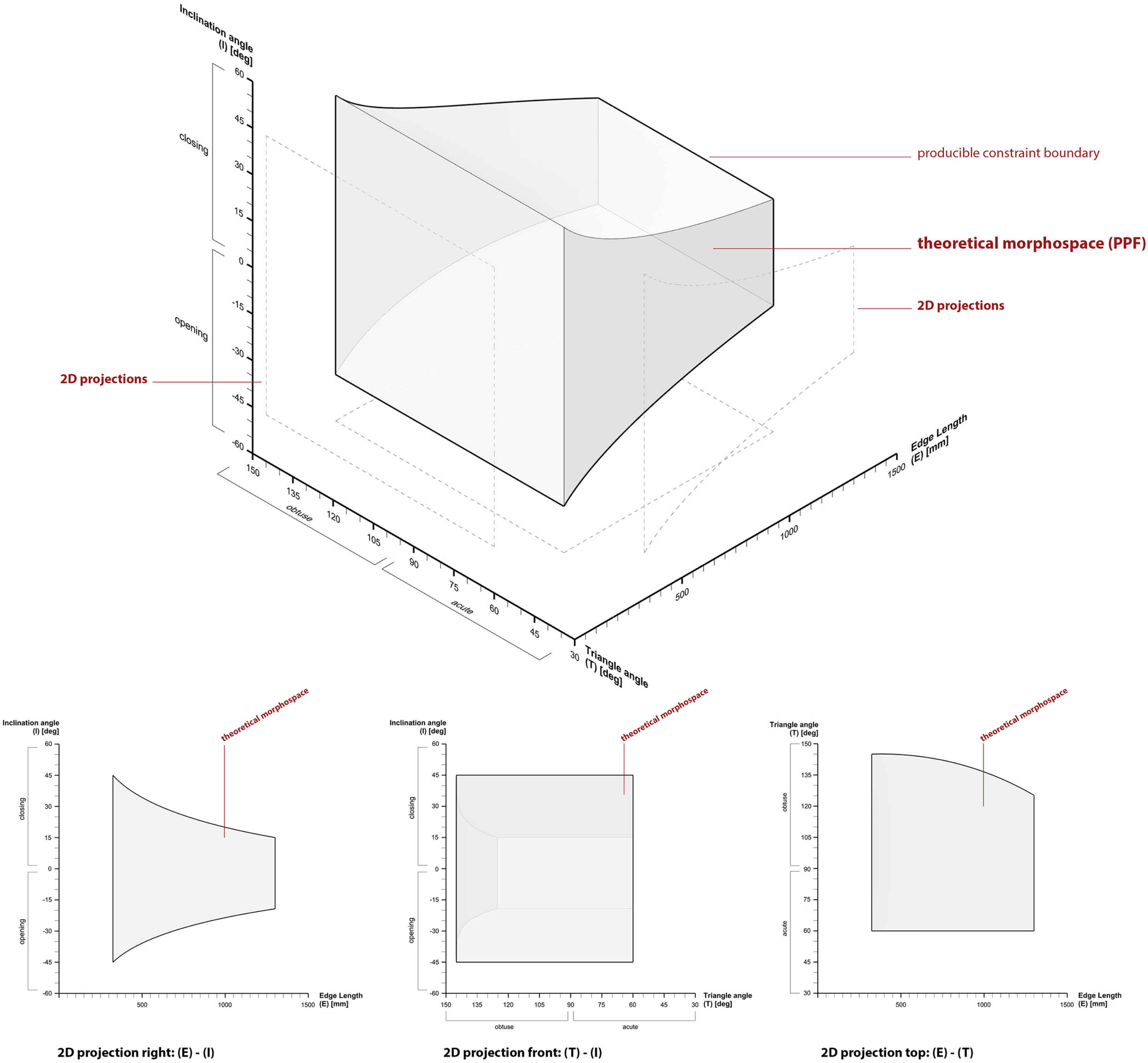

Figure 7.56: The theoretical machinic morphospace of Case Study 4 is visualized as a gray volume with thick outlines. 2D projections of the theoretical morphospace are overlaid on the planes of each pair of axes and plotted at the bottom of the diagram as parallel projections.

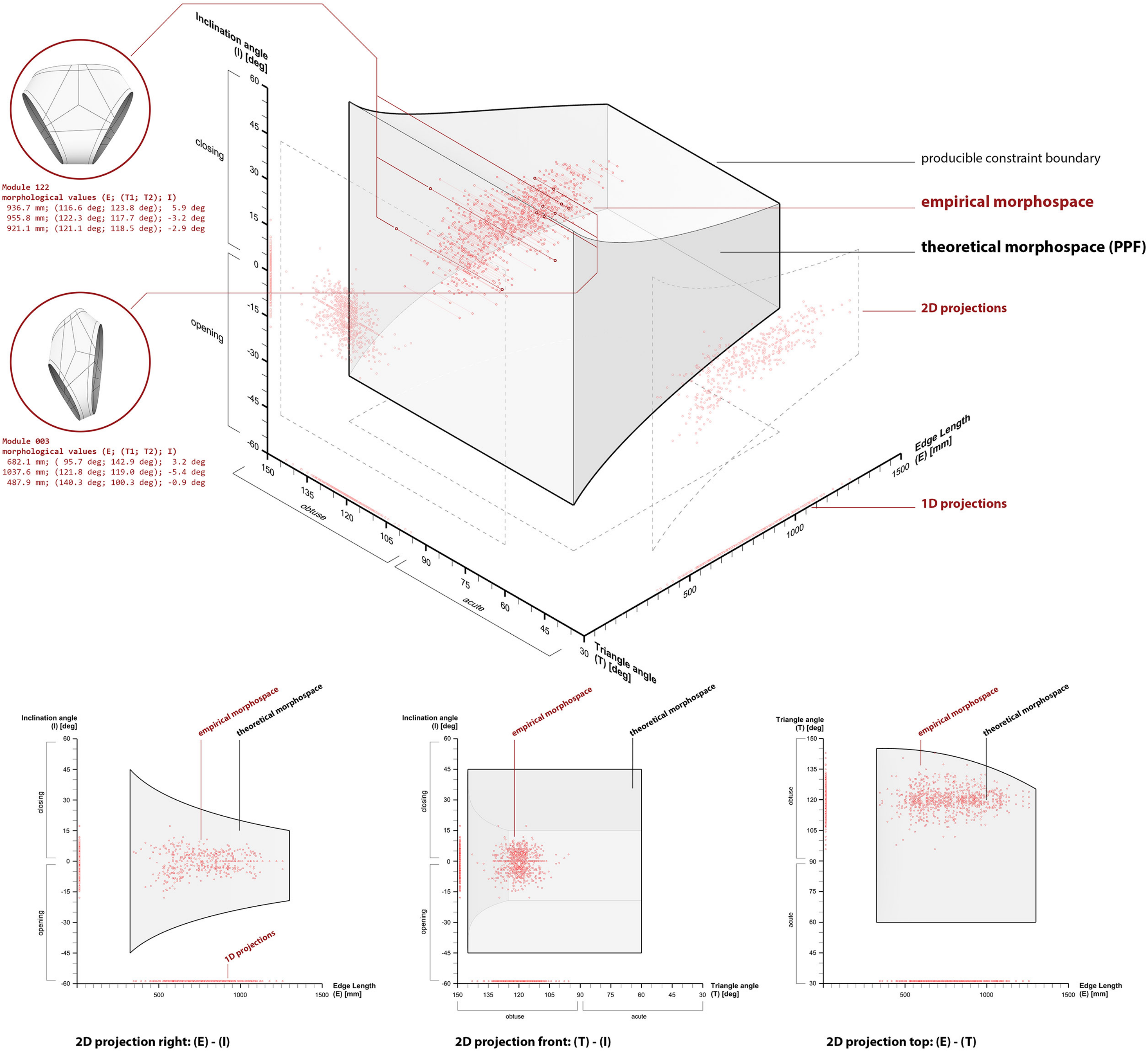

Figure 7.57: The empirical machinic morphospace of Case Study 4 is visualized by red measurement points that represent each parameter value of each edge of a building module of the ICD/ITKE Research Pavilion 2015-16. Two example modules are shown on the top left to exemplify the variety of morphology within the building system. Module 3 is one of the most skewed and smallest modules, while module 122 is one of the largest.

7.4.9 Acknowledgements

This project was a collaboration between several researchers and students.

ICD Institute for Computational Design – Prof. Achim Menges
ITKE Institute of Building Structures and Structural Design – Prof. Jan Knippers

Scientific Development
Simon Bechert, Oliver David Krieg, Tobias Schwinn, Daniel Sonntag

Concept Development, System Development, Fabrication & Construction
Martin Alvarez, Jan Brütting, Sean Campbell, Mariia Chumak, Hojoong Chung, Joshua Few, Eliane Herter, Rebecca Jaroszewski, Ting-Chun Kao, Dongil Kim, Kuan-Ting Lai, Seojoo Lee, Riccardo Manitta, Erik Martinez, Artyom Maxim, Masih Imani Nia, Andres Obregon, Luigi Olivieri, Thu Nguyen Phuoc, Giuseppe Pultrone, Jasmin Sadegh, Jenny Shen, Michael Sveiven, Julian Wengzinek, and Alexander Wolkow

With the support of Long Nguyen, Michael Preisack, and Lauren Vasey

In collaboration with
Department of Evolutionary Biology of Invertebrates – Prof. Oliver Betz
Department of Paleontology of Invertebrates – Prof. James Nebelsick
University of Tuebingen

Many of the innovative aspects of this case study were developed by the participating students over the course of a year. The author contributed to this project in a supervisory role together with his research colleagues Simon Bechert, Tobias Schwinn, and Daniel Sonntag. Other contributors to the aspects covered in this dissertation are listed below.

7.4.9.1 Material System

In the first term of the year-long project three students groups developed several options and variations of material systems related to double-layered timber shells, elastic bending and sewing. The main concepts that were translated into the material system as it was presented in this case study were developed by Sean Campbell, Gene Kao, Tim Lai, Riccardo, Manitta, Andres Obregon, Jasmin Sadegh, Giuseppe Pultrone, Martín Alvarez, Masih Imani, Thu Nguyen, Lani Herter, Becca Jaroszewski, and Erik Martínez.

7.4.9.2 Biomimetic Transfer

The transfer of all biomimetic principles involved in the development process of the material system, joint design and structural design was primarily executed by Alexander Wolkow, Jasmin Sadegh, Mariia Chumak, and Luigi Olivieri.

7.4.9.3 Joint Design

The design of the finger joints and the laced connection for on-site assembly was primarily developed by Jan Brütting, Eliane Herter, Kuan-Ting Lai, Guiseppe Pultrone, and Dongil Kim.

7.4.9.4 Global Design

The design of the demonstrator, its function and shape and its relation to the material system and the available time and budget was primarily done by Joshua Few, Hojoong Chung, Erik Martinez, Riccardo Manitta, and Ting-Chun Kao.

7.4.9.5 Structural Design

The structural analysis of the material behavior, the development of the feedback loop from curvature to plywood lay-up, and the finite element analysis of the global design and the final demonstrator was mainly executed by Jan Brütting, Joshua Few, Rebecca Jaroszewski, and Riccardo Manitta, and supervised by Simon Bechert and Daniel Sonntag.

7.4.9.6 Computational Design

The overall computational design system, including initial design process, distribution of segments, and manufacturing data generation was led by Thu Phuoc, Ting-Chun Kao, Kuan-Ting Lai, Andres Obregon, and Guiseppe Pultrone.

7.4.9.7 Fabrication Design

The technology necessary to fabricate the components included the development of the sewing process, the connection of the sewing machine to the robot control, the establishment of the robot system and prototyping of the process. These aspects were primarily developed by Artyom Maxim, Hojoong Chung, Eliane Herter, Masih Imani Nia, Erik Martinez, and Martin Alvarez.

7.4 Case Study 4: ICD/ITKE Research Pavilion 2015-16, 2016

Figure 7.58: The Landesgartenschau Exhibition Hall, 2014 (Image by ICD/ITKE/IIGS University of Stuttgart).

7.5 Case Study 5: Landesgartenschau Exhibition Hall, 2014

7.5.1 Project introduction

The project Landesgartenschau Exhibition Hall is a large-scale architectural prototype building conceived at the University of Stuttgart as part of the "Robotics in Timber Construction" research project from 2013 to 2015, and realized in collaboration with Müllerblaustein Holzbau GmbH, Landesgartenschau Schwäbisch Gmünd 2014 GmbH, the forest administration of Baden-Württemberg (ForstBW) and KUKA Robotics GmbH (Figure 7.58). It was developed at the Institute for Computational Design and Construction (ICD), the Institute of Building Structures and Structural Design (ITKE), and the Institute of Engineering Geodesy (IIGS), and realized in collaboration with Müllerblaustein Holzbau GmbH. The building was part of the biannual state horticultural exhibition, where it hosted an exhibition by ForstBW. The project was partly funded by the European Fund for Regional Development (ERDF), Forst und Holz Baden-Württemberg, as well as by the project partners.

The demonstrator was developed and built under the umbrella of a multi-disciplinary research project and was preceded by a smaller research study on the feasibility of large timber plate structures. The study was led by Tobias Schwinn in 2012, and the author participated in this study as a student assistant. The research study formed a bridge between the ICD/ITKE Research Pavilion 2011 project, and the large-scale demonstrator building presented in this section.

The goal of the research project was to develop and evaluate the feasibility of timber plate structures for industrial manufacturing and large-scale architectural applications. The resulting demonstrator building was a showcase for the possible developments in computational design and robotic fabrication for lightweight timber construction at the time. The building was the first to have its primary structure made from robotically prefabricated timber elements. The newly developed structural system allowed the load bearing timber plates to be made from just 50mm thin beech plywood. Using locally sourced and processed material, it was also a demonstrator for local resource effectiveness. The project was the first in the thesis' series of case studies that incorporated industry collaboration.

The author participated in this research project as a research associate at ICD in a team of four researchers and three professors. The author was primarily involved in the design process, the development of the building system and manufacturing system, and assisted in the development of the computational design system. The author also participated in the planning and execution of the demonstrator. MuellerBlaustein Holzbauwerke GmbH acted as the industry partner in this case study. Further acknowledgements are in sections 7.5.5 and 7.5.9.

Some of the project details of this case study were published in the papers "Behavioral Strategies: Synthesizing Design Computation and Robotic Fabrication of Lightweight Timber Plate Structures" by Schwinn et al. [331], focusing on the computational design strategies, and "Biomimetic Lightweight Timber Plate Shells: Computational Integration of Robotic Fabrication" by Krieg et al. [195], focusing on the general development process and the result. Two papers regarding the structural behavior of the demonstrator, and timber plate structures in general, were also written by Li and Knippers [217; 218]. Some results presented in this case study are unpublished, particularly details on the manufacturing development in section 7.5.3 and the machinic morphospace analysis in section 7.5.8.

7.5.2 Investigative motivation: industrialized adaptive processes for gradient building systems

As part of an ongoing investigation into lightweight timber plate structures by the research group, this project continued the work presented in Case Study 1. While the project was conducted with the goal of designing, manufacturing, and constructing a potentially permanent demonstrator building for an outdoor exhibition, it was combined with multiple investigative motivations, some of which are not part of this case study. For example, the introduction of behavioral computational design tools such as agent-based modeling, for solving the planar, polygonal subdivision of double-curved surfaces [331], as well as refining the previously established biomimetic principles for structural connections of plate structures, which have been mentioned in in section 7.1, are not the focus of this case study.

This case study will only focus on the investigative motivation that relates to industrialized manufacturing processes and collaboration with industry partners for planar timber plate structures as an example for the transition of gradient building systems into industry application, and how criteria of industry collaboration drove the development of such a timber plate building system when compared to a more prototypical state of a gradient building system such as Case Study 1. Building on previous research, the biomimetic principles for segmented shell structures were still equally valid and kept as a corner stone for this research to guide the development of an industry-applicable building system.

The transition from an academic prototype to an industry prototype was undertaken partly for the purpose of a more generally applicable segmented timber shell building system, and partly for the purpose of constructing a demonstrator building for the Landesgartenschau 2014 exhibition. While the interdisciplinary nature of a purely academic development in previous research allowed for constant feedback and seamless interdisciplinary work within a team throughout all phases, industry collaboration did not always allow for the same level of interdisciplinary development and feedback.

The main goal in this project was to adapt the development process of timber plate structures towards an industry context so that an industry partner would be able to participate, and later manufacture and assemble the building system on, what could be considered, a typical construction site [196]. This required further development of the manufacturing system, design system, and, ultimately, the development of a building system that would adhere to the local building codes, be waterproof, and durable enough for a life span of more than five years.

Due to the requirements for a full-scale, permanent structure, glued connections such as those used in Case Study 1 were replaced with a combination of finger joints and crossing screws. Additionally, given standard industry rates for labor and machine time, an approach to the planar segmentation of double-curved surfaces was taken that would result in a smaller number of building elements per structural surface area. It was especially important to find a degree of material efficiency while keeping manufacturing and assembly time within the time frame given by the project. These cost and time related constraints steered the development of the material system towards larger and thicker plates, with large finger joints that incorporate screwed connections. However, the geometrical and structural adaptability of such a material system still required an integrated manufacturing process with the kinematic flexibility of an industrial robot for the geometrical uniqueness of each timber plate to pose no additional difficulties.

Most importantly, the integration with an industry partner in this project meant that the manufacturing of the building elements would take place at the partner’s facilities. A transportable robotic setup was lent from the industrial robot manufacturer KUKA Robotics. With that, most of the operational responsibility for the execution of the demonstrator would also reside with the industry partner, although it was agreed on that the research team would run the robotic manufacturing process, therefore integrating the most innovative aspects of the manufacturing system within the industry partner’s workflow. The oversight of the process as well as all preparation for, and post-processing of, the building elements would be the responsibility of the industry partner.

This meant that the building elements produced by the newly developed robotic manufacturing process would have to be quality controlled by the industry partner and implemented into a typical preparation and construction sequence. Not the robotic milling process, but the general data flow and documentation of a gradient building system was the challenge of this project. It can be argued that this project was the first proof of concept of a combined and interdisciplinary development process of a gradient building system for a full-scale industry application.

Another investigative motivation of this project was the development of computational design tools for an automated but user-controlled and interactive segmentation process for double-curved surfaces that implement geometric constraints in relation to the machine setup. While the previous project presented in Case Study 1 ended with a static geometric rule set that ensured planarity of the individual building elements with truncated pyramids, the development in this case study was geared towards the direct relationship between planar segments and the underlying doubly curved design surface.

Other aspects of the computational design system were part of a coherent digital chain from the geometry generation to the structural analysis and digital fabrication: the generation of geometry for additional building layers such as insulation, waterproofing and cladding, as well as the generation of manufacturing data for all layers, and lastly, manufacturing documentation.

7.5.3 Development of the manufacturing system

In previous research documented in Case Study 1, the finger joints developed for timber plate structures had specific structural and architectural purpose [193; 329]. The purpose of this research was to prove that individual plates could be arranged such that they are the primary load bearing elements with distributed in-plane shear forces along the plate edges, which, in turn, would make interlocking connections such as finger joints specifically suitable [331].

One of the major changes to the material system previously developed was the adaptation of the finger joint connections for connection angles close to coplanarity, or 0 degrees. The material system's finger joints in Case Study 1 required connection angles in a range above 20 degrees while using material thicknesses below 20 mm. Both requirements changed in a full-scale building application: The timber plates acting as the main structural layer for a permanent building would need to be 50 mm or more in thickness for their application in spans of 10 m or more, as well as for incorporating crossing screw connections [218]. Further, in order to reduce the number of building elements segmenting an area, the plates would be generated directly from a design surface by using a Tangent-Plane-Intersection (TPI) method [331]. While the TPI method allows for an effective segmentation of double-curved surfaces, the resulting connection angle between the timber plates would be equal to the angle (δ_a) between the design surface's normal vectors at the centroid of each plate outline (Figure 7.59). Taking a dome-like or half-sphere surface as an example, a total δ_a of 180 degrees is available when populating it with plates from one end to the other. Divided by ten plates, each connection would be 18 degrees, on average. Divided by 20 plates, each connection would be 9 degrees, and so on. Therefore, while a higher number of plates results in smaller plates and a closer approximation to the double-curved surface, it also results in very low connection angles close to 0, or coplanarity. A balance between this kind of "plate resolution" (or plate density per surface area), proximity to the double-curved surface, and size of plates was the focus of the building system development process presented in this case study. The relation between the size of the building and the available δ_a generally led to connection angles of less than 20 degrees.

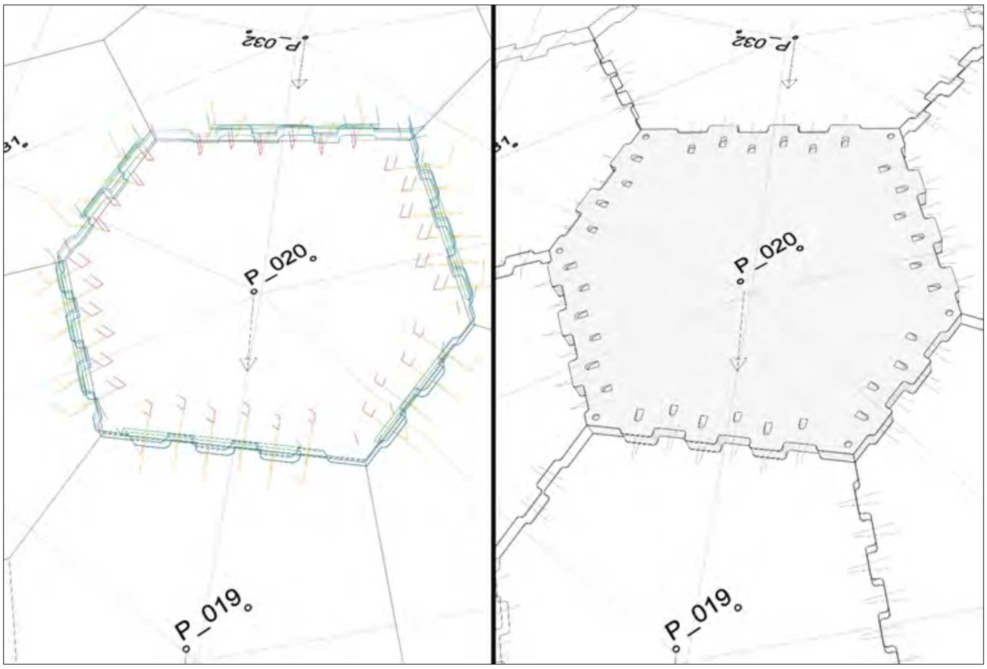

Figure 7.59: Tangent-Plane-Intersection method on double-curved surfaces results in the connection angle being equal to the angle between the normal vectors of each plate (Image by ICD/ITKE/IIGS University of Stuttgart).

Further, the TPI method results in concave polygonal outlines in areas with negative gaussian curvature. As explained by Schwinn *et al.* [331], the polygonal outlines are highly sensitive to the underlying surface curvature. The resulting concave polygon angles pose further challenges to the finger joint connection (Figure 7.60). It was therefore of particular interest to develop a computational design tool that would enable a level of control of the polygonal outlines necessary to stay within the bounds of manufacturing constraints.

Figure 7.60: Photograph of concave plates with finger joint connections. The finger joints at the edges that form a negative polygonal angle are facing inwards (Image by ICD/ITKE/IIGS University of Stuttgart).

With respect to robotic milling possibilities and constraints, the finger joints for this building system were developed to accommodate low angles and thicker material [195]. Instead of milling with the tip of the milling bit, the finger joints are milled with the flank of the milling bit. Instead of generating the geometry of the milling paths or the finger joints through the intersection of the planes of adjacent plates, the geometry is derived from the sum of the normal vectors of adjacent plates (Figure 7.61), which results in the face of the finger joints to be in plane with the average between both adjacent normal vectors. In concave situations, the finger joints' face could be rotated along the plate edge so that assembly is still possible. This was a necessary implementation because otherwise the assembly direction of one plate would be different for each edge, not allowing for any valid geometric assembly solution [296].

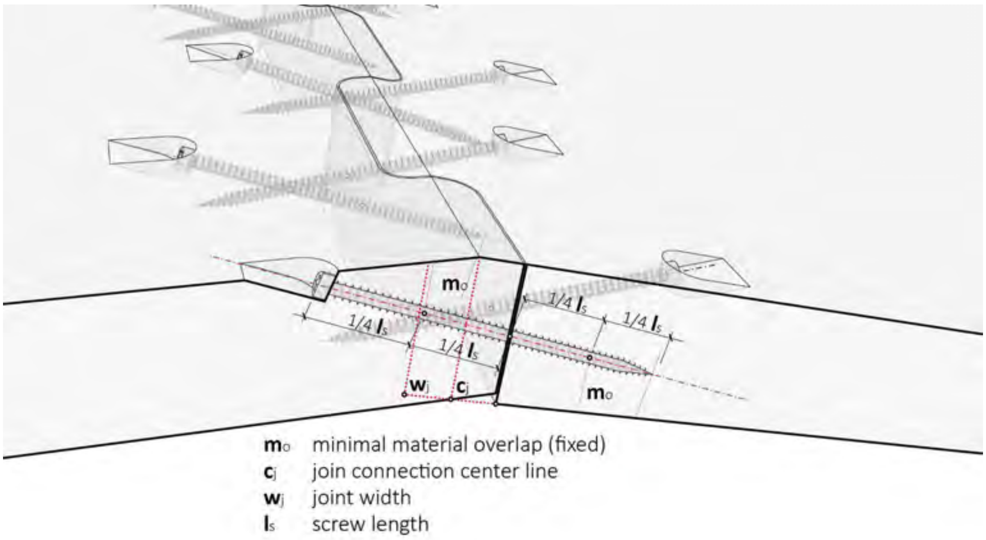

Figure 7.61: Geometric relationship between plate angles, finger joint geometry, and the crossing screw connection. The specific surfaces of the finger joints are derived from the angle towards the neighboring plate as well as the sum of the normal vectors. The crossing screws are parametrically defined to have a minimum material overlap (Image by ICD/ITKE/IIGS University of Stuttgart).

