Integrated material practice in free-form timber structures

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Publication date:
2020

Document Version:
Publisher's PDF, also known as Version of record

The Royal Danish Academy of Fine Arts,
Schools of Architecture, Design and Conservation

Integrated material practice in free-form timber structures

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A thesis presented for the degree of
Doctor of Philosophy

Supervised by:
Professor Mette Ramsgaard Thomsen
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2021/01/14

Title: Integrated material practice in free-form timber structures
PhD Thesis

Printing and binding:	LaserTryk.dk A/S
Edition:	2
Published by:	The Royal Danish Academy of Fine Arts Schools of Architecture, Design and Conservation
Academic partner:	CITA (Centre for IT and Architecture), KADK
Industrial partners:	Blumer Lehmann AG, White Arkitekter
Primary supervisor:	Professor Mette Ramsgaard Thomsen[1]
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Industry supervisors:	Jonas Runberger[2], Kai Strehlke[3], Martin Antemann[34]
Published in:	2020

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[2]White Arkitekter
[3]Blumer Lehmann AG
[4]Design-to-Production GmbH

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 642877.

For my father

Acknowledgements

I owe an enormous debt of gratitude to a large number of people that have contributed - directly and indirectly, knowingly and unknowingly - to this thesis. There is no chance that I can list them all here, so I must only briefly summarize. Beginning with Professor Manuel Baez and Dr. Thomas Mical at Carleton University for pushing me beyond my intellectual boundaries and encouraging me to go further. To Eric Schlange and Aldis Sipolins for all the adventures and escapades during those formative years. To my friends at the Bartlett - particularly my friends in Unit 23 without whom that time would have not been as fun. To my tutors there - Professor Bob Sheil, Emmanuel Vercruysse, and Kate Davies - for revealing an entirely new path in my architectural wanderings. To my colleagues in teaching - Carlos Jimenez, Thomas Pearce, Mara Kanthanak, and Sarah Firth - for the fun, energy, and endless curiosity. To Matthew Shaw and William Trossell at ScanLAB Projects for taking me in and letting me take part in so many adventures in so many strange places. To my colleagues at ScanLAB - Thomas Parker, Soma Sato, and Thomas Pearce. To my colleagues in Bmade - Inigo, Peter, Johnny, Bim, Abi, Mads, Rob, Justin, Olga, William, and others - for teaching me so much about making and being so fun to be around. To Peter Scully - technical director of Bmade - for taking me aside to tell me that, as much as he liked having me around, I would be a complete idiot not to apply to the InnoChain project.

Thanks to my friends and colleagues in Copenhagen - where I have truly felt at home for the past four years. To the workshop leaders at KADK - Mads, Henrik, Bo, Lars, and Torben - for their generous help and advice about all sorts of issues related to making. To the IT and campus service teams for their help and support throughout my whole stay at CITA. To the incredible team in CITA - Mette Ramsgaard Thomsen, Martin Tamke, Phil Ayres, Paul Nicholas, Paul Poinet, Kasper Ax, Anders Holden Deleuran, Esben Clausen Nørgaard, David Andres Leon, Henrik Evers, Ida Katrine Fritz Tinning, Yuliya Sinke Baranovskaya, Danica Pistekova, Mateusz Zwierzycki, Ayoub Lharchi, Scott Leinweber, Mary-Katherine Heinrich, and others. To Anders and Henrik for introducing me to Eiffel. To the pirates on Tøsen - Emil, Henrik, Mateusz, Niels, Pi, Kristian, Rasmus, Philipp, and the rest. To my wonderful flatmates - Lauren, Joe, and Fei.

Thanks to my friends and colleagues in Aarhus and Aalborg - Jens Pedersen, Ryan Hughes, Niels Martin Larsen, Anders Kruse Aagaard, Isak Worre Folged, Max Butke, Jan Hørløck Jensen - for their help and collaborations on various projects and events, and especially for the help in producing the final exhibition piece of this thesis.

Thanks to the InnoChain network for making it all happen. To the EU

Horizon 2020 programme for funding it. To the supervisor board for the monumental task of organizing and steering it. To all the industrial partners. To my fellow InnoChainers - Evy Slabbinck, Angelos Chronis, Zeynep Aksoz, Dimitrie Stefanescu, Paul Poinet, Efilena Baseta, James Solly, Vasily Sitnikov, Giulio Brugnaro, Helena Westerlind, Saman Saffarian, Arthur Prior, Ayoub Lharchi, Kasper Ax, Stephanie Chaltiel - for all the support, friendship, and the good times. To my industrial partners - Blumer Lehmann AG and White Arkitekter - for their willingness to involve me in their work and for sharing so much of their time and knowledge. To Kai Strehlke, Martin Antemann, Patrick Jaksic, Katherina Lehmann, and the rest of the team at Blumer Lehmann AG for letting me watch over their shoulders and snoop around the workshop during the production of the Swatch building. To Jonas Runberger, Vladimir Ondejcik, and everyone else in the Dsearch network and at White Arkitekter for sharing their insights, experience, and letting me participate in some great projects. To Hanno Stehling and Fabian Scheurer at Design-to-Production GmbH for their generous sharing of their experience and friendly openness to all manner of questioning and discussion.

Saving the best for last, an immeasurably large thanks to my partner Carmen and my family for their endless love and support.

Abstract

The advent of digital tools and computation has shifted the focus of many material practices from the shaping of material to the shaping of information. The ability to process large amounts of data quickly has made computation commonplace in the design and manufacture of buildings, especially in iterative digital design workflows. The simulation of material performance and the shift from models as representational tools to functional ones has opened up new methods of working between digital model and physical material.

Wood has gained a new relevance in contemporary construction because it is sustainable, renewable, and stores carbon. In light of the climate crisis and concerns about overpopulation, and coupled with developments in adhesives and process technology, it is returning to the forefront of construction. However, as a grown and heterogeneous material, its properties and behaviours nevertheless present barriers to its utilization in architecturally demanding areas.

Developments in adhesives and production technology have changed the paradigm of wood construction from subtraction to aggregation with the introduction of engineered wood products (EWPs) and glue-laminated timber (glulam). This allows the composition of glue-laminated timber assemblies that can be tailored for specific applications and can therefore respond to specific performance requirements. However, the integration of the properties, material behaviours, and production constraints of glue-laminated assemblies into early-stage architectural design workflows remains a challenging specialist and inter-disciplinary affair.

This research examines the design and fabrication of glue-laminated timber structures and seeks a means to link industrial timber fabrication with early-stage architectural design through the application of computational modelling, design, and an interrogation of established timber production processes. A particular focus is placed on large-scale free-form glue-laminated timber structures due to their high performance demands and the challenge of exploiting the bending properties of timber. By proposing a computationally-augmented material practice in which design intent is informed by material and fabrication constraints, the research aims to discover new potentials in timber architecture.

This research is a partnership between CITA (Centre for IT and Architecture) at KADK, Dsearch - the digital research lab at White Arkitekter that examines the integration of computational design strategies within multi-disciplinary architectural practice - and Blumer Lehmann AG - a leading Swiss timber contractor that specializes in the planning, development, and delivery

of complex timber structures. This partnership positions the project between contrasting realms of architectural practice, design modelling, and industrial timber production. The project methodology draws on embedded secondments at both industrial partners, material prototyping, and the interplay between design modelling and fabrication in a multi-scalar approach.

The central figure in the research is the *glulam blank* - the glue-laminated near-net shape of large-scale timber components. The design space that the blank occupies - between sawn, graded lumber and the finished architectural component - holds the potential to yield new types of timber components and new structural morphologies. Engaging with this space therefore requires new interfaces for design modelling and production that take into account the affordances of timber and timber processing.

The research finds that the encoding of timber properties and production constraints into lightweight modelling tools can speed up the modelling of free-form timber structures and provide valuable insights into the consequences of design decisions for downstream fabrication. This can provide the basis for building a convincing case for a free-form timber project and for lowering risk at very early design stages. However, the research also finds that additional non-computational processes such as the brokering of information and interdisciplinary communication are still required. The research further finds that the introduction of digital sensing systems within production processes and a challenging of the sequencing and linear nature of timber processing can yield novel types of glue-laminated morphologies that are different and geometrically more complex than existing standard glue-laminated products. Along with the computational workflows to model them, these offer new perspectives in what future timber architecture can be and what kinds of spaces it can engender.

The contribution of this research is a framework for a material practice that integrates processes of computational modelling, architectural design, and timber fabrication and acts as a broker between domains of architectural design and industrial timber production. The research identifies four different notions of feedback that allow this material practice to form.

Contents

1

INTRODUCTION

1.1 Overview

The digital revolution has brought profound changes for all aspects of the design and materialization of the built environment. The ability to acquire and manipulate enormous amounts of data has led to the proliferation of computational tools, simulation, and automation across all involved disciplines in the architecture-engineering-construction (AEC) industries. Machines are driven by abstract data models at tolerances unachievable by the human hand. The ubiquitous availability of such high computational power and the ease of managing complexity are unprecedented. Material practices have typically involved notions of craft and tacit relationships between maker and material. These, too, have undergone transformations borne from the maturation of computational methods. How can these relationships be made explicit in light of advances in modelling, simulation, and digitally-driven production? Digital models transcend the role of representation and become functional tools in themselves, able to reveal insights and to direct decision making. How can they move further into an encoding or embedding of material knowledge into design workflows that happen at arm's length from the material? How can experience, material behaviour, and a notion of craftsmanship be embodied in computational processes and digital modelling interfaces? These questions - how can otherwise internalized material and process knowledge be transferred to explicit tools and functional models - are the foundations of this research.

The crafting of wood structures has long and rich histories, many of which are centred on the craftsman's innate knowledge of the behaviour and character of the material at hand. Wood is heterogeneous, active, and fickle, responding to environmental factors over time through complex deformations and transformations. The following research places these considerations against the introduction and maturing of computational power, digital sensing, and information modelling in architectural design, and asks how this complexity can be stored and embedded in tools, objects, and processes that extend beyond the innate experience of the individual craftsman to the frameworks of large-scale industrial fabrication.

This thesis articulates the development of a digitally-augmented material practice in large-scale free-form structures, through three domains of modelling, materialization, and design integration.

This introduction is divided into seven main sections. This first is this overview. The second declares the hypothesis of the research. The third describes its research context. The fourth describes the personal motivations for this work. The fifth contains an overview of the research objectives and the questions that this thesis seeks to answer. The sixth section is an overview of the main contributions and findings of the thesis, with respect to the research questions. The final section describes the structure of this thesis and enumerates the main experimental projects developed over the course of the research.

1.2 Hypothesis

This research hypothesizes that distinct notions of feedback - expressed through processes of modelling, materializing, and integrating - throughout the design-to-production chain can lead to a digitally-augmented material practice that can confront the complexity of planning and constructing large-scale free-form timber structures. By doing so, the material practice will extend the architectural design space of these structures into strategic material composition of individual, performative glue-laminated timber elements, and lead to new morphologies that benefit and arise from this tailored and specific design approach. The characteristics of this new material practice will be *specificity* of engagement with site and material, *awareness* of material behaviour and process, and *integration* through a traversal of the broader timber value chain.

(a) Dimensioned lumber, the raw input for the production of a glulam blank.

(b) The free-form glulam blank.

(c) The finished glulam component. Photo: *Blumer Lehmann AG*

Fig. 1.1: The glulam blank (b) is the object between dimensioned lumber (a) and finished architectural component (c).

1.3 Research context

This research is a practice-led research project primarily situated in the field of architectural design. It examines how the material and fabrication knowledge embedded within industrial timber production can be accessed and communicated to early-stage architectural design processes. It does this by putting forth the *glulam blank* as a particular design focus, and developing digital design tools for modelling and analysing free-form timber structures.

The glulam blank - or simply *the blank* - is the rough glue-laminated assembly of individual timber planks or lamellae which approximates the final glulam element - *near-net shape* of the designed and anticipated final component (Fig. 1.1). It is formed in a glulam press and subsequently operated on: drilled, planed, and machined into its final, finished form. Therefore, within the broad field of architectural design, this thesis is concerned with topics of digital modelling, fabrication, and how knowledge is communicated between designers and makers. To this effect, it also draws on concepts and tools from computer science and manufacturing. It is positioned between academia - hosted at *CITA* at the Royal Danish Academy of Fine Arts Schools of Architecture, Design, and Conservation (KADK) - and the AEC industry, where it is supported by industrial partners *White Arkitekter* and *Blumer Lehmann AG*. The research is part of the EU-funded *InnoChain ETN* network (Fig. 1.2).

1.3.1 Timber and the timber industry

The timber industry at large has seen large advancements in the application of digital technology to the processing of wood: from harvesting and sawmilling, to the production of timber elements and construction. Schindler (2007) charts these advancements as an evolution of the combination of energy, material, and information, resulting in the automation and digitization of timber production today. The role of the operator has shifted from a direct application of human power to material process to one where the operator steers and plans the process, which in turn is powered by machine energy. CAD and CAM have become the standard ways of operating within timber production, and this has allowed the resurgence of individualized part production while retaining the speed and accuracy of serial production. This fusion of design and digital modelling with automated manufacturing has defined a new ”digital craftsmanship” in timber (Scheurer 2012).

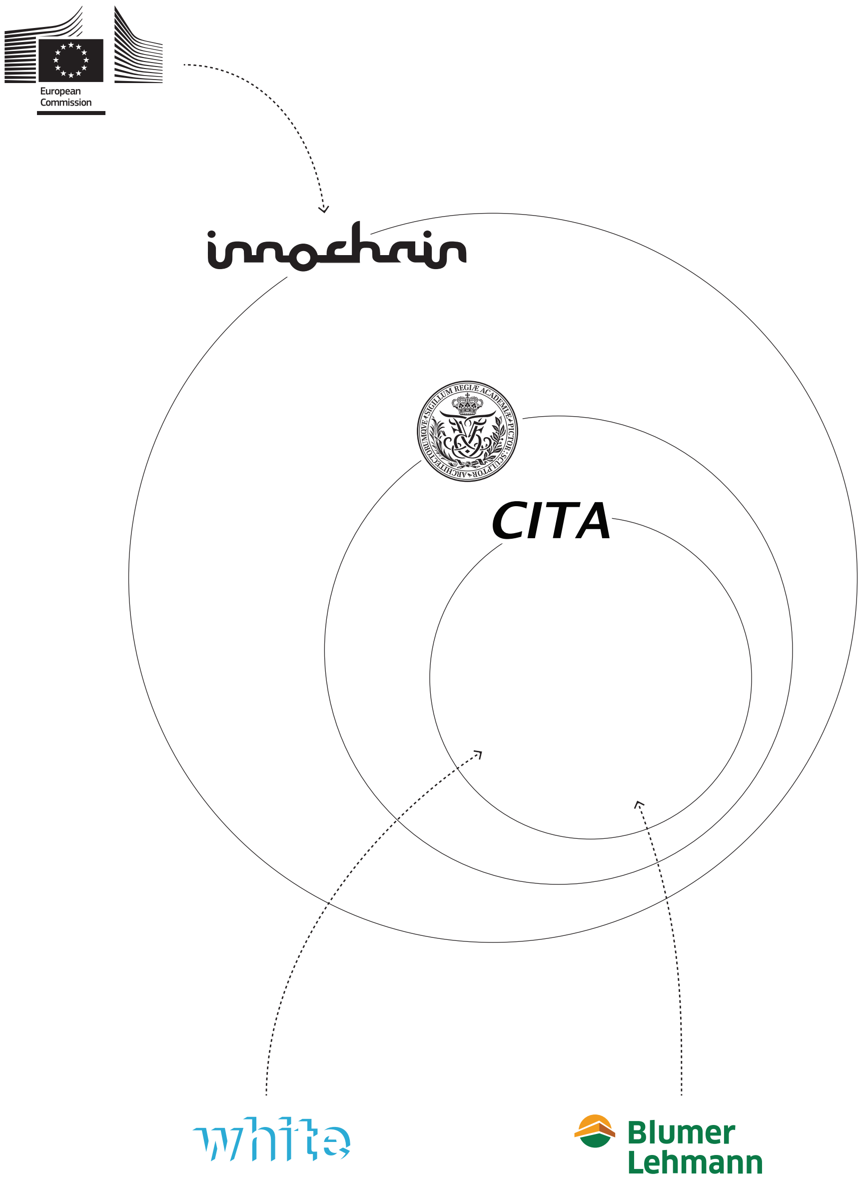


Fig. 1.2: The research context of the thesis.

Timber itself, as a material, has developed from elements sawn from a tree to modern varieties of engineered wood products (EWPs), formed from boards, veneers, chips, strands, and fibres bonded together with structural adhesives. The material complexity and fickle behaviour of wood remains, however the development of EWPs has begun to use the properties of wood advantageously, mitigating much of the weaknesses and uncertainties that plague the use of such a heterogeneous, unpredictable, and ”live” material.

Despite all of these advancements, challenges remain in the integration of these developments into architectural practice. The translation from an architectural design to a timber building is fraught with decisions that impact the outcome in different ways. Scheurer et al. (2013) highlight the importance of early communication between timber fabricator and architect as a way to avoid costly design decisions and downstream complications during manufacturing and assembly. Davis (2013) supports this by calling for more flexibility throughout the progression from design through to planning and construction - the design chain - and for impacting the design as much as possible earlier in the process, where changes are cheap and flexibility is high. The need for this kind of feedback - from material and fabrication back to early-stage design - is apparent.

1.3.2 Material practice in architecture

As a field that is intimately tied to the making of space through manipulation of material objects, the notion of material practice finds a comfortable home in architecture. Ramsgaard Thomsen and Tamke (2009) point to Stan Allen’s rejection of the theory / practice distinction and emphasize the ”material focus” of practice-led research in architecture. This puts thinking and designing into a reflexive dialogue with making and crafting, and, by extension, with the particularities and behaviours of specific materials and material systems. Further, this dialogue is seen through the lens of digital technology and especially techniques of digital simulation. The premise is that a digitally-augmented material practice in architecture is one that links processes of design to material behaviours and processes through the virtual-material dialogue and simulation of material phenomena and fabrication processes. The outcome is that ”a new material understanding can lead to a new spatial imaginative” (Ramsgaard Thomsen and Bech 2012).

1.3.3 Performance-oriented architecture

The integration of material performance, therefore, becomes a key task for a developing material practice. Hensel (2010) also defines architecture as ”a material practice that transforms the human environment through material and environmental interventions.” He further puts forth that material ”responds to stimuli and can thus be utilised strategically in the orchestration between material and energetic exchanges” and - conveniently - uses wood as a particular example of this. Hensel uses this to establish a biological paradigm in architecture where materials gain an active agency and design is largely driven, or at least influenced by, the interaction between material, environment, and forces.

1.3.4 The InnoChain research network

Both the need for feedback between early- and late-stage processes as well as the material focus in architecture are the subject of the InnoChain research network, of which this thesis is a part of. InnoChain questions the linearity of the design-to-production chain - where actions proceed sequentially, in successive steps, from concept to design development, engineering, construction planning, fabrication, and assembly, and so on. The pitfalls of this linearity are highlighted by Scheurer above in the context of timber construction. The InnoChain project seeks to disrupt this linearity and introduce notions of feedback and recursion to propose new materially-based models of working between design and making.

InnoChain links together 6 different academic institutions and approximately 14 industrial partners across Europe. This collaboration between academia and industry is an integral component to the research projects, and places an emphasis on trans-disciplinary ways of working and integrating multiple knowledge domains. InnoChain consists of 15 Early Stage Researchers (ESRs) who are, in effect, PhD researchers based at one of the 6 institutions. Each ESR is partnered with one or two industrial partners from the network. The range of topics is varied: other research projects address AEC data interoperability, ice form-work for concrete casting, carbon- and glass-fibre winding, computational fluid dynamics, and design for assembly, to name only a few.

The InnoChain research projects are organized into three work packages: *WP3: Communicating design*, *WP4: Simulating design*, and *WP5: Materialising design*. This thesis project is part of *WP3: Communicating design* and is the second project of all fifteen projects - ESR 2. The original brief for ESR 2 was entitled ”Integrating material performance” and called for a particular focus on timber.

1.3.5 CITA (Centre for IT and Architecture)

The impact of digital culture on architectural design and making is also a point of focus for *CITA*, where this research is conducted. *CITA* is part of the Institute for Building Technology (IBT) at the Royal Danish Academy of Art, Architecture, Design, and Conservation (KADK) in Copenhagen, Denmark. *CITA* has a strong track record working with wood and wood behaviour, addressing the rise of computation and automation in the design, modelling and fabrication of wood structures: previous projects in this area include *Parawood* (Ramsgaard Thomsen and Tamke 2009), *Lamella Flock* (Tamke, Riiber, and Nielsen n.d.), and *Dermoid* (Burry et al. 2012). Each of these investigate the interface of wood craft and performance in relation to digital production, digital simulation, and design. As a base for exploring a material practice in glue-laminated timber, the interfacing of digital and material technologies at *CITA* and the focus on developing new architectural and material practices align very closely with the aims of this research.

1.3.6 Industrial partners

The project is undertaken in collaboration with two industrial partners: *Blumer Lehmann AG* and *White Arkitekter*. The role of these industrial partners is to provide guidance on their respective domains of expertise: timber processing and construction, and architectural design and computation. This includes *demonstrating* the state of the art - both partners are reputable in their fields and therefore exemplify the current state in their fields - *grounding* the research in real-world problems and therefore increasing the relevance of the research project for the wider architectural community; and providing a platform for developing the research within a non-academic context.

Blumer Lehmann AG

Blumer Lehmann AG is a globally-leading timber contractor and producer of timber products, based in Gossau, Switzerland. The *Lehmann Group* is the parent company of *Blumer Lehmann AG* and comprises over 300 employees split between 3 different companies: *Lehmann Holzwerk AG* operates a sawmill with an approximate annual throughput of 125 000 cubic metres of locally sourced logs, and turns these logs into construction lumber, wood pellets, and briquettes for energy production; *BL Silobau AG* specializes in silo and system construction for winter road services; and *Blumer Lehmann AG* focuses on timber construction, modular construction, general contracting, and free-form timber structures. As such, *Blumer Lehmann AG* is connected to the entire wood value chain - from log to on-site assembly of engineered timber components - with the exception of the glue-lamination process and glulam blank production. For various practical, economical, and political reasons, the company sells lumber to other firms which perform the glue-lamination process, and buys back glulam blanks for further processing and machining. Single- and double-curved glulam blanks are often sourced from *HESS TIMBER GmbH*, another timber producer and contractor, based in Kleinheubach, Germany. Multi-axis machining of large-scale timber members is performed with a custom built machining centre - the Technowood TW-Mill C5500 3U8C.

Fig. 1.3: The multi-axis CNC production centre at *Blumer Lehmann AG*.

Blumer Lehmann AG has been involved in the fabrication of several notable timber projects, which describe the leading edge in complex timber architecture. To name a few, the company has fabricated the *Tamedia Building*, the *Heasley Nine Bridges Golf and Country Club*, and the *Omega Swatch Headquarters* buildings designed by Shigeru Ban Architects; the *Cambridge Mosque*, designed by Marks Barfield Architects; and *Maggie's Centre, Leeds*, designed by Foster and Partners.

In this research project, *Blumer Lehmann AG* provide guidance and input regarding processes, constraints, and issues in industrial timber production. A 4-month secondment is undertaken in the TW-Mill workshop in Gossau, during which methods for digital feedback in production are explored with the fabrication team. The secondment occurs during the live production of the *Omega Swatch Headquarters* building by Shigeru Ban Architects, providing an up-close look at the planning, logistics, and machining of large-scale free-form glulam beams.

White Arkitekter and Dsearch

White Arkitekter is a multi-disciplinary architecture practice with offices across Scandinavia and the UK. Its headquarters are in Stockholm, Sweden, however it also has satellite offices in London, UK and further. Employing over 900 people, it is the largest architecture practice in Scandinavia. The practice's portfolio is diverse, ranging from large-scale urban development projects to urban furniture; from schools to residences and civic buildings.

Fig. 1.4: The Forumtorget public furniture project by *Dsearch* and *White Arkitekter*. Photo: White Arkitekter

The *White Research Lab (WRL)* is the research and development initiative within *White Arkitekter*, consisting of three main ”development networks”: *Wood*, *Light and Tectonics*, and *Dsearch*. These development networks are spread out across the offices and design teams, as opposed to being isolated, independent units in themselves. This enables a more relevant and immediate embedding of research within the project teams, and a closer alignment between the needs of the practice and the research efforts of the networks.

Dsearch focuses on the application of computation and parametric design to architectural design and fabrication processes, how the use of new technologies is integrated into a large and diverse practice, and how knowledge of such technologies is communicated and disseminated throughout the practice. In this respect, *Dsearch* provides guidance and input in matters relating to processes in architectural practice, architectural design projects, and how new tools and modes of working might be integrated into existing architectural practices. As with *Blumer Lehmann AG*, a three-month secondment is conducted in Stockholm with *Dsearch* which explores the application of this research project to several on-going *White Arkitekter* projects.

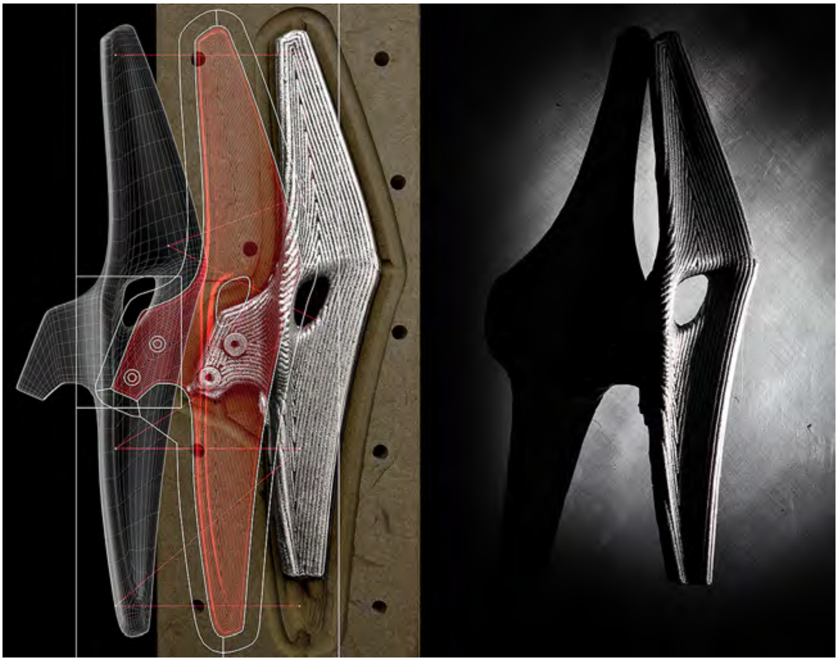


Fig. 1.5: Translating the virtual into material effect (2012).

1.4 Motivation

The motivation for this research comes from a personal history of working with digital technology in architecture and media, a fascination with practices that move between the ”real” and the ”virtual”, and the desire to revisit the working and shaping of wood through the lens of novel design and simulation techniques. I am fascinated by the transformation of abstract representation into material effect, and all its intermediary translations, displacements, layers of data, and collateral objects (Fig. 1.5). I see the proliferation of digitization and computation as empowering and as something that allows us to reconsider established and familiar things - such as wood and wood craft - in a new light. Physical objects are not simple aggregations of inert, dumb material, but an amalgamated cluster of overlapping and nebulous layers of meaning, data, politics, and behaviour, connected by abstract linkages of references and cross-pollinations.

I explored these types of translations during my graduate studies at the Bartlett School of Architecture, with a focus on making and speculating with new technology. Unit 23 explored ”fabricating the real” and its counterpoint: ”the unreal”. The unit's agenda was to develop a critical practice centred around architectural production and an oscillation between representation and realisation. The unit's work emphasized physical testing, craft, and experimental production design. My graduating project - *The Bradbury Transcripts: Collateral Realities and the Saturated Blur* - centred on the slippages and mistranslations between reality and digital representations, and specifically around the many lives and alternate personalities of the Bradbury Building in Los Angeles - the site of many stories, myths, and movies and therefore a mythological locus of sorts. The project relied on the use of robotics, 3D scanning, and digital animation, and questioned how the new realities that these tools opened up related to the physical spaces and artefacts that they described or created (Fig. 1.6). I identified the gap between the virtual and the material as a potential source of enriching ”slippage” and proposed that the digital could be used as much as a source of myth and storytelling in architecture as much as an enabler of complexity and material economy. I went on to work extensively with digital technology: as the technical director for *ScanLAB Projects*, as well as a teaching fellow, technician, and roboticist in the *Bartlett Manufacturing and Design Exchange (Bmade)* in London.

Fig. 1.6: The Bradbury Transcripts (2013).

Extracurricular activities also included a collaborative ”field robotics” project (Vercruysse et al. 2014) which explored the performative nature of manufacturing equipment such as 6-axis industrial robotic arms. Small experimental ”rehearsals” combined video, 3D scanning, photography, and choreographed movement to create new realities between the digital and the material (Fig. 1.7).

At ScanLAB, while the work was primarily image-based, certain projects nevertheless developed interfaces with the material world through software-hardware workflows. In the installation project *Phantom*

Fig. 1.7: Performative ’field robotics’ with Emmanuel Vercruysse, Kate Davies, and Inigo Dodd (2014).

(kingdom of all the animals and all the beasts is my name) with artist Daniel Steegmann Mangrané (exhibited at the New Museum in New York, and later as part of the 8th Nordic Biennial of Contemporary Art in Moss, Norway), I integrated 3D LiDAR scan data with real-time motion tracking and a VR headset to create an immersive opportunity for a viewer to experience the Mata Atlântica rainforest in Brazil as a ghostly black-and-white simulacrum. The phantom of the Mata Atlântica was summoned through the interfacing of virtual models with real-time sensor data and an integrated system of distinct hardware platforms.

Fig. 1.8: *Phantom (kingdom of all the animals and all the beasts is my name)* by ScanLAB Projects and Daniel Steegmann Mangrané (2015).

Apart from my day-to-day duties as a teacher and technician at *Bmade*, I continued my pursuit of these ”ghosts” and slippages in the domain of production. The integration of cyber-physical systems focused on the relationship between the information model and the physical artefact: Where are they in relation to one another? How does one affect the other? A key project in this exploration was a collaboration with carpenter and fellow Bmade colleague Jonny Martin. Combining Jonny’s knowledge of wood craft and making with my knowledge of robotics and programming, we developed a prototypical project around the cyber-physical ghost of laminated wood veneers during the after-hours peace and quiet of the workshop. Creatively entitled *Optically-guided free-form vacuum lamination*, the project explored the bending and laminating of wood veneers without form-work. We set up a stage where a robotic arm dynamically bent and pulled a stack of laminated veneers - still wet - while an optical motion capture system - typically used for tracking the movements of actors and animals for movies - relayed real-time positional data from reflective markers placed on the laminated assembly. The sensor data created a virtual stand-in for the bending and twisting wood, which was overlaid onto its simulated digital ghost. The gaps, errors, and slippages in between were chased by the robot: it moved and contorted in an attempt to close the gaps and sew shut the seam between the sensed and the simulated.

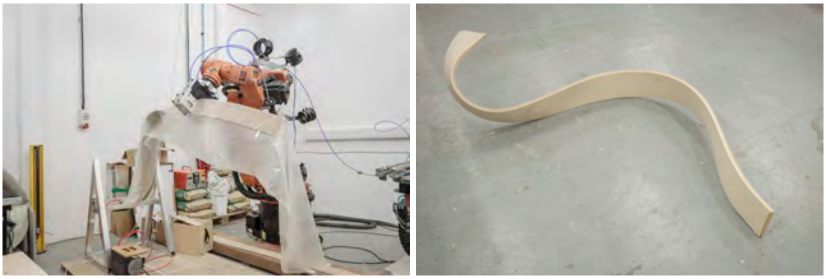


Fig. 1.9: Free-form optically-guided vacuum lamination with Jonny Martin (2015).

In many ways, this chasing of ghosts and deployment of digital technologies of sensing, simulation, and production to the lively, unpredictable nature of wood are the direct precursors to this research project. What this research asks, however, is how this way of thinking can be expanded to industrial scales and large buildings - beyond the individual and tactile relationship between craftsman and workpiece: what are the ghosts and slippages in the industrial production of laminated wood, and what mediums are required to summon them?

1.5 Objectives and research questions

1.5.1 Research aims

The aim of this research is to find a closer relationship between early-stage architectural design processes and the production of free-form glue-laminated timber buildings. The hypothesis is that such a relationship will lead to a digitally-augmented material practice that can confront the complexity of planning and constructing large-scale free-form timber structures. By doing so, the material practice will extend the architectural design space of these structures into strategic material composition and lead to new morphologies that benefit from a tailored and specific design of individual timber components.

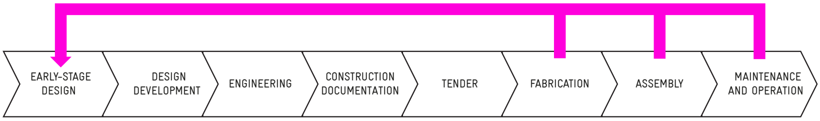


Fig. 1.10: Introducing feedback in the linear design chain.

This aim is founded on the notion that the progression of steps from initiating a project, design development, and engineering, to fabrication and assembly - the design chain - is largely *linear* and highly *directional*. This means that the transfer of information between steps happens in a single direction, with very little opportunities for feedback or a re-informing of processes earlier in the chain by processes that come later. Each step along the chain also involves various stakeholders within very different specialist knowledge domains. This gives rise to two fundamental challenges: the flexibility of implementing changes diminishes as one progresses down the chain while the cost and complexity of those changes rises, and interfaces are required to bridge the gap between knowledge domains at different points on that chain - such as early-stage design and late-stage fabrication.

Davis (2013) refers to a representation of this relationship - the MacLeamy Curve - which is used to illustrate how the front-loading of the design-to-production chain using Building Information Modelling (BIM) can help avoid costly downstream changes, but proposes instead that an alternative approach is to maintain as much malleability in the information model throughout the design chain by using flexible parametric models. This front-loading is a subject also touched on by Scheurer et al. (2013), specifically for the case of complex timber buildings in the context of digital design tools. They conclude that an early involvement of stakeholders is necessary for a successful timber project - with everyone ”sitting around the same table”, which also begins to address the second challenge posed by the linearity of the design chain. In discussions with both *Design-to-Production GmbH* and *Blumer Lehmann AG*, this is expressed as a three-part model - consisting of architect, engineer, and contractor - centred around some common knowledge base (Fig. 1.11).

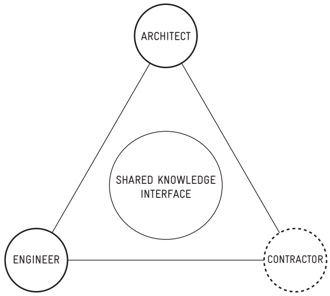


Fig. 1.11: The model put forth by *Blumer Lehmann AG* and *Design-to-Production GmbH*. The contractor is determined by the market and therefore must be interchangeable. The shared knowledge interface must therefore allow this.