The geometric rule set of the finger joints was developed with additional metal fasteners in mind. To act as a permanent structural connection, the finger joints need to transfer out-of-plane shear forces and tension forces in addition to the in-plane shear forces typical for plate structures. Previously, these forces were taken by the glued connection of Case Study 1. In this case study, a crossing screw connection was implemented with each finger joint. At every finger, one pair of crossing screws would be added and matched with the angle of the connection. The concept of crossing screws was first introduced by Blaß & Bejtka [36]. Depending on the connection angle, the crossing screw connection was parametrically adapted so that the meeting point between the two screws would always be in the center of the finger joint's face (Figure 7.61) [195; 218; 331].

The feedback of the industry partner was necessary early in the development process for the finger joint geometry, crossing screw connection, and assembly of the timber plates on site. Without changing many of the typical on-site processes such as scaffolding, lifts and tools used, the plates were lifted by a crane and positioned and fixed by skilled workers. Potential tolerances or deviations on site were accommodated in the individual building element's tolerances. The team decided for a general tolerance between plates of 1mm, meaning that every plate would be 0.5mm smaller than its digital counterpart. Material contact would be established by pulling the pulling the plates together with the screwed connection.

The robotic manufacturing setup defined many of the fabrication parameters and constraints. It consisted of a KUKA industrial robot with a 12kW spindle mounted on its flange, and an additional external rotary axis as a turntable. The robotic setup was preconfigured as a transportable cell. Because the robot cell had a fixed enclosure that could only be opened towards one side, the size of plates was restrained not by the machine setup but by the housing of the cell. Two different locations for the turntable were therefore digitally evaluated and later implemented: In a first machine setup configuration the turntable would remain within the housing and only smaller plates would be manufactured. In a second configuration, the turntable was moved outside the housing (Figure 7.62). Therefore, two overlapping machinic morphospaces will have to be analyzed in this case study.

Figure 7.62: Photograph of the robot cell used in this case study and analyzed for the machinic morphospace. Its enclosure was permanent and restricted some of the parameters of the gradient building system (Image by ICD/ITKE/IIGS University of Stuttgart.

Overall, the following process steps were developed and executed inside the industry partner's premises to manufacture the main structural building elements:

(1) Manufacturing data was generated by the computational design tools. This included data for a timber processing center to cut oversized raw polygonal plates, as well as the robot code for the subsequent robotic milling process to fabricate all geometric features of each plate.
(2) The raw, oversized, polygonal plates are formatted from large stock material. Their outline is offset by 20mm to give enough room for error when mounting the plates onto the robotic setup. They are marked with a center point and a second point in the direction of the plate's local X-Axis by small holes drilled by the processing center, similar to the localization strategy in Case Study 1.
(3) Raw plates are sorted and stored temporarily in a buffer zone before moving into the robot cell.
(4) The plates are mounted on the turntable in the robotic milling cell, where all features including the finger joints, pockets for the screw connections, and, in some instances, pre-drilled holes for the screws. The finger joints are milled with shaft milling, while the inclined pockets are milled with the tip of the same milling bit. The turntable rotates while the robot's milling spindle stays in an approximate location relative to the base of the turntable as seen in Figure 7.62.

Each plate has its own set of shop drawings for quality control and identification purposes. After robotic milling, every tenth plate was measured using a laser system by the collaborating research institute [331].

Additional building layers for functions that could not be fulfilled by the timber plate structure were also developed, parametrized, and integrated in the manufacturing process. This included the waterproofing EPDM layer, which was cut out using a waterjet cutter as oversized polygons for each plate. Each polygon would later be overlapped and welded together on site. In addition, an underlying insulation layer and a protective cladding layer was developed to protect the building from harsh weather conditions. The insulation layer was made from wood fiber boards and cut using the same timber processing center with automatically generated machine code. The edges of each polygonal insulation plate are mitered so that, when assembled, the insulation would be a continuous layer of material. The cladding layer was cut from 3-ply larch timber plates and supported by counter battens.

It was important to develop a building system that could be assembled manually and without any special skills or knowledge about the structure, so that it could be executed in a professional, industrial environment. Assembly on site was assisted by a scaffolding structure that would support the timber plates during construction and provide a guide to ensure the angle of connection between each plate was correct. However, the building system turned out to be mostly self-correcting. Because most plates would be connected to at least two other plates, the right angle would be automatically found.

Robotic fabrication represents a crucial aspect of the manufacturing system. It enables the morphological flexibility of the plate structure and the complexity in the joint geometry. However, additional digital fabrication methods such as CNC milling or waterjet cutting complemented the robotic fabrication process. Together, these technologies formed a coherent manufacturing sequence. The manufacturing system developed in this case study was meant to bridge the gap between academia and practice and become a replicable process. It was intended to be repeated and by the industry partner, independent from the research team, after the demonstrator was finished.

7.5.4 Development of the computational design system

The project's timber plate structure was designed with advanced computational design and simulation methods, which allowed for the generation and optimization of biomimetic construction principles. The computational design tools developed during this research project combine material properties and fabrication constraints in the design process. The integration of the latter was key during the development of the computational design system.

Two methods were used for the design process, which, although not the focus of this thesis, will be summarized in this section for the purpose of elaborating on the data flow from design to fabrication. Their development was led by the author's colleague Tobias Schwinn over the course of the project.

First, for the purpose of dividing a double-curved surface into individual, planar, polygonal segments, a variation of the tangent plane intersection method (TPI) was used [225; 364]. This method had been employed for computer graphics and geometry in the past, and was used in this case study to quickly solve the intersection of planar plates on a given design surface [331]. The method takes points on a NURBS surface as an input, and by using the surface's normal vector at each point location, intersecting their respective plane to generate a polygonal outline (Figure 7.63).

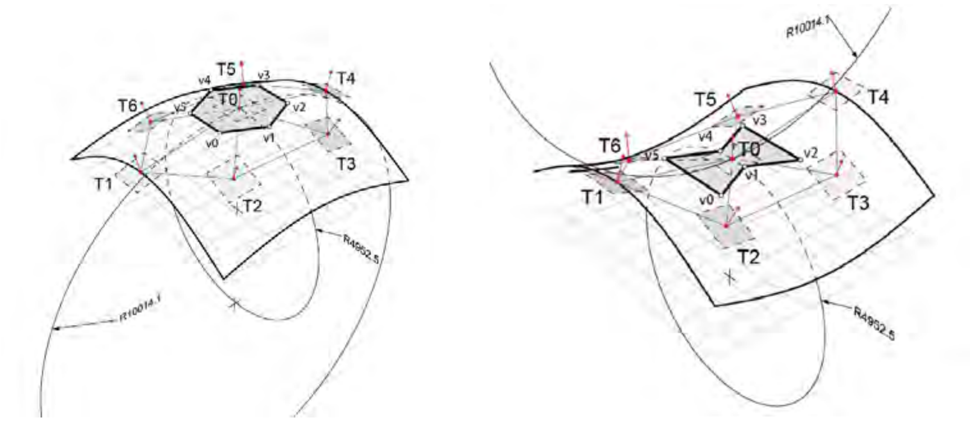

Figure 7.63: Diagrammatic visualization of the TPI method. The top plate's hexagonal outline is the result of the intersection of planes of all neighbors. In negative Gaussian curvature, the resulting outline is partially concave (Images by Schwinn et al. [331]).

Based on the TPI method, a computationally assisted design process for a user-controlled distribution of plates on a double-curved surface was developed. It maps the distribution on a 2D plane, representing the topology of the plates, their neighbors, and connections, but distorting their distance. This method allows to represent the geometric relationship of points on a complex surface on a flat and rectangular surface [331]. It can act as a control tool or a visualization tool of the plate structure's topological relationship. This tool could either be used to build a fully custom plate structure arrangement without any automatically generated input, or to take an already generated arrangement and alter it. The latter is especially useful for geometrically challenging situations such as areas where the gaussian curvature changes from negative to positive. In these areas, angles between plates are close to 0 degrees, thereby making the intersection result extremely sensitive to the smallest changes in point or plate location. User intervention can help to finalize the plate arrangement in these situations.

Second, for the purpose of integrating manufacturing and material constraints within a more automated and computationally intelligent design process, an agent-based modeling method was developed. Agent-based modeling (ABM) is a computational methodology for decentralized decision making and control of multiple entities with locally defined rules within a simulation for the design and optimization of complex systems [331]. It has been developed and used in a variety of fields such as robotics, logistics, finance, and computer games. When multiple agents interact with their own set of rules, they can negotiate solutions without a centralized control system. Recent applications of ABM in this field include the integration of design and fabrication constraints [15; 16].

In this case study, the TPI method was implemented within an ABM process for the development of a design tool that would distribute plates across a design surface while taking into consideration manufacturing and material constraints. As described by Schwinn *et al.* [331], each plate acts as an agent with a specific set of rules by which its movement across the design surface is governed. These rules relate to geometric characteristics such as the plate's size, its edge lengths, and the angle to its current neighbors. All these characteristics are solely dependent on the plates' position on the design surface and its distance to adjacent plates (Figure 7.64). The desirable values for these characteristics were defined by the feedback from the manufacturing development. While each parameter has a range of valid solutions, every agent in the simulation will aim for the center of the range and change its color according to the distance towards this optimum. Plates would indicate an invalid solution with a strong red color if one of their parameters is outside of its range.

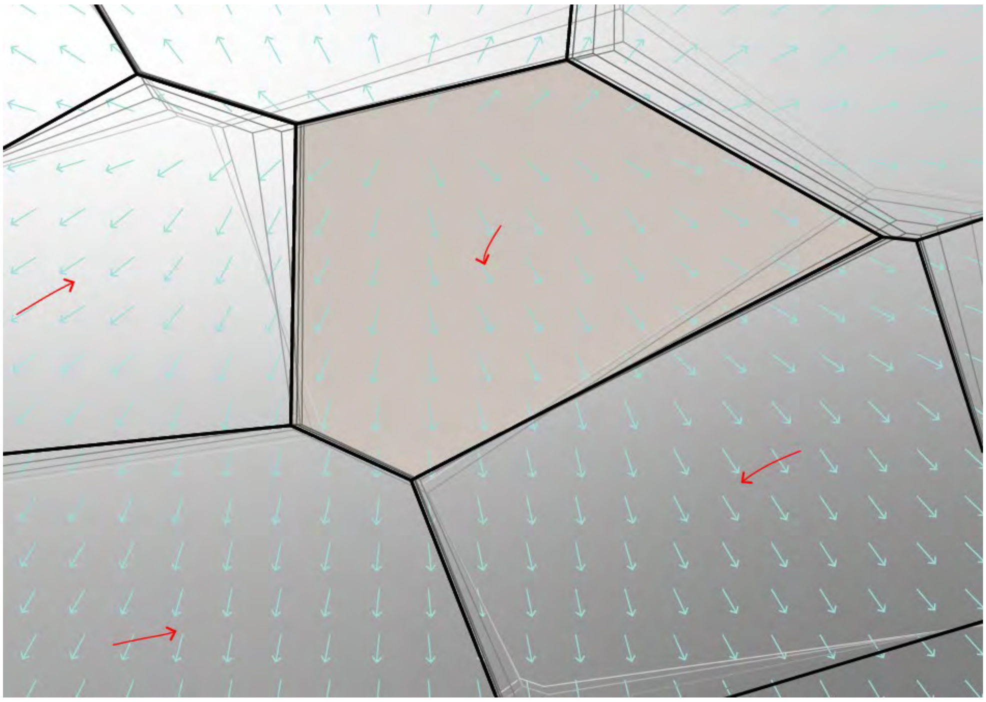

Figure 7.64: Agent-based modeling method for plate movements. Each plate is represented as an agent with a polygonal outline based on the TPI method. The red arrows in indicate the desired movement. The further away agents are from each other, the larger their resulting connection angle (Image by Schwinn et al. [331]).

Like Case Study 1, the geometric result from either of the two methods is a trimmed surface, or boundary representation (BREP) representing each plate. Material thickness and connection details such as joints and screws are not represented in this output. Instead, a single surface or planar polyline is enough geometric information for the subsequent generation of manufacturing data. The resulting 3D model is therefore much more lightweight compared to fully detailed representations, which are still necessary for the purpose of representative drawings, renderings, or instruction-based visualizations. Especially when working with an industry partner, it proved useful to visualize the outcome with fully detailed 3D models. For the data flow of the computational design system, however, there is no need for such geometrically intense models. As explained by Schwinn *et al.* [331], an internal topology analysis maintains a topological database of the connectivity information of the model. The topology and angle of all plates, edges, and their respective neighbors is stored in the computational model and can be retrieved for subsequent steps.

For the purpose of structural analysis, a process was developed to generate structural models from trivalent polyhedrons. As a result, the structural analysis and the configuration of connections was easily varied and tested for an optimal solution [195; 219]. The result of the analysis was also fed back into the design model with information on the number of required crossing screws.

A second set of tools was developed to generate manufacturing data for the timber processing machine (Hundegger SPM) trimming the raw plates, insulation panels and cladding; the robot cell processing the main structural timber plates; and waterjet cutters trimming the weatherproofing membrane. Each computational tool would use the topology analysis and B-rep information to generate the manufacturing data. For the panel processing machine, the manufacturing data was post-processed into xml-formatted files, with each edge indicating a cut, orientation, and material thickness.

For generating robot control code, the computational design tool takes the geometric relationship of each plate BREP, the material thickness, and pre-defined variables such as the preferred finger joint width, to geometrically build top and bottom outline of each plate. This included the outline of the finger joints as well as rectangles indicating the faces of the finger joints that would need to be trimmed off to match the surface of the adjacent plate, and other geometric indicators such as curves and rectangles for the screws and screw pockets. This intermediate geometric information would be saved as individual files for each plate to protect the information of the desired geometry before generating tool paths. This is due to the nature of CNC milling, where small changes in the milling parameters such as the speed of the tool or the tool diameter must be changed and adapted regularly due to tool sharpening, breaking, or simply measured deviations that require adjustments.

Also included in this process are special indicators that induce special cases in the geometry and tool path generation, such as pockets for the steel columns, column connections, connections to the foundations or special situations in the crossing screw connections. Each of these indicators would either be a point or curve on a specific layer in the 3D model, which would be cross-referenced to the plate object (Figure 7.65).

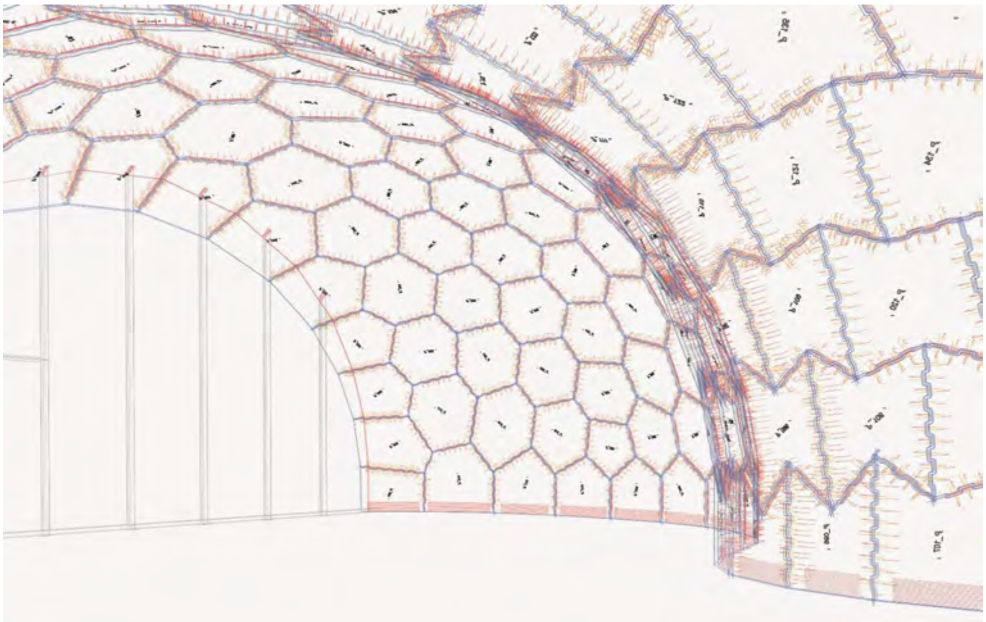

Figure 7.65: Visualization of all milling paths in the 3D model (Image by ICD/ITKE/IIGS University of Stuttgart).

Once tool type, diameter, and other CNC parameters are determined, the last part of the algorithm generates the robotic tool path and allows the user to simulate the robot movement of all milling processes for the selected plate. Because CNC milling bits can change their diameter by sharpening or simply replacing them, this step needs to happen at or close to the prefabrication process, in time and location. Similarly, tolerance settings for CNC milling need to be adjusted sometimes multiple times per day to achieve the most accurate results.

Further, final adjustments to the spindle orientation on the robot can be made, similar to those in Case Study 1. For example, for larger building elements, the robot's spindle position needs to be adjusted in relation to the turntable. At this point, the robot cell is displayed in its entirety to check for collisions between workpiece, robot, effector, and cell enclosure. A post-process translates the information into robot code that can then be run on the robot cell.

All the steps described above are taken in a Rhinoceros and Grasshopper environment. Geometric information is saved in Rhinoceros files and read back into the following algorithms into Grasshopper. Dividing the process from design to manufacturing data into three distinct computational tools allowed the research team to save and backup data, and to evaluate the geometry and manipulate it manually if required.

Last, an algorithm was developed to create individual drawings of each raw plate, milled plate with finger joints, and measurements of important dimensions. This set of shop drawings was used throughout the manufacturing process to confirm tolerances and quality. Although not necessary for the robotic manufacturing process, it was important for the overall process to clearly communicate plate identification and allow for visual confirmation for the industry partner.

7.5.5 Project Result

The development process took place with the goal of designing and building a full-scale prototype building as a demonstrator. The demonstrator was built for as part of the Landesgartenschau in Schwäbisch Gmünd, Germany, in 2014. Named the Landesgartenschau Exhibition Hall, the demonstrator is a fully enclosed, insulated, and waterproof building that hosted an exhibition during the duration of the event. At the point of writing the building is still in use.

With a surface envelope of 245 m² and dimensions of about 17 x 11 x 6 m the building offers a floor space of 125 m² and a gross volume of 605 m³. The very thin load bearing structure required only 12 m³ of beech plywood. The shell consists of 243 individual plates with a total of 7600 finger joints and crossing screw connections. Additionally, almost all off-cut produced during fabrication was re-used as parquet flooring. After robotic fabrication of the primary structure and digital prefabrication of all other building layers such as insulation, waterproofing and cladding, the building was set up on site in only four weeks.

Although it was set up as a temporary structure, the building is still standing for eight years, as of the publication date of this thesis. It has since received upgrades to its foundation, waterproofing layer, and heating system. The plate structure did not need any repairs or upgrades.

7.5.6 Research result: Process analysis

To evaluate how the integrative development process was enabled in this project, the relationship between the gradient building system, manufacturing system, and computational design system is analyzed in this section.

When evaluating the development process of this case study it is necessary to reflect on the team structure and collaboration of Case Study 1. The ICD/ITKE Research Pavilion 2011 project was purely academic and combined resources and disciplines in an academic environment, which allowed for daily knowledge exchange and feedback. Since all disciplines – design, software development, structural analysis, manufacturing, fabrication, and construction – were part of the same team, this unique setup is what allowed innovation to cross-pollinate otherwise fragmented fields.

However, for scaling up this process and progressing from academic prototyping to industrial application, the challenge for this project is that the interdisciplinary nature would dissolve if adapted to typical industry processes (Figure 7.66). Instead, the research team took a targeted approach: While the core of the research process remained academic, important points of interaction with the industry partner were determined as interfaces, either for (1) development feedback; or to (2) integrate the resulting manufacturing process within the larger planning and construction process of the industry partner.

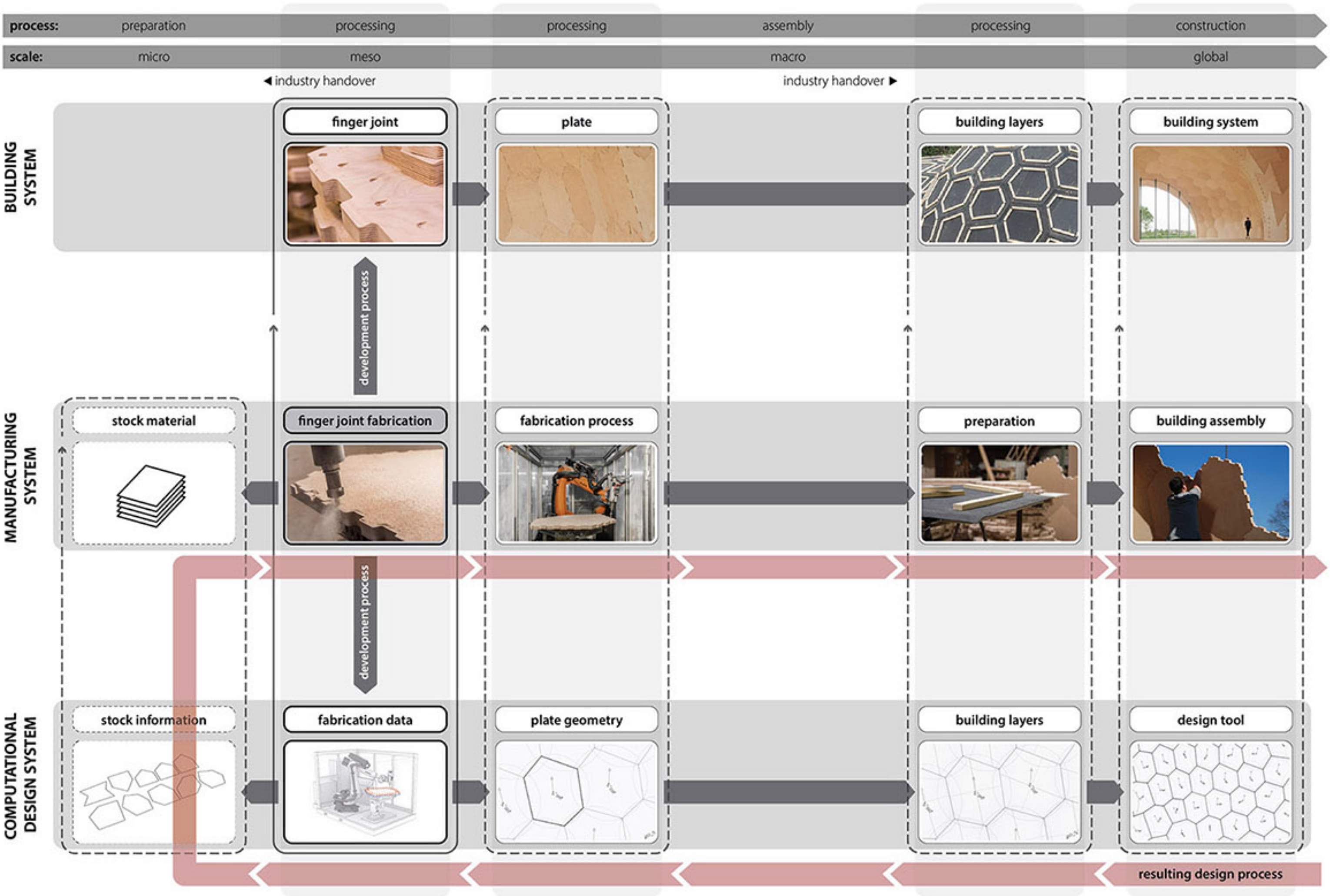

Figure 7.66: Development process overview of Case Study 5. The development process is highlighted with dark gray arrows, and the resulting design process of the demonstrator with red arrows. Similar to Case Study 1, the process originated around the robotic fabrication of finger joints. In this case study, however, it incorporated handover points towards the industry collaborator as well as additional building layers as part of the design process. This diagram contains images by ICD/ITKE/IIGS University of Stuttgart.

In order to receive valuable and constant feedback from the industry partner and to provide enough information to confirm the viability of the building system and manufacturing system, early concepts for the joints and the manufacturing process were presented and discussed in meetings. While it was of interest to the industry partner how the robot cell would be used and how the individual plates would be trimmed in the robotic milling process, these were not intersection points of the teams' responsibilities and merely discussed on a higher level. Actual intersection points were discussed in depth, such as the following examples:

(1) Tolerances between plates needed to be small enough to ensure full material contact for structural reasons, but large enough to ensure ease of assembly on site. A zero-tolerance approach, which was preferred by the academic team, could not be agreed on because assembly on site was too uncertain at the time.
(2) Additional building layers for waterproofing and insulation were discussed for best fit and ease of assembly. Here, the general experience of the industry partner was of great value.
(3) The prefabrication sequencing, use of equipment, cycle times and general manufacturing management was the responsibility of the industry partner and determined how data would be prepared by the academic team. Most of the manufacturing data for all building layers would be prepared by the researchers, even if all other machines were controlled by the industry partner.
(4) Assembly on site was discussed to determine feasibility of the shape of the demonstrator, number of plates, schedules and required equipment and scaffolding.

While the computational design development process took place independently from these discussions, and simply accommodated decisions taken, the manufacturing process development was greatly influenced by this collaboration. Still, the robotic manufacturing development was the responsibility of the research team and remained their responsibility during execution. This allowed to minimize intersection points, and provide clear interfaces and transfer of responsibilities:

(1) Determining and ordering the required amount of material was the responsibility of the research team after all building materials were agreed upon collectively.