The challenges created by the material complexity of timber are well-known. Wood is a highly anisotropic and heterogeneous material, which compounds the challenges for its use and application in construction. Its utility in architectural design and production depends heavily on how it is grown and how it is processed. Beyond formal and basic structural considerations, designing with timber needs to take into account its anisotropic material behaviours and orientation. Knowledge of wood comprises the whole field of wood science, and its processing and fabrication add further layers of demand on the designer and user. The integration of timber properties and performance into architectural design therefore is a specialist and interdisciplinary endeavour, requiring additional mechanisms for communicating between these domains.

Runberger and Magnusson (2015) describe the problem of interfacing with differing knowledge domains within a large, multi-disciplinary practice such as *White Arkitekter* and propose using the concept of *boundary objects* to help integrate computational knowledge across a diverse field of practice. This thesis puts forward that the integration of material performance and fabrication knowledge presents similar challenges and thus can benefit from similar considerations.

Taking the central tenets of both *InnoChain ETN* and *CITA* - how can digital tools and digital culture open up new ways of working with materials and material processes - this thesis sits at a locus: between academic research and industrial practice - which is further divided into contrasting realms of architectural design and industrial fabrication - and between the digital and the material (Fig. 1.12). The linear digital chain involves the move from the virtual to the material through the translation of 3D computer geometry into tool paths and further into CNC-machined material elements - this is well understood. The aim of this thesis is to approach from the other direction: to inform the virtual processes of design and modelling with material behaviour, properties, and fabrication constraints - specifically within the field of large-scale glue-laminated timber. As described in Svilans, Tamke, et al. (2019), this embedding of aspects of materialization within digital design tools leads to novel timber morphologies, tailored and optimized building components, and better-informed design decisions.

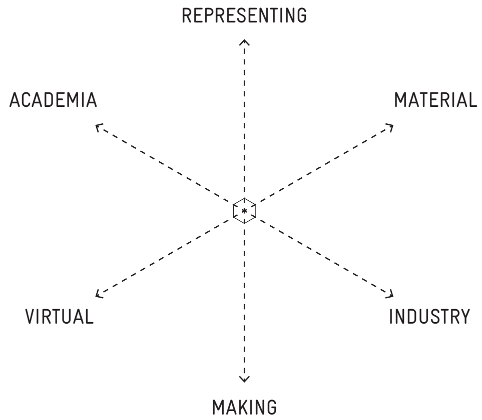


Fig. 1.12: The orthogonal dimensions of the thesis.

The main objective of this thesis is therefore to develop and elucidate a material practice - consisting of a set of tools and processes - which acts both as the boundary object between architectural designer and timber fabricator in the way suggested by Runberger and Magnusson (2015), as well as the central knowledge interface referred to by Scheurer et al. (2013).

1.5.2 Methodology

The thesis develops the material practice in three ways. The first is the acting out of the material practice: *mirroring* the tools, processes, and frameworks of the design and production of free-form timber buildings, and incrementally refining them. The second is a close dialogue with the industry partners: a *shadowing* of larger, more complex processes to align the ambitions of the practice with real-world constraints and thus increase its relevance. The third is *brokering* knowledge between the realms of architectural design and fabrication, enacting the boundary object that straddles both.

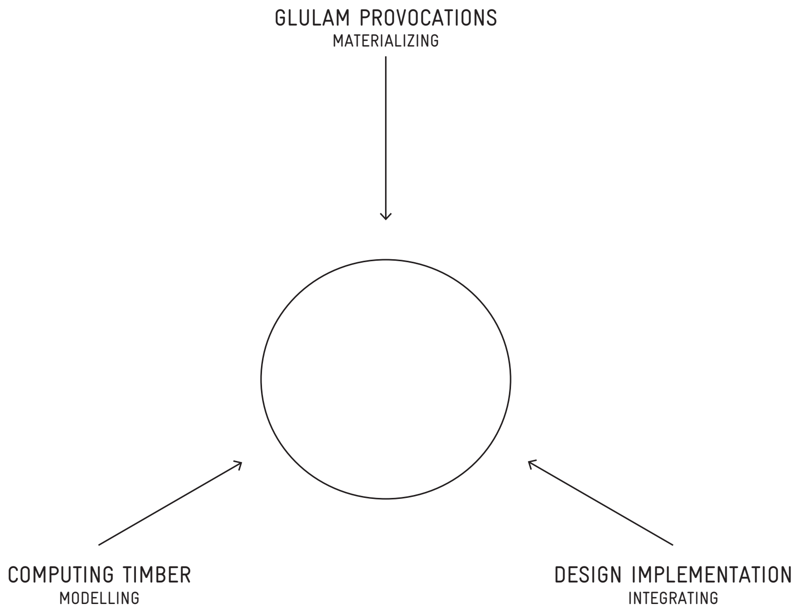


Fig. 1.13: The tripartite approach of the thesis to forming the material practice.

The thesis is a practice-led research project, and develops a methodology based on the notion of ”research through design” as first defined by Frayling (1993). Since it is a practice of digitally modelling and physically producing glue-laminated timber artefacts, it operates primarily through various types of virtual and material prototyping: coding, 3D modelling, and physical making. This is in line with the definition of practice-led research in architectural design described by Ramsgaard Thomsen and Tamke (2009) which brings the role of material evidence to the forefront. This thesis therefore also adopts their *probe*, *prototype*, and *demonstrator* differentiation of material evidence. The material practice is based on the integration of digital modelling and simulation tools with material prototyping as described by Tamke, Hernández, et al. (2012):

> The key research inquiry is a speculation on the new kinds of design practices required to link architectural design practice and the field of material performance simulation, which is traditionally part of engineering practices.

However, this thesis draws less from simulations from engineering practices and more from the fabrication affordances within industrial timber practices. Material performance is thus expanded from being centred on the material itself to including performances related to its processing and handling.

Tamke, Hernández, et al. (2012) further conclude that ”the integration of material behavior into design demands a holistic understanding where scales are both conceptually and logically linked”. To address this, this methodology employs a *multi-scalar modelling* framework. Multi-scalar modelling is a framework that considers multiple scales of the same overall phenomena in tandem, and recognizes that different scales require not only different models, but different *types* of models. This means that interfacing between different models at different scales becomes the central benefit, allowing these multiple scales to be considered together through an ecology of communicating models. This method is particularly relevant for wood because it presents multi-scalar characteristics: from local material properties at the level of the fibre to the assembly of multiple, different architectural timber elements in a structure.

Being based in the context of architectural design, this thesis also uses design as a tool for developing the material practice. Together with the digital modelling and physical prototyping, it puts forth a tripartite structure that encircles the central aim of the thesis, and provides three main interpretive lenses or facets through which to consider the experiments: modelling, materializing, and integrating (Fig. 1.13).

1.5.3 Research questions

Each chapter therefore answers the central research question from a different point of view, which is:

> **How can tacit knowledge of glue-laminated timber behaviour and performance be encoded through computational tools of modelling and simulation?**

The experiments described throughout each of the three main project chapters explore secondary research questions.

The domain of *modelling* is concerned with *digital representation* and the *interrelation between models at different scales*. It asks:

- How can the heterogeneity of timber be stored and represented across digital architectural models at micro, meso, and macro scales?

- What computational modelling methods are able to communicate the performance and production implications of free-form timber structures to the architectural designer?

The domain of *materialization* looks at the individual glue-laminated element, and is therefore concerned with *expanding the design space* and *merging the digital and material*. It asks:

- How can a reflexive interrogation of the wood value chain and glulam production line lead to alternative morphologies of free-form glue-laminated elements?
- How can digital sensing methods during production be used to more closely relate virtual production model and material workpiece?
- How can this closer linkage between model and material lead to an encoded and persistent experience?

Finally, the domain of *design implementation* is focused on *brokering* and *knowledge transfer*. It asks:

- How does the digitally-augmented material practice developed in this research transfer to the context of architectural design practice?
- How can the brokering of knowledge between stakeholders introduce productive feedback loops at the early-stages of a design project within an architectural practice setting?

1.6 Contributions

The research contributions of this thesis can be categorized in three levels of relevance and importance: the main contribution of the thesis, secondary contributions of each domain - modelling, prototyping, design - and collateral contributions which mostly comprise tools and techniques developed along the way in aid of the primary and secondary contributions.

> **The main contribution of this thesis is a framework for a digitally-augmented material practice that is centred around the concept of the glulam blank. This material practice extends the architectural design territory to encompass the design of the glulam blank, which considers the particular material properties and behaviours of glue-laminated timber. In doing so, it allows an informed interfacing with timber behaviour through the lens of architectural design and leads to new morphologies of timber structures through the invention of non-conventional glulam components. The framework consists of differing notions of feedback within the domains of digital modelling, material fabrication, and design integration.**

This includes demonstrations of how digital technologies such as computational modelling and 3D scanning can be deployed within existing architectural design practices to link material performance and affordances to the planning and development of timber structures. The thesis shows how different forms of feedback and iterative thinking lead to a deeper engagement with material and fabrication considerations throughout the design of architectural projects. The thesis formulates and demonstrates four main types of feedback:

- *Simulated feedback* informs the designer of the consequences of design decisions on later fabrication stages and is exposed through digital modelling tools and workflows.

- *Direct feedback* is a sampling of material reality which allows the linking of the virtual model and material artefact through 3D scanning and digital sensing methods.

- *Process feedback* is the introduction of new loops and iterations within the network of individual timber manufacturing processes in order to challenge established linear processes.

- *Brokering feedback* is the transfer of knowledge between contrasting domains of architectural design and production through the involvement of an independent agent, which offers up an alternative way of operating between design and production and new potential constellations of stakeholders within an architectural project.

The secondary contributions are more specific to each domain:

- From the modelling domain, the main contribution is a software library for modelling free-form glulam blanks - developed in Prototype 1: Glulam blank model - as well as a set of example workflows that demonstrate its application to architectural design projects.

- From the materializing domain, the main contribution is the design space of the glulam blank - or *blank space* - as well as the procedures involved in it, such as the iterative re-thinking of industrial timber processes and the integration of 3D scanning and digital sensing within industrial timber workflows. In particular, Prototype 3: Four methods of digital feedback contributes an overview of different types of sensing technology for use within industrial free-form timber machining workflows.

- From the design implementation domain, the main contribution is a set of example workflows and case studies that apply the contributions from the two preceding domains to a variety of architectural design projects, at different scales: Probe 3: Future Wood workshop, Probe 5: Branching Probe, Prototype 2: Grove, Prototype 4: Slussen benches, Prototype 5: Magelungen Park Bridge, and Demonstrator: MBridge.

Collateral contributions are contributions that do not directly relate to the research questions and aims of the thesis, but nevertheless have been developed throughout the course of the thesis and experiments. These comprise software utilities, scripts, and other ”helpers” which have made the research possible. In terms of software, most of these are publicly available. Details and links to these are found in *Appendix C: Software*.

- **carverino** - A .NET wrapper, Rhino plug-in, and Grasshopper plug-in for the Carve mesh boolean library.
- **tetrino** - A .NET wrapper and Grasshopper plug-in for the Tetgen library.
- **rhino_faro** - A Rhino plug-in for loading and manipulating Faro scan files.
- **bpy_triangle** - A Python wrapper for the Triangle library, exposed as an add-on (plug-in) for Blender.
- **SpeckleBlender** - An add-on (plug-in) for Blender for interfacing with the Speckle framework.
- **rhino_natnet** - A plug-in for Rhino that allows the real-time gathering and visualization of data from NatNet’s Optitrack motion tracking system.
- **fls2pcd** - A conversion utility for converting Faro scan files to PCD files, used by the open-source Point Cloud Library (PCL).
- **PySpeckle** - A Python client for the Speckle framework.
- **CITA Robots** - A fork of the open-source Robots plug-in for off-line industrial robot programming, with specific tools for the CITA robot lab and applications.

1.7 Thesis structure

The thesis is explored through a series of projects that overlap the three experimental domains. Because it investigates the confluence of digital and material objects and processes, the thesis is structured according to these contrasting domains as well as their synthesis. As such, the projects appear in multiple places, discussed in the context of a particular domain. After this chapter, the methodology of the research is presented in greater detail. The thesis then reviews the state of the art in the design and production of free-form timber buildings and identifies initial research trajectories. The three following chapters describe the research development and experimental work. Finally, the thesis concludes with a discussion of the accomplished work, answers to the research questions, and an overview of future perspectives.

1.7.1 Experimental domains

The three experimental domains of *modelling*, *materializing*, and *integrating* form a tripartite structure around the central research aim. These also map onto three experimental environments that are the host institution - *CITA* - and the two industrial partners - *Blumer Lehmann AG* and *White Arkitekter*. This enables the experiments and projects within the thesis to be examined through different lenses: digital modelling, physical prototyping, and architectural design. The three domains are therefore mapped onto the three main project chapters:

- *Chapter 4: COMPUTING TIMBER* concerns the multi-scalar computational modelling of timber and glue-laminated timber elements and structures.

- *Chapter 5: GLULAM PROVOCATIONS* examines the fabrication of glue-laminated elements, including methods of production and the link between material and digital model.

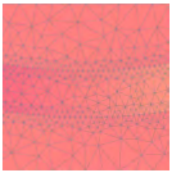
- *Chapter 6: DESIGN IMPLEMENTATION* describes the implementation of the previous two domains and how an architectural practice can be formed around this material integration into design.

It is important to note that the experiments and projects do not map cleanly onto the experimental domains. Because the material practice entwines modelling with making, most experiments address multiple domains in different weightings. How these projects are mapped onto the domains is explained in the next chapter.

1.7.2 Projects

The experimental projects in the thesis appear throughout the ensuing chapters in various guises, discussed in different contexts. As the primary means of discovering and investigating the research questions across the three experimental domains, the projects are highly interrelated and multi-faceted. Subsequent chapters will discuss aspects of several projects together, therefore a full image of each project only comes into focus through a cross-referencing across all domains. This section serves as an index of the projects.

Probe 1: Modelling wood properties

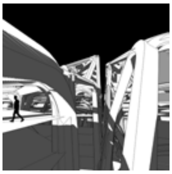


The heterogeneous properties of wood are encoded and represented in digital models that are commonly used in computational and architectural modelling. The discretization of digital models - from 2D to 3D - is used to map varying properties onto models of architectural objects. A particular focus is placed on the varying material orientation - the fibre direction of the wood - and how this can be qualitatively represented using techniques drawn from the field of computer graphics. Interfaces to material simulation and computer-aided engineering (CAE) are revealed.

Probe 2: IBT glulam workshop

A one-week workshop is prepared and taught for undergraduate students from the Institute of Building Technology at KADK. The task is to digitally model free-form glulam beams and physically fabricate them. It is an introduction to the world of glue-laminated timber and is therefore used to probe the landscape of the research topic. The workshop reveals both the challenges of 3D modelling free-form glulams using conventional techniques and the material limits of bending and laminating timber. It seeds further efforts at developing techniques for the constrained modelling of glulams as well as improvements in the forming and machining of free-form timber components. The workshop is co-tutored by Mette Ramsgaard Thomsen and Martin Tamke.

Probe 3: Future Wood workshop

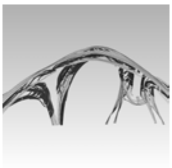


A three-day workshop is attended as part of the InnoChain training events, which encourages a visionary or extrapolated reconsideration of the in-progress research for each Early-stage Researcher (ESR). The task is to explore the morphological and spatial potentials of the research at an early stage. It is a collaboration with Paul Poinet and Kasper Ax.

Probe 4: CITAstudio glulam workshop

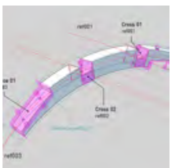
A two-week workshop is prepared and taught for masters students in *CITA* that explores the idea of creating novel glulam blank types by varying specific process parameters and controlling the distribution of material orientation throughout a laminated timber component. This builds upon the first workshop and advances the tools for modelling glulams and begins the integration of digital sensing and 3D scanning into a cohesive workflow. The workshop yields five speculative glulam blanks each of which addresses particular questions and challenges in the glulam fabrication process. This workshop is assisted by Paul Poinet.

Probe 5: Branching Probe



A small free-form structure is designed and modelled as part of a collaborative effort to establish links with another InnoChain research project by Paul Poinet which investigates multi-scalar modelling for timber structures. The glulam modelling tools are deployed towards the design of a free-form timber structure, combining aspects of both research projects. The project reaches the stage of physical prototyping and robotic fabrication.

Prototype 1: Glulam blank model



A constrained glulam blank model and associated models for the modelling of free-form glulam components are developed. The focus is on providing a lightweight but informative method for quickly modelling complex glulam structures while respecting fabrication constraints such as lamella sizing in relation to curvature. The model helps calculate material specifications, creates driving geometry for cutting joints, offers different types of glulam blanks (straight, single-curved, and double-curved), and several options for how the glulam cross-section is oriented along its centreline curve. Additional models link individual glulam components with graph-based methods of managing entire structures and connections. This model is developed throughout the thesis and forms the computational modelling backbone of the research. It is employed in almost all of the design projects.

Prototype 2: Grove

An entry for the 2017 Tallinn Architecture Biennale folly competition builds on the collaboration with Paul Poinet in Probe 5: Branching Probe. An architectural design proposal is formed, allowing the research and modelling tools to be deployed in a real-world design scenario. The project proposes a vault-like aggregation of free-form glulam members that enclose an area in front of the Estonian Museum of Architecture. The glulam modelling tools are used extensively and a graph representation of the proposal provides an overview and means to manage the complexity of several hundred glulam elements. The entry wins second place.

Prototype 3: Four methods of digital feedback

A series of four 3D scanning and tracking experiments is conducted during the three-month secondment at *Blumer Lehmann AG*. Each experiment explores a different technique during a live production process. Each also aims to bring together the digital model with the material reality of the production in a different way: a laser rangefinder records points using the machining spindle, real-time motion tracking brings data capture into other areas of the factory, and 3D LiDAR scanning creates dense point clouds at very high resolutions. Interfacing between the user and each technology, as well as the processing and usage of the capture data are key considerations.