(2) The industry partner was responsible for preparing all raw plates and all other building layers after receiving the manufacturing data from the research team.
(3) The research team was responsible for organizing the robot cell, commissioning the equipment, and running the manufacturing process for all plates.
(4) Upon confirming accuracy and quality, the industry partner took full ownership of the remaining process, which required adding some of the additional building layers inside the facility, shipping all building elements on site, and construction.

The interfaces discussed allowed the research team to develop the computational design system and provide the required data to the industry partner. Aside from the robotic manufacturing process, all other physical preparation and manufacturing remained the responsibility of the industry partner. The handover points were therefore minimized while allowing for of innovation taking place within the facilities of the industry partner. For example, the material flow within the facility, the data flow, and details of the manufacturing process were developed with academic and industry staff in the facility during the final weeks before manufacturing started.

The development process started with the discussion about structural performance and building codes, 3D modeling and prototyping single building elements. Small-scale tests with individual plates, connections, or a small number of plates were completed to evaluate structural performance and ease of assembly. In addition, prototypes were produced to test situations of negative gaussian curvature where plate outlines would switch between convex and concave. Those tests already required computational design tools to generate either the joint geometry or the machine code, as well as for simulating the robot movements. At several stages along the prototyping process, the industry partner was involved to provide feedback. For example, the finger joints and the accessibility of the crossing screw connection for on-site assembly were discussed.

Iteratively, more information was added to all fields collaborating in this development process: Information regarding design requirements, information regarding assembly requirements or construction requirements, information regarding manufacturing constraints and possibilities, as well as information regarding required data processes and visualization. In the meantime, more building layers were added to the building system to provide weather protection and ensure longevity. Structural tests determined the number of crossing screws needed in relation to the global structural performance of the building system, and a connection between the design model and the structural FEA model ensured that enough structural feedback was provided.

This case study is an example for a highly collaborative development process between academia and industry, and a first step for an industrial application of robotically manufactured gradient building systems. The main challenge when scaling up and applying innovative development processes in industry is that information can no longer remain within a single person or team but rather needs to be constantly transferred and translated between multiple teams. In this case, the academic team and the industry partner needed to exchange and translate information. Part of this evolution means that while information gets distributed, control is distributed across multiple entities or teams, too. However, clear communication of interfaces and responsibilities allow for this innovation to take place at the intersection of academia and industry.

7.5.7 Research result: Information flow analysis

To evaluate how the morphological differentiation of the building system was digitally generated, processed, visualized, and stored, the computational design process is analyzed in this section.

Similarities and differences can be identified when compared to Case Study 1. Although a similar design and manufacturing system was developed in this case study, there are some additional contributions to the discourse that are analyzed in this section.

As previously mentioned, the computational design process was guided by an agent-based design system that resulted in a planar subdivision of a double-curved surface. This design tool allowed for quick design iterations with a very lightweight representation of the building elements. Finger joints or material thickness were not visualized at this stage. However, the author added a topological representation of the plate structure connectivity through a two-dimensional mesh during the research project. The mesh would be geometrically distorted but topologically correct in its representation of visualizing the neighbors of each plate element.

This added control allowed for manual intervention and adaptation to the plate structure layout, and it was used after the agent-based design tool concluded. With this tool, plate elements could be moved manually, or their topology could be changed if necessary. The result of these first design steps was a BREP representation of the plate outlines. In this case study, the BREP outlines represented the top surface of the material. The material thickness would extend towards the inside of the building design.

Similar to Case Study 1, the finger joint geometry was only generated to visualize the expected result in full detail. This was a separate algorithm that generated the geometry accordingly. However, for the generation of manufacturing data, this process could have been avoided. Instead, the lightweight design model was used to generate manufacturing data for each plate. The only information required for generating robotic milling information was the outline of a plate and the angle towards its neighboring plates.

In another, separate process, the water protection membrane and cladding were generated. Here, the material thickness was included to provide enough geometric information for industry-standard software that would be used to cut these layers.

In conclusion, the division between a lightweight design model, manual adaptation, and manufacturing data was not only a convenient method to allow for quick design iterations, but also to allow for the interfacing with industry-standard software.

7.5.8 Evaluation of the machinic morphospace

To evaluate how the morphospace analysis can be effectively used to analyze the relationship between the machine setup and the gradient building system's design space, the author applied this method to the project in this section.

The machine setup in this case study is very similar to that of Case Study 1 except for the enclosure that constraints certain movements of the industrial robot. The setup contains one large industrial robot with a milling spindle attached, and a turntable on which the timber plates are placed during machining. However, differences can be observed in the type of robot, the type of spindle, and in the milling strategies used in this case study.

The difference in processing lies in the orientation of the tool to mill the finger joints, and that leads to a difference in kinematic constraints and collision scenarios that define the design space, or morphospace, of the building element. Additionally, the fact that the turntable was moved to a position further away from the robot to accommodate larger plates, makes the study of this machinic morphospace particularly interesting. In the analysis, the difference in the resulting morphospace depending on the position of the turntable will be highlighted.

7.5.8.1 Parameters of the machine setup

The machine setup in this case study consisted of a KUKA KR-120 industrial robot. The robot's kinematic information can be seen in Figure 7.67. The robot was equipped with a water-cooled 8kW high-frequency spindle for milling wood. Further, the industrial robot was connected to a one-axis positioner, or turntable, KPV-1 500. For all fabrication steps the same flank milling bit was used, measuring 120mm in length and 20mm in diameter. For some plates, robotic drilling was tested as a method to pre-drill screw holes. However, this was not fully implemented in the process because of time constraints.

Because of the constrained space inside the robot cell enclosure, the researchers developed a variation of the manufacturing setup where the turntable would be outside of the enclosure with the doors opened and an additional enclosure around the now open area. As a result, larger plates could be processed. The difference between these two setups can be seen in the machinic morphospace analysis below.

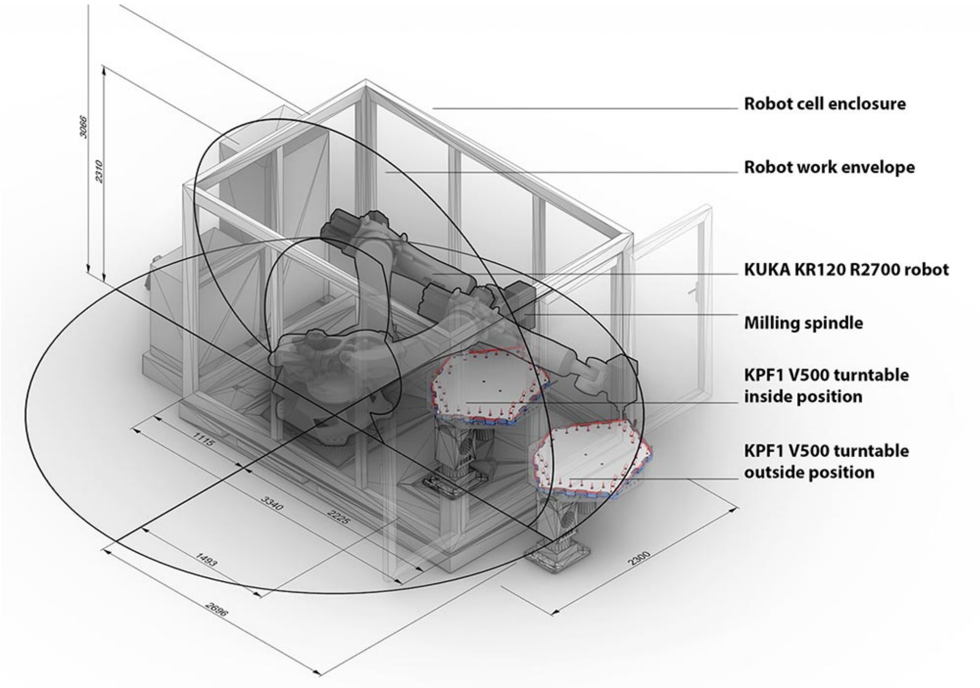

Figure 7.67: Machine setup of the manufacturing process in Case Study 5. The enclosure was part of the robot cell as it was temporarily supplied by the project partner KUKA Robotics. The enclosure was kept closed for manufacturing the first batch of building elements, and then the turntable was moved to a position outside the cell to allow for manufacturing larger plates. Both setups are overlaid in this diagram.

7.5.8.2 Morphological parameters of the building element

Parameter selection is a critical step for the analysis of the building element's morphospace and its relation to the manufacturing process. Generally, the building element can be described as a polygonal plate made from beech plywood, with finger joint connections added to all or some of the edges. In order to define morphological parameters that have the most influence on the building system's design space while at the same time being directly influenced by the machine setup or through an interdependence of parameters, Table 7.5 below is used.

	Morphological parameter	Influence on design space	Influence of machine setup
	Microscale (from molecular to cellular makeup)		
	Material density	medium	medium
	Average or individual cell length/width ratio	medium	low
	Average or individual veneer layer thickness	medium	low
	Average or individual grain direction	high	low
	Mesoscale (building element or part thereof)		
	Material thickness	high	medium
	Plywood veneer lay-up	medium	medium
	Single finger joint dimensions	medium	high
	Crossing screw angle	medium	medium
scale increases	Polygon edge length	high	medium
	Crossing screw length	low	medium
	Number of finger joints along single edge	medium	medium
	(P) Polygon-internal angle	high	high
	(A) Finger joint connection angle on single edge	high	high
	Macroscale (building component or aggregation of elements)		
	Number of polygon vertices	medium	low
	Number of polygon edges	medium	low
	Number of finger joints	low	medium
	(D) Circumcircle diameter	high	high
	Plate surface area	medium	medium
	Plate directionality (ratio of min to max width)	high	medium
	Gaussian curvature at plate location	high	medium

Table 7.5: Analysis of morphological parameters in Case Study 5. The higher the rating, the more direct the impact toward the building system's design space or the impact from the machine setup. Based on the rating, the highlighted parameters are selected to evaluate the relationship between the machine setup and the design space of the building system.

In this case study, some of the highest rated morphological features appear multiple times within a single building element, such as the connection angle along a single edge, or the polygon-internal angle. Because these features can have significantly different values, it is not possible to evaluate the building element with a single value, but instead with a collection of values.

Based on the above analysis, three morphological parameters are selected that are most indicative of the resulting design space of the building system, and most indicative of the influence of the machine setup. Because of the relationship between the scale and the parameters, two out of the three selected parameters refer to a part of the building element, while one parameter refers to the whole building element. This relationship is further explained below:

- *(D) Diameter of the smallest circumcircle of a plate (in mm)*
  The smallest circumcircle is calculated for every plate to define the center point that results in the least space required for its rotation on the turntable. This is beneficial for the machine setup because the turntable will rotate every plate many times during manufacturing. At the same time, the minimum circumcircle is the closest numerical description of the building element's overall size. Here, a single value is used to characterize the size of the building element.
- *(A) Finger joint connection angle (in degrees)*
  This parameter directly relates to the angle between two neighboring plates. At the same time, this parameter also has a direct impact on the machine movement as different connection angles are milled by tilting the milling spindle. The angle is measured by evaluating the angle between the normal vectors of adjacent plates that share an edge. Zero degrees means a coplanar connection, positive values refer to a convex connection, and negative values refer to a concave connection. Here, a single value refers to a single edge of a building element. A building element can have several edges with different connection angles.
- *(P) Polygon-interior angle (in degrees)*
  This parameter describes the angle between two adjacent edges within the plate, which relates to the overall plate outline. The angle is measured by evaluating the vectors of two edges meeting in one point. Values below 180 degrees refer to convex polygon angles, and values above 180 refer to concave polygon angles. While both are possible, concave polygon angles only occur in situations with negative gaussian curvature, as explained in section 7.5.4. Here, a single value refers to a single vertex of a building element.

Similar to Case Study 1, parameter (D) occurs once within each building element, while parameters (A) and (P) occur multiple times because each plate has multiple edges. Therefore, a building element has multiple values for (A) and (P) but a single value for (D). All three parameters are described in Figure 7.68.

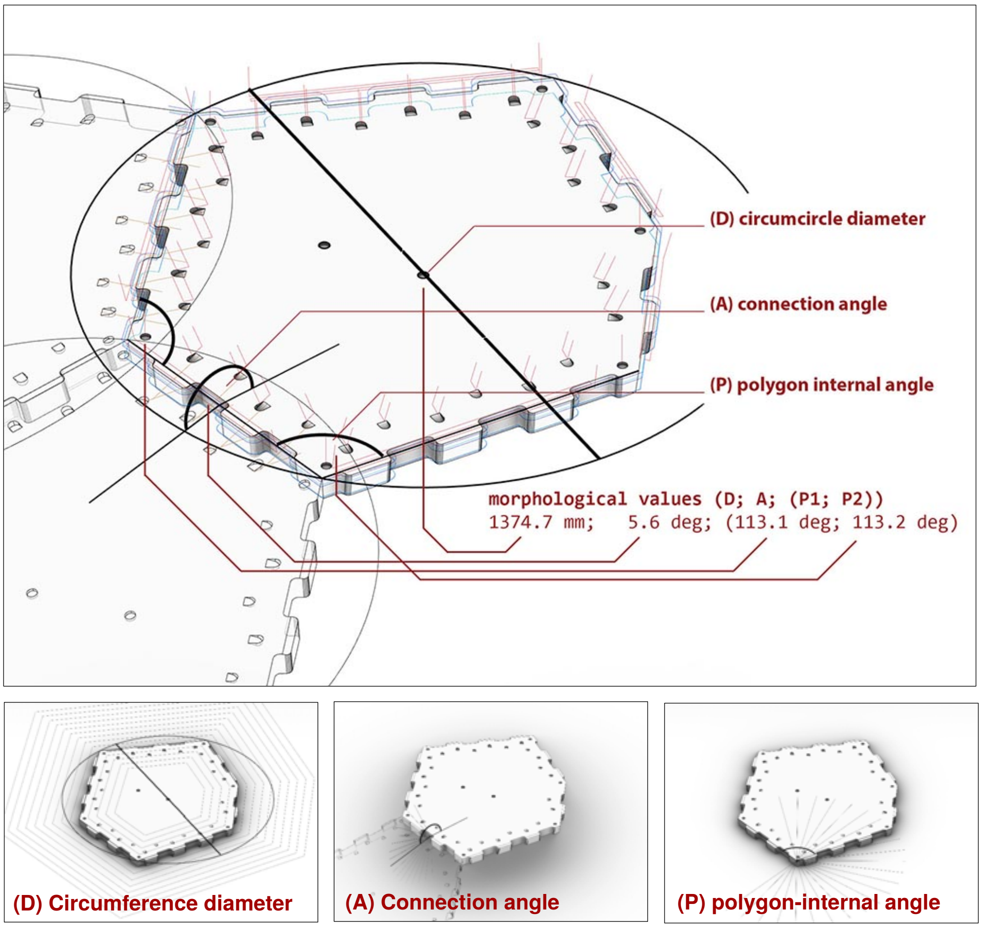

Figure 7.68: Top left: Overview of the three morphological parameters of the building element surrounded by other building elements within the building system. The resulting morphological values of a building element's edge are shown within the image to explain the relationship between the three parameters. Bottom left: (D) as the diameter of the minimal circumference. Bottom middle: (A) as the connection angle between two plates at one edge (referring to a single edge within the plate). Bottom right: (P) as the interior polygon angle between two edges.

Typical boundary situations of these morphological parameters are described in more detail in the below series of images (Figure 7.69). In these images, the variation of the parameters and example situations for their boundary constraints are shown. The min/max constraints of the parameters due to the machine setup, and their interdependencies, can be described as follows:

- The minimal circumcircle, or plate, diameter (D) is constrained by the physical boundaries of the robot cell either when the turntable is inside the cell or outside the cell. The minimal size of plates is given by the collision between the milling spindle and the turntable as well geometrical requirements of having at least one set of finger joints on every edge. Further, the connection angle (A) is constrained by the plate size due to the milling process. Smaller plate sizes reduce the parameter range of (A).
- The connection angle (A) is constrained by the inclination of the milling spindle at higher angles and its collision with either the work piece or the turntable. Compared to Case Study 1, here the milling spindle intersects much earlier because of the fabrication method and the material thickness. Further, the usability constrains the finger joint connection, which is not designed for angles higher than +/-45 degrees. Higher angles have less material overlap and crossing screw connections no longer work. Higher connection angles also reduce the range for (P) due to geometric intersection, which would lead to the milling spindle cutting off parts of the plate.
- The internal polygon angle (P) is constrained by the geometrical self-intersection of finger joints at higher angles, which would lead to the milling spindle cutting off parts of the plate. Extreme values of this parameter can also cause reach problems, which is why the polygon angle influences the maximum value of (D).

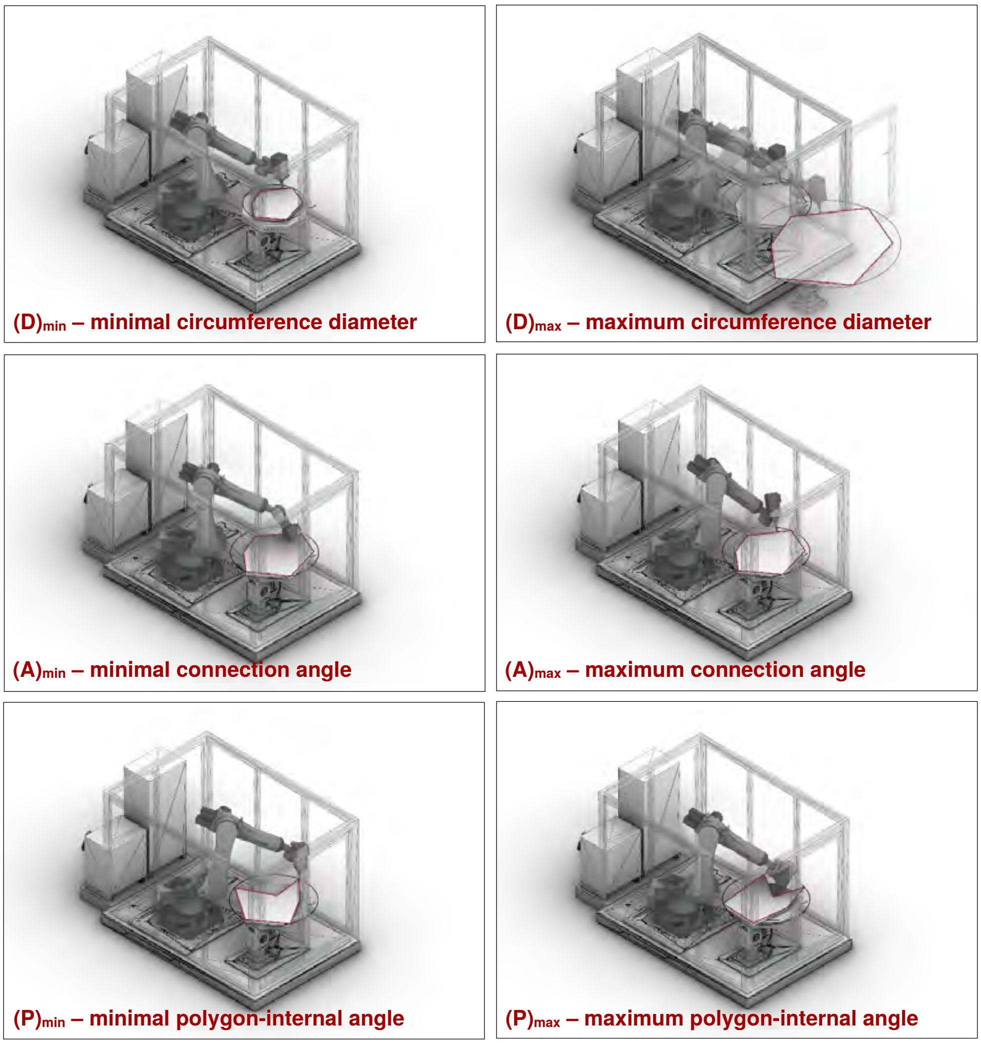

Figure 7.69: Exemplary boundary conditions of all three parameters. Top row: minimal and maximum plate diameter (D). Middle row: Minimal and maximum connection angle (A). Bottom row: Minimal and maximum polygon-internal angle (P).

7.5.8.3 Result: theoretical and empirical machinic morphospace of Case Study 5

In Figure 7.70, the resulting theoretical morphospace is represented by a light gray volume within the three-dimensional parameter space described by (A), (D), and (P). The theoretical morphospace is further divided into two volumes, where the smaller volume in the front represents the *producible region of possible form* (PPF) for the machine setup with the turntable inside the robot cell enclosure, which mostly results in a constraint in the size of the plates and therefore the parameter (D). The larger volume represents the PPF for the machine setup with the turntable outside the robot cell enclosure, allowing for the fabrication of larger plates, although still being restricted by the enclosure, as described in the previous section.

If no robot cell enclosure existed, larger plates would be possible, which is visualized as a dotted outline. If the turntable were positioned any further away from the robot base, the min as well as the max value for the plate circumference diameter (D) would be raised. In this case study, the enclosure only limits the circumcircle diameter (D) of the three parameters evaluated.

In Figure 7.71, the empirical morphospace of all 243 building elements of the demonstrator building Landesgartenschau Exhibition Hall is visualized in red. Each building element is represented by a collection of measuring points representing individual connection angles and polygon angles, and a faint polygonal area indicating that they belong together. This polygonal area is in a single plane on the axis of (D) because each plate only has one value for its circumcircle diameter. The parameters (A) and (P) are related in that every edge represents one connection angle and the adjacent polygon angle. Further, the diagram shows 2D and 1D projections of the measurement points for better readability.

Only about 15% of the theoretical morphospace was populated by building elements in the demonstrator building, with most plates in the region of low convex connection angles (A) and obtuse convex polygon angles (P). Due to the negative gaussian curvature area in the demonstrator, several building elements had concave connection and polygon angles. The circumference diameter ranged from 950 mm to 2150 mm.

It is important to note that the theoretical morphospace includes region of possible form that might not be considered practical or functional, such as connection angles (A) above 45 and below -45 degrees. Looking at the (P)-(A) projection, it becomes evident that a large region of the theoretical morphospace remained unoccupied. While (P) had a large variety of convex and concave values, with some very sharp polygon angles that are close to or on the minimal boundary, values for (A) have much less variance. This observation can be explained with the design intent of the demonstrator building: A uniform shell with many smaller plates results in equally distributed connection angles close to 0 degrees. However, low connection angles in transition zones between positive and negative gaussian curvature can lead to very sharp polygon angles with building elements that exhibit a concave, or bow-tie-shaped outline. A second explanation for the small range of (A) in the demonstrator building is of a structural nature. Connection angles above 30 degrees or below -30 degrees were not recommended by the structural engineers on the team because of a reduced material overlap between adjacent joints as well as a problematic angle between the crossing screw connections. This could be described as the functional constraint boundary. However, it can be argued that the functional constraint boundary of building elements can vary depending on how they are used within the larger context of the manifestation of the building system. During the research project, the exact threshold was not tested for the demonstrator as all connection angles remained much lower than the recommended values, and determining the boundary was not part of this thesis.

This analysis shows that other sub-regions of functional form are considered during the development and design process, such as regions of design performance or structural performance. Because they can be highly dependent on the context or specific design intent of a project, they are difficult to generalize. However, by evaluating the empirical morphospace of the demonstrator building, a relationship between design intent and preferred regions of form can be established.

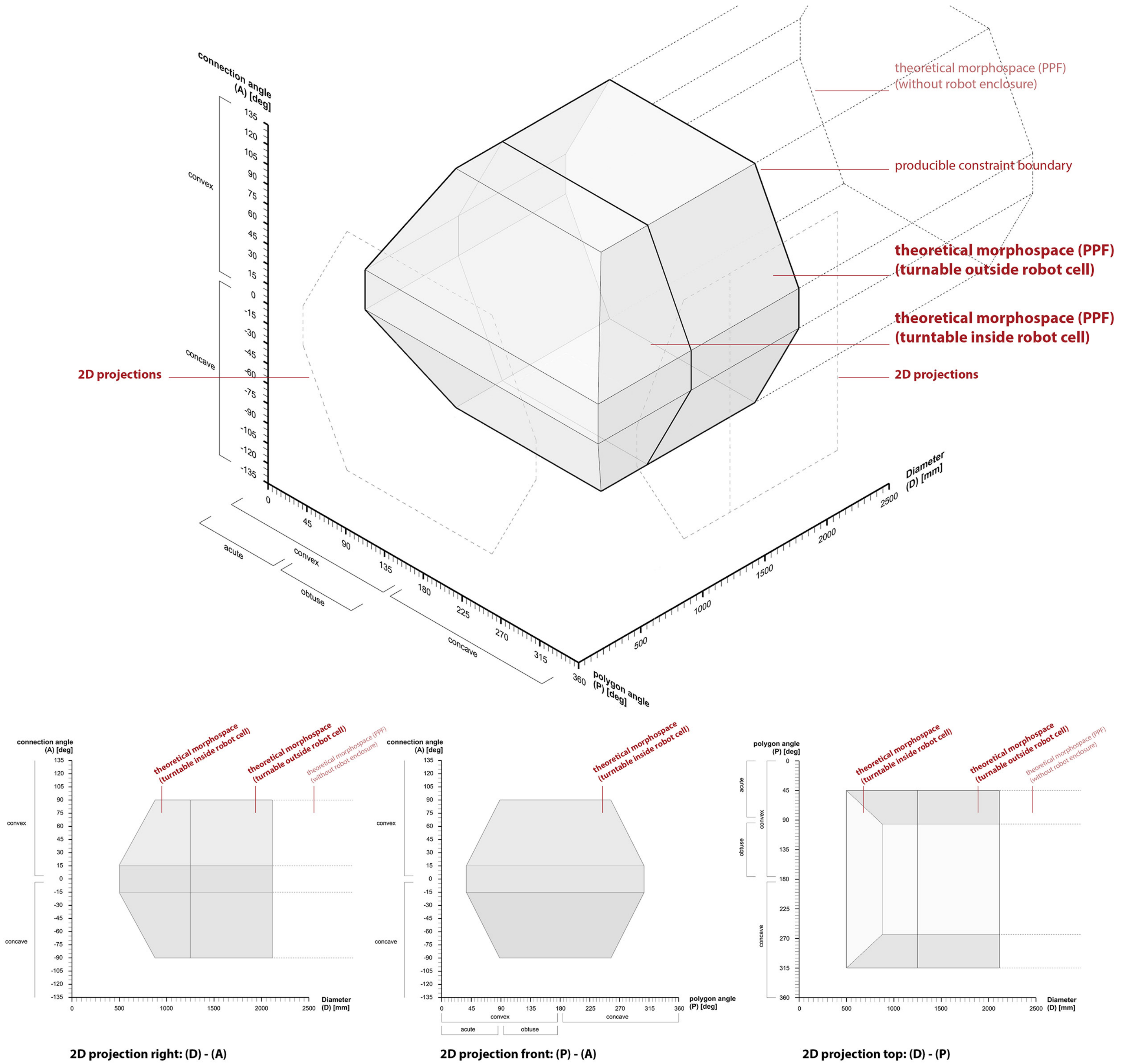

Figure 7.70: The theoretical machinic morphospace of Case Study 5 is visualized as a gray volume with thick outlines, which is further divided into a front part to visualize the smaller volume for the machine setup with the turntable inside the robot cell. The theoretical morphospace without any robot enclosure is shown as a dotted outline extending further.

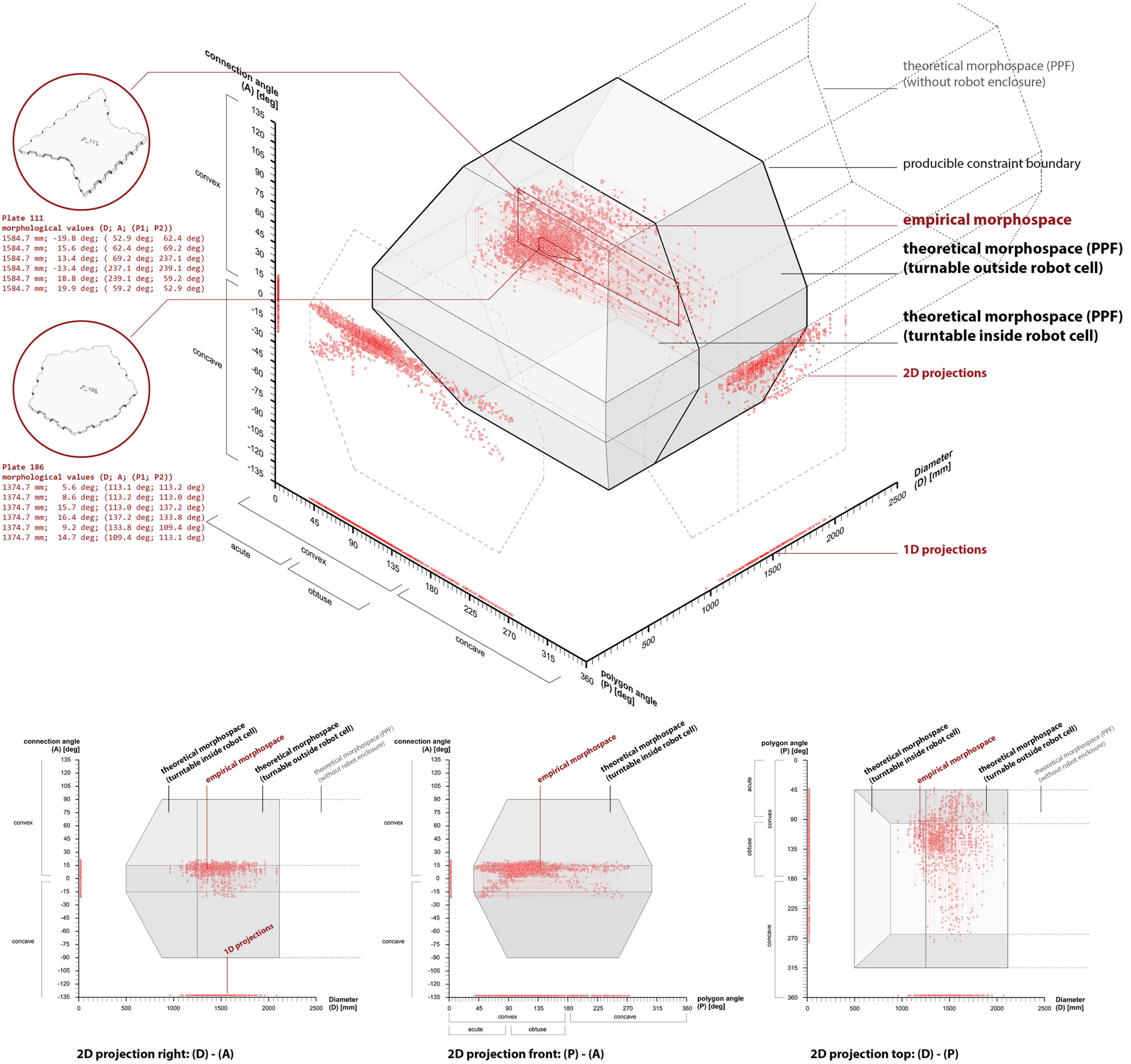

Figure 7.71: The empirical machinic morphospace of Case Study 5 is visualized by red measurement points that represent each parameter value of each plate of the demonstrator building "Landesgartenschau Exhibition Hall". Two example segments are shown on the top left to exemplify the variety of morphology within the building system. Plate 186 has very similar values for both (A) and (P), while plate 111 has a larger range of variation.

7.5.9 Acknowledgements

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Other contributors to the aspects covered in this dissertation are listed below.

7.5.9.1 Initial Study

Before the project in this case study started, an initial feasibility study was completed by Tobias Schwinn, in which the author participated as a student assistant. The study evaluated the potential size of the demonstrator and included a small prototype of the building system, which was developed and manufactured by the author.

7.5.9.2 Agent-based Simulation Method

While most of the remaining work of this case study was executed in close collaboration between Tobias Schwinn, Jian-Min Li and the author, the agent-based simulation method was specifically developed by Tobias Schwinn and used as a tool to achieve an initial distribution of plate segments on the design surface.

7.5.9.3 Manufacturing and Construction

While the research team was responsible for the execution of the robotic manufacturing at the location of the industry partner MuellerBlaustein Holzbau GmbH,

7.5.9.4 Accuracy Evaluation and Geodesic Analysis

Annette Schmitt from the Institute of Engineering Geodesy scanned and analyzed a number of plate segments after manufacturing for quality assurance. She also 3D-scanned the demonstrator after it was finished and after a longer period had passed. Tobias Schwinn evaluated the data to compare the scanned model against the design model.

Figure 7.72: The BUGA Wood Pavilion (Image by ICD/ITKE University of Stuttgart).

7.6 Case Study 6: Wood R3 – Resource Effective, Regional, Robotically Fabricated, 2018

7.6.1 Project introduction

As a successor to the project in the previous case study, and a precursor and proof-of-concept for the "Bundesgartenschau Wood Pavilion 2019" demonstrator project, the Institute for Computational Design and Construction (ICD), Institute of Building Structures and Structural Design (ITKE) and the Chair in Building Physics (LBP) worked on a research project for modular, robotically prefabricated timber plates between 2015 and 2018 (Figure 7.72). Implementing the experience gained from segmented timber shell building system in previous research projects, the goal of the project Wood R3 was to advance the development of gradient building systems towards longer spans, larger scales, and applications for slabs or horizontal structures. The project involved further development of the building system (construction build up and connection details) as well as analysis of building physics (heat, humidity, and acoustics), with specific attention to criteria of durability. Additionally, an automated structural analysis was integrated to achieve a direct feedback loop between design iteration and structural performance. Most importantly, the project aimed at expanding manufacturing technologies previously developed towards multi-step processes that included both additive and subtractive fabrication.

The focus of this case study will be on the underlying development of a computational design and manufacturing system, which, when compared to the previous case study, improved the structural capacity through a higher complexity and information density of the building system and the building components. In this case study, the term complexity refers to the introduction of an additional level of material aggregation for the prefabrication of building components, or modules, from smaller and already processed building elements. As a result, the building components are not only described by their ranges of geometric variables and characteristics but also inherit certain morphological features from the building elements they are made from. The premise of the research project was that this additional complexity, and therefore information density, would be achievable with an equally more sophisticated manufacturing process involving not only subtractive CNC processes but also additive, or robotic assembly, processes.

The author participated in this research project as a research associate and group leader at ICD in a team of four researchers and three professors. The author was primarily involved in the development of the building system and manufacturing system, including the production of prototypes. The author also assisted in the development of computational design processes for the design exploration and manufacturing data generation. MuellerBlaustein Holzbauwerke GmbH acted as the industry partner in this case study.

This research was later continued and applied for the planning, fabrication, and construction of the BUGA Wood Pavilion demonstrator. The author participated in this project only during the first part of the design and development process, but not during its implementation and execution. Because development of the building system and manufacturing system continued into the pavilion project, this case study analyzes the development as a single process up until the execution of the pavilion. Further acknowledgements are in sections 7.6.5 and 7.6.9.

Some of the project details of this case study were published in the paper "Affordances of Complexity" by Krieg *et al.* [198], focusing on the life cycle analysis, cycle time and costing of the proposed manufacturing system, and "Ökobilanzierung von Lebensende-Optionen" by Horn *et al.* [161], focusing on the life cycle analysis of the building system. Papers about the BUGA Wood Pavilion demonstrator were also published, most notably "The BUGA Wood Pavilion" by Alvarez *et al.* [11], "Towards digital automation fleixibility in large-scale timber construction" by Wagner et al. [387], and a structural paper called "Lightweight Segmented Timber Shell" by Sonntag *et al.* [345]. paper about the agent-based computational design framework was also published by Groenewolt *et al.* [137]. Some results presented in this case study are unpublished, particularly details on the manufacturing development in section 7.6.3 and the machinic morphospace analysis in section 7.6.8.

7.6.2 Investigative motivation: multi-step additive and subtractive manufacturing

After previous research projects investigated different aspects of integral joints for segmented timber shells, the research team built on the existing knowledge to investigate one of the main advantages of industrial robots and adaptive manufacturing: A combination of multi-step assembly processes and subtractive fabrication for the manufacturing of high-fidelity building components. In the context of timber plate structures, this led to the development of an expanded manufacturing process with the intention to develop a material-efficient and adaptive building system.

As part of the research project, different methods for fabricating and connection segmented timber shell structures were investigated (Figure 7.73). The investigative motivation and main trajectory of the research originated from the insight that hollow plate segments can achieve higher structural capacity while saving a large amount of material. Because most of the forces in a segmented shell structure are transferred through the skin of a plate as well as its polygonal edges, there is no structural requirement for material in the center of the plate [198; 345]. If an appropriate manufacturing method could be developed, a hollow plate segment could be assembled from a top and bottom layer connected with beams along its edges. This method would allow to increase the effective structural depth of the plate segment without increasing material consumption or weight, and therefore, the construction method of plate structures could eventually be used in larger spans as well as planar, horizontal slabs for applications in multi-storey buildings [198]. By expanding the structural and constructional capabilities, the building system's performative design space could therefore also be expanded.

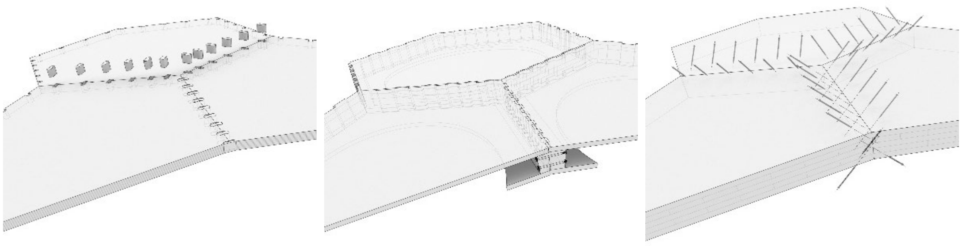

Figure 7.73: Three different segmented timber shell structure prototypes. Left: a single solid plate made from laminated veneer lumber (LVL) with dovetail plug joints. Middle: a hollow cassette with edge beams and a hole in the bottom plate. Right: a CLT-based plate system with crossing screw connections and no integral joints (Image by ICD/ITKE/LBP University of Stuttgart).

Compared to a solid timber plate such as in Case Study 5, a hollow plate—also called a cassette—significantly reduces weight and material. However, it also increases the number of individual building elements that need to be processed and assembled. It is assumed that a more complex manufacturing process for a more complex building system would result in higher material efficiency and building system adaptability [11]. This would be in accordance with biomimetic principles of reducing material and energy consumed and increasing information density. By introducing an additional hierarchy, the building element (timber plate) becomes a building component or group (timber cassette) made from individual building elements (top layer, bottom layer, and edge beams). Although off-the-shelf building materials are still used to produce the building elements (such as LVL or plywood) the resulting building component has a much higher sophistication in geometry, material deposition, and differentiation. When compared to a solid timber plate from Case Study 5, the geometric information necessary to describe a cassette is much higher [198].

Therefore, it can be argued that by progressing towards higher resource efficiency, a more complex manufacturing process is also required. In this case study, a manufacturing setup is required that involves more than one robot and multiple manufacturing stations at which several process steps will take place in sequence. It was the intention of the research team that through its adaptability, the building system could be applied for many different projects and therefore enable a quick return on the investment of additional manufacturing equipment. The capital expenditure was not a primary concern for the research project but needed to be considered for the evaluation of the manufacturing system's potential application in an industrial context.

The building system developed for this case study is a hollow, polygonal cassette, following the same structural and biomimetic principles of previous research in segmented timber shells. In this case, compression and tension forces are guided through the top and bottom layer, while bending forces are taken by the large edge beams along the connections. The individual cassette components will still be connected to their adjacent components with finger joints, but accompanied by bolted connections instead of crossing screws, which have the advantage of tightening the connections and being easily reversible (Figure 7.74). Because of the thick material around the edges of the cassette the joint was considered stronger than the center of the plate, which is contrasting the previous material system in Case Study 5 where the joint was considered the weak spot. Similar to the building system developed in Case Study 5, the outside of the plate components is protected by a waterproofing membrane and a cladding layer made from larch 3-ply panels.

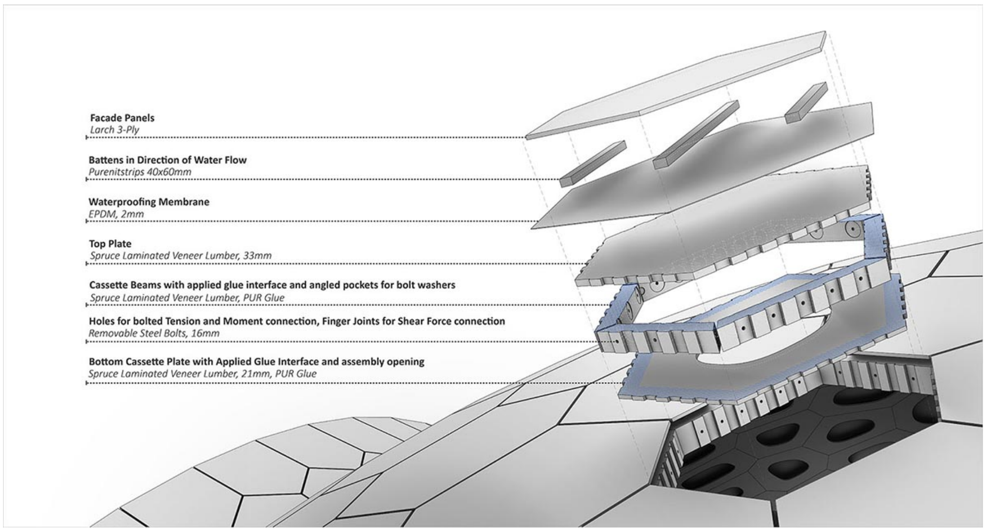

Figure 7.74: Visualization of the building system and an exploded view of a single plate component (Image by ICD/ITKE University of Stuttgart).

7.6.3 Development of a Manufacturing System

The building system was developed in reciprocal relation to the manufacturing development. By advancing the complexity of the individual building component, more complex manufacturing technology is also required [198]. A typical process found in natural structures is the balance of morphogenesis and homeostasis for finding the most effective distribution of material, effectively employing both additive and subtractive processes. To achieve a more informed material deposition such as the accumulation of smaller building elements into larger building components, a more intricate and complex manufacturing process is required. As a result, more material-efficient structures can be achieved.

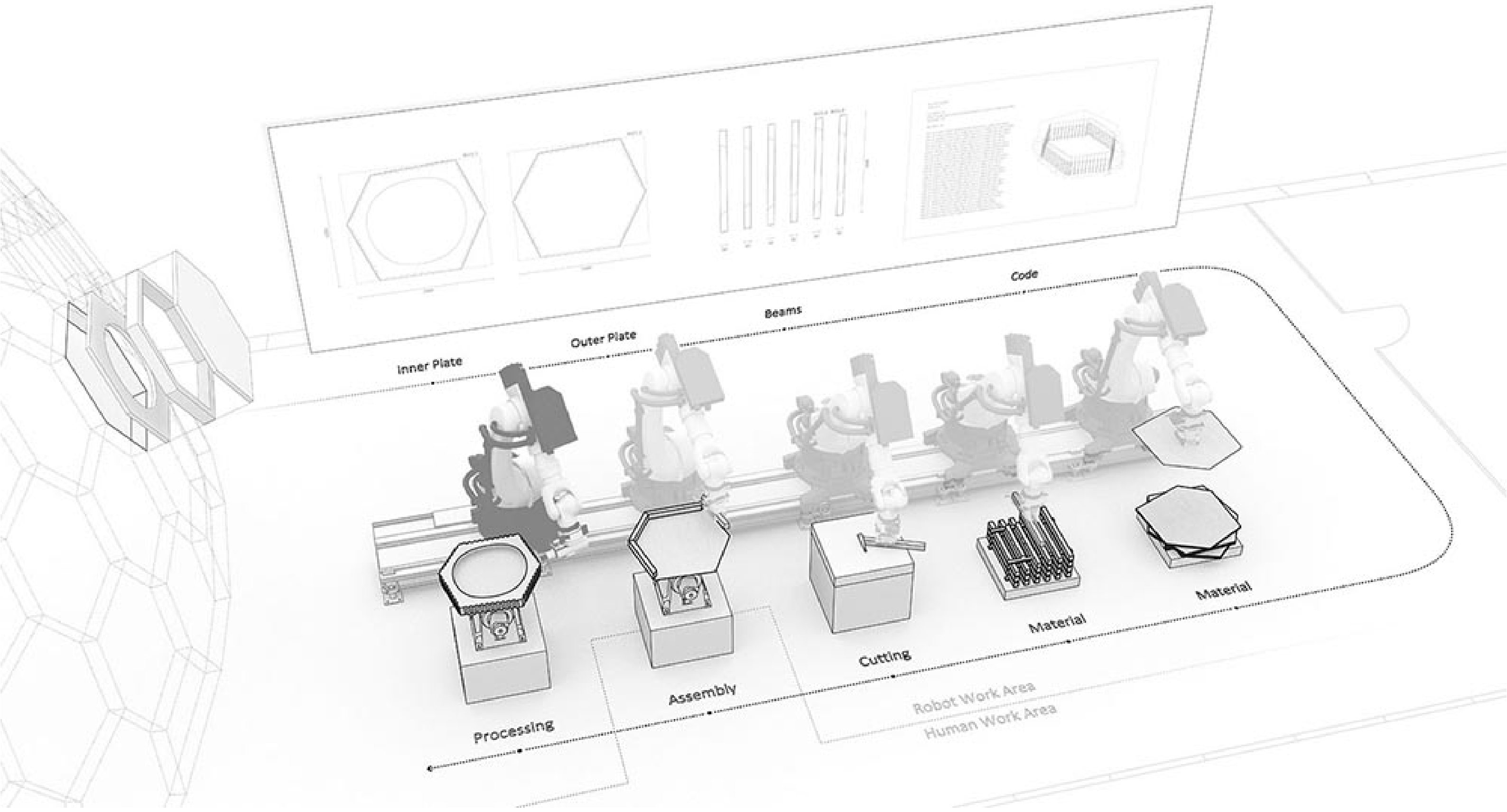

Figure 7.75: Overview of the manufacturing system of Case Study 6. Starting on the top left, the computational design system generates all necessary manufacturing data, which is then translated into individual robotic manufacturing steps.

The flexibility of industrial robots and their effectors allowed for the development of all necessary prefabrication steps of this material system. For assembling unique building elements into unique building components with high accuracy, a manufacturing system with one robot on a track with one or two turntables, was developed. In the later phases of the BUGA Wood Pavilion project, this concept was further developed into a setup with two stationary robots and a single turntable [11]. Although different, the individual processing steps remained the same. For the purpose of this case study, the former manufacturing system will be evaluated (Figure 7.75).

In the value chain of production, the added complexity of building components consisting of aggregates of building elements results in multiple additional robotic manufacturing steps without changing the general process of using stock material upfront or handling the building component after the robotic manufacturing process is finished. However, the manufacturing steps required to process the individual building elements need to be considered as well. For their required data transfer, machining, ordering, and stacking, preparation steps are required. Therefore, the overall manufacturing system can generally be divided into four parts:

(1) Manufacturing data transfer, stock material processing, building element preparation.
(2) Robotic assembly of building elements into a stock component, or cassette.
(3) Robotic CNC milling of features into stock cassette to finish all connection details with high precision.
(4) Post-processing of cassettes, shipping, on-site assembly.

In the first part, the computational design system explained in the next section produces data sets for each type of building element and for each building component individually. To manufacture the stock cassette in the next step, all building elements are assumed to be offset towards the outside of the cassette boundary to allow the CNC milling in step three. The following building elements are prepared for the assembly of the cassette in the second step:

(1) Edge beams made from LVL, which are cut with mitered ends to meet adjacent beams within the cassette.
(2) Top plates made from LVL, which are cut with the same offset and straight edges.
(3) Bottom plates made from the same LVL.

The bottom plates can be thinner than the top plates as they do not carry the weatherproofing layer or cladding layer. The bottom plates also include a large opening in their center, which provides access to the connections between cassettes during assembly, but also act as a distinctive architectural feature.

All these elements are cut and trimmed on common timber processing machines, labelled, and stacked in order of assembly. In preparation for assembly, a cart and stacking system had to be developed, which would allow the robot to locate every element precisely. For the edge beams, precise grooves were cut into a shelf plate, while the shelf itself would be placed in the proximity of the robot system with the help of rails and guides. For the plates, a similar rail and guide system was developed, but their placement on the shelf was guided by their geometrical bounding box aligned towards their longest edge. These material input stations were later further developed by the BUGA Wood Pavilion team [386].

In the second step, the robotic assembly of the stock cassette is executed using a mix of automation and human-robot collaboration:

(1) The bottom plate is picked and placed with a vacuum area gripper onto the turntable, which activates its vacuum suction cups to hold the plate.
(2) Glue is applied along the edge of the bottom plate with a glue extrusion gun.
(3) Edge beams are picked from the shelf with a parallel gripper, and placed on the glued edges of the bottom plate.
(4) Edge beams are fixed temporarily with a beech nail gun by a human collaborator.
(5) Glue is applied along the top of the edge beams.
(6) The top plate is picked and placed on top of the edge beams.
(7) The top plate is fixed temporarily with a beech nail gun by a human collaborator.
(8) The combined assembly is taken off the first turntable and placed on the second turntable for robotic CNC milling.

Task division during the assembly process are an essential aspect of machine occupancy, tact time and design space, and the developed process had to be virtually tested with a variety of polygonal shapes in order to ensure an optimal configuration of equipment and layout. Within a constrained space there is an optimal configuration of equipment that allows for the largest design space of the building components, given that the right evaluation parameters are selected.

It is important to note that the glue application and hard wood nails were conceptualized in the research project but only physically implemented during the BUGA Wood Pavilion project, at which point the author was not part of the research team anymore. In the later machine setup developed for the BUGA Wood Pavilion, the beech nail gun was also automated using a second robot [386].

In the third step, the stock cassettes are CNC processed on the second turntable by the industrial robot. Tolerances and deviations in location of up to 5mm can be accommodated because of the added material offset around the stock cassette's outline. The following milling steps are then executed:

(1) Outline and finger joint geometry with a large flat milling bit.
(2) Top surface angles around the finger joints to match the neighboring surface normal.
(3) Drilling holes for the bolted connection on site.
(4) Contour cutting the hole into the bottom plate.

This is the third case study in which finger joints are robotically milled. In this variation of the integral joint type, the finger joint faces share the bisector of two adjacent plates similar to Case Study 5, but the milling bit is used in the same way it was in Case Study 1 [198]. This leads to a difference in kinematic constraints and collision scenarios that define the machinic morphospace, of the building component.

To cut the hole of the bottom plate, the cassettes are assembled and processed upside down. The hole of the bottom plate is only cut in part to allow the first robot to pick While the robotic CNC milling instructions are generated separately from the assembly instructions, they are both generated by the same digital model, similar to previous case studies.