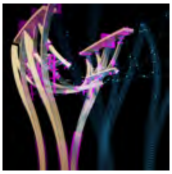
Prototype 4: Slussen benches

A proposal is designed and prototyped for an on-going project at *White Arkitekter* for free-form timber urban furniture during a three-month secondment. The durability and fabrication of exterior timber elements is a point of focus. Knowledge of timber performance gleaned from the previous secondment at *Blumer Lehmann AG* as well as the modelling tools from Prototype 1: Glulam blank model are used to propose alternative designs. Material prototypes are fabricated to explore the key concerns at 1:2 scale.

Prototype 5: Magelungen Park Bridge

A design for a pedestrian bridge is developed during the three-month secondment at *White Arkitekter*. It shifts the design of a conventional concrete overpass towards an advanced free-form timber bridge and addresses questions of durability and fabrication. The expertise of *Blumer Lehmann AG* and *Design-to-Production GmbH* are brought on board through the scope of this research and the InnoChain network collaborations. The brokering of knowledge and data is necessitated by the many involved parties, including a larger project team, engineers, and fabrication consultants. The glulam tools from Prototype 1: Glulam blank model are used to facilitate the modelling of the bridge as well as to effect a rationalization process to drive down construction complexity. The bridge is further geometrically rationalized by *Dsearch* after the secondment to accommodate the abilities of fabricators and to modularize its construction and assembly.

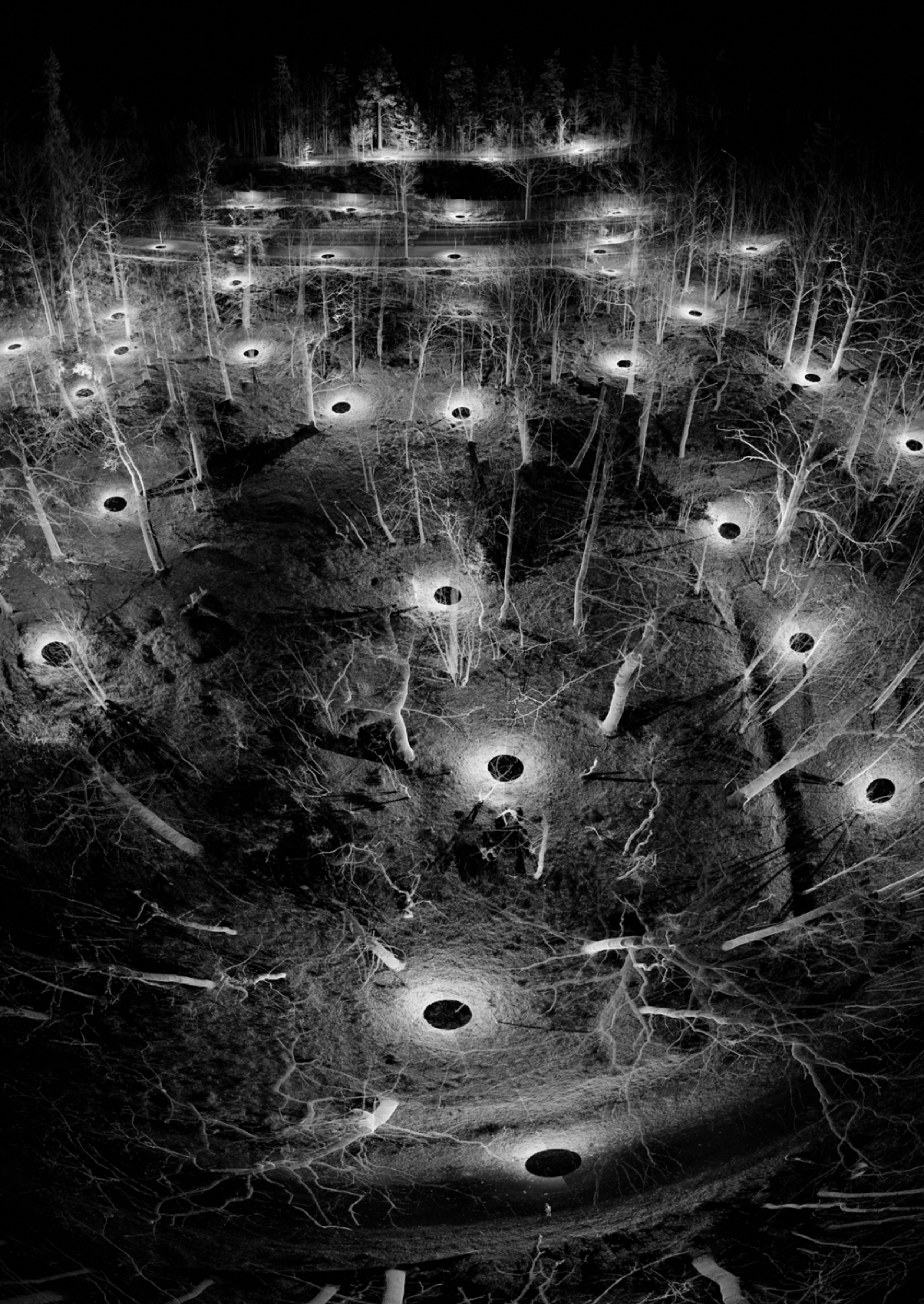
Demonstrator: MBridge



The proposed material practice of this thesis is demonstrated through the development and physical prototyping of a bridge design that diverges from Prototype 5: Magelungen Park Bridge. The design places an emphasis on using free-form glulams in order to challenge the developed methods of modelling and materialization. It employs the branching motifs present in the speculative glulam blank types to avoid a surface-based approach. LiDAR scanning is used extensively during fabrication to enforce the link between model and material, allowing the free-form components to be successfully executed. The glulam modelling tools are used to calculate the material and fabrication requirements, as well as to accommodate logistical limitations.

2

METHODOLOGY



2.1 Overview

This chapter establishes the methodology of this research. It centres the practices of designing and fabricating free-form glue-laminated timber structures as the main focus of investigation, and begins with a notion of *research by design* that is defined by a reflexivity between digital modelling and physical materializing. It proceeds by linking this reflexivity to the relationship between practices of architectural design and industrial timber production - embodied by the two industrial partners - and defining actions of *shadowing*, *mirroring*, and *brokering* that are used to interface with and mediate these practices. In order to confront the multi-scalar nature of timber structures, the research employs a *multi-scalar modelling* framework which allows a cohesive development across multiple scales of inquiry - material, component, and structure. Three domains - modelling, materializing, and integrating - provide thematic lenses through which to examine the experimental development and discuss different aspects of the projects. The thesis employs a *probe-prototype-demonstrator* strategy to discover and develop the experimental work, which is synthesized into and evaluated through a final demonstrator.

2.2 A practice-based approach

2.2.1 Material practice

This research is explored through practices of architectural design and fabrication. As such, it is an example of *research by design* as put forth by Frayling (1993) and contextualized within architecture by Verbeke (2013). This is taken further into the domain of computation and architecture by Ramsgaard Thomsen and Tamke (2009) who define a form of material practice that privileges a reflexivity between modelling and materializing, in a similar way that ’drawing’ and ’making’ have been reflexive and mutually-informing acts in architecture. Because the research progresses by an enactment of its own objective - a new material practice - it is self-reflective and self-analytical. Such an approach encourages acts of reflection by the practitioner, both by ”reflecting in action” and ”reflecting on action” (Schön 1983) which translate to *doing* and *teaching*. While teaching occurs with students in an academic setting, it is also expanded into a wider notion of *brokering* due to the industrial partnerships. That is, the processes of transferring knowledge from one domain to another - from industrial timber fabrication to architectural design - is an opportunity to reflect on the research actions, in a manner similar to teaching.

The interplay of research, practice, academia, and industry requires a clarification of terms. Here, the distinctions between *research* and *practice* provided by Niedderer and Roworth-Stokes (2007) are helpful:

> (...)the term ’research’ is being used to denote the systematic inquiry to the end of gaining new knowledge, and a ’researcher’ is a person who pursues research (e.g. in art and design). ’Practice’ is used to refer to professional practice (in art, design, etc.) or to processes usually used in professional and creative practice to produce work for any purpose other than the (deliberate) acquisition of knowledge. ’Practitioner’ accordingly refers to anyone who pursues professional/creative practice.

This distinction illuminates the nature of practice-based research in this context: the discovery of new knowledge through a systematic inquiry during the production of work. In this research, the practices of designing, modelling, and fabricating free-form glulam components are used to discover new integrative modes of design and making, and to create the required reflexivity between them.

Running orthogonal to these, the contrast between *academia* and *industry* separates work done at *CITA* from work done with or by the industrial partners. Both industrial contexts present different practices - timber fabrication at *Blumer Lehmann AG*, architectural design at *White Arkitekter* - which are different from the academic context at *CITA*. The collaboration with the partners is therefore indispensable to the development of the research. These two practices - *architectural design* and *glue-laminated timber fabrication* - therefore also constitute the two cornerstones of the new material practice, and their synthesis is the process by which the research goals are attained.

2.2.2 Characterising the practices

The employment of these two practices relies on two assumptions. The first is that the practice of architectural design is inherently *propositional*. As such, it is an anticipatory action, which simulates and models a future material reality. The result of this is that design actions inform later actions which are translated into material processes - of which fabrication, construction, and assembly are but three. Information that guides decisions - to perform one design action over another - therefore has a fundamental effect on the end result.

The second assumption is that the practice of industrial timber fabrication is *not propositional*. It involves actions that directly affect material objects - material processes. This direct engagement with material prioritizes considerations of material behaviour, properties, limits, process constraints, and challenges. This helps to characterize architectural design as a domain concerned with modelling or representation, and timber fabrication as a domain concerned with materializing or realization. Additionally, these two practices - the ”making-of-intent” and the ”making-of-artefact” (Ayres, Tamke, and Ramsgaard Thomsen 2012) - are sequentially linked: realization and materialization come after modelling and representation; making comes after intent.

This characterization therefore implies that synthesizing these two practices into a new material practice requires the transfer of material and process concerns to the architectural design domain through informational means, and a corresponding transfer of propositional strategies to the domain of timber processes through prototyping and realization.

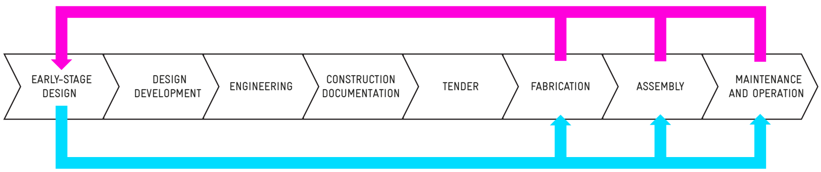


Fig. 2.1: Introducing feedback in the linear design chain.

This synthesis therefore means imbuing the modelling of architecture with material concerns - integrating timber behaviour and performance into design decisions - and expanding the reach of architectural design to encompass the glulam blank and its associated processes (Fig. 2.2).

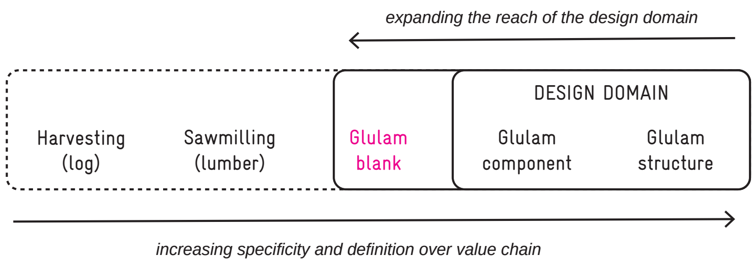


Fig. 2.2: Expanding the scope of timber design.

2.3 Shadowing, brokering, and mirroring

Synthesising these practices requires ways of reconciling the differences between the academic environment and the industry contexts it seeks to engage with. The industry collaborations raise the question of *how* the research can be conducted with each industry partner, and in what capacity does the researcher perform work in each context - in essence the logistics of the collaboration. This is accomplished by a *shadowing* of the production process at *Blumer Lehmann AG* and the *brokering* of material and fabrication knowledge at *White Arkitekter*. Further, this has an impact on the experimental apparatus of the research: replicating the tools and methods of both *White Arkitekter* and *Blumer Lehmann AG* enables the proposal of more relevant and useful practices. A *mirroring* of their practices therefore allows an integration of both contexts to be proposed, however it raises issues related to the scale and complexity of each environment. Svilans, Runberger, and Strehlke (2020) describe these relationships in the specific context of Prototype 5: Magelungen Park Bridge and its divergence into Demonstrator: MBridge, where knowledge gleaned from the secondment at *Blumer Lehmann AG* diverts the original concrete foot bridge scheme at *White Arkitekter* into a free-form glulam proposal.

The active production context at *Blumer Lehmann AG* means that the production apparatus cannot be paused or redirected towards research aims for any period of time. This precludes the research project from driving the production apparatus with its own experiments and prototypes. Instead, the active production during the time of the secondment - a free-form glulam project by Shigeru Ban Architects, in this case - is observed and used for the development and testing of the digital feedback experiments in Prototype 3: Four methods of digital feedback. This means that the actions of the researcher during the secondment *shadow* the production, using its data and models as a basis for the feedback and modelling experiments. This allows development to happen in tandem with production, with the feedback tests happening at precise points during breaks in production. This injection of smaller tests throughout the shadowing also allow an incremental contribution to the processes at *Blumer Lehmann AG*: if a feedback test is successful and useful to the production - increasing the speed of registering a free-form blank on the CNC machine, for example - it is kept, and if it isn't, it is rolled back.

The secondment at *White Arkitekter* enables a different role for the researcher: that of a broker of information between production and design. Arriving after the secondment with *Blumer Lehmann AG*, fabrication information, modelling methods, and constraints observed during the active production there can be transmitted to the design teams at *White Arkitekter*, which in turn helps to steer the early proposals of projects in Prototype 4: Slussen benches and Prototype 5: Magelungen Park Bridge. A collateral result of this brokering use during the secondment is a validation of the need for the kind of material practice proposed by this thesis: knowledge gleaned through an involvement in the industrial production of glue-laminated timber elements proves advantageous in a design environment.

The *mirroring* of each secondment context enables their synthesis into an integrative practice that combines aspects of both. While this is difficult from an organisational and political point of view - such complex and unique organisational structures and political, not to mention cultural, relationships cannot be replicated by a single researcher located in another country - it is more feasible to mirror the *tools and processes* used in both the practice of designing buildings and the practice of fabricating large timber elements.

Because of the ubiquity of design software and the architectural background of this research, this is easier with *White Arkitekter*. For example, the software platforms - McNeel's Rhinoceros 3D and Grasshopper - used in their design processes are the same as used by schools and many other practitioners. Especially in the early stages of design, sketches done with pens on paper are used to convey strategies and principles.

The context of *Blumer Lehmann AG* presents a much more specialized and less generalist condition: the scale and complexity required to manage and produce large-scale free-form glulam members is not simply transferable to a research context. The mirroring of workflows and tools in this case must be one of *similarity*, not of *congruency*. Therefore, in aspects relating to the production of glulam elements, the reproduction of the industrial processes at *Blumer Lehmann AG* happens at scale: with smaller elements and smaller machines. The production of Demonstrator: MBridge strives to remain true to this objective by using equipment that is very similar to that used by *Blumer Lehmann AG* albeit at a smaller scale: a 5-axis CNC wood processing centre that uses a standard form of G-code that is very similar to that used to drive the 13-axis CNC portal mill at *Blumer Lehmann AG* (Fig. 2.3).

(a) The 5-axis CNC wood processing centre at Aarhus Architecture School, Aarhus, Denmark.

(b) The multi-axis CNC production centre at *Blumer Lehmann AG*.

(c) A prototype glulam blank at *CITA*.

(d) A free-form glulam blank at *Blumer Lehmann AG*.

(e) Robotic machining at *CITA*.

(f) Multi-axis machining at *Blumer Lehmann AG*.

Fig. 2.3: The contrast in scale between the research context and industry.

2.4 Multi-scalar modelling

The presence of multiple, interrelated scales is a characteristic both of architectural design as well as timber - both as an organism and as a material system. As discussed later on, the morphology and structural performance of a tree is tightly related to the distribution of differentiated wood fibres throughout its mass. The design of timber structures profoundly affects the types of joints and material orientation at a local scale. In a very general sense, three important scales within the design of buildings are the detail, the element, and the overall structure. In modelling architecture, this can be seen as the difference between the finite-element model used for simulations of material deformation, geometric models of components and structural elements, and overall models which position individual elements in relation to one another. Engaging with the design and production of timber structures therefore necessitates a framework for linking these different scales.

Multi-scalar modelling is a framework used to simulate systems of high complexity which involve different interdependent phenomena occurring over several separate scales. With its origins in the nuclear programme at the US Department of Energy (DOE) labs, the concept has developed into an interdisciplinary activity in a wide variety of industries and fields (Horstemeyer 2009). The concept is used in the study of physical phenomena such as, fluid mechanics (Chen, Wang, and Xia 2014), digital signal processing (Barth, Chan, and Haimes 2001), and weather, as well as in the automotive and aeronautics industries (Horstemeyer 2012). With regard to wood and the material sciences, this technique has been used to investigate phenomena such as the drying of porous hygroscopic materials (Carr, Turner, and Perre 2013).

Its application to architectural systems has been the topic of research at *CITA*. Multi-scalar modelling is explored in other projects at *CITA* such as *Dermoid* (Burry et al. 2012), *A Bridge Too Far* and *Lace Wall* (Ramsgaard Thomsen, Tamke, et al. 2017), and the phase-change material (PCM) prototype described by Faircloth et al. (2018). The methodologies employed within these multi-scalar projects are further described by Nicholas, Zwierzycki, and Ramsgaard Thomsen (2015), where they are considered as ”nested organizations from which features, behaviors, and properties emerge on the basis of interactions across scales and systems”. Negotiating these nested organizations takes different forms: Nicholas, Zwierzycki, Nørgaard, et al. (2017) use a mesh refinement and coarsening strategy to move between local panel geometries and overall structural form in the design of a bridge using incremental sheet forming; Faircloth et al. (2018) use a mechanistic model of phase-change materials, supported by physical testing, to drive larger facade designs based on expected and desired solar performance.