Apart from the timber plate cassette that is referred to as the building component, other building layers are processed and prepared in a similar manner. Like the layers in Case Study 5, the data transfer and generation of machining data is prepared for a weather protection layer made from EPDM and a cladding layer seen in Figure 7.74.

7.6.4 Development of a Computational Design System

Similar to the progress made in the building system and manufacturing system in comparison to Case Study 1 and 5, the computational design system was equally progressed towards higher integration and functionality. Manufacturing and building information data, as well as structural analysis were the focus of the development process. In response to requirements for the collaboration with industry partners, a multi-step computational process was developed that allowed the safe storage of data, manual intervention, and data interfaces:

(1) Computational design process of the segmented plate shell
(2) Data transfer and automatic analysis of the structural performance
(3) Generation of building parts, components, and geometric indicators
(4) Generation of manufacturing data

During the development process, increasingly complex designs were generated to test the overall functionality of the system. During this project, the design for the BUGA Wood Pavilion was already being developed and will be shown in the following diagrams and the machinic morphospace analysis.

For the first step, the research team built on the previously developed agent-based modeling tools and methods [137]. An updated design tool for a more interactive and intuitive design process was developed for the purpose of quickly iterating through many options, as well as being able to make small corrections manually. The tool can be described as a computationally assisted design process based on an agent-based design method. While plates represented as BREPs or Polylines still act as agents with their own behavior in this process, user-interactive functionalities and global rules were added to it [137].

The agent-based method distributes the plate segments across a given design surface, with the plates finding the right distance to their neighbors to stay within preferred geometric parameters such as their size, edge length and connection angle. In addition, an agent's location on the design surface will have an influence on these parameters. For example, the closer an agent plate will get to a predefined edge, the smaller its optimal size will become [137].

More specifically in the context of this case study, this global behavior resulted in a size gradient from smaller plate components along the edges of a shell to larger components in the middle. The structural motivation behind this behavior is that since each component has the same sized edge beams no matter its circumference diameter, smaller components structurally perform better than larger components [345]. Therefore, material can be globally distributed within a shell structure where it is needed based on component size. As the research transitioned into the design process of the BUGA Wood Pavilion, this functionality was employed to create a dense plate pattern along the creases of the shell, as well as to elongate plates along the cantilevering wings (Figure 7.76).

Other additional functions include the possibility to pause the agent-based design process, fix plate agents via mouse click, move individual plate agents with the mouse, or add additional plate agents during the simulation. This can help to induce movement of certain plate agents that might be stuck in an invalid geometric configuration, or to fine-tune a solution in certain locations. Further, it can be seen in Figure 7.76 that special components were inserted along the creases of the pavilion design. These situations were recognized as structurally important spine-like connections, and the design tools therefore introduced a secondary type of plate component [11; 345].

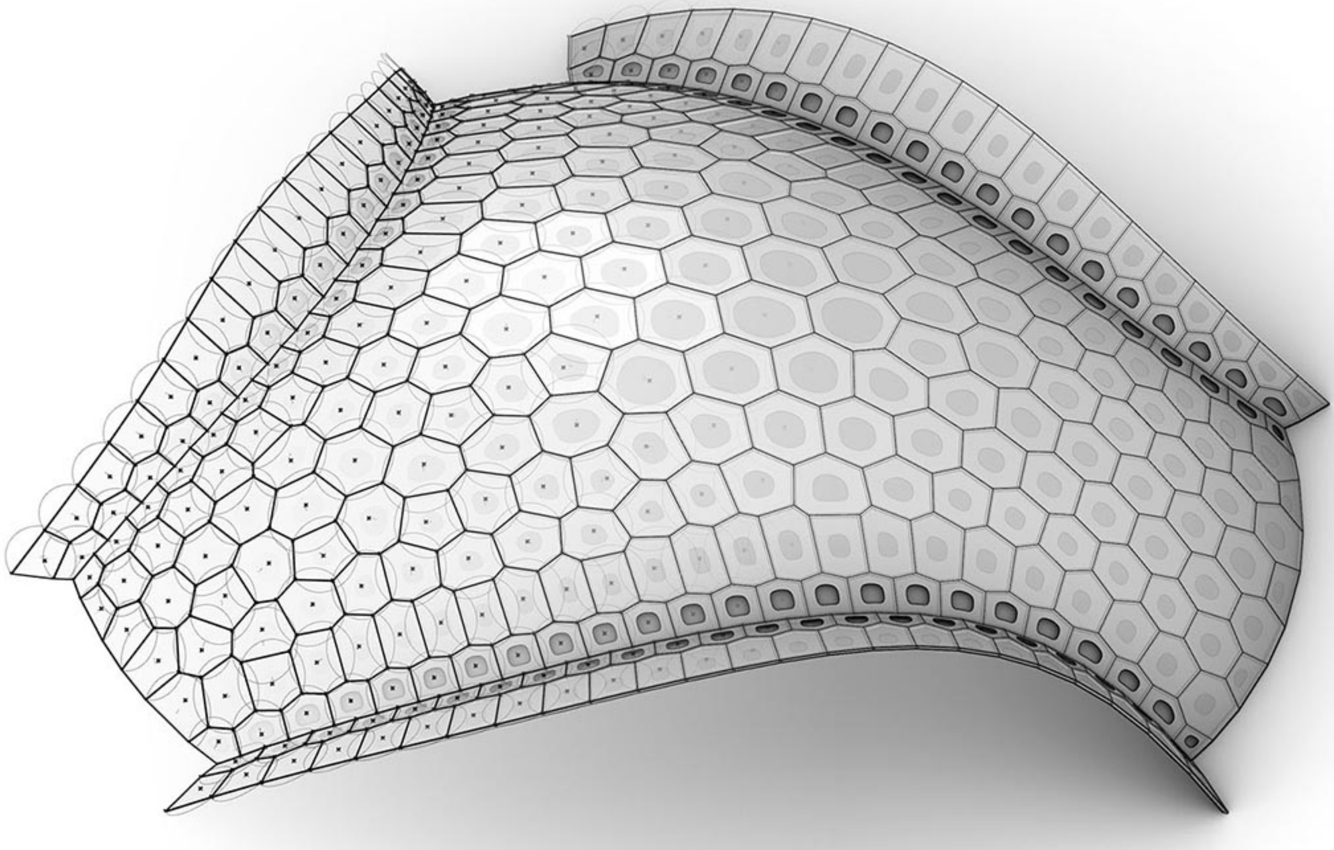

Figure 7.76: The agent-based modelling method is represented by the plate component outlines, center points, and the component's circumcircle. The figure transitions into the resulting three-dimensional geometry of the building components towards the right.

The geometric result of this computationally assisted design process is very similar to the result in Case Study 5. Instead of representing any material thickness, only a BREP representation is used to indicate the location and size of each plate. Only in further steps will this geometric information be expanded.

The second step was developed during the research project to effectively evaluate the structural performance of segmented shells with different parameters for their connections as well as different segmentations. Instead of manually loading the geometry into a finite element analysis tool, a transfer protocol was developed that would export the geometry as well as connection data, which would be translated into a spring model for finite element analysis in the program Sofistik [343]. This allowed the research team to evaluate slight changes in the plate segmentation or the overall shape of the shell structure. During the design phase of the subsequent BUGA Wood Pavilion project, this process was used to fine-tune the design and find a solution with minimal deformation under load [345].

In the third step, and in contrast to previous computational workflows, some of the 3D geometry representing individual building elements are generated, such as the cassettes' plates and edge beams. To properly track the geometry of each building element, visually verify the computationally generated results, and to view the building elements for the subsequent manufacturing simulation and code generation, a representation of the building elements became necessary. Particularly in the context of industry collaboration, other parties need to be able to verify the information before going into manufacturing. In addition, point and line indicators were generated to represent drilled holes, bolts, openings, and special situations that require the computational process in the next step to trigger a conditional function [11].

In the fourth step, all manufacturing data and documentation is generated from the parametric information model described above. In part, the lightweight data model using the BREP representation of the plate cassettes is used to generate manufacturing data such as the CNC milling tool paths. That way, the geometry of the finger joints does not have to be generated. For the translation of the geometric data into robotic assembly instructions, each cassette has its own coordinate system, which relates to where the material stacks are located within the robotic setup [11; 387]. From there, the motion to pick up and place elements is being generated with individual points, which will then be translated into robot code. As a result, every building element not only carries its geometric data but also its own set of robot motion instructions. These instructions are usually parametric and depend on the location of equipment within the manufacturing environment, such as the material stacks or the turntable.

The robot motions are simulated within the same algorithm through a kinematic solver developed by the research team. The simulation is not accurate in the cycle time but in the relative movement of all robotic equipment and serves as feedback for collisions or errors in the robotic motion. Once confirmed, the assembly process and CNC milling process get exported as individual files for the robot cell. Early iterations of the manufacturing simulation helped determine design space boundaries. However, a comprehensive machinic morphospace analysis was not executed during the research project.

7.6.5 Project results

The result of the initial research project Wood R3 was a detailed report on the manufacturing processes for the segmented timber shell structure as well as prototypes with three or more cassette plates. While the research project was still ongoing, work started on the BUGA Wood Pavilion in 2017, which informed the development process towards industry collaboration. The specific details of the building system such as the size and distribution of finger joints and bolt connections were developed during this time.

To deliver the demonstrator for the Bundesgartenschau 2019 exhibition, a transportable, 14-axes robotic cell was developed by the ICD research team in collaboration with BEC GmbH, which was transported to and installed at the industrial partner MuellerBlaustein Holzbauwerke GmbH for the production phase of the pavilion. The platform includes two high-payload industrial robots mounted on a 20-foot standard container base. For the segmented timber shell of the pavilion spanning almost 30 meters, all 376 cassette components were manufactured with sub-millimeter precision. On average, the assembly time per component was 8 minutes, with the robotic milling taking another 30 minutes.

The BUGA Wood Pavilion provided an architectural attraction at the central summer island of the Bundesgartenschau 2019 exhibition in Heilbronn, Germany. The shell structure consisted of a main shell body resting on three base points, with three creases along its opening to which cantilevering wings of different sizes are attached. The creases act as a geometric reinforcement, and their cassette components were deeper and had stronger connections than the other cassette segments.

7.6.6 Research result: Process analysis

To evaluate how the integrative development process was enabled in this project, the relationship between the gradient building system, manufacturing system, and computational design system is analyzed in this section.

The development process described in this case study is an expansion of both robotic manufacturing capabilities and the design space of gradient building systems. On the example of segmented timber shell structures, it is shown that added complexity in the manufacturing process can lead to more material efficiency, higher structural performance, and larger ranges for certain morphological parameters that are important for the building system's design space.

As in other case studies, the development process can be described as a digital loop or spiral, where aspects of the building system, computational design system, and manufacturing system inform each other as they progress. Once the development process is completed, the design and delivery of the demonstrator building can be described as a digital chain that connected these systems (Figure 7.77).

By expanding the complexity of a timber segment from a solid and homogenous shape to a hollow cassette made from individual building elements, the design space of the resulting cassette also becomes the combined design space of the individual building elements. In this case, the processing of the individual building elements did not require robotic manufacturing processes and instead could be executed using stock material and standard CNC machines. It could therefore be assumed that the individual design space of the building elements was larger than that of the building component, and the defining parameters that constrain the design space are all derived from the robotic assembly or robotic milling process.

The higher morphological complexity of a timber cassette plate structure and the gradation of the morphology of its individual building elements becomes affordable with the right robotic machine setup. In this case, affordability refers not only to the economics of a building system but also the manufacturing time and handling of parts and data. In the manufacturing and construction of the subsequent BUGA Wood Pavilion, it was shown that a large amount of building components could be manufactured within a short time frame [386].

7.6 Case Study 6: Wood R3 – Resource Effective, Regional, Robotically Fabricated, 2018

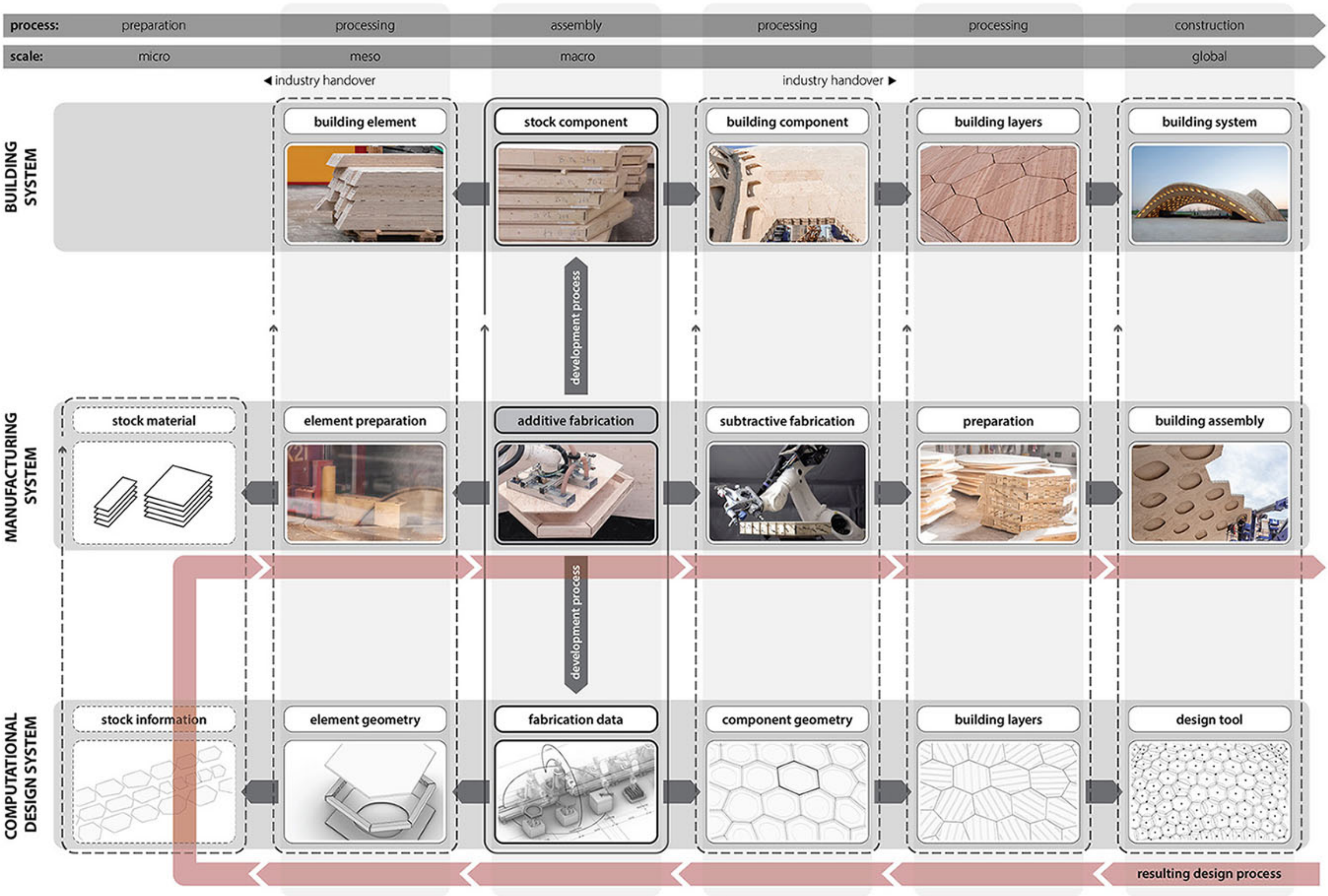

Figure 7.77: Development process overview of Case Study 6. The development process is highlighted with dark gray arrows, and the resulting design process of the demonstrator with red arrows. Contrary to Case Studies 1 and 5, this latest iteration of a segmented timber plate structure originated around the promising capabilities of robotic assembly processes. As such, an additional level of hierarchy was introduced. Similar to Case Study 5, handover interfaces to the industry collaborator had to be defined for both the development process as well as the resulting design process for the demonstrator. This diagram contains images by ICD/ITKE University of Stuttgart.

The integration of user-friendly computational design processes, automatic structural analysis and manufacturing development allowed for continuous computational feedback within an interdisciplinary team. As in Case Study 5, it was important to communicate with the industry partner during several development steps to confirm concepts of the building system and manufacturing system.

In the context of an industrial manufacturing process involving an industry partner similar interfaces as in Case Study 5 had to be established. This is one of the reasons that more 3D geometry had to be generated than necessary for the computational design process. It ensured visual confirmation and allowed the interdisciplinary team to avoid misunderstandings.

When expanding the size of the interdisciplinary team for this case study, the high frequency of interdisciplinary feedback that was established in Case Study 5, is more difficult to achieve, and the collaboration between teams and disciplines has to be emphasized. When decisions are being made across several working groups within a larger team, the complete knowledge about the development process does not reside within a single person or small team but it is distributed across many teams or persons. Therefore, in this case study, the building system that the larger team was developing can be considered not only as a building platform but also as a knowledge platform. It is the platform that owns all information and knowledge about itself, and it collects information as the development process progresses. While the individual team member may not be in control of a large part of the process anymore, the platform will establish information collection and sharing more democratically, if properly managed.

Ultimately, it was the intention of the research and industry team that the building system becomes a building platform upon which multiple iterations of projects could be realized. Because of its geometric adaptability and therefore the design space, it was intended that many different projects could be built. From an economic standpoint, the return of investment of complex manufacturing technology is easier and faster to achieve, the more versatile the building system is that it can produce. Here, a larger machinic morphospace is in direct relation to the potential applicability or market segment of a building system.

7.6.7 Research result: Information flow analysis

To evaluate how the morphological differentiation of the building system was digitally generated, processed, visualized, and stored, the computational design process is analyzed in this section.

This case study can be seen as a continuation of the previous case study, and as such, the computational design system and its information flow is also a continuation and adaptation of the previous case study. The same methods that were used to represent complex information with a lightweight CAD model during the design phase of the project were also applied in this case study. It is worth noting that the representational model, which contains only BREP surfaces representing the outline of a plate segment or module, has the same structure and logic in this case study as for the previous case study. Both design CAD files could be used interchangeably. The additional building element information needed in this case study to visualize and, ultimately, manufacture the hollow plate components unique to this case study, is only generated in subsequent steps.

In this next step, geometric information of the building components was added for several purposes. The components received their material thickness and individual building elements were generated for the top and bottom plates as well as the edge beams. The bolted connections were also generated, as well as the holes that needed to be drilled into the edge of the finished components. This model was multi-purpose information model: It was used to generate manufacturing data, to exchange information for on-site construction and coordination, and it was used to analyze the structural performance of the design using finite element analysis. The type and nature of geometry such as axis lines and point locations for the bolted connections, as well as foundation geometry, were decided on for these multiple purposes. Once generated, they could still be manually adjusted if necessary. Then, a subsequent process would generate all required manufacturing data for the robotic assembly of each component in an individual file, as well as a bill of materials and the sequence of assembly for the manual preparation of each assembly process.

In conclusion, the data flow expanded to accommodate a variety of uses. However, the amount of information required for interfacing, coordination, and manufacturing, remained as low as in any other case study.

7.6.8 Research Result: Machinic morphospace analysis

To evaluate how the morphospace analysis can be effectively used to analyze the relationship between the machine setup and the gradient building system's design space, the author applied this method to the project in this section.

The machine setup in this case study is unique in that there are multiple fabrication stations within which several fabrication steps are executed. This is more akin to typical industrial manufacturing processes where building elements and components are passed down assembly lines. The manufacturing setup was chosen during the development process because it represents the available equipment at the institute's laboratory.

It could be argued that each effector has its own machinic morphospace or influence on the overall design space but changes in their parameters will not be considered in this analysis. The effectors represent the state of development at the point of the machine setup development before the BUGA Wood Pavilion platform development started.

For this case study, the constraints of the machine setup are evaluated for the assembly as well as the robotic CNC milling process. Both machinic morphospaces will be overlaid to show their overlap and differences.

7.6.8.1 Parameters of the machine setup

The machine setup in this case study consisted of a KUKA KR-420 industrial robot on a 12m track. The robot's kinematic information can be seen in (Figure 7.78). The robot was equipped with a water-cooled 12kW high-frequency spindle for milling wood, a parallel gripper, and a glue application effector. Further, the industrial robot was connected to two two-axis positioners, DKP-400. For milling processes, mainly a 120mm long straight milling bit with a 20mm diameter was used.

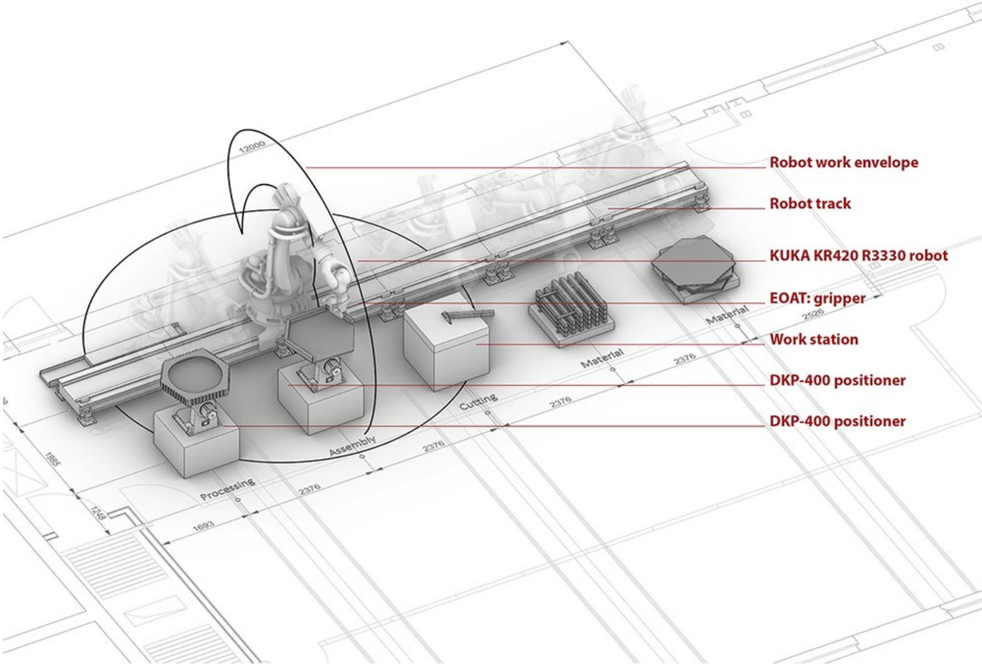

Figure 7.78: Machine setup of Case Study 6. The industrial robot is positioned on a 12m long track so that it has access to multiple fabrication stations. In total, five stations were developed for material positioning, processing, and assembly. The available space of the individual stations and the kinematic constraints of the industrial robot and the turntables have the most impact on the machinic morphospace.

7.6.8.2 Morphological parameters of the building element

Parameter selection is a critical step for the analysis of the building element's morphospace and its relation to the manufacturing process. Generally, the building element can be described as a polygonal hollow plate component made from edge beams between a top and bottom layer, and finger joint connections added to all or some of the edges. To define morphological parameters that have the most influence on the building system's design space while at the same time being directly influenced by the machine setup or through an interdependence of parameters, Table 7.6 below is used.

	Morphological parameter	Influence on design space	Influence of machine setup
scale increases	**Microscale (from molecular to cellular makeup)**		
	Material density	medium	medium
	Average or individual cell length/width ratio	medium	low
	Average or individual veneer layer thickness	medium	low
	Average or individual grain direction	high	low
	Mesoscale (building element)		
	Plywood veneer lay-up	medium	medium
	Top layer or bottom layer material thickness	high	medium
	Cassette depth or edge beam height	medium	high
	Edge beam thickness	medium	medium
	Single finger joint dimensions	medium	high
	Bolt connection dimensions	medium	medium
	Polygon edge length	high	medium
	Number of finger joints along single edge	medium	medium
	(P) Polygon-internal angle	high	high
	(A) Finger joint connection angle on single edge	high	high
	Macroscale (building component)		
	Number of polygon vertices	medium	low
	Number of polygon edges	medium	low
	Number of finger joints	low	medium
	(D) Circumcircle diameter	high	high
	Cassette surface area	medium	medium
	Cassette directionality (ratio of min to max width)	high	medium
	Gaussian curvature at plate location	high	medium

Table 7.6: Analysis of morphological parameters in Case Study 6. The higher the rating the higher and more direct the impact towards the building system's design space or the impact from the machine setup. Based on the rating, the highlighted parameters are selected to further evaluate the relationship between the machine setup and the design space of the building system.

In this case study, many morphological parameters on the building element and component level are of interest for defining the design space of the building system. However, in order to better compare this case study with the previous case studies that evaluated segmented plate structures, the same morphological parameters will be evaluated.

Based on the above analysis, three morphological parameters are selected that are most indicative of the resulting design space of the building system, and most indicative of the influence of the machine setup. Because of the relationship between the scale and the parameters, two out of the three selected parameters refer to a building part or a segment of the building component, while one parameter refers to the whole building component. This relationship is further explained below:

- *(D) Diameter of the smallest circumcircle of a component (in mm)*
  The smallest circumcircle is calculated for every component to define the center point that results in the least space required for its rotation on the positioner. The minimum circumcircle is the closest numerical description of the building element's overall size. Here, a single value is used to characterize the size of the building element.
- *(A) Finger joint connection angle (in degrees)*
  This parameter directly relates to the angle between two neighboring components. It also has a direct impact on the machine movement as different connection angles are milled by tilting the milling spindle. The angle is measured by evaluating the angle between the normal vectors of adjacent segments that share an edge. 0 degrees refers to a coplanar or flat connection, positive values refer to a convex connection, and negative values refer to a concave connection. Here, a single value refers to a single edge of a building component. A building component can have several edges with different connection angles.
- *(P) Polygon-interior angle (in degrees)*
  This parameter describes the angle between two adjacent edges within a component, which relates to the overall polygonal outline. The angle is measured by evaluating the vectors of two edges meeting in one point. Values below 180 degrees refer to convex polygon angles, and values above 180 refer to concave polygon angles. While both are possible, concave polygon angles only occur in situations with negative gaussian curvature. Two values refer to both corners of a single edge of a component.