There are three main scales that are addressed in this research, corresponding to the small-, medium-, and large-scale considerations in timber structures: the localized distribution of material properties such as fibre direction, the modelling and fabrication of individual glulam components, and the management of architecturally-scaled glulam assemblies and structures. These map onto a *micro, meso, macro* categorization, terminology which is borrowed from other considerations of multi-scale systems such as in mathematics and biology (Lachowicz 2011). Whereas in other fields the micro-scale corresponds with the world of atoms and the macro-scale with what can be seen with the human eye, in this architectural context the micro-scale instead corresponds to the particular material resolution - in this case, the cellular make-up of timber and its locally-varying properties - and the macro-scale corresponds to the building or structural assembly, which does not take into account localized material variability. This characterisation of the different scales is described by Faircloth et al. (2018):

> (...) the macro scale encompasses the resolution of global design goals, overall geometric configurations, and a full-scale understanding of structural performance. The meso scale considers the project at an assembly and sub-assembly level, and is concerned with material behaviours tied to geometric transformation, detailing and component-level tectonic expression. The micro scale is concerned with relevant material characteristics at the most discretized level (...)

Applying this differentiation to glue-laminated timber structures, this research addresses:

- the scale of the wood fibre or *micro/material scale*
- the scale of the glulam blank or *meso/component scale*
- the scale of the glulam structure or *macro/architectural scale*

With regard to the density of information found in architectural models with many components, a *concurrent coupling* approach (Weinan 2011) offers a way to keep the overall model light and computationally agile. In this case, computationally expensive operations such as generating the complete glulam geometry are performed only when required.

As described by Poinet (2016) and Svilans, Poinet, et al. (2017), multi-scalar modelling is particularly useful in the material modelling of glue-laminated timber, since it involves intertwined considerations of local fibre direction, glulam types and composition, and role within the larger structural system. It recognizes the multi-scalar nature of timber - from fibre to branch to tree - of engineered timber - from fibre to lamella to glulam - as well as the multi-scalar nature of constructing buildings - from element, to assembly, to structure. The digital modelling experiments Probe 1: Modelling wood properties and Prototype 1: Glulam blank model integrate the notion of multi-scalar modelling in their development: the representation of localized fibre orientation throughout a single piece of timber is expanded to a laminated timber model, further into an abstracted glulam and lamella model that is useful at an element scale, and, finally, to a graph-based relational model describing entire structures. The interrelated scales and cascading effects of changes in this modelling method are developed in Prototype 2: Grove and especially Demonstrator: MBridge. The negotiation between scales happens through an iterative change at the macro level and verification at the micro level.

2.5 Industrial partners

2.5.1 Role of the industrial partners

As discussed before, the project methodology relies heavily on the collaboration with the industrial partners. The relationships with *White Arkitekter* and *Blumer Lehmann AG* serve as a conceptual base and springboard to investigate the topic through real-life examples and issues directly related to practice and industry.

The differing nature of the industrial partners serve as a model for the tension between their respective knowledge domains - between design and production. The partnership with *White Arkitekter* - a multi-disciplinary architectural practice - and *Blumer Lehmann AG* - a timber contractor - represent both sides of this divide. In this sense, the partners are stand-ins for the whole domain of architectural design and the whole domain of industrial timber production. Although this generalization is problematic because of the diversity and uniqueness of every architectural practice and timber contractor, the disparities between early-stage design and late-stage production are not unique. The portfolio and type of office that *White Arkitekter* possesses are representative of similarly-sized practices that operate in similar ways. As a timber contractor responsible for some of the most prominent examples of contemporary timber architecture, *Blumer Lehmann AG* are well positioned to represent the current state-of-the-art in timber construction and its challenges.

The research engages both partners separately and together to identify needs, opportunities, and potential avenues of exploration. In addition to the methods of *shadowing*, *brokering*, and *mirroring* discussed before, this creates a *knowledge extraction* from the partners which is used to validate the research. Digital modelling and design tools - developed in Probe 1: Modelling wood properties and Prototype 1: Glulam blank model, and utilized in Probe 5: Branching Probe and Prototype 2: Grove - are tested during the secondment at *White Arkitekter* for their usability and for whether or not they are helpful in developing a robust case for a free-form timber project in the early design stages in Prototype 4: Slussen benches and Prototype 5: Magelungen Park Bridge. The glulam prototypes from Probe 4: CITAstudio glulam workshop are validated by feedback from *Blumer Lehmann AG* to gauge their feasibility - whether or not they are realistic proposals or folly. The glulam blank model is validated in the same way: by acquiring feedback from *Design-to-Production GmbH* and *Blumer Lehmann AG* about its use, applicability, and whether or not it provides advantages against current modes of modelling glulam blanks.

2.5.2 Secondments

To create an opportunity for this collaboration and validation of research developments, an industry secondment is conducted with each partner: 4 months with *Blumer Lehmann AG* in Gossau, Switzerland; followed by a 4-month break to reflect and develop the research back at *CITA* in Copenhagen, Denmark; and further followed by 3 months with *Dsearch* and *White Arkitekter* in Stockholm, Sweden. The length of time allows the research to gestate and better understand the needs and particularities of each context, and to develop experiments that could be meaningful for both the research as well as the industrial partner.

The secondment with *Blumer Lehmann AG* results in the digital feedback experiments in Prototype 3: Four methods of digital feedback as well as an understanding of the glulam fabrication process that is integrated into the on-going glulam blank model in Prototype 1: Glulam blank model. The procedures for digital feedback are further developed and tailored afterwards for use in the fabrication of the final Demonstrator: MBridge.

The subsequent secondment with *White Arkitekter* creates the opportunity to deploy the digital modelling tools developed in Prototype 1: Glulam blank model and the thinking from novel glulam prototypes in Probe 4: CITAstudio glulam workshop in active architectural projects there. This results in the development of Prototype 4: Slussen benches and Prototype 5: Magelungen Park Bridge, where these tools and thinking are applied to projects that involved larger project teams. The preceding secondment with *Blumer Lehmann AG* also enables the brokering of fabrication knowledge between *Blumer Lehmann AG* and *White Arkitekter* in an unofficial capacity. This is explored in Svilans, Runberger, and Strehlke (2020) and forms the basis for the notion of *brokering feedback*.

The work performed during the secondments is therefore used to strengthen the applicability and relevance of the research, as well as to provide new insights into the nature of the material practice that the research seeks. These developments feed into the final Demonstrator: MBridge demonstrator: directly using an evolution of the modelling and digital feedback techniques explored with *Blumer Lehmann AG* and using the Prototype 5: Magelungen Park Bridge project at *White Arkitekter* as an architectural driver for the final demonstrator.

2.6 Experimental domains

The multi-scalar approach in this research is thus explored through the domains of modelling and materialization, which direct the type of experimentation that occurs. These two experimental domains are synthesized and deployed through a third domain: design implementation. This domain encompasses the interrelation between modelling and materialization, and how that is transferred to the context of design projects with multiple stakeholders. This leads to a tripartite organization of the thesis which reflects the tension between digital model, material fabrication, and their synthesis and implementation into architectural design projects. While the experimental work traverses all the domains, certain projects are better suited to a particular domain than another. For example, Probe 1: Modelling wood properties and Prototype 1: Glulam blank model are primarily software-based modelling experiments that reside in the domain of digital modelling. They are used and developed in tandem with fabrication activities and within design projects, however their weighting within the tripartite structure is heavily towards the computational model. Similarly, most of the design projects and architectural case-studies combine both modelling and materializing aspects, but are primarily acts of synthesis and implementation.

The tripartite structure of the research is further linked to specific research environments. This means that, within each domain, the experimental work is of a different nature and also reflective of a different operating context that it draws upon.

- The domain of architectural *modelling* and *computation* is linked to the research environment at *CITA*.
- The domain of glulam *materialization* is linked to the industrial fabrication environment at *Blumer Lehmann AG*.

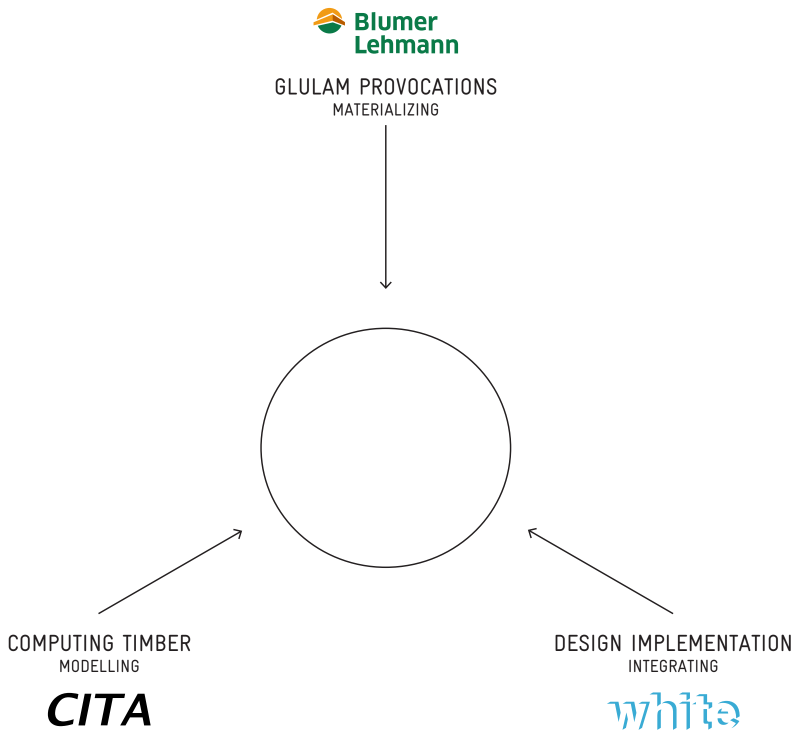


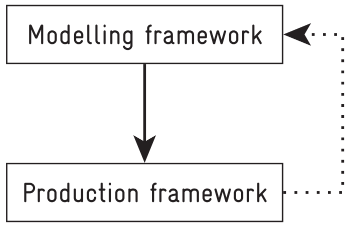
Fig. 2.4: The tripartite approach of the thesis to forming the material practice.

- The domain of *design implementation* and *brokering* is linked to the architectural design practice environment at *White Arkitekter*.

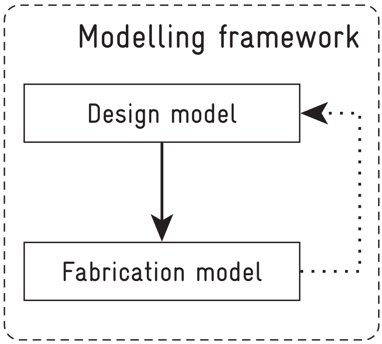
2.6.1 Subdomains

The domains of modelling and materialization are further broken down into more specific frameworks that address design modelling to the purposes of fabrication and the production framework of glue-laminated timber elements. The feedback from materializing to modelling proposed by this research is also reflected within these two subdomains (Fig. 2.5c).

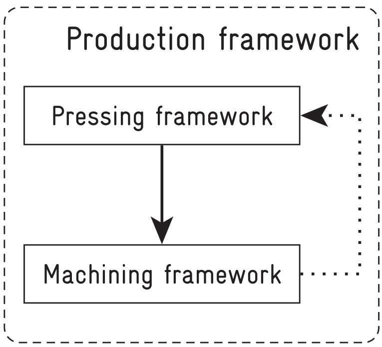
The domain of modelling seeks to create a link between fabrication concerns and design modelling. This challenges the linearity of graduating from a design model to a fabrication model. Similarly, the materialization of glue-laminated timber components involves a fabrication of the glulam blank within a pressing framework and its subsequent transformation into the finished glulam component through the machining framework. The domain of materialization therefore seeks to reconnect the machining framework to the pressing framework.



(a) The proposed feedback link between production and modelling.



(b) The proposed feedback link between models for fabrication and models for design.



(c) The proposed feedback link between the machining framework and the lamination framework.

2.7 Probe, prototype, demonstrator

Across the experimental domains, the experimental projects have different roles in the overall development of the research. Continuing the adoption of the definition of material practice by Ramsgaard Thomsen and Tamke (2009), the *probe, prototype, demonstrator* strategy is used to separate exploratory forays - probes - from more defined and convergent work - prototypes and demonstrators.

Probes are used to explore the research territory and look for relevant research questions and productive areas of focus. Prototypes develop questions raised by the probes into prototypical solutions and manifestations of specific topics. These include prototypical software tools, implementations of sensor systems into production workflows, speculative new glulam types, and new design methods. The modelling and materialization domains are generally focused on probing and prototyping new processes. The design implementation domain deploys these processes in prototypical design workflows. The experimental work culminates in a final demonstrator which synthesizes all three domains into a design-to-production practice.

2.7.1 Mapping the projects

In Fig. 2.6, the experimental work around the fringes of diagram is classified as *probes*. Moving towards the centre, the experimental work becomes more intertwined and synthesized as *prototypes*, and finally is demonstrated as an integrative material practice at the very centre - the *demonstrator*.

2.7.2 Probing through teaching

Teaching performs an integral role within this research as an initiator of new ideas and as a probing of the research topic. While undertaken through workshops as well as informal on-going interaction with students, the two taught workshops throughout this research play crucial roles in driving ensuing experimentation and development work.

Probe 2: IBT glulam workshop is a primary driver of both the domain of modelling and the domain of materializing. It represents the first entry point into the research and creates the base work that allows further digital and material probes to evolve. The workshop is a 1-week exploration of how free-form glue-laminated timber beams are digitally modelled and how they are fabricated. As a basic introduction to computation in the service of material processes, this early workshop is used to outline the research problem and find paths for further inquiry. As a key driver of the work in

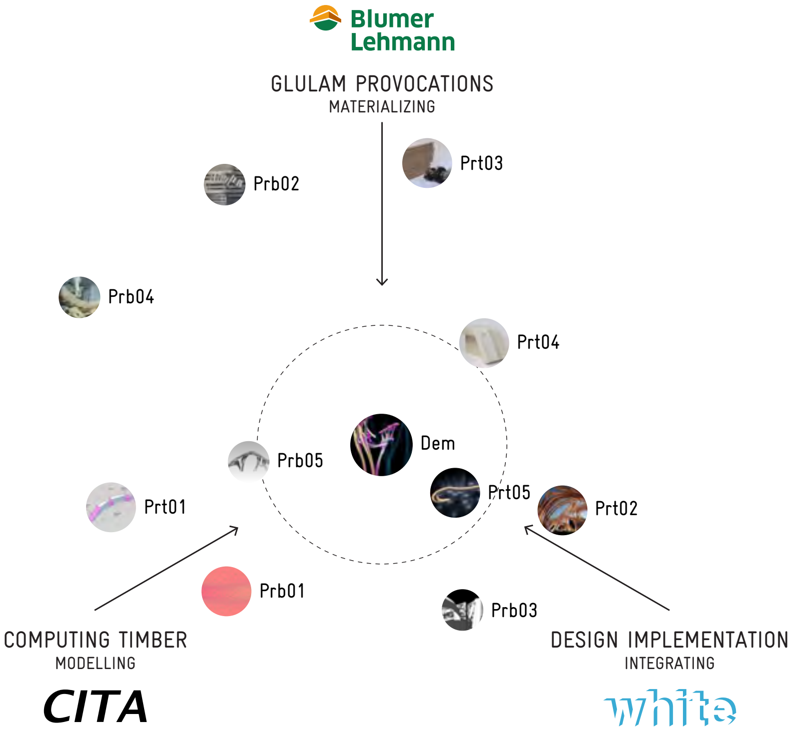


Fig. 2.6: Mapping the projects onto the experimental domains.

Probe 1: Modelling wood properties
Probe 2: IBT glulam workshop
Probe 3: Future Wood workshop
Probe 4: CITAstudio glulam workshop
Probe 5: Branching Probe

Prototype 1: Glulam blank model
Prototype 2: Grove
Prototype 3: Four methods of digital feedback
Prototype 4: Slussen benches
Prototype 5: Magelungen Park Bridge

Demonstrator: MBridge

both domains of modelling and materializing, it appears in both of their respective chapters, albeit from different perspectives. In terms of modelling, it seeds the development of Prototype 1: Glulam blank model which is then used throughout all the design projects such as Probe 5: Branching Probe, Prototype 2: Grove, Prototype 5: Magelungen Park Bridge, and Demonstrator: MBridge. In terms of materializing, it lays out the framework for questioning the glue-lamination and machining processes and begins the direct engagement with this process, which leads to Probe 4: CITAstudio glulam workshop and the five speculative blank types.

Fig. 2.7: Exploring new glulam morphologies in Probe 4: CITAstudio glulam workshop.

Probe 4: CITAstudio glulam workshop comes later in the experimental development of the research and is used to reaffirm the boundaries of the research project as well as to physically articulate notions of bespoke and novel glulam morphologies (Fig. 2.7). Again, this workshop becomes a key driver in later projects which then employ the new glulam blank types that result, as well as the methods of scanning and merging the digital model with the material artefact. Examples of this are the Branching Blank from the workshop being used in Prototype 2: Grove and in the final Demonstrator: MBridge, and the Kinky Blank being used during the industry secondment at *White Arkitekter* during Prototype 4: Slussen benches. The digital feedback developed here is subsequently explored in an industrial context in Prototype 3: Four methods of digital feedback.

2.7.3 Prototyping through doing

"Reflection in action" underlies the practice-based approach and consists of performing the actions associated with glue-laminating timber and designing architecture to achieve new insights. The questions generated in the probes are investigated further and are developed into tools, methods, and strategies that also involve the industrial partners. In this respect, prototyping - either software or physical objects - relies on the methods of shadowing and mirroring due to the differing scales and boundaries of the industrial practices.

The practice of doing is present in all experimental projects in some form. For example, Probe 1: Modelling wood properties and Prototype 1: Glulam blank model are experiments in digital modelling and representation, but enact the type of tool-building and creation of relationships between material and model that the practice promotes. Projects such as Prototype 2: Grove and Prototype 4: Slussen benches demonstrate a physical hands-on prototyping of glue-laminated elements as well as relating these prototypes to the practice of architectural design.

Discussing the overarching nature of the practices establishes the main targets for this research, however the specific and practical activities that comprise the "doing" part of the research also need to be enumerated. What follows is a summary of the constituent practices that are performed as part of the experimental work. Each in turn could be elaborated into a detailed practice with its own conceptual underpinnings and implications.

Integrating sensors and models

The link between the material and the model constitutes an important step in creating a measure of direct feedback. This activity is the most technically-involved as it requires knowledge of electronics, signal types, communication protocols, hardware development, software APIs for manufacturer-specific hardware-software libraries, as well as knowledge of how to connect the outputs from these processes to software APIs for the digital modelling environments.

The development in Prototype 3: Four methods of digital feedback is particularly demonstrative of this complexity, as it involved designing and

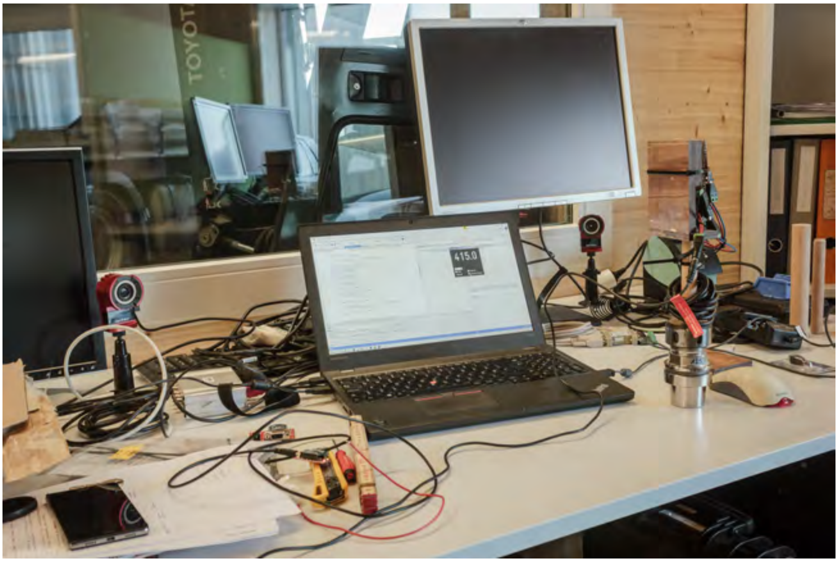


Fig. 2.8: Designing, building, and wiring a scanner system at *Blumer Lehmann AG* during Prototype 3: Four methods of digital feedback.

constructing a wireless 3D scanning head for the custom-built multi-axis machining centre at *Blumer Lehmann AG* along with a software interface that both allowed the machine operator to monitor the sensor data in real-time (Fig. 2.8), as well as saving and accessing this data within the 3D fabrication model used for generating tool paths. Other parts of this experiment involved using manufacturer-specific APIs to access data from sensor products and pipe it into the modelling environment in McNeel's Rhinoceros 3D (Rhino3D).

Developing software

In order to create new types of digital models, knowledge in software development is necessary. This constitutes both using the visual programming interfaces such as Grasshopper in Rhino3D, as well as more extensive program-building and plug-in development. Once again, software APIs need to be understood and known in detail to permit a useful navigation of their capabilities.

The software development in this research can be organized into several levels, delineating the level of involvement in the functions of the computer - from so-called "high-level" languages and approaches such as visual or node-based programming to "low-level" programming languages such as C++ which allow a much finer control over the manipulation of data at the cost of programming complexity:

- Visual, node-based programming using Grasshopper, a plug-in for McNeel's Rhinoceros 3D modelling environment. This includes creating Grasshopper "definitions" - node layouts which together form a program, taking specific inputs and processing them into specific outputs.

- Embedding scripts within the node-based programming workflows. This combines Python or C# scripts with the node-based workflows described above and is a useful way of combining high-level and low-level approaches.

- Developing plug-ins and software interfaces to other programs. This includes creating new nodes that fulfil a unique function within the node-based environment or creating new menu options or commands for functions that are not in the original program.

- Developing new programs entirely. These are developed as stand-alone software programs that accomplish a variety of functions, depending on their needs. The simplest type are command-line programs that use command-line arguments or network connections to load variable data and generate useful output. Examples include a program written in C++ to monitor sensor data in real-time and distribute it on-demand to other client programs that need it, or a utility to batch-convert scan files from a proprietary format to an open-source format. More complex examples include a program to load scan files, display their data as an image, allow the selection of reference points on the image, and use those points as helpers for the coarse alignment and registration of point clouds.

Modelling material properties

This research uses the notion of the model "as a means of understanding the material reality of our built environment and of probing its possible configuration" (Ramsgaard Thomsen and Bech 2012). Situated primarily in the domain of computation and digital representation, this activity involves the abstracting of material properties, behaviours, and constraints and superimposing them onto digital models, or attaching them to geometric models of material objects. An example of this is the Eurocode-enforced bending limit relationship between the thickness of a glulam's lamellae and the minimum bending radius of that glulam. Converting this material constraint to a digital model means translating it into a parametric formula: the glulam model must be sampled for curvature, the maximum curvature is algebraically translated into a maximum lamella thickness, and this thickness is reflected in the glulam model and in the number of lamellae required to fabricate the glulam. Another example is the relationship between grain orientation and model geometry: given some indicator of grain direction, the surface normals of the geometry can be compared to this direction, and from this the amount of simulated ”end grain” can be determined through simple vector transformations and algebra. Performing these translations and conversions requires an understanding of mathematics, geometry, and the principles behind the material properties that are to be simulated.

Here it is useful to refer to how material behaviour is considered in manufacturing: behaviour in the context of material production is characterized by the response of the material to the conditions of the unit process (National Research Council 1995). This means that deriving the behavioural relationships between a material and a particular unit process is the first step in simulating this process. In this research, this occurs through a haptic and intuitive distillation of principles through material manipulation as in Probe 2: IBT glulam workshop, references to codes and regulations such as the Eurocode section relating lamella thickness to bending radius, and through a working-through of geometric principles, which are discussed later in the context of Probe 1: Modelling wood properties and Prototype 1: Glulam blank model. Through these ways, material behaviour, properties, and constraints are encoded and embedded into digital models and data structures.

Designing

The final, and most over-arching activity, is designing objects and structures with glue-laminated timber which employ, and are informed by, the prior activities. While this is most clearly elucidated in the architectural design projects such as Prototype 2: Grove, Prototype 4: Slussen benches, Prototype 5: Magelungen Park Bridge, and the final Demonstrator: MBridge (Fig. 2.9), design also takes place in the tool-building, software development, and material prototyping activities of the research.

The key characterisation of designing in this research is that it happens through a haptic engagement with glue-laminated timber and an oscillation between modelling and making. This imposes a requirement to understand the fabrication processes in question: ”the architect who wishes to engage in the direct instruction of fabrication must develop the requisite knowledge of the procedures under consideration, and their material implications.” (Ayres, Tamke, and Ramsgaard Thomsen 2012)

Fig. 2.9: Designing the bridge in Prototype 5: Magelungen Park Bridge at *White Arkitekter*.

2.7.4 Demonstrating through synthesis

The research sets out to develop an integrated material practice between the modelling and materializing free-form glulam structures. To this end, it creates a set of models and methods at different scales and ties them together using a multi-scalar modelling approach. This multi-scalar ecology of models is developed through applied design proposals and physical prototyping. To evaluate the synthesis of the experimental work, a final demonstrator project deploys the modelling tools and materializing strategies towards the architectural design of a timber footbridge: Demonstrator: MBridge.

The successful execution of the demonstrator - whether or not the developed methods successfully allow the demonstrator to be designed, managed, and fabricated - is the main criteria for evaluation. The probes and prototypes result in a set of part studies that are orchestrated into the final demonstrator: modelling, representing, and materializing a free-form glulam structure and leveraging the different notions of feedback (Fig. 2.10).

Different notions of feedback are exposed through the experimental work in all three domains. These are brought together in Demonstrator: MBridge and serve as mechanisms for synthesizing the materialization of free-form glulams with their design and modelling. Their contribution towards the successful realization of the demonstrator validates their role in defining an integrated material practice in free-form timber structures.

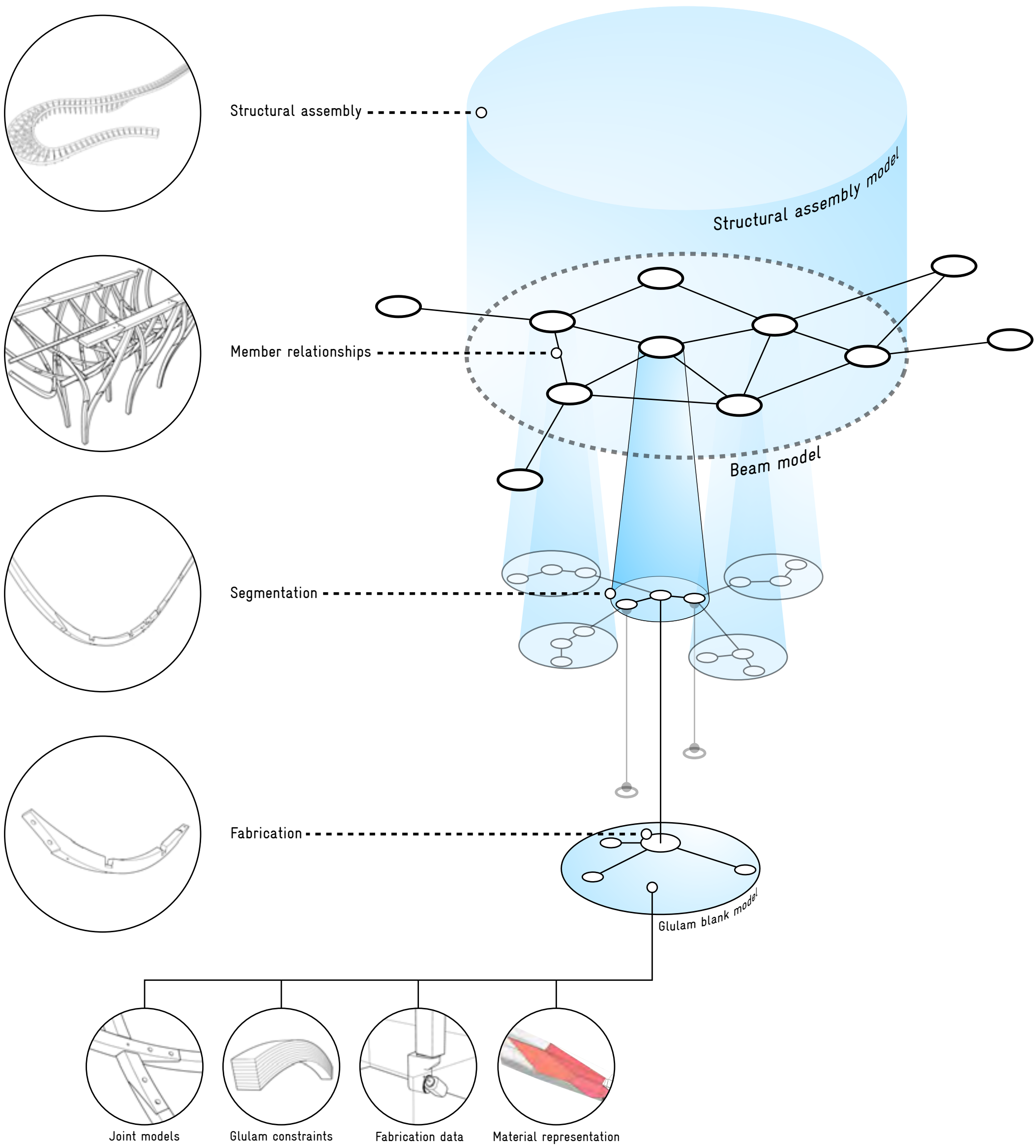


Fig. 2.10: The research develops a multi-scalar model consisting of multiple sub-models: from a graph-based model at the scale of the structural assembly, to geometry models of individual components, to the mapping of material properties on smaller elements.

3

STATE OF THE ART


Lehmann

3.1 Overview

This chapter is structured around the goal of understanding the contemporary foundations of a new material practice in free-form timber structures. In relation to this goal, it asks:

- Where is the understanding of timber today?
- What is the state of glue-laminated timber today?
- What are current developments in architectural design and production today, and how have new notions of material practice come about?

As a point of focus, it is centred around the notion of the *glulam blank* - the object that occupies the space between sawn lumber and the finished architectural glulam component - its origins, its properties, and its evolution alongside current modes of digital design practice (Fig. 3.1). The glulam blank is identified as the convergence of the material complexity of timber, industrial sawmilling and fabrication processes, geometry and performance demands, and contemporary digital design culture.

As such, the chapter is divided into five sections:

- The first section provides an overview of the contemporary relevance of timber and timber construction, along with an enumeration of its immediate benefits and its growing importance in design and construction today.
- The second section explains the material complexity and key characteristics of wood, as well as its multi-scalar nature. This is important to establish the fundamental properties which impact the design and use of glue-laminated timber components: anisotropy and elasticity. The diversity and variance of wood are identified as

key challenges for the processing of wood, however the strategic allocation of fibre orientation throughout the tree is conversely identified as a possible model for the design of laminated timber components.

- The third section describes the translation from wood as a natural organism to timber as an industrial construction material. A similarity is drawn between the multi-scalar nature of wood in nature and the multi-scalar taxonomy of engineered wood products (EWPs) made from various types of industrialized wood fibre. This section also establishes the main categories of shaping wood - subtracting, bending, and aggregating - and relates these to the wood characteristics identified in the first section - anisotropy and elasticity. The *glulam blank* is identified as the convergence of all these factors: anisotropy and strength / durability, bending and elasticity, glue-lamination and the EWP taxonomy.

- The fourth section provides an overview of the development of glue-laminated timber construction, from its beginnings in the pioneering work of Otto Hetzer to its resurgent use in contemporary architecture. A comparison with experimental, lightweight timber typologies such as grid-shells situates glulam structures as more predefined and stereotomic assemblies, in opposition to the filigree and materially-active grid-shell structures. This differentiates the field of free-form glue-laminated timber from other fields that investigate the properties and behaviours of timber.

- The final section looks at the use of glulams in architectural design today and the development of new types of digitally-enabled material practice. Beginning with the overall digital shift in architecture, current developments in the design of free-form timber structures are traced from the digitally-enabled automation of timber manufacturing, to the resurgence of prefabrication paradigms, and finally to renewed notions of craftsmanship in architecture. The *digital craftsman* is a reunion of the architect and the tools of architectural production - the architect-maker. The role of digital technologies such as sensing and simulation is emphasized in the return of a material agency in architectural design, provoking discussions about feedback and material simulation.

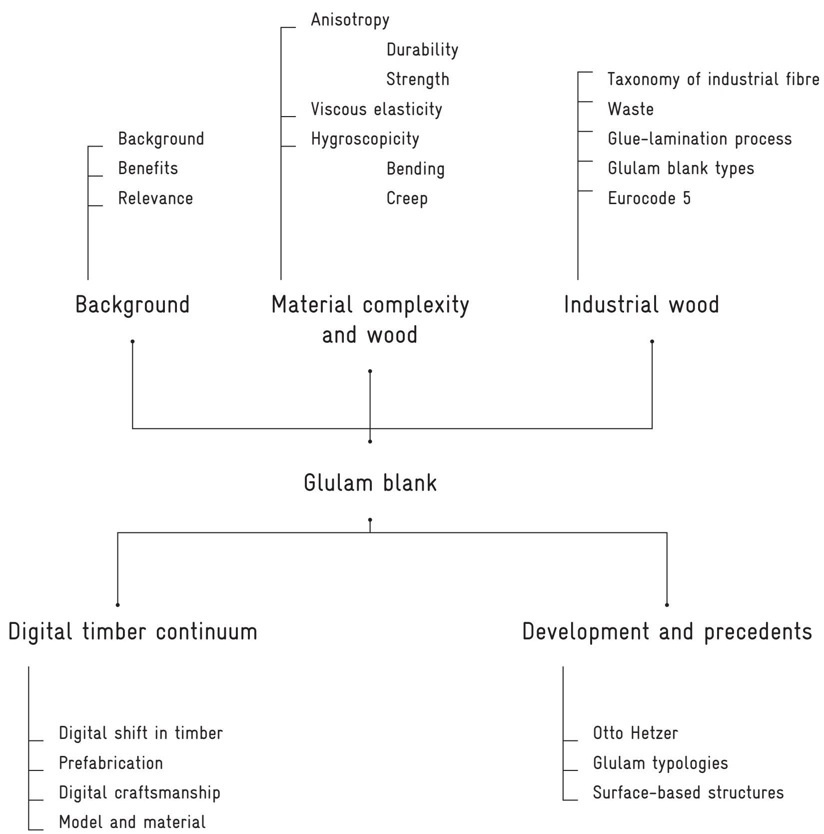


Fig. 3.1: The chapter is divided into five sections which impact the understanding of the glulam blank.