Similar to Case Studies 1 and 5, parameter (D) occurs once in each building component, while parameters (A) and (P) occur multiple times because each component has multiple edges. Therefore, a building component has multiple values for (A) and (P) but a single value for (D). All three parameters are described in Figure 7.79.

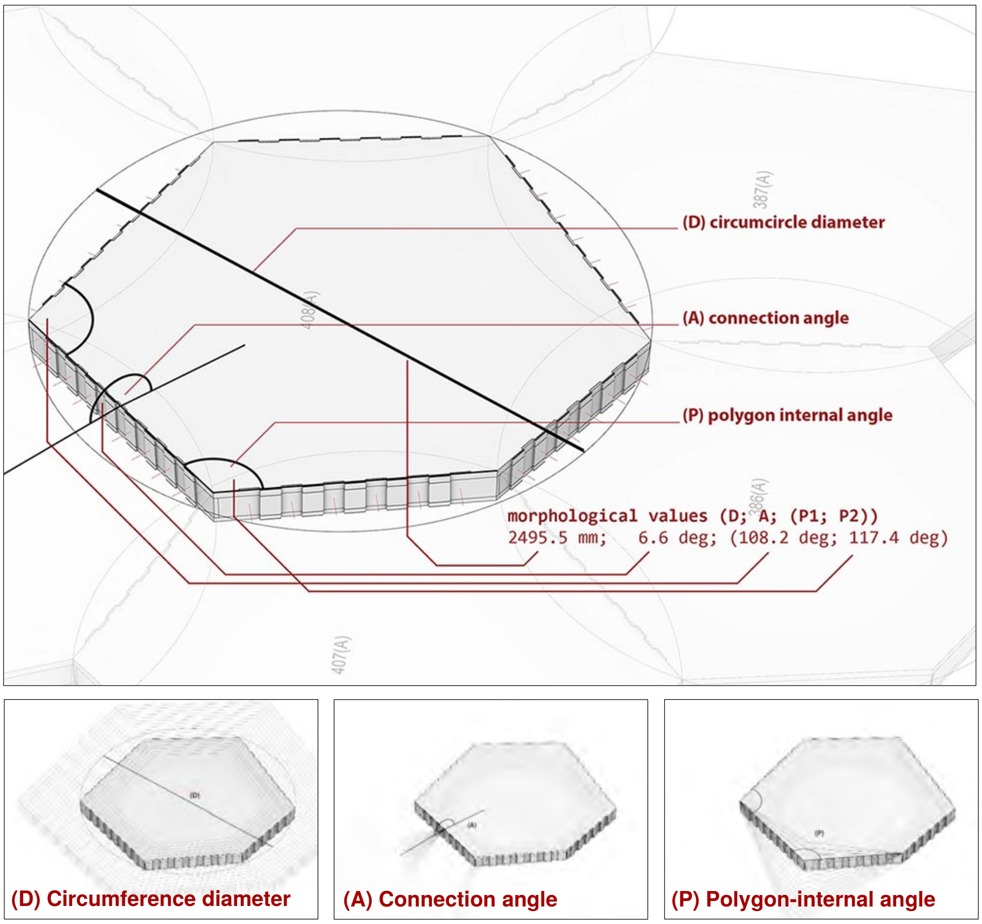

Figure 7.79: Top left: Overview of the three morphological parameters of the building component surrounded by other components within the building system. The resulting morphological values of a building element's edge are shown within the image to explain the relationship between the three parameters. Bottom left: (D) as the diameter of the minimal circumference. Bottom middle: (A) as the connection angle between two components at one edge (referring to a single edge within the component). Bottom right: (P) as the interior polygon angle between two edges (referring to a single vertex within the component).

Typical boundary situations of these morphological parameters are described in more detail in the below series of images (Figure 7.80). In these images, the variation of the parameters and example situations for their boundary constraints are shown. The min/max constraints of the parameters due to the machine setup, and their interdependencies, can be described as follows:

- The minimal circumcircle, or component diameter (D) is constrained by the physical boundaries of the robot cell. This includes the enclosure as well as the distance to the neighboring stations. Since the robot is on a track it could theoretically process much larger plates. The minimal size of components is constrained by both the positioner as well as the minimum length of individual edge beams that are gripped by the robot effector. Further, both the connection angle (A) and polygon-internal angle (P) are constrained by the plate size due to the milling process. Smaller plate sizes reduce the parameter range of (A) and (P).
- The connection angle (A) is constrained by the inclination of the milling spindle at higher angles and its collision with either the work piece or the turntable. Compared to Case Study 1, here the milling spindle intersects much earlier because of the fabrication method and the material thickness. Further, the usability constrains the finger joint connection, which is not designed for angles higher than +/-45 degrees. Higher angles have less material overlap and bolted connections no longer work. Higher connection angles also reduce the range for (P) due to geometric intersection, which would lead to the milling spindle cutting off parts of the plate.
- The internal polygon angle (P) is constrained by the geometrical self-intersection of finger joints at higher angles, which would lead to the milling spindle cutting off parts of the plate. Extreme values of this parameter can also cause reach problems, which is why the polygon angle influences the maximum value of (D).

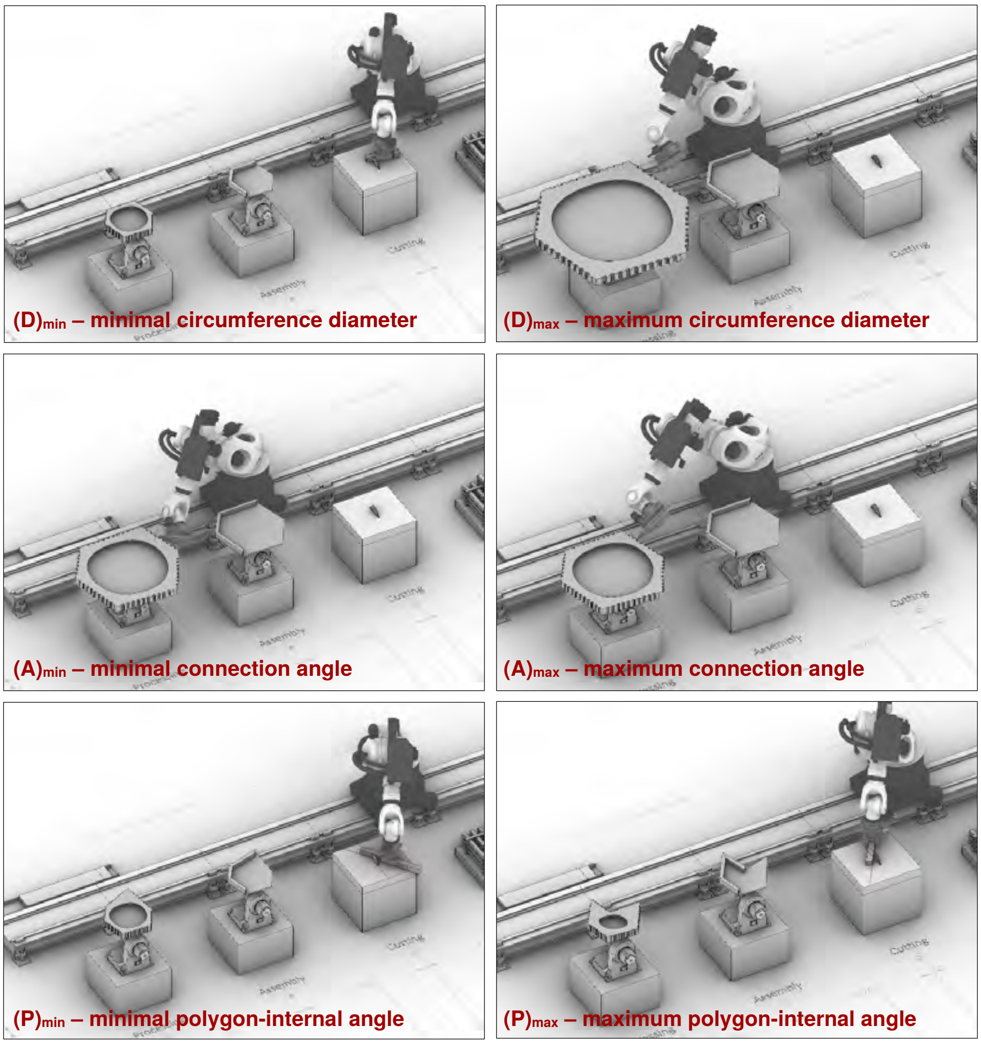

Figure 7.80: Exemplary boundary conditions of all three parameters. While other boundary conditions exist, these are the most prominent ones. Top row: minimal and maximum plate diameter (D) is constrained by both the assembly and the milling process. Middle row: Minimal and maximum connection angle (A) is mostly constrained by the milling process. Bottom row: Minimal and maximum polygon-internal angle (P) are mostly constrained by the assembly process.

7.6.8.3 Result: theoretical and empirical machinic morphospace of Case Study 6

In Figure 7.81, the resulting theoretical morphospaces of the assembly and milling process are represented by light gray volumes within the three-dimensional parameter space described by (A), (D), and (P). Both volumes represent the *producible region of possible form* (PPF) for the machine setup described above. One volume describes the constraints of the assembly and processing steps, while the other volume describes the constraints of the robotic milling process.

The theoretical machinic morphospaces of the milling process and the assembly process differ in several parameter combinations. The maximum size (D) of the component is constrained equally in both cases because of their similar rotation on the positioner. The minimal size is more constrained in the assembly process because of the effectors used to pick, cut, and place the edge beams. This is a typical observation in automated manufacturing and was also mentioned in Case Study 3. If the assembly process were executed by a human worker, the space required to hold the edge beam would be smaller, and smaller plates would be possible. Automating this process resulted in an effector with more spatial requirements, thereby constraining short edge beams, and consequently, smaller components.

For the assembly process, the connection angle (A) is only constrained in that extreme values would require a thicker edge beam to accommodate enough glue surface area even after milling. This constraint is independent from the size of the component. Last, extreme values of the polygon angle (P) constrain the size of the component in an exponential relationship but have otherwise no effect on the connection angle (A). For the milling process, the relationship between the parameters is very similar to Case Study 5. However, because of the novel joint geometry, the polygon angle (P) constrains the connection angle (A) in a similar way as Case Study 1 in that the spindle can collide with the building component at very concave polygona angles.

The 2-axis positioner did not give the machinic morphospace an advantage compared to a 1-axis turntable. While it avoids potential collision scenarios between the milling spindle and the floor for concave connection angles, it does not prevent collisions with the milling bed that is fixed on the positioner.

For Figure 7.82, the combined theoretical machinic morphospace was calculated using a Boolean intersection operation. In the figure, the empirical morphospace of all 376 building components of the demonstrator building BUGA Wood Pavilion is visualized in red. Each building component is represented by a collection of measuring points representing individual connection angles and polygon angles, and a faint polygonal area indicating that they belong together. This polygonal area is in a single plane on the axis of (D) because each component only has one value for its circumcircle diameter. The parameters (A) and (P) are related in that every edge represents one connection angle and two adjacent polygon angles. Further, the diagram shows 2D and 1D projections of the measurement points for better readability.

The empirical machinic morphospace reveals the design intent and two distinct types of components. Most plate connections angles (A) are between 0 and 10 degrees, which represent the smooth and continuous surface of the demonstrator's shell. However, looking at the relationship between (A) and (P), a secondary type of component becomes visible. Several measurement points with concave connection angles visualize the morphological characteristics of the components that are placed along the three creases, or spines, of the demonstrator. These components have concave connection angles (A) of -58 to -68 degrees, and because of the negative gaussian curvature at this point, they also have one concave polygon angle (P) just below 180 degrees. It is also visible that these types of components are smaller with a range of 1250mm to 1900mm for (D). The smoother and more symmetrical components of the main shell are characterized by their measurement points being close together, revealing that both their connection angles (A) and polygon angles (P) are very equal. Their size ranges from 1500mm to 2570mm.

This analysis shows that by evaluating the empirical morphospace of the demonstrator building, a relationship between design intent and preferred regions of form can be established. In this project, a clear design intent resulted in the occupation of very distinct regions of form, whereas many other designs could be realized.

7.6 Case Study 6: Wood R3 – Resource Effective, Regional, Robotically Fabricated, 2018

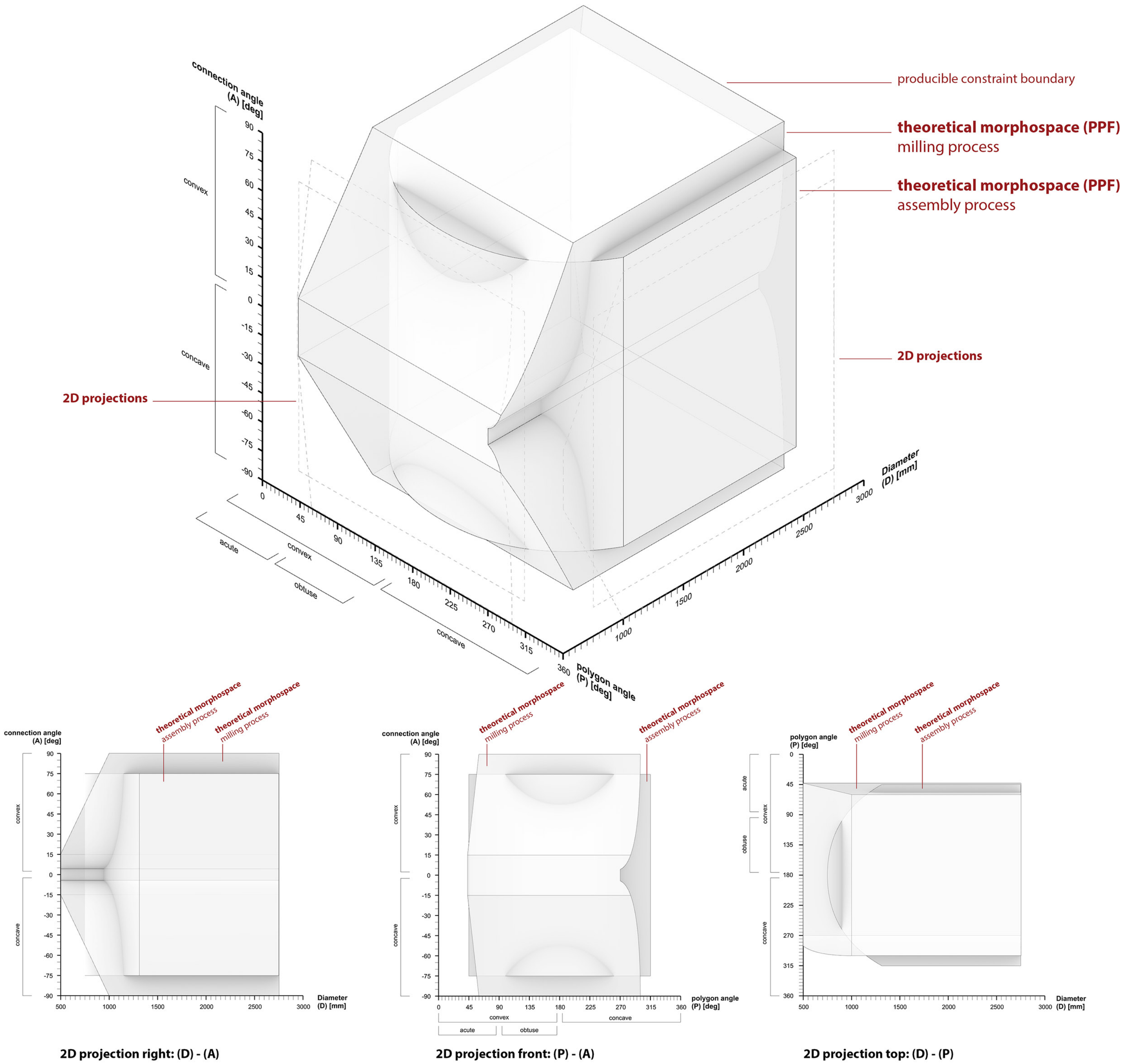

Figure 7.81: The two theoretical machinic morphospaces of Case Study 6 are visualized as intersecting gray volumes. One volume represents the PPF of the assembly process, and one volume represents the PPF of the milling process. 2D projections of the theoretical morphospaces are overlaid on the planes of each pair of axes and plotted at the bottom of the diagram as parallel projections.

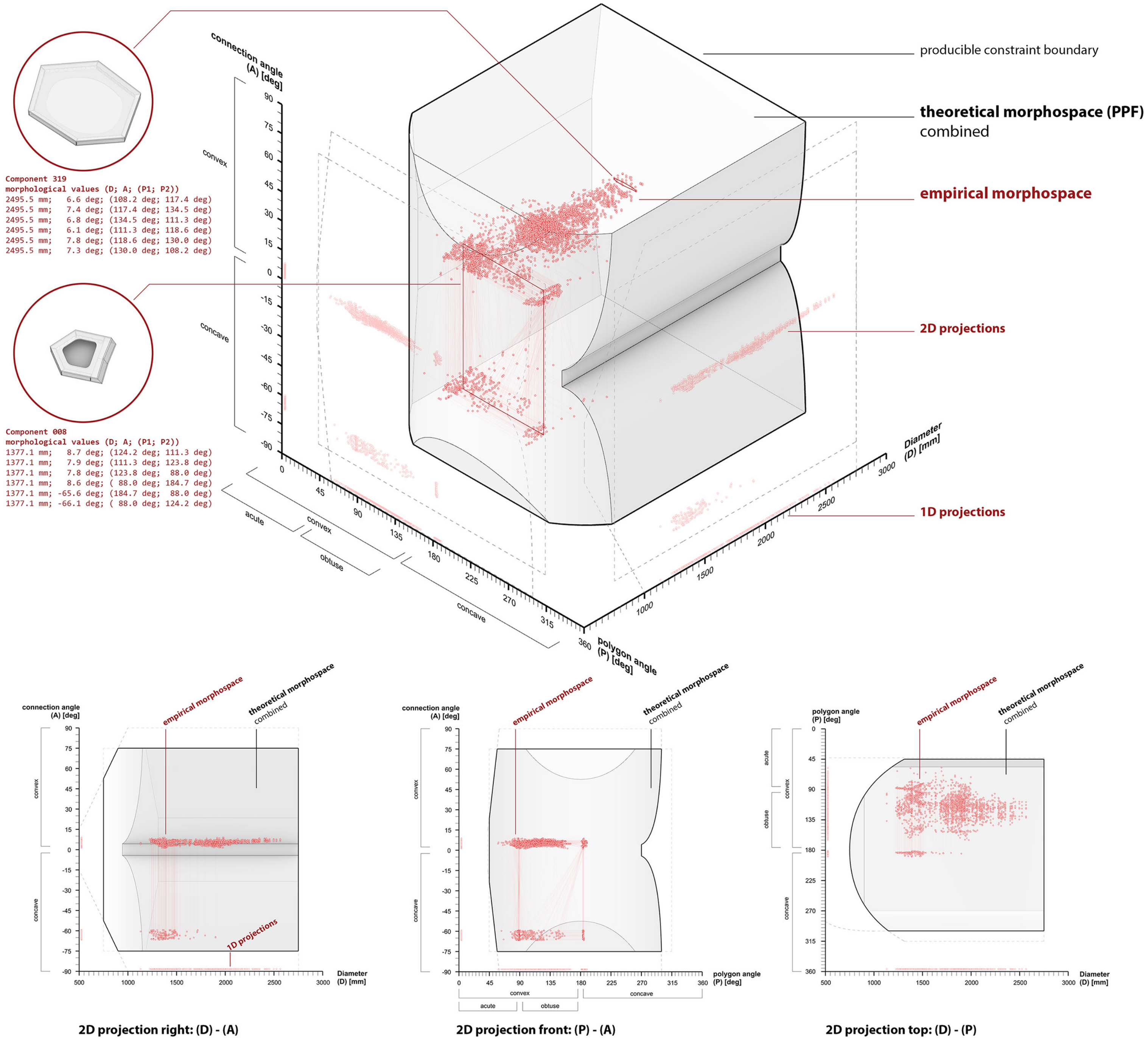

Figure 7.82: The combined theoretical machinic morphospace is visualized as a single gray volume. The empirical machinic morphospace of Case Study 6 is visualized by red measurement points that represent each parameter value of each component of the demonstrator building BUGA Wood Pavilion. Two example segments are shown on the top left to exemplify the variety of morphology within the building system.

7.6.9 Acknowledgements

This research project was a collaboration between several researchers and students.

ICD Institute for Computational Design and Construction
Prof. A. Menges (PI), Oliver David Krieg, Abel Groenewolt

ITKE Institute of Building Structures and Structural Design
Prof. J. Knippers, Simon Bechert

LBP Chair in Building Physics
Matthias Fischer, Rafael Horn

The subsequent research project that resulted in the BUGA Wood Pavilion was executed by a larger project team and included industry collaboration. The author participated in this project only during the first half up until implementation and execution of the manufacturing technology started.

ICD – Institute for Computational Design, University of Stuttgart
Prof. Achim Menges, Martin Alvarez, Monika Göbel, Abel Groenewolt, Oliver David Krieg, Ondrej Kyjanek, Hans Jakob Wagner

ITKE – Institute of Building Structures and Structural Design, University of Stuttgart
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Prof. Volker Schwieger, Laura Balange, Urs Basalla

Other contributors to the aspects covered in this dissertation are listed below.

7.6.9.1 Material system

The material system described in this case study was mainly developed by the author, with the help of his colleagues at the ICD and ITKE. The student assistants Bahar Al Bahar, Kyriaki Goti, Matias Maierhofer and Valentina Soana assisted in the production of prototypes. Details of the connection properties such as finger joint depth, width and the size and spacing of the bolt connections were developed by Lotte Aldinger, Simon Bechert and Daniel Sonntag.

7.6.9.2 Manufacturing system

The initial manufacturing process was developed as part of the research project Wood R3 by the author and his colleague Abel Groenewolt. Bahar Al Bahar took part in this process as a student assistant. The concept was not realized but instead continued development as the project transitioned into the BUGA Wood Pavilion project. Here, a robot cell solution was developed with two robots around one turntable on a container platform, under the supervision of the author and with ICD research associates Martin Alvarez, Abel Groenewolt, Ondrej Kyanek and Hans Jakob Wagner. This robot cell was ultimately assembled and commissioned by Martin Alvarez, Ondrej Kyianek and Hans Jakob Wanger in collaboration with BEC GmbH, a machine integration company that handled the equipment order and integration.

7.6.9.3 Computational design system

The development of the agent-based modeling tool was spearheaded by ICD researchers Long Nguyen in collaboration with Tobias Schwinn and Abel Groenewolt. The author assisted by developing agent behaviors that guided the simulation in order to fine-tune the user-interactivity. The data transfer to the finite element analysis software Sofistik was developed by Abel Groenewolt in collaboration with Simon Bechert during the Wood R3 research project.

7.6.9.4 Manufacturing and assembly process

The initial prototypes during the project Wood R3 were built at the ICD laboratory spaces by the author and Abel Groenewolt. As the project "BUGA Wood Pavilion" moved into manufacturing preparation, the manufacturing process took place at the industry partner Muellerblaustein Bauwerke GmbH and the robotic manufacturing was supervised by Martin Alvarez, Monika Göbel, Ondrej Kyjanek and Hans Jakob Wagner. The assembly on site was the responsibility of the industry partner and supervised by the research team.

7.6 Case Study 6: Wood R3 – Resource Effective, Regional, Robotically Fabricated, 2018

8

Conclusion and Discussion

The aim of this thesis was to propose, evaluate, and establish a method for providing systemized feedback between computational design and manufacturing innovation in timber construction for the development of functional and morphologically gradated building systems. For this purpose, three hypotheses were evaluated at the intersection of the research fields of biomimetics, robotic manufacturing systems in timber construction, and computational design systems:

1. It was shown that architectural design innovation such as gradient building systems can be enabled by a parallel and integrative development process in robotic manufacturing as well as computational design, and that this development process collapses interdisciplinary boundaries of form, material, and materialization.
2. It was shown that new computational design strategies are necessary to control, process, and visualize the high level of information density that arises from the design workflow with gradient building systems, which also integrate the information flow from design to manufacturing.
3. It was shown that methods from biology such as the morphospace analysis can be translated into the fields of computational design and robotic manufacturing to systematically relate the two parameter spaces of design possibilities and manufacturing setup.

This thesis contributed to the field of biomimetics in architecture in two ways. First, it established bottom-up and top-down methods to find or filter biomimetic principles that can be translated into functional, morphological, or process principles for the development of gradient building systems. Second, it translated the biological method of morphospaces into an analysis tool to relate the solution space, or design space, of gradient building systems to their specific manufacturing setup.

Further, the thesis contributed to the fields of manufacturing systems and computational design systems by establishing six innovative manufacturing processes for gradient building systems in timber construction, as well as accompanying computational design systems that allow for the design exploration and the effective generation of necessary building information data for the manufacturing and construction of building demonstrators.

In the following sections, the author will discuss the findings of the case studies, and then summarize and discuss the contributions to each hypothesis individually. The chapter will be followed by an outlook and future work.