3.2 Background

3.2.1 Wood and civilization

It is easy to understate the importance of timber in the development of modern civilization. Timber is one of the oldest material resources exploited by humankind for so many aspects of its survival and progress - shaping its environment, sustenance, creating habitats, economics, and waging war. In *Technics and Civilization*, historian and philosopher of technology Lewis Mumford expounds upon the qualities of wood that set it apart from any other natural materials, asserting that it is the most fundamental material in the shaping and development of civilization: its role in delivering man ”from the servitude to the cave and to the cold earth itself”, in the tools that enabled digging for stone and minerals, its versatility in processing, and its adaptivity to a huge multitude of functions and purposes. Even stone was secondary, according to Mumford: ”Wood, then, was the most various, the most shapeable, the most serviceable of all the materials that man has employed in his technology: even stone was at best an accessory” (Mumford 1934, p. 77-79). Later on, wood remained a pivotal element in the growing pains of Central Europe, both in terms of its technological potential as well as in the politics of its access and distribution. Joachim Radkau describes the political struggles between those who owned forests and those who lived in and used them. Economics, politics, and wood resources - both as fuel for the furnaces of the mining industry and as a building material - were tightly bound together, especially in the face of wood shortages (Radkau 2012).

In light of this foundational role that wood plays in the shaping of our physical surroundings, it is no surprise to find it in all sorts of corners of society and culture, including language. Linguistically, the word *architect* and its roots derive from terms associated with wood: ”master builder” in some accounts and - more precisely - ”master carpenter” (Perlin 2005). So does it appear in more recent architectural theory as well: Kenneth Frampton writes that the origin of the term ”tectonic” comes from Sanskrit words relating to carpentry and Auguste Choisy suggests that important elements of the Greek Doric order are direct translations from carpentry principles and methods (Picon 2014). Further in tectonic theory, Gottfried Semper’s prototypical primitive hut is a wood hut, again relating the origins of tool-making and building to the use of wood before anything else (Semper 1851). In this discourse, tectonics and wood sit in opposition to stereotomics and clay; filigree and lightness versus mass and solidity. However, as will be later discussed, glue-laminated timber in fact presents an opposing character: a stereotomic aggregation of wood mass that is carved into highly complex forms.

Wood has driven many building traditions around the world: the stave churches of Norway are an example of enduring Scandinavian wood architecture from many centuries ago (Fig. 3.2); the highly respected Japanese tradition is well known and still finds application today, either with traditional means or with modern reinterpretations using numerically controlled machines and new technologies.

The contemporary usage of wood is still vast and diverse: its use as a source of energy has expanded from firewood to the production of wood pellets for furnaces and power plants; the industrial revolution brought standardized lumber and stick framing traditions for the production of mass housing; it permeates the household in furniture, utensils, and fashion. Indeed, the presence of wood has permeated all facets of life in all of its different manifestations - from its figure and aesthetics to its utility in building and

Fig. 3.2: Heddal stave church, Notodden. The largest stave church in Norway. Photo: Micha L. Rieser

toolmaking.

3.2.2 Benefits

The benefits of timber as a construction material are several. As a grown organism, its supply requires only sunlight, water, and good soil. Once cut, forests can be replanted. Properly maintained and with good stewardship, they can be harvested and replenished indefinitely. In contrast to concrete and steel, wood begins its life with a carbon negative footprint, absorbing carbon from the atmosphere through the leaves of trees and sequestering large amounts of carbon in the dense mass of their trunks. This head start over the energy-intensive extraction and smelting processes required to bring other materials into existence often keeps it ahead all the way to the building site - and sometimes by a very hefty margin, depending on the type and degree of processing along the way (Robertson, Lam, and Cole 2012). Further, the responsible harvesting and usage of timber for engineered wood products provides a greater sequestration of carbon than in unharvested forest stock (Oliver et al. 2014), meaning that the usage of wood in construction has more benefits than simply letting the wood grow.

The easy workability of wood translates into less energy and time spent turning it into a finished product as well as a particular accessibility, flexibility, and versatility. Wood is machined with multi-axis CNC machines in large dedicated production halls, but it is also carved by hand in backyard workshops, or shaped by electric hand tools on the building site. The ease with which trees can be turned into comfortable homes and warm shelters is well known, even in the cold northern climates, as evidenced by building traditions in Scandinavia and North America, for example. If maintained correctly, wood provides a pleasing interior environment and helps to mitigate fluctuations in moisture. Due to its porous cell structure and fibrous mass, it is also a decent heat insulator.

From a technological point of view, advances in material sciences, manufacturing technology, and material engineering have led to an explosion of new types of timber products, new applications for timber in construction, and an increased precision and economy of processing and assembly. Increased precision in industrial processes has decreased the margin of error typically attributed to crafted wood construction and made its structural analysis more robust and predictable (Radkau 2012). The evolution of timber processing has shifted from haptic and immediate involvement by the workman to an information-based production which privileges automation and the use of machines to ”replace both physical and intellectual labor” (Schindler 2007). Developments in structural adhesives throughout the 20th century have enabled timber to surpass the limits of the log - important as the older, larger stock of forest becomes more scarce - and use smaller trees or timber stock of a lower quality to produce higher-quality building products. An example of this is the strong surge in adaptation and acceptance of cross-laminated timber (CLT) by the building industry (Brandner 2014; Karacabeyli and Brad 2013; Amy Frearson 2015). Developed as a way to utilize lower-quality timber and otherwise unusable stock, CLT panels are finding a particularly strong uptake in the design and construction of multi-story buildings and large-scale housing projects as an alternative to concrete construction.

Glue-laminated timber is being used as an alternative to steel and concrete construction, and is seeing an increase in formal and technical complexity due to advances in computer-controlled machining and advanced timber engineering (Müller 2000). New adhesives and lamination techniques have introduced new possibilities, such as hardwood glulams (Muraleedharan, Reiterer, and Bader 2016) - which allow the utilization of new hardwood timber stocks previously left untapped for large-volume construction; block gluing - the structural gluing of finished architecturally-scaled components, exemplified in bridge construction (Aicher and Stapf 2014); and reinforcement via fibres and other composite means (Romani and Blaß 2001).

Comparisons to other building materials

Timber and engineered wood products also provide certain advantages over other common building materials such as concrete and steel. Mumford emphasized these, noting that ”wood has the qualities of both stone and metal: stronger in cross section than is stone, wood resembles steel in its physical properties; its relatively high tensile and compressive strength, together with its elasticity” (Mumford 1934, p. 78).

Compared to concrete, timber has a much higher tensile strength, is stronger per unit weight, and has a much smaller carbon footprint: the production of reinforced concrete accounts for between approximately 5% (CSI 2002) and 8% (Rodgers 2018) of the world’s CO_2 emissions. Although the cost of building with cast-in-place concrete is lower than building out of wood for mid-rise buildings, the gap is rapidly narrowing (CKC Structural Engineers 2018).

In comparison to steel, timber is also stronger per unit weight. Construction lumber has a strength of about a tenth of that of mild steel, though at considerably less than a tenth of the density. The greater unit strength of timber means taller buildings can be made lighter. This comes at the cost of more bulky beams and panels, however this increased sizing has a silver lining: the larger cross-section of timber elements means they are less prone to buckling than steel members of a similar strength.

Also, despite occupying a greater volume than a comparable steel beam, timber members demonstrate a much better performance in fire due to the differing way in which fire acts upon the material. Steel loses the majority of its strength when heated at the temperatures typically experienced in a building fire - about 700-1000°C - making its failure sudden and catastrophic (NZ Wood n.d.). The charring of mass timber in a fire insulates the underlying wood from the heat, while also depriving it of oxygen, thereby slowing down the rate of burning. The result is that the timber cross-section retains much of its structural integrity under high temperatures more consistently than steel and for a longer period of time.

3.2.3 Relevance

Today, timber has acquired a new and particularly pressing relevance as a building material in light of mounting concerns about the causes and effects of global climate change, sustainability, and the general health and well-being of our built environment. Two of the major social issues confronting architects and builders today - overpopulation and climate change (Gopu 2010) - are calling into question the continued usage of high input-energy materials and their untenable value chains, as well as the optimization of material yield and efficiency. More homes and cities must be built - which puts an ever-increasing toll on the planet's resources - meaning the effects of material extraction, processing, and usage will be more keenly felt along with the enormous amounts of energy expenditure involved. This seemingly presents a paradox of requiring less environmental impact on the one hand, but more usage and greater exploitation on the other hand. In face of the depletion of oil resources and shortages of aggregate for the concrete industry, more and more focus is turning towards the world's forests - replenishable, green, and familiar. Wood is seen as "the steel and concrete of the 21st century" by some (Green 2012; Kunkel 2015), demonstrating its favourable return to the forefront of social and architectural discourse.

Coupled with technological advances in computation, digital sensing, and software-hardware interfaces, new opportunities arise for the re-evaluation and re-conception of existing timber practice and a closer look at recent timber developments in light of these advances. The rise of computation especially allows "reconnecting the material's inherent capacities with the characteristics of contemporary design and construction processes" (Menges 2016, p. 98). These benefits and new technological developments have positioned timber as an attractive, economical, and effective building material in contemporary architectural design.

3.3 The material complexity of wood

3.3.1 Properties and behaviours

Despite this positive outlook, wood still presents many challenges for its use in construction, many borne out of its fibrous composition and organic origins. The complexity of wood is underscored by Mumford and defies an understanding of it as a singular, homogenous material: "Stone is a mass: but wood, by its nature, is already a structure" (Mumford 1934, p. 78). Thus, he continues, despite its ancient roots, wood perseveres as an important material today in the "age of synthetic compounds: for wood itself is nature's cheaper model for these materials" (Mumford 1934, p. 80). Indeed the structure of wood has a profound influence on its uses and manifestations, and the aggregation of its constituent "materials elements", as Frei Otto calls them, leads to more complex behaviours at a higher scalar level (Otto 1992).

There are several fantastic accounts of the microstructure and properties of wood and it is beyond the scope of this introduction to attempt to match their comprehensiveness and detail. John Dinwoodie's *Timber: Its Nature and Behaviour* is an oft-cited source for the fundamentals of wood make-up

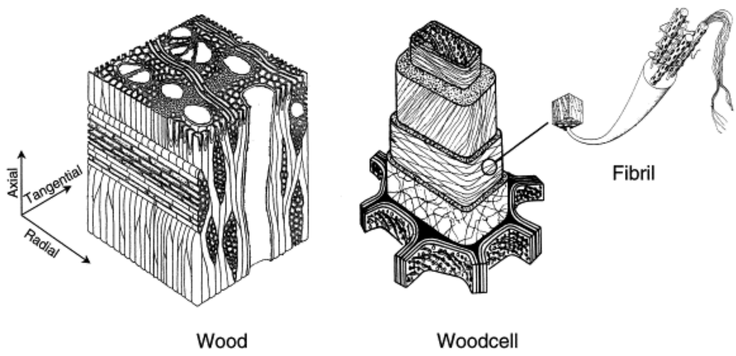
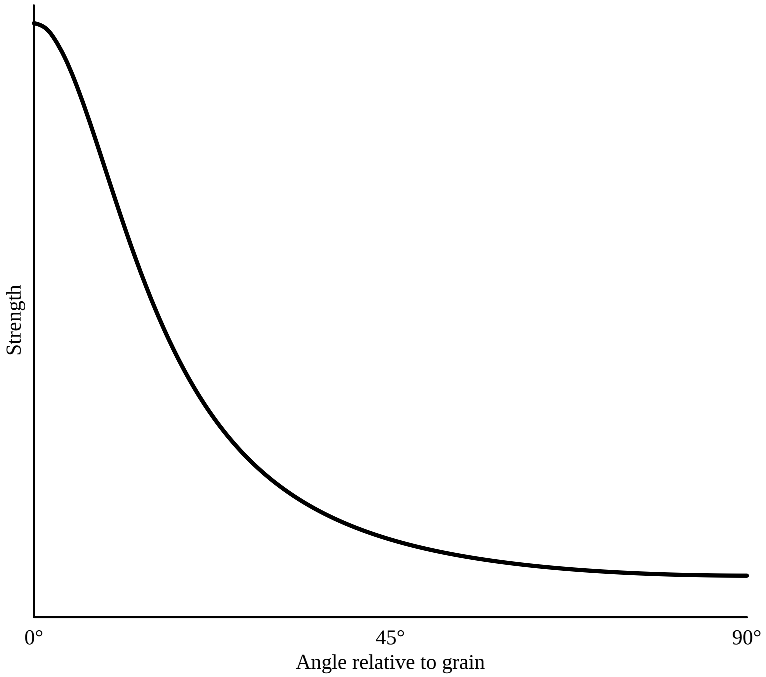


Fig. 3.3: The microstructure of wood from Greil, Lifka, and Kaindl (1998).

and behaviors (Dinwoodie 2000). Bruce Hoadley's *Understanding Wood: A Craftsman's Guide to Wood Technology* is another volume aimed more towards the carpenter and non-scientist, though still providing a good base of knowledge (Hoadley 2000). The United States Department of Agriculture Forest Service's *Wood Handbook: Wood as an Engineering Material* covers a wide range of topics, beginning with the biological makeup of wood to the use of wood in buildings (Service n.d.). These three examples - of many more - cover the nuances of wood composition, which are only briefly summarized here.

Wood is essentially a composite material made up of different types of long and narrow cellulose cells, bonded by a matrix of lignin (Fig. 3.3). These elongated, hollow cells - tracheids in softwoods, or fibres in hardwoods - constitute the main structural and transport mechanisms of a tree. They are arranged parallel to the growth direction of the tree or branch and grow outward, in concentric layers around this growth axis. The thickness of the cell walls and the cell density at any given point relate to the mechanical strength at that particular point in the wood sample. These long cells are strong in tension, while the binding lignin matrix is relatively strong in compression, perhaps evoking comparisons in principle to the steel rebar and cement in reinforced concrete.

Being a composite material with a hollow and elongated cell type, wood possesses characteristics that have a great impact on its behaviours. In particular its *anisotropy*, *viscous elasticity*, and *hygroscopicity* give rise to most of the properties and behaviours that impact its use in construction.



$$\sigma_\alpha = \frac{\sigma_0 \ \sigma_{90}}{\sigma_0 \ \sin^2 \alpha + \sigma_{90} \ \cos^2 \alpha}$$

Fig. 3.4: Hankinson's equation describes the relationship between wood grain orientation and the compressive strength of wood (Hankinson 1921). This is generally true for the tensile strength as well and other wood species.

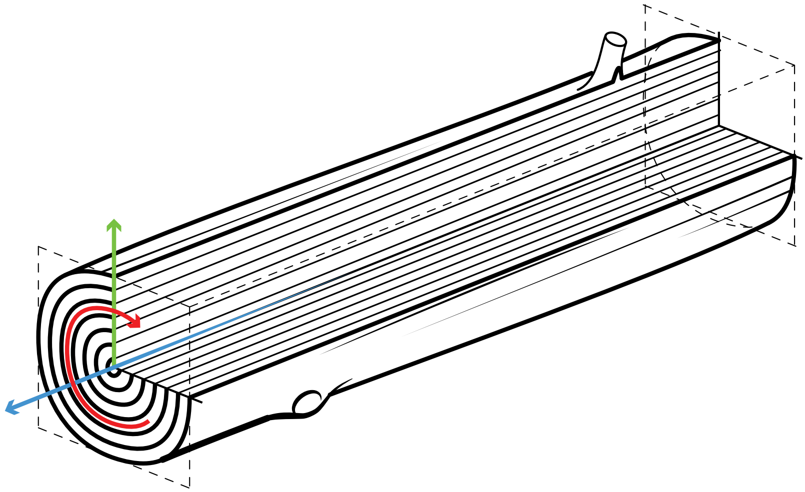
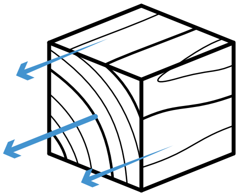


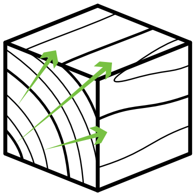
Fig. 3.5: The three primary axes of wood, relative to the growth direction of the tree and the growth rings.

Anisotropy

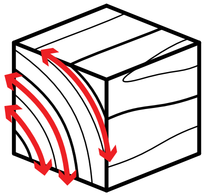
The elongated cellulose cells, arranged parallel to the growth axis of the tree result in one of the most important characteristics of wood: its anisotropic nature. This anisotropy colours nearly every aspect of wood - from its mechanical strength and shape stability to the topology of tree branches and visual appearance. This has fundamental implications for the use and analysis of wood, as it means that its properties will express themselves differently in relation to this fibre orientation (Fig. 3.4). There are three main axes of orientation - *longitudinal*, *radial*, and *tangential* (Fig. 3.5) - which are typically assumed to be locally perpendicular to each other, meaning that wood can be assumed to an *orthotropic* material (Fig. 3.6). In terms of strength, this means that wood is about ten times stronger along the wood fibres than across them (Hankinson 1921). This impacts the directionality of trees and the way that wood is used in construction. The fibre direction results in wood grain - the overall orientation of wood fibres across a specific area (Dinwoodie 2000). Due to the morphology of the tree, the grain direction is not constant but instead deviates on a global level as well as on a local level (Denzler and Weidenhiller 2014). This variation and local change in fibre direction and cell growth allows the tree to adapt locally to different environmental or mechanical factors by strategically orienting fibres in the direction of larger stresses.



(a) Longitudinal axis.



(b) Radial axis.



(c) Tangential axis.

Fig. 3.6: The three orthotropic axes of wood.

Viscous elasticity

One of the most characterizing properties of wood is its capacity to be bent and formed easily. The pliability of wood is present in the swaying branches of trees as well as in many common human-made objects such as boats, skis, and furniture. The elasticity of wood is a function of its material stiffness, which in wood is closely related to the type and thickness of the wood: the large flexibility of the upper branches and twigs contrasts with the rigid solidity of the tree trunk. The mechanical properties of wood in general also vary throughout a tree's cross-section: older heartwood is generally more dense and stiff than younger sapwood (Treacy, Evertsen, and Dhubháin 2000).