8.1 Summary of the case studies

Each of the six case studies presented in this thesis describe an interdisciplinary research project in the field of architectural design research, which resulted in a demonstrator structure or building. All research projects can be characterized by their pursuit to question traditional architectural design processes through the lens of manufacturing innovation in timber construction. While all case studies show similarities in the structure and approach of their development process, they differ in their investigative motivation and scope. Since the research projects in the case studies were completed between 2011 and 2018, an overarching trend can be observed. From early to later projects, the investigative motivation evolved from individual inventions of fabrication steps towards innovation in more elaborate manufacturing systems. While earlier research projects focused on integral timber joints, later research projects added novel assembly processes and other fabrication steps, thereby increasing the complexity of the manufacturing technology and associated computational design systems. Further, early research projects resulted in small-scale demonstrators, while later projects included industry collaboration and resulted in large-scale applications.

8.1.1 Manufacturing development analysis

Several trends can be observed in Case Studies 1, 5, and 6 that relate to the sophistication and purpose of the manufacturing system (Figure 8.1). First, the average building element's size produced by the robotic manufacturing setup increased with every case study. This can be attributed to the human scale: The ICD/ITKE Research Pavilion 2011 was a prototypical process and as such required a high degree of human interaction and material handling. Smaller and lightweight building elements allowed the researchers to work more effectively. In later projects, building elements became larger and heavier, requiring equipment to carry them, but also covering a larger surface area when installed on site. It can also be attributed to the scale of the projects and the available robotic manufacturing setup: The first project was developed in the institute’s early robotic laboratory, and building elements were constrained in their size. The resulting demonstrator building was prototypical in nature and temporary, therefore requiring a lower structural performance. The later demonstrator buildings were intended to be permanent and needed to adhere to building codes. The manufacturing systems of the later projects had more steps, more automation equipment, and enabled the production of larger and more geometrically complex building components.

Every case study evaluates the relationship between manufacturing innovation and design innovation from a different starting point. However, as the development process unfolded in each case study, the manufacturing system development revolved around the question of how material can be manipulated into building elements with gradient morphologies. As such, the manufacturing system has to offer the flexibility for a motion or process step to have a variable range. For example, to accommodate the placement of building elements of different lengths, the bounds of the range of lengths have to be explored in relation to the robot’s EOAT and general setup.

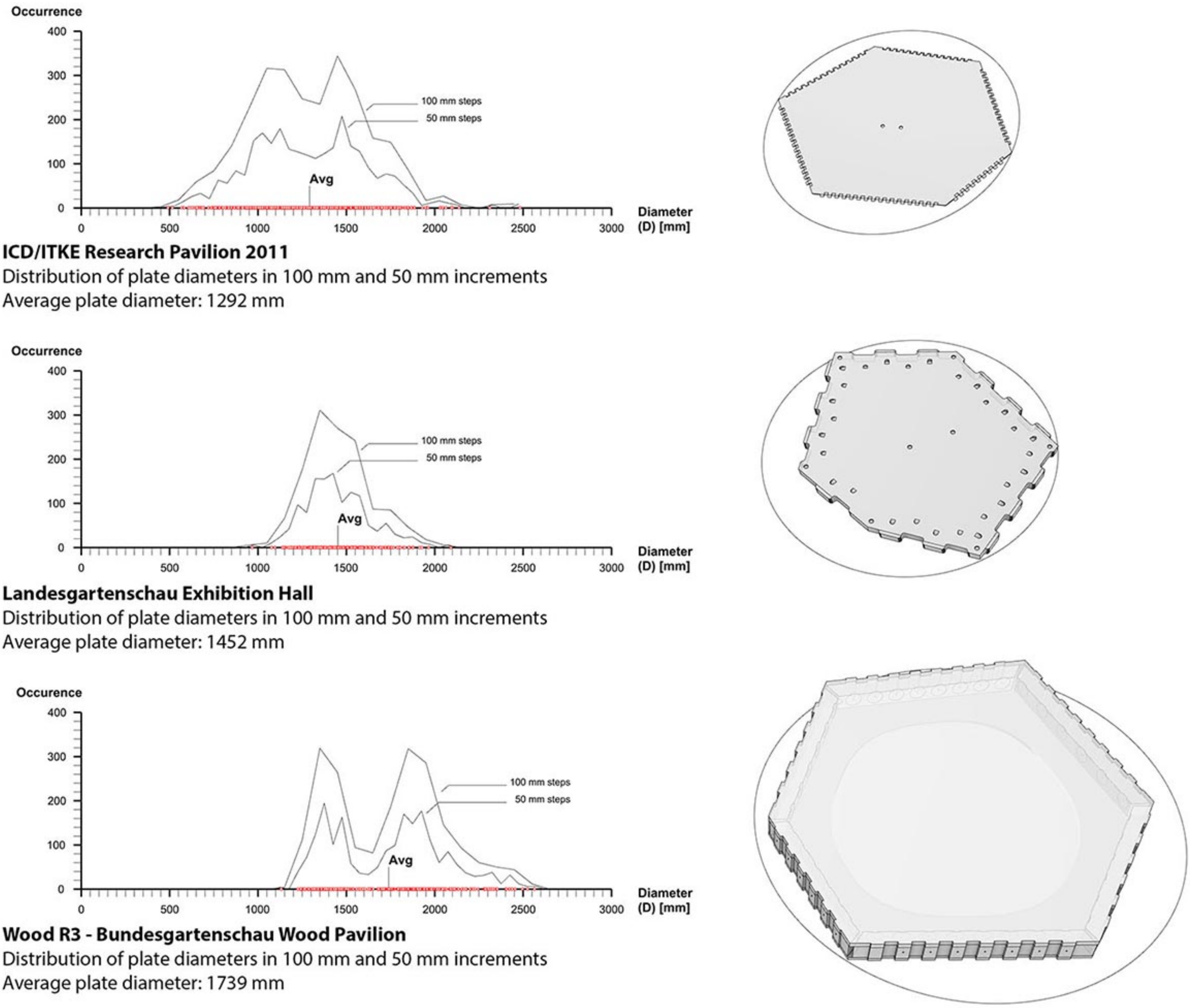

Figure 8.1: Comparison between the diameters of building elements of Case Studies 1, 5, and 6. On the left side, the distribution of plate diameters is mapped between 0mm and 3000mm. On the right side, a typical plate morphology is shown. Top: A building element from the ICD/ITKE Research Pavilion 2011; Middle: A Landesgartenschau Pavilion building element; Bottom: A BUGA Wood Pavilion building component.

In the research projects, parameters of the machine setup were occasionally changed to analyze their influence on the design space. However, they were not varied as much during the course of each project. Instead, the development process was more of a refinement, where those parameters that the researchers had an influence on were adjusted while the manufacturing system was still under development. The analysis of the variation of machine setup parameters on the design space was most often done after the demonstrator building was completed. Systematically changing the manufacturing parameters in an effort to understand their effect on the design space was a secondary method not fully evaluated in this thesis, but very promising for the development of optimization tools.

The above observation poses an interesting question that will be discussed more in the next section: When should the machinic morphospace be analyzed if both the development of the computational design system and the manufacturing system happen simultaneously? For the machinic morphospace to become a tool for the development process, it must be implemented as part of that process. However, in the case studies, the method was only implemented after the research project was completed and applied with a fixed manufacturing setup.

8.1.2 Collaboration analysis and disciplinary boundaries

When it comes to all case studies' overall development process, similarities and differences can be observed. In what can be seen as a general trend throughout the different research projects presented in the case studies, the level of complexity increased in terms of collaborating entities and disciplinary fields involved. While the early research projects were primarily worked on by small teams of architectural and structural researchers from the Institute for Computational Design and Construction and the Institute of Building Structures and Structural Design, later projects also involved biologists, geodesic engineers, and industry experts in manufacturing, robotics, and permitting.

Through the step-by-step increase of collaborators, the core of the development process as a spiral model remained the same, but the input from different disciplines increased. In fact, the number of collaborators increased not only with each research project, but over the course of the research projects as well. With an increasing level of sophistication of the building system and manufacturing system development process, more collaborators joined, and small sub-groups spun off into individual, short-term, spiral development processes.

8.1.3 Conclusion

The case studies were successful in establishing a qualitative and quantifiable relationship between manufacturing and design parameters. Analyzing these parameters and understanding the constraints of the manufacturing setup was crucial for this process. By understanding this relationship, the design space of the gradient building system under development could be explored, and a demonstrator building could be constructed. The case studies were also successful in analyzing the interdisciplinary relationship between academia and practice and established a role model for enabling industry innovation.

The gradient timber building systems developed in the research projects of the case studies can all be characterized by a large range of morphological features. In many research projects, a certain level of functional integration and gradation was also achieved. In the ICD/ITKE Research Pavilion 2011, building components could adjust in their morphological features to function as an internal opening within the shell structure or switch between a double-layered and single-layered structure. In the ICD/ITKE Research Pavilion 2015-16, building components could invert their main morphological features to function as columns supporting a horizontal shell structure. In the Wood R3 project, building components could change their morphological features to function as both a shell structure and a beam structure.

The case studies did not map parameters of the manufacturing setup or systemize them to evaluate their impact on the design space. If manufacturing parameters were changed in the research project, it was due to constraints or possible manufacturing adaptation that was already established during the research project. In the future, analyzing manufacturing parameters to evaluate their impact on the design space promises a feedback loop within the machinic morphospace method.

As timber-based manufacturing processes become more complex, it is vital to engage with and analyze other equipment as well as the human component. In Case Studies 5 and 6, it was already mentioned that CNC processing centers were used in the manufacturing process. In the future, more automation equipment might be developed that acts as a robotic actuator. In what can be called a multi-species manufacturing environment [40; 100; 405], many different forms of robotics could act together to produce more complex and sophisticated building elements that exhibit higher levels of morphological or functional variation. Further, human-led process steps can play an equally important role in a manufacturing process if they constrain certain morphological parameters of the resulting building element or component.

8.2 Innovation in manufacturing technology as a path towards gradient building systems

This thesis showed that innovation in robotic manufacturing processes in conjunction with computational design processes enables architectural design innovation such as gradient building systems, which exhibit high levels of morphological and functional variation akin to biological systems. It further showed that the utilization of an integrated development process can collapse interdisciplinary boundaries between form, material, and materialization, which have traditionally been separated in the AEC industry.

8.2.1 Biomimetic principles for gradient building systems

In this thesis, the gradual variation of building elements or components has been identified as a biomimetic principle found in natural structures. In nature, complex microscopic arrangements of matter that make up a material, as well as macroscopic shapes in natural structures, require more geometric information within a certain volume of material when compared to human-made structures [379]. For example, the microscopic arrangement of matter that results in cavities such as in foams or bone structures, or shapes of cells that define the structural properties of wood, requires a much higher amount of geometric information per volume than homogeneous materials such as steel. Further, the gradual variation of such structures, such as the differentiation of bone density within a single bone, does not allow for a simple or homogenous representation of the material within a given volume. Therefore, more complex shapes require more information density. However, this argument only considers geometric information that is meaningful, resulting in measurable differences in the material that cannot be neglected, as is usually the case in the abstraction process required for the structural engineering of steel, brick, or engineered timber. If the molecular and atomic information of a material were always considered, every material would have the same or similar geometric information density. This argument therefore focuses on geometric information that results in measurable or meaningful function on a human scale.

Further, the arrangement of matter can result in complex material behaviors such as wood's expansion in relation to relative humidity or its elastic bending characteristics [234]. This behavior can be described as material intelligence in that the number of rules that describe the material behavior is high. As can be observed in wood, higher information density results in higher density of material intelligence.

8.2.2 Natural and human-made structures

In nature, information density and geometric complexity result in a high degree of functionality with as little material usage as possible. Evolution naturally progresses towards the highest amount of information density with the lowest amount of energy and material. When compared to nature, human-made structures solve engineering problems through an increase in material or energy rather than information or geometry [379].

In our industrialized world, higher information density is difficult to handle, design with, control, and manufacture. In addition, the high specificity of a building element or any volume of matter required to approach that of natural structures is not compatible with the standardization of data of the industrial age. During the Industrial Revolution and after, human-made structures not only neglected information density within building materials but also within building elements and their aggregation into building groups and structures [320]. Standardization as such can be considered a loss of information density and material intelligence. If every building element is the same size and shape, there is no need to transmit this information individually. For example, the material makeup of a building element such as a brick or concrete block does not need to be transmitted individually through a volume within the material but as a general, singular variable that applies to every building element made from that material. The limitations of our early information systems in the 20th century were built around that method and did not allow for the transmission and handling of more information density.

Still, new variations in building materials due to differentiation in their ingredients or manufacturing processes have led to an increased amount of information that a building element can possess. Variations of concrete, steel, or bricks are regularly used within a building structure. However, the limit of information density is in direct relation to the information models used in the design, manufacturing, and construction process. In the spirit of industrialization, standards are used to limit the number of variations, and only a few variations are typically used within a building system. The amount of information necessary within a building if every building element had different dimensions or variations of material makeup would be dramatically higher compared to a singular material makeup and only a handful of variations. This simplified approach to embedded information and information transfer between scales is in stark contrast to the embedded information in natural materials and structures. As described in Chapter 3, one of the most fundamental principles of natural systems is the gradual adaptation of material and form.

Industrialized manufacturing, or standardization, is in direct relation to this limited information density. It is not clear whether industrialized manufacturing technologies with highly limited variability during the early stages of industrialization ultimately led to standardization, or the limited information processing capabilities of humans and systems that were used at that time led to standardized manufacturing. However, the result of industrialization was manufacturing technology that mirrored the limited information density in standardized building systems. Hence, even recent innovation in manufacturing usually reflects standardization of the materials it is processing and the building elements it is producing.

Wood differs from human-made building materials because it already exhibits a high density of information embedded in its cellular makeup. In the pre-industrial era, the material complexity was not questioned but also not fully understood. By relying on human strength and dexterity, building structures were highly individualized but also heavily reliant on the natural material properties. Wood's natural complexity exhibited certain material characteristics that were accepted and used for their benefits. During the First and Second Industrial Revolutions, the machines that were developed to process large quantities of materials did not have the right interfaces to access the material complexity, and the design tools used were not equipped to handle the amount of information density. Because the material's embedded intelligence was too complex to understand and handle, it was mostly neglected or suppressed [67].

Today, the re-appreciation of the material is enabled by digital tools that allow us to understand and work with wood's complexity, we now have access to a very deep connection: the information we are adding to the material through human-made manufacturing processes can add to the natural information already embedded in the material. But instead of continuously increasing the number of standards and variations, a paradigm change is required to truly approach natural systems and enable a much higher material efficiency through geometric and functional adaptation without steps or standards.

8.2.3 A new manufacturing and data processing paradigm

The author does not argue that every manufacturing process and every technology must transition to gradients instead of fixed or stepped values. In fact, even the research projects presented in this thesis used many standardized materials and standardized processes. However, the employment of gradients for building elements or materials in the research projects demonstrate that even when some areas of a manufacturing paradigm change from standardized values to gradients, the design space of material systems and building systems, and their adaptability and efficiency, changes and expands accordingly. They also demonstrate new design methodologies because information processing for such gradient building systems, even if they employ standardized materials with only varying shapes, needs to be reconceptualized.

The thesis provides a new method for integrated design and manufacturing information processing. Only if a variable manufacturing technology is developed to a level of sophistication where its constraints are known as multi-dimensional ranges, a gradient building system can be developed and employed in a computational design process. The thesis also provides evidence that a higher amount of information within materials and building elements requires different information models and methods that control and work with such a high degree of information density. Gradient building systems, and their required manufacturing technology, can only be developed in a computational design environment due to the amount of information and its variation that needs to be controlled and transferred.

In order to reach new levels of information density within materials and assemblies, innovation in manufacturing as a means to approximate natural processes is required. The case studies in this thesis provide examples of different strategies of how this approximation can be achieved by developing new manufacturing methods for gradient building systems with information-dense configurations. To achieve this paradigm shift and approximate this level of complexity and intelligence, two innovations become necessary: (1) more adaptive manufacturing processes embedded within manufacturing systems that are rule-based and computationally controlled, and (2) computational design systems that allow for the manipulation of geometry in virtual models that are within the design space that the developed machine setup allows. The case studies show that with innovation in manufacturing technology, innovation in design is possible. Through innovation, these two disciplines become re-connected, and their traditional inter-disciplinary boundaries collapse. Here, the case studies further show that an engagement with manufacturing innovation for the purpose of architectural design research will automatically lead to the collapse of their inter-disciplinary boundaries.

Ultimately, working with gradient building systems has a profound impact on design as architecture is no longer defined by discrete and repetitive building elements assigned for a certain function, but rather by building systems that offer gradients in shape and functionality. The more parameters a building system has, the more it can adapt to internal and external conditions. However, describing those parameters and their ranges, or their boundaries, is not possible without relating the building element to its manufacturing process. In the short history of parametric design, this relationship has rarely been described as clearly as in computational wood design in the last decade.

Traditional, form-driven, and top-down design processes do not question the constraints or possibilities of a building system. Because of the lack of feedback from manufacturing parameters, the design parameters' bounds are not understood or controlled, leading to design systems that are disconnected from their manufacturing process or to design iterations that are not producible. A bottom-up development process of a convergent design and manufacturing system implements and reflects on manufacturing constraints and possibilities, resulting in highly informed design systems. Part of this development process also involves the exploration of design possibilities through testing and implementation. Computational design tools are necessary to explore the design space of a gradient building system during development and to reflect on how changes in the manufacturing parameters can lead to changes in design parameters, and vice versa. In this sense, the method of machinic morphospaces enables an informed development process, and ultimately, an informed design exploration of gradient building systems.

On a conceptual level, developing manufacturing systems through the definition of their parameters allows the designer to relate two parameter spaces: that of the manufacturing setup and the building system’s design space. The thesis therefore also confirms that by engaging with novel manufacturing technologies for gradient building systems, boundaries between disciplines collapse, and manufacturing-oriented innovation that enables innovation in architectural design becomes possible. In that sense, relating manufacturing technology to design technology is a means to induce systemic innovation in our industry.

8.3 Information density, control, and processing

The case studies showed that gradient building systems with a high level of morphological and functional differentiation result in a much higher level of information density within the digital model and its data flow. To have enough control over the design and subsequent manufacturing process, new computational design strategies need to be developed for generating, processing, visualizing, and storing information. As such, the following observations can be made.

8.3.1 Information density in design and manufacturing

Rationalizing design has always been an effort of the architectural process – segmenting designs into buildable elements, relating shapes to building materials, or relating building elements to their production and assembly. However, while the rationalization of architectural design can be seen as a process of *abstracting* shape and function into buildable components, manufacturing can be seen as the opposite: *implementing* information into a material, or as Sanford Kwinter wrote: *"the refinement of matter is always the refinement of the intelligence embedded within it."* [205]

The physical manifestation of a building design can be seen as the meeting point between an abstraction process and an implementation process. While abstracting is about reducing, or systemizing, the amount of information to be able to process it, the latter – manufacturing – is a method for concretizing material into building elements, and therefore adding information to matter. Depending on the sophistication of data processing on the one hand and manufacturing technology on the other, the intelligence, or information density, of the built result will vary. One could argue that throughout the history of human civilization, the sophistication of data processing and manufacturing varied independently from each other (Figure 8.2). During the pre-industrial era, information processing was limited by the human capacity to plan and communicate, but material processing was intricate, sophisticated, and customized due to the dexterity of manual work. This level of customization was lost during the First and Second Industrial Revolutions. It is argued that with the onset of the Third Industrial Revolution, material processing became more sophisticated than data generation and processing.

As discussed in Chapter 2 and Chapter 5, only with the introduction of computational design methods could the level of information processing expand enough to accommodate hyper-customized variation in material characteristics as well as building element morphologies enabled by industrial robots and other digital manufacturing technologies.

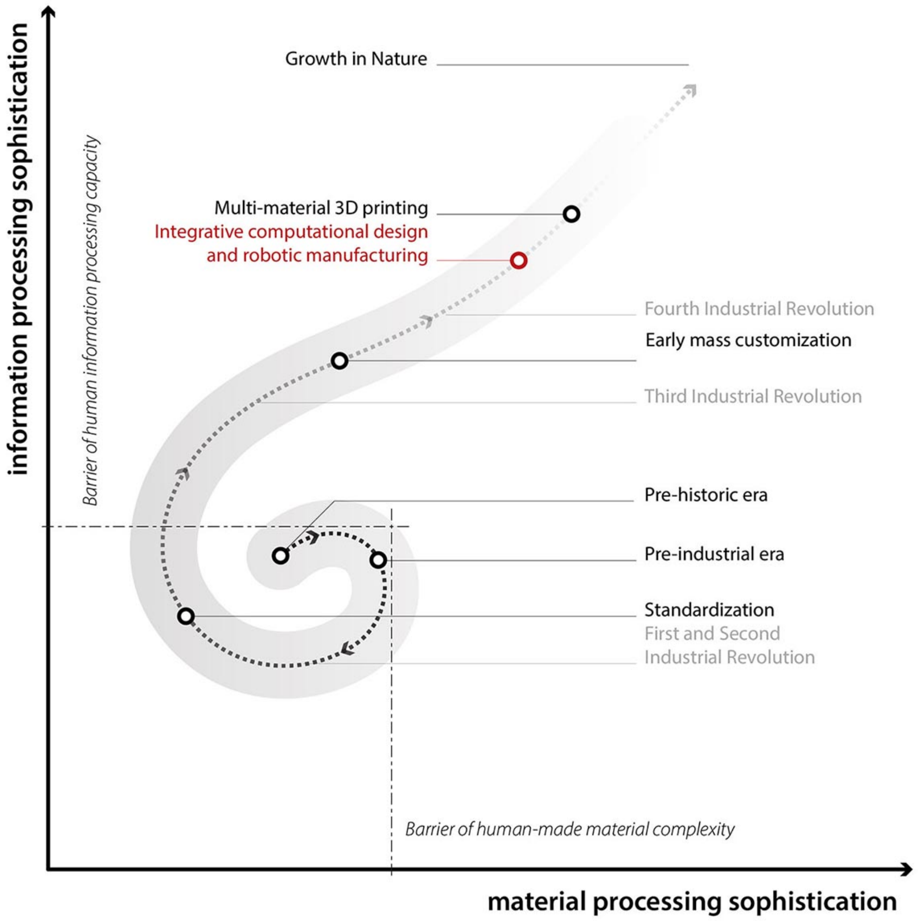

Figure 8.2: A qualitative diagram of information processing sophistication (x-axis) and material processing sophistication (y-axis) relating to information density in the abstraction process of design and the implementation process of manufacturing throughout human history.

The refinement of matter through manufacturing is not a new concept: Natural growth processes change, reconfigure, and refine material and have been doing so for billions of years. On this level, manufacturing and biological growth share a fundamental concept. During growth, the material, its microscopic structure, and the resulting macroscopic form are created in the same process [165]. However, between industrialized manufacturing and biological growth, the degree of refinement of the information embedded within matter, and the density of information added to it, differ widely [379]. It is at this fundamental level that digitally controlled and adaptive manufacturing processes can be seen as a method to approach the information density and level of refinement of the intelligence embedded within the material that can be found in natural structures.

In that sense, it can be argued that biomimetic principles can be transferred to building systems for approximating either the generation of information, the representation of information, or the handling of information. In other words, the manufacturing of a building element, the physical result of a building element, or the design process. In this thesis, the notion of gradient building systems is discussed as the result of a convergent innovation in design and manufacturing to approach the level of information density, and therefore the level of performance that is found in natural structures.

It is essential to mention that transferring biological principles derived from the growth and configuration of material is only one of many biomimetic methods for learning from natural structures and processes for the optimization of human-made structures and processes. Apart from morphogenesis and homeostasis, natural organisms have found many ways to optimize towards varying and changing criteria. Moreover, growth cannot be entirely related to manufacturing, as an organism needs to function during morphogenesis, whereas a building can be fully assembled before becoming functional. In this sense, this thesis only compares and aligns a subset of biomimetic principles found in nature that, on a fundamental level, refine matter into material, and then into structures.

Lastly, aside from questioning the validity of the biomimetic principles, the focus of this thesis has been to relate innovation in design to innovation in manufacturing, and only to find relationships to natural processes in both. Independent from those relationships, it was shown that gradient building systems, and higher information density in building systems in general, can result in more adaptable and material-efficient structures. It can therefore be argued that if more information needs to be included in the design process, it becomes necessary to break down interdisciplinary boundaries such as in the case studies in this thesis.

8.3.2 Representation of information in computational design

Intuitive and user-friendly digital design processes rely on a high level of visual sophistication to provide the designer with the right amount of feedback. However, as exemplified in many of the case studies, a complete representation of the individual building elements is neither necessary nor feasible given the limited computational performance of personal computers and the high amount of geometry that would need to be processed. Although the latter is a real constraint in visualizing the precise geometry of building elements in Computer Aided Architectural Design (CAAD) in general [3; 223], the former is a unique aspect of a connected computational design and manufacturing systems.

In connected computational design and manufacturing systems, geometry does not always have to be represented in full, as the information required by the manufacturing process in each research project is often different from the visual representation of a building element. As explained in the case studies, information related to the manufacturing process often consisted of polylines or two-dimensional NURBS surfaces, which were then translated into manufacturing instructions in the last steps of the computational data flow. Every research project demonstrated that material thickness and connection details were not required to be visualized for this process. Instead, the values for material thickness were stored as numbers, and their implications for the manufacturing process could be mathematically derived.

As a result, in many research projects, the computational design system only processed and visualized a simplified representation of the building elements during the design phase, reducing the required level of detail. For example, in the research project in Case Study 5, the polygonal and finger-jointed timber plates were visualized only with a polygonal outline, neglecting geometric information for the material thickness or the connection details. In fact, detailed geometric information was never required as it could be calculated mathematically or stored as meta-data or properties attached to the objects representing building elements. Therefore, visual feedback during the early design phases, and in particular, the exploration of the design space, needed to allow the designer to understand important aspects of building elements and groups, such as, for example, building element boundaries, size, location, and connection to neighbors.

The type and amount of geometric information visualized can change and evolve as the development process progresses. If the geometric information required for the manufacturing system is less than what is deemed an accessible level of detail for the user to understand design-relevant aspects, additional geometry can be added simply for visualization purposes. For example, in the research project in Case Study 1, the geometry of the finger-joint connections was represented by points along the edges of the BREP surfaces that represent the plates, indicating the size and distribution of finger joints.

8.3.3 Strategic division of design steps and transfer of information

One characteristic of the prototypical computational design tools in the research projects is that during their use, information is stored temporarily and discarded once the program is closed. Generating alternatives can happen online, but storing variations is not implicit unless programmed as such. Therefore, the computational design processes were developed to have specific save points or interfaces in which the geometry and information are stored permanently as 3D geometry and meta-data within the CAD program.

In most research projects, these steps occurred between the design generation and the generation of manufacturing data, as well as between the manufacturing data and the generation of manufacturing instructions. Each interface allowed for the geometry and information to be stored outside of the computational design process and to be loaded back into the process to proceed to the next phase.

The first interface enabled iterations through design variations and the storage of iterations within one CAD file. The low level of required geometrical detail in all research projects ensured that many iterations could be generated quickly without impacting the computer's performance. In some cases, the saved geometry could also be edited manually for minor adjustments or corrections as long as the changes were accepted by the read-interface of the next step.

The second interface was essential for manufacturing planning and quality assurance. In most research projects, manufacturing instructions were only generated for one building element at a time. Due to the complexity and novelty of the developed processes, users needed to evaluate and confirm the manufacturing simulation and information before generating the instruction files for the machine setup. Therefore, a second interface was implemented that allowed the user to call the geometry and information of all building elements, select one single element, and visualize its manufacturing process before generating the instruction files.

User interactivity and experience, as well as data management, are an essential aspect of computational design systems. Although the processes presented in the research projects were advanced digital workflows, their dependencies were not sufficient to always remain online, and therefore save points were integrated. This can also be seen as a question of interface and system sophistication. In many research projects, specific adjustments were not possible because of a lack of control over the design system, requiring manual intervention. It is expected that with further development, the design systems' sophistication will outgrow these workarounds.

8.4 Machinic morphospaces and design innovation

To quantify and visualize the relationship between the range of morphological parameters of building elements and the machine setup, the method of machinic morphospaces was explored and evaluated in the case studies. The method was used to visualize the design space of novel timber building systems using up to three morphological parameters, and to understand their relationship to manufacturing constraints. The establishment of the machinic morphospace has been shown to enforce the analysis of machine setup parameters that constrain the design space and, as such, enable the evaluation of how rigid those limits are.

While many manufacturing and design processes presented in the case studies draw from biological principles, the method of machinic morphospace is itself a biomimetic method specifically for relating the morphospace of building elements to the method with which they are made.

All biomimetic processes mentioned in the case studies share the principle of gradient morphologies. No building element is defined by fixed or standardized dimensions but rather by ranges of parameters. This, too, can be related to natural structures by comparing the physical manifestation of a building element to the result of a natural organism's morphogenesis. While standardized values for traditional building element shapes define the "phenotype" as in the organism's actual observed properties or the result of the process, the definition of variables and the manufacturing process that allows for a range of each variable is comparable to the definition of the “genotype” as in an organism’s full hereditary information.

In this sense, gradient building systems are a diametrically opposed method compared to the traditional development of building systems, which are usually based on pre-defined and standardized dimensions. But they are also a direct result of the development of machinic morphospaces, which itself is a method that results from relating manufacturing technology, design technology, and biological principles. As such, although the concept of machinic morphospaces emerged from the necessity of quantifying changes in the machine setup with changes in the design space, it could also be a method of design exploration and encourage reflection on the parameter space of building elements and the information density necessary to describe this space.

Identifying prominent morphological features of building elements and how their manufacturing process constrains them is a widely applicable method that can be used for any manufacturing system and any product. However, especially for the development of gradient building systems, it has the potential to become a guide and feedback tool to navigate between design intent and manufacturing potentials.

8.4.1 Morphological parameters

As mentioned in Chapter 6, morphological parameters can be challenging to define and quantify. First, the usefulness of a parameter is defined as its potential impact on a building system's design space, which is a qualitative description. Quantifying the usefulness in relation to a building system's overall design space deserves more attention and should be researched further. Second, parameter descriptions can often be broken down into sub-parameters, which adds hierarchical layers to their definition. For example, a valuable morphological feature might be an edge of a polygonal, finger jointed building element. However, the edge of that building element is made from several finger joints, with each of them having morphological features that could be described in individually or summarized in a single parameter.

Here, a question of scale arises as some features depend on the perspective of evaluation. If a single CNC cut is important to analyze in the manufacturing setup, then a single finger joint edge might be a valuable parameter. However, the length of a polygonal edge (which has multiple finger joints in it) might be more valuable because its impact on the design space is more tangible, and the manufacturing of a complete edge with multiple finger joints is constrained by the manufacturing in the same way a single finger joint or a single cut is constrained. Further research is necessary to develop more rigorous methods for defining morphological parameters and their impact on the building system's design space.

8.4.2 Implementation challenges

The machinic morphospace analyses were conducted in the case studies once the projects' development processes and the demonstrator buildings were completed. While the relationship between the design space and the manufacturing system was occasionally evaluated during the development process, fully analyzed diagrams that relate the parameter spaces were not generated at the time of the research projects. In addition, and as previously mentioned, manufacturing equipment was not changed in an experimental way during the development in order to determine how the bounds of morphological parameters could change. Instead, equipment choices and the mechanical build of the manufacturing setup was detailed step by step as the building system development progressed. While this turned out to be a cost- and time-effective strategy, it did not allow for feedback from the machinic morphospace method.

This poses the question as to how the machinic morphospace method could be implemented during the development process of gradient timber building systems. As an important feedback tool, it would allow navigating decisions on the manufacturing equipment and balance design intent and equipment complexity. However, for the method to become usable, a specific machine setup and morphological parameters must be decided upon while the development process is still ongoing. It could be considered a contradiction that the method would explore design boundaries while these boundaries are still under development. However, this contradiction could be solved by automatically iterating through variations of many possible assumptions. The method could also be used only at decision points in the development process to evaluate the resulting design space of two options.

8.4.3 Automation and feedback

In the case studies, the machinic morphospace analyses were performed by manually simulating the manufacturing process, exploring the bounds of the industrial robot's movement or collision events. Therefore, establishing the boundaries of the morphospace was a time-consuming effort and only applied to a particular machine setup.

However, in order to fully employ the advantages of the machinic morphospace method, not only will its implementation within a development process be necessary, but the automation of this implementation will also become necessary. A computational tool could be set up to iterate through building element variations by automatically simulating their manufacturing process and tracking any collision or out-of-reach events. With an automated process established, the boundaries of the theoretical machinic morphospace could be found automatically by iterating through a preset of parameter values. Variations in the building element's morphology could be tested one parameter at a time, and more than just three parameters could be tested as well. Changes in the machine setup could be evaluated quickly, and an automated feedback loop could be established from an early point in the development process. More research will be required to explore the potential of an automated machinic morphospace method.

8.4.4 Human and robot capacities

Every manufacturing system development process can be characterized by capacities that lie within a human worker, a building component, or a machine. Energy and information processing, as well as kinetic constraints can be both human and machine capacities, which can be characterized by clear constraints and therefore a quantifiable design space. However, the more complex the machine, the more parameters can be used to describe the machine setup. If only a certain number of parameters are considered, such as in this thesis, the remaining parameters could still be adjusted in boundary situations and therefore create an unknown zone of the design space boundary.

When considering a human worker, the number and boundaries of parameters that describe their capabilities are unknown, further blurring the boundaries of the design space. It is therefore important for every machinic morphospace analysis to consider in which capacity a human worker operates. By giving the robot the capacity to place elements, the machinic morphospace becomes focused on placing and assembly steps, adding potential constraints in each step that the robot is involved. In the research project in Case Studies 3 and 6, the manufacturing process involved placing and assembly processes. In the research project in Case Study 3, a human-robot collaboration process was developed. Each of these decisions have consequences on the machine setup and its capabilities. It is important to consider if adding a parameter to the machinic morphospace analysis can clearly define its boundaries or blur them.

8.4.5 Design innovation and design intent

The case studies have shown that the theoretical and empirical machinic morphospace can have considerable differences. In many case studies, most building elements accumulate around a particular region close to one of the theoretical machinic morphospace boundaries, while some regions are left empty. This leads to the question of design intent, and, more generally, as to how the machinic morphospace method can be used to evaluate the producible region of possible form for functional or high-performing sub-regions (Figure 8.3).

Early design explorations during a development process can help determine regions of design intent even before the machinic morphospace boundaries are defined. This method would allow for a feedback loop within the method: design intent boundaries and producible boundaries can be compared. For example, in Case Study 1, this method would have helped during the development of the research project to determine that smaller plate diameters were desired but not producible with a given machine setup. By automating the empirical machinic morphospace method, every design iteration could be immediately mapped into the region of possible form. With every following design iteration, it would become clearer where most building elements lie and how blurry or smooth the boundaries of the design intent are. Establishing a dialogue between design intent and boundaries of the producible within the machinic morphospace diagram could help to inform decisions and track the development process.

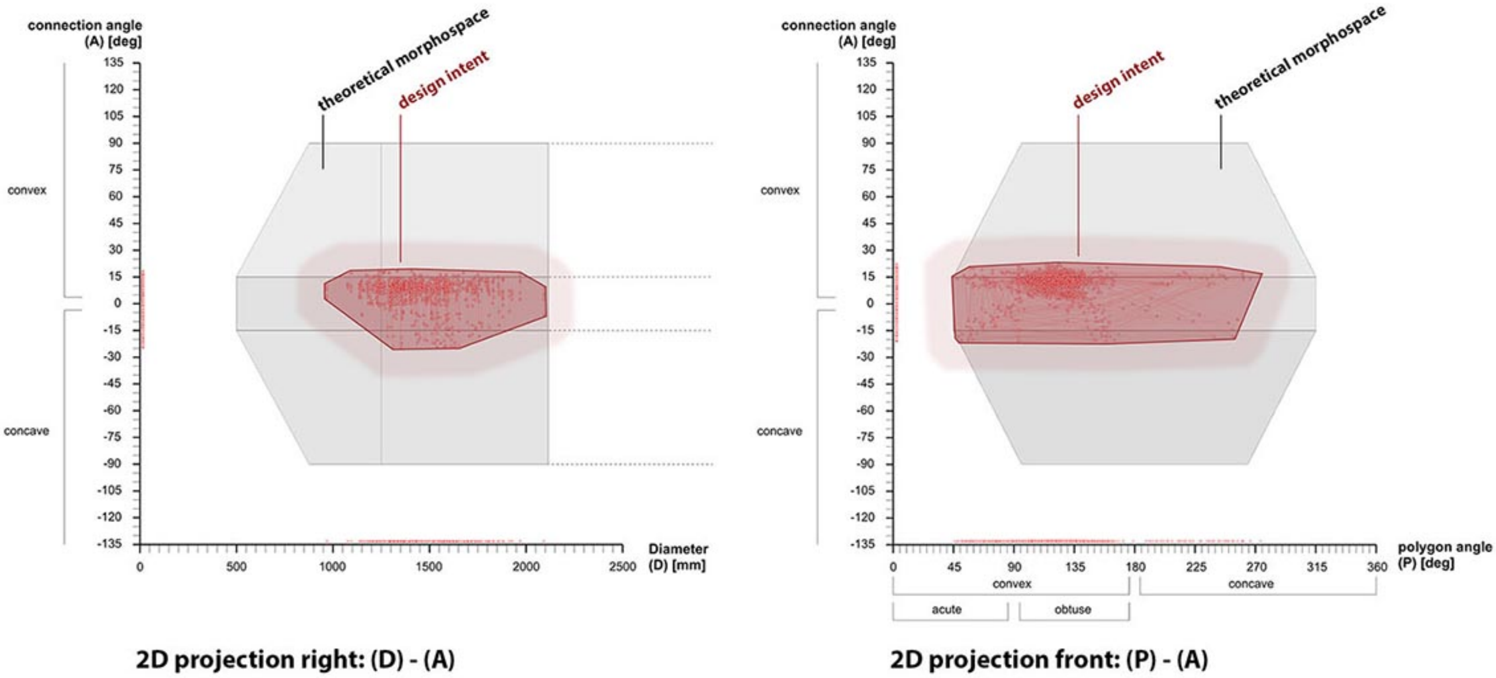

Figure 8.3: On the example of Case Study 5 (Landesgartenschau Exhibition Hall), the design intent can be visualized. Here, the empirical morphospace can give an indication of the design intent of the demonstrator building. Two observations can be made: First, the design intent is much smaller than the theoretical morphospace. Second, the design intent collides with the boundaries of the producible in terms of diameter as well as polygon angle.

Projecting this strategy further, design iterations could be analyzed based on other performance criteria such as a structural or energy analysis. By adding a performance analysis to every design iteration, not only could the design intent be tracked within the region of possible form, but also sub-regions of high performance could be found [237]. This would equal an explorative method to determine a fitness landscape, although it is not clear at this point if tendencies towards regions of high performance would be easy to find. Performance measurements can be highly dependent on the overall design of a structure. For example, the Landesgartenschau Exhibition Hall was designed as a double-curved shell, which gained most of its structural performance through the global curvature of the shell [218; 219]. As a result of this design strategy, the connection angles between each plate were shallow. However, if the global shell surface would have approached the shape of a flat roof, the overall structural performance would have been very different. Therefore, it could be concluded that the connection angle is not a morphological parameter particularly suitable to determine the structural performance. Similarly, many other morphological parameters could be determined that directly impact the structural performance but only minorly impact the design space.

Nevertheless, the case studies have shown that a design intent can be tracked within the diagrams of machinic morphospaces and potentially used to guide decisions on the machine setup to adjust the producible region of possible form towards the intended or preferred design space. Further implementing performance analyses could help inform this feedback process even more in the future.

8.4 Machinic morphospaces and design innovation

9

Outlook and Trends

The case studies have shown that with the increasing complexity of building systems and manufacturing systems, an increasing amount of information needs to be processed. To achieve such information processing without overwhelming the user or designer, higher levels of automation are required. For example, in the research projects in Case Studies 5 and 6, a design tool was developed that automatically distributed plate elements over a pre-defined design surface. Instead of manipulating every single plate, the design process only required either changing the input parameters of this simulation or occasional manual intervention.

The author argues that design tool interfaces that control gradient building systems will require a higher level of control in the future. This is because increasing complexity will be implemented by automating information processing. While the human capacity to process information cannot increase, the background information processing can become faster and smarter. The challenge will lie in determining which information should be automatically processed and which information needs to be visualized and manually controlled. If more information processing is automated, control systems will become more powerful and impactful. As a result, the development of these algorithms is equally important and impactful. Particularly in relation to manufacturing constraints and possibilities, information processing, visualization, and feedback will be essential.

Aside from this general outlook, two trends at the intersection of research and industrial application can be identified.

9.1 Integrative architectural design research will break the mirroring trap

The mirroring hypothesis states that an organization's formal structure tends to mirror the design of a product or underlying system [64; 143]. While mirroring can be effective in developing a product, companies tend to reinforce their organizational structures and communication channels around the product or process, and therefore risk missing out on, or resisting, innovation on a systemic level. This is also true for the inter-organizational network of the AEC industry in general. When communication channels rely on two or more companies, changing them becomes a question of cooperation. In the AEC industry, either the inter-organizational system needs to change, or companies need to leave the industry [143].

By engaging with manufacturing technology in the context of architectural design research, reciprocities between the material, the manufacturing process, and design exploration within a bottom-up process become apparent. Unsurprisingly, the change in focus and engagement with different aspects of a traditionally divided and hierarchical process necessitates the reconceptualization of the typical communication channels. While manufacturing would have previously been thought of as a subsequent process that would not have much influence on the design, the process presented in the case studies proposes manufacturing technology, and sometimes biomimetics, as the starting point of an experimental design research project. Boundaries between manufacturing, assembly, material science, design, and tectonics dissolve by enforcing a shortcut between manufacturing and design, which is usually considered the starting point and the end of a traditional design and delivery process in the industry. Therefore, vertical fragmentation is avoided through vertical integration.

Innovation in architectural design has always happened in relation to the available tools, materials, and manufacturing processes. To explore new design potentials, a feedback loop with new tools has to be established. However, the industry’s vertical fragmentation has impeded this feedback loop. The case studies are a proof of concept for how engaging with manufacturing technology from an architectural design research viewpoint leads to a collapse in the boundaries between manufacturing and design. Understanding the boundaries of the design space can ultimately lead to its expansion.

In the future, this approach could also be applied to the AEC industry. By collapsing disciplinary boundaries, the development process becomes a knowledge platform that collects information from each discipline involved. The last two case studies in this thesis have shown the first step towards industrial application. Instead of developing manufacturing technology and design tools in a laboratory environment, the integration of industry experts, or even moving the manufacturing environment into a factory space by collaborating with a manufacturer, integrates industry processes with manufacturing and design innovation.

Further, sharing knowledge and providing feedback throughout the development process is also a key strategy for enabling functional integration and morphological adaptation. By treating the development process as a knowledge platform, discipline-dependent constraints become tangible and can be adapted.

William Mitchell identified that the computational design tool is developed before the design of the artifact itself, and therefore the tool is constrained by the set of parameters and variables that were conceived a priori – the range of knowledge that we are able to embed in the design process [246]. As such, the fundamental concept of computational design questions the hierarchical steps of the industry. Creating knowledge platforms short-circuits inter-disciplinary boundaries. This can be considered radical innovation according to Slaughter's definition of the term [341]. In this case, previous linkages and interactions between organizations become irrelevant once they are collapsed within a team or single organization. However, we have yet to see this paradigm fully realized in the industry.

9.2 A trend towards parametric platforms

The transfer of integrative architectural design methods and vertical integration strategies towards industry application and for the design and delivery of buildings poses additional challenges. Compared to the case studies in this thesis, buildings are not only made from structural systems and their weather protection but incorporate many other systems such as mechanical, electrical, and plumbing. Through the integration of disciplines involved in designing and delivering buildings, a platform-based approach is the natural consequence of an integrative development process such as the one presented in this thesis [17]. A platform-based approach allows for the collection of knowledge from different disciplines as the platform is in development, which enables systematic reuse.

However, with an increase in the number of disciplines that need to be vertically integrated, the complexity, scope, and capital cost of the resulting manufacturing systems also increase. Therefore, the question arises as to how broadly such platform-based manufacturing systems, and in extension, building system and design system, could be applied. When compared to other industries, architecture, engineering, and construction require context-specific adaptation and a high degree of customization. It is questionable as to how capital-intensive, platform-based manufacturing setups could offer a viable business model within a competitive construction industry [386]. It is, therefore, crucial that such building platforms incorporate a high level of adaptability.

The case studies in this thesis have shown the potential for so-called parametric platforms. While parametric platforms follow the same approach of incorporating inter-disciplinary knowledge during their development, they are defined parametrically, and as such, they exhibit a high level of morphological adaptation. When the concept of a gradient building system, as presented in this thesis, extends beyond the structural and envelope systems, it can be described as a parametric or gradient building platform.

A research group at the Department of Structural Engineering at the Norwegian University of Science and Technology developed a digital toolkit that combines the parametric detailing, architectural representation, manufacturing data generation, and structural analysis for the design, engineering, and fabrication of timber structures [250]. This project aims to establish a parametric process from design to manufacturing that can be applied to a variety of different projects, thereby providing a software platform that allows mass customization. In a similar manner, researchers at the Estonian Academy of Arts developed a parametric platform for the design and manufacturing of a high voltage pylon, which incorporates structural engineering, form-finding, and optimization, as well as manufacturing data generation [276]. In multiple projects, UCL Bartlett School of Architecture lecturer and architect Gilles Retsin developed timber platforms based on modular construction of a discrete set of components [290; 291].

Daniel Hall identified "integrated hierarchical firms" and "core-periphery platform structures" as types of companies that "benefit from total product architecture and the ability to push the limits of technical change" [143]. Although only a few startups in the industry exist that offer a platform-based approach, they can be considered an extension of this research. Companies such as Project Frog, BoKlok, and Intelligent City are developing digital or physical platforms, or a combination thereof, to deliver product-based architecture [199].

In conclusion, a trend can be observed from academic experimentation towards industrial commercialization. Parametric platforms that are based on gradient building systems and incorporate innovative manufacturing concepts offer the opportunity to combine the scalability of industrial production with the adaptability of parametric design. When developing parametric platforms, the importance of reciprocal feedback between manufacturing and design will become evident. Should the industrial implementation of the methods presented in this thesis be successful, a global shift towards an integrative architectural design and delivery paradigm could be possible.

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Curriculum Vitae

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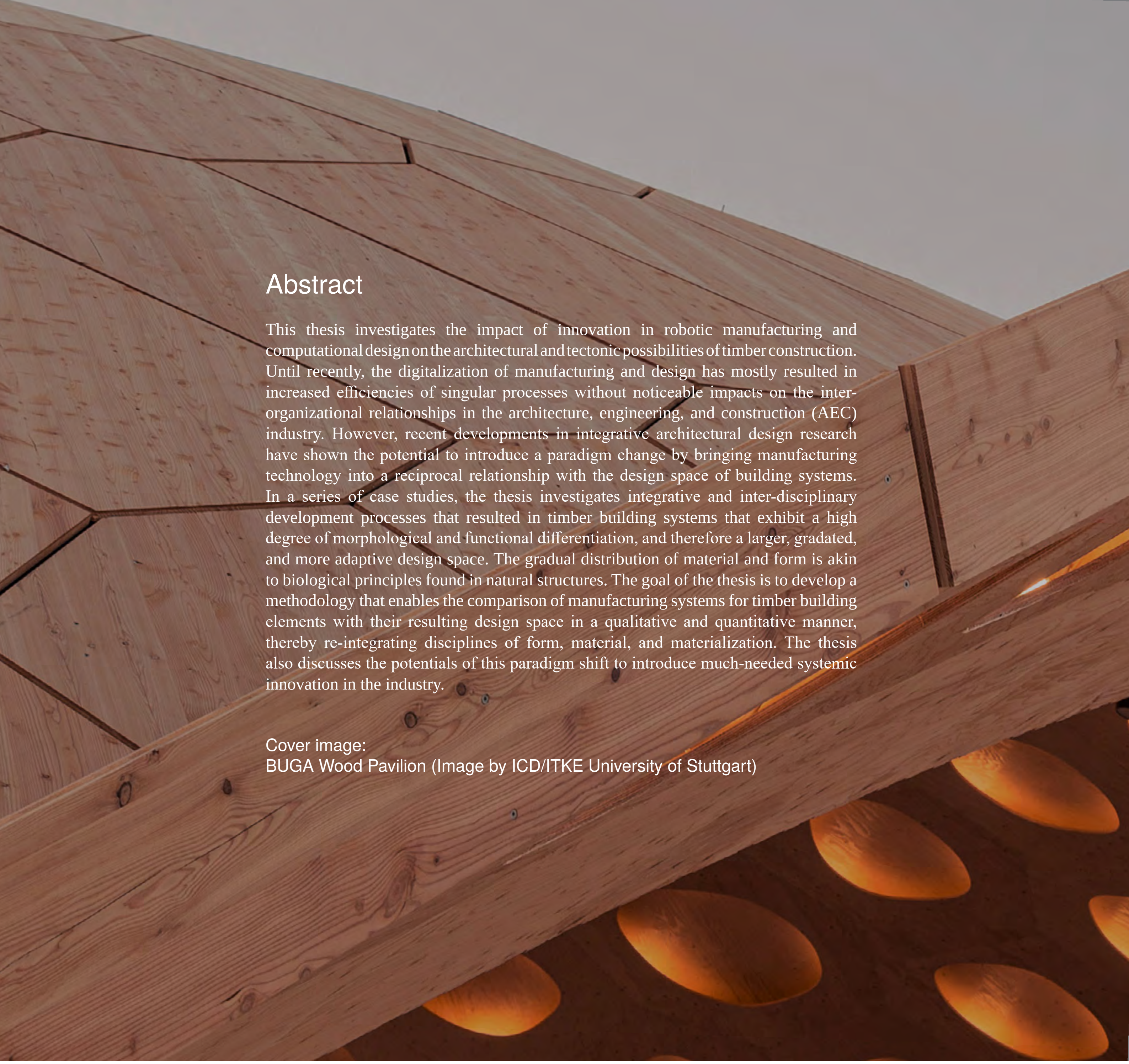

Abstract

This thesis investigates the impact of innovation in robotic manufacturing and computational design on the architectural and tectonic possibilities of timber construction. Until recently, the digitalization of manufacturing and design has mostly resulted in increased efficiencies of singular processes without noticeable impacts on the inter-organizational relationships in the architecture, engineering, and construction (AEC) industry. However, recent developments in integrative architectural design research have shown the potential to introduce a paradigm change by bringing manufacturing technology into a reciprocal relationship with the design space of building systems. In a series of case studies, the thesis investigates integrative and inter-disciplinary development processes that resulted in timber building systems that exhibit a high degree of morphological and functional differentiation, and therefore a larger, gradated, and more adaptive design space. The gradual distribution of material and form is akin to biological principles found in natural structures. The goal of the thesis is to develop a methodology that enables the comparison of manufacturing systems for timber building elements with their resulting design space in a qualitative and quantitative manner, thereby re-integrating disciplines of form, material, and materialization. The thesis also discusses the potentials of this paradigm shift to introduce much-needed systemic innovation in the industry.

Cover image:
BUGA Wood Pavilion (Image by ICD/ITKE University of Stuttgart)

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