Wood is set apart from other elastic materials such as steel or GFRP, again due to its organic origins and cellular structure. The lignin bond between its cellulose fibres is not completely elastic, meaning that, over time, the bonds between cells will relax under imposed stresses and settle into a new configuration. This makes wood a time-based *visco-elastic material*: bending a piece of wood for a longer period of time will result in it retaining some of the bent shape, even after the forces are removed. This is known as *creep* and is quite noticeable in old, wood buildings such as barns (Gibson, Ashby, and Harley 2010, p. 106). Under a constant load, the wood will slowly become used to its deflected state, leading to sagging roofs and the settling of houses. For this reason engineering loads on wood structures are directly related to their life expectancy: structures that are expected to last more than 50 years need to be engineered for about twice the load than temporary ones (Morlier 2014). This reinforces the idea of wood as a "live" material, as even after it is cut, processed, and assembled, it continues to slowly shift and change over time.

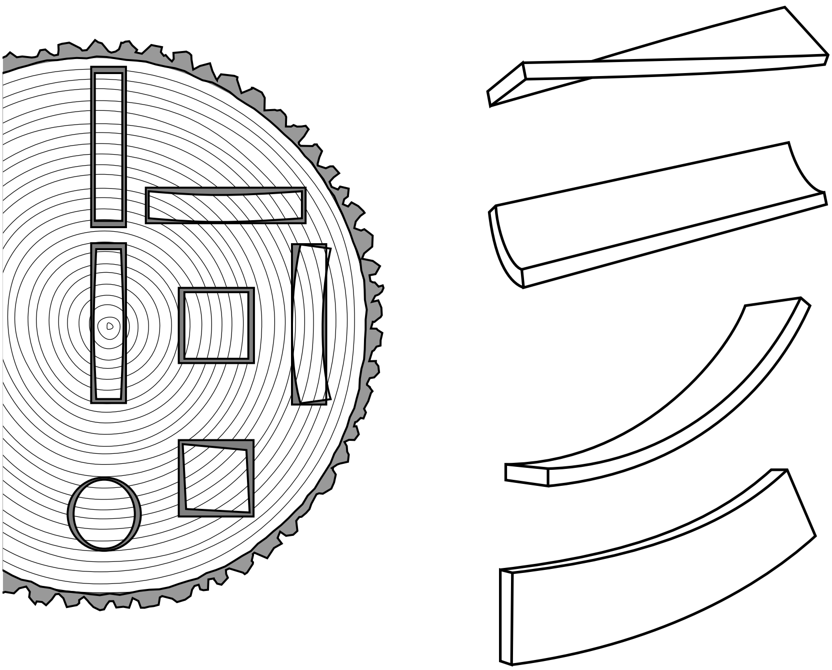


Fig. 3.7: The distortions of sawn timber caused by changes in moisture content. Cross-sectional distortions (left) and twisting, cupping, bowing, and crooking (right, top to bottom).

Hygroscopicity

Wood absorbs water through various mechanisms, both within the cell all through a chemical mechanism as well as within the empty space of the cell through *capillarity condensation*. Water held in the cell wall is called *bound water* and water held in the free spaces is called *free water*. Water in the cell wall has the effect of displacing the cellulose, thereby expanding the wood cell, which leads to the swelling of wood due to moisture increase - and a complementary shrinkage due to moisture decrease. Since these behaviours involve the absorption or desorption of water, the mass and density of the wood therefore fluctuates with changes in moisture.

Once again, the long wood cells and resultant anisotropy affect how this swelling and contracting of wood is expressed: wood swells and contracts more along the radial and tangential axes than along the longitudinal axis. This simple variation in degree of swelling, along with the varying fibre orientation throughout a log, leads to the different distortions of wood planks during the drying process (Fig. 3.7). The effect of moisture on shape stability of engineered wood products is therefore tightly controlled during production.

3.3.2 The multi-scalar nature of trees

As described in the previous section, many of the larger-scale behaviours of wood are caused by variations at a cellular scale. In turn, the type and quality of a cell is dependent on its location within a tree as well as the overall growth and climatic conditions of the three. This interrelation between different scales again challenges the conception of wood as a singular material and requires a more nuanced approach to its use and consumption. A multi-scalar approach needs to take into account behaviour at a global scale and cellular variation simultaneously. A particular example of this is the cellular variation and grain topology of a tree in the case of *reaction wood* and *branching*.

Mattheck (1998) describes the gradual structural self-optimization of trees throughout their growth as ”the axiom of uniform stress realized as an average over time”. He describes how the mechanisms for tree growth - such as apical dominance, geotropism, and phototropism - are driven by a varying allocation of new growth. Reaction wood illustrates the relationship between external forces on a tree and local cell adaptation or speciation. It is formed by a tree in response to external stresses such as wind, self-weight, or its growth mechanisms and tropisms. In broad-leaved trees or hardwoods this takes the form of *tension wood*, where cellulose is allocated more densely and tightly in the area of the tree that is under greater tension. In conifers or softwoods, this takes the form of *compression wood*, where the cells are enlarged and bulked up with lignin in order to better resist compressive forces.

Branching introduces a relationship between loading forces and grain topology. At branching junctions in a tree, a complex intertwining and weaving of fibres and tracheids occurs at the crotch of the branch, where the splitting forces are highest. This prevents the concentrated forces at the crotch from splitting the tree along the weaker tangential and radial planes of the wood, and ensures that the branch is supported or tied back to the trunk of the tree. Mattheck further shows that a large mechanical optimization occurs through seemingly small, local changes in form at branching and forking points (Fig. 3.8).

In both instances, effects and conditions at a global scale - the tree - are met and counteracted by small-scale - the cell and the wood grain - changes and variations. This highlights the strategic allocation of material type and

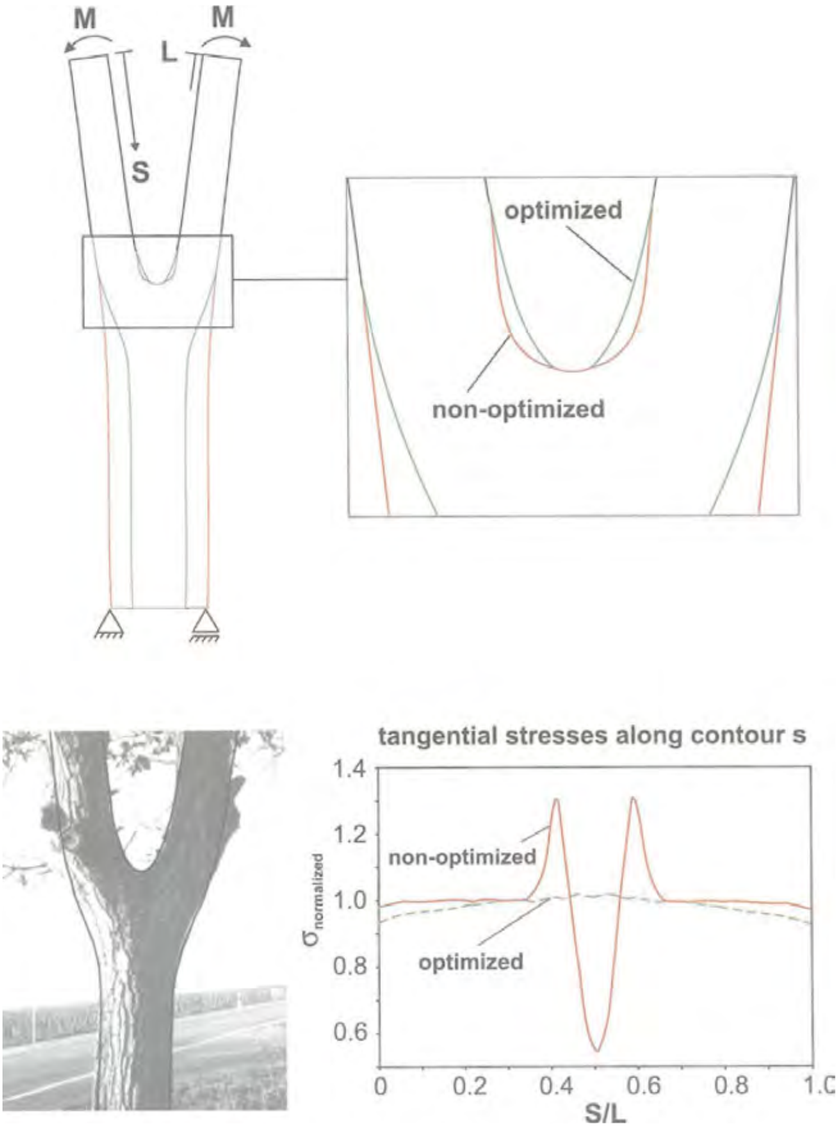


Fig. 3.8: The form optimization of tree forks and branches from Mattheck (1998).

orientation in response to stresses. This process can be interpreted as a localized strengthening - or *functional grading* - of the tree as a whole to promote its structural integrity. Thus the growth process of the tree - also potentially reframed as the *iterative aggregation of wood fibres and generation of wood fibre topology* - is a multi-scalar, time-based, and spatial self-optimization of the tree in response to its structural and functional demands. This understanding of material variation and distribution in a tree presents opportunities for an analogous conception of glue-laminated timber elements and the design of glulam blanks. As discussed later, glue-lamination creates the possibility to aggregate a timber element, using different forms and grades of timber in response to specific performance demands. Mattheck and Tesari (2003) propose learning from the self-optimizing growth of trees and fibre to design more efficient components made from composite materials. Transferring this approach to larger-scale glulam components is therefore a promising avenue of exploration.

3.3.3 Diversity and variance

Returning for a moment to the issue of reaction wood, although it is typically characterized as a defect in timber processing, it is not necessarily its presence that causes difficulties. Chauhan et al. (2006) discuss it in length, but, importantly, note that ”the principal problem with severe compression wood in sawn timber is not so much its excessive longitudinal shrinkage (...) the problems are local variability and, where present, the gradient of severity” . To generalize, it is not solely the presence or degree of a particular property of wood that makes it difficult to work with, it’s the high localization and variation across the wood that creates challenges for its processing and use.

Diversity in the properties and behaviours of wood is caused by cellular and genetic variation, material orientation, wood age and position within a tree, external forces, local environmental factors, seasonal variations, and regional climate. The breadth and scope of these factors means that no two trees are alike, and no two timber elements can be assumed to be the same. These factors are also largely time- and growth-based: seasonal variations cause the differences between fast-growing, less dense *earlywood* and slower-growing, more dense *latewood*, or *growth rings*. The outwardly expanding growth of a tree creates the difference between stiffer, more inert *heartwood*, and more elastic and biologically active *sapwood*. Reaction wood is deployed over time to gradually steer the growth of a tree in response to a constant stress.

The large diversity of wood properties is further compounded by the large diversity of wood species. Genetic differences between species result in variations in cell density, fibre and tracheid length, prominence of grain, chemical make-up, and so on. Wood species greatly impacts its supply and utility: wood species are particularly suited for different applications, from bowling balls to aeroplane frames.

3.3.4 Effects

The properties and diversity of wood impact the use of wood in construction in several ways. Particularly, the anisotropy, viscous elasticity, and hygroscopicity have profound effects on the *strength* and *durability* of timber and timber structures. In both instances, the avoidance of *end-grain* is a positive factor in maintaining the strength and increasing the durability of wood.

Strength

The anisotropic or orthotropic character of wood means that its strength depends strongly on the material orientation. Wood is stronger along the fibres (longitudinal axis) than across them (radial and tangential axes). The fall-off of strength as the material orientation changes is described by Hankinson (1921) and illustrated above (Fig. 3.4). Of particular note is the great reduction in strength around the five-degree point, which leads to the notion of the *fibre cutting angle* in timber processing. This angle is the acceptable angle limit of cutting across the wood fibres for a particular purpose: cutting at a greater angle than this can compromise the strength performance of the element due to the sharp fall-off in strength against material orientation.

The hygroscopicity of wood impacts its strength insofar as a higher moisture content in wood leads to lower strength and, conversely, a lower moisture content has a positive impact on strength. For this reason, keeping wood dry is an important factor in maintaining its strength.

Durability

The durability of wood is also highly influenced by its anisotropy, viscous elasticity, and hygroscopicity. A higher moisture content decreases the strength of wood which increases the likelihood of creep under a long-term constant load. Higher moisture content also makes wood more attractive to organisms, leading to rot, decay, and mould. For this reason, durability is increased by keeping wood dry.

The anisotropy caused by the long, tubular cells in wood affects the way in which water is absorbed and taken up by wood. The surface of wood which is cut across the longitudinal axis (the tangential-radial plane) exposes the cross-section of these tubular cells and is known as *end-grain*. Being open, hollow tubes, end-grain greatly accelerates the absorption of water by wood. For this reason, minimizing exposed end-grain is another important factor in increasing the durability of wood.

3.4 Industrial wood

3.4.1 From wood to timber

Weston (2012) remarks that ”the history of the development of architectural materials has been guided by a hostility toward the natural tendencies of materials as found in nature”. Nowhere is this more apparent than in the transformation of the tree into timber products: every effort is made to standardize form and dimension, and the science of cutting, drying, and using wood is primarily focused on ensuring the form stability and predictability of the wooden element, minimizing distortion through swelling or springback, or the removal of perceived defects.

The transformation of trees into lumber and engineered wood products encompasses a wide variety of processes with different end goals, and begins at the saw mill (Fig. **??**). As with the biological structure of wood summarized before, there are many great resources that describe the particularities of saw milling and wood processing in great detail. John Walker's *Primary Wood Processing: Principles and Practice* describes itself as an overview, however it offers more than enough material for a designer to understand the many processes behind turning logs into all manner of timber products - lumber, composites, paper (Walker 2006). The second half of Bowyer, Shmulsky, and Haygreen's *Forest Products and Wood Science: An Introduction* provides a good overview of the American timber industry, including standards, the different methods of breaking down logs, and detailed illustrations of timber composite products (Bowyer, Shmulsky, and Haygreen 2007). All of them generally agree on the key elements within the saw milling process, though they stress that ”every sawmill is unique. There can be no standard design” (Blackwell and Walker 2006). What characterizes a well-designed sawmill is ”the smooth flow of wood through the mill with no bottlenecks and with no machine waiting for material to cut” (Blackwell and Walker 2006).

Processing a log into wood products displays a varying degree or resolution of dismemberment. Sawing a log into boards or columns can be likened to 'cropping' the log: the irregular outer surface is removed by a large saw called the *head rig*, and the core is further resawn into rectangular sections. As such, most of the internal grain orientation and fibre topology remain intact. Peeling or slicing logs into veneers destroys much of the cohesive,

Fig. 3.9: Incoming logs at the *Blumer Lehmann AG* sawmill are sorted according to diameter.

original structure of the tree, keeping a thin, almost 2-dimensional record of its original topology. Shredding logs into chips reduces the output to small pieces with a hint of the local fibre topologies but the loss of any greater structure. Flaking logs into strands and grinding them into fibres completely destroys the original fibre topology of the input log. Each process results in distinct end products, though they are also highly inter-related, as the waste output of the one process can be used as the input for another. For example, the waste sawdust from sawmilling can be further shredded for the manufacture of fibre-based products (Fig. 3.11).

Fig. 3.10: The sawmill at *Blumer Lehmann AG*.

3.4.2 Taxonomy of industrial wood fibre

EWPs are a particular category of timber products which use different types of sawmill outputs - lumber, veneer, chips, fibres - together with structural adhesives to form panels and beams that mitigate the variable behaviours of wood. By arranging the constituent timber elements in a way where their individual behaviours are resisted or counteracted by their neighbours, the overall form stability and predictability of the EWP can be greatly improved.

If EWPs such as glulam, CLT, plywood, or MDF are the output products from which timber structures are created, then the various types of industrialized wood together form a palette from which the different EWPs are composed in themselves. Together, the inputs in this palette can be described as a *taxonomy of industrialized wood fibre* (Fig. 3.12), representing different resolutions of processed wood with varying characteristics. The way in which a log is transformed into the elements of engineered timber therefore has different implications for the preservation of its natural characteristics and

Fig. 3.11: Smaller elements of the saw milling process. Waste from the debarking process (left), compressed wood pellets ready for packaging and use as fuel (centre), and wood chip waste from the saw milling process (right).

structure. The resolution of processing - from fibre, to chip, to lumber, to log - impacts how much of the original tree structure, figure, and fibre topology remains in the output product.

This taxonomy moves from a larger scale element, less processing, and more of an intact fibre topology from the original tree to a smaller scale element, more processing, and no remnant of the original tree's idiosyncrasies:

- Log (log construction, mass timber construction)
- Lumber (dimensioned lumber, glulam (GLT), crosslam (CLT))
- Veneer (laminated veneer lumber (LVL), plywood)
- Strand (laminated strand lumber (LSL))
- Chip (oriented strand board (OSB), oriented strand lumber(OSL))
- Fibre (medium-density fibreboard (MDF), high-density fibreboard (HDF))

A similar categorization is presented as a "non-periodic table of wood elements" by George Marra (Marra 1972) (Fig. 3.13) and again re-iterated in (Youngquist 1981; Youngquist 1988), addressing the multiple scales of processed timber - from logs down to cellulose. Developments in adhesives and the study of the micromechanics of wood and wood cells have led to an expansion of this table of elements to also include microcrystalline cellulose and cellulose nanoparticles (Gardner 2006), along with documentation of the wood-adhesive interactions at different scales.

This presents a kind of industrial mirror to the multi-scalar nature of the tree: small, base elements are individually simple and vary across few parameters,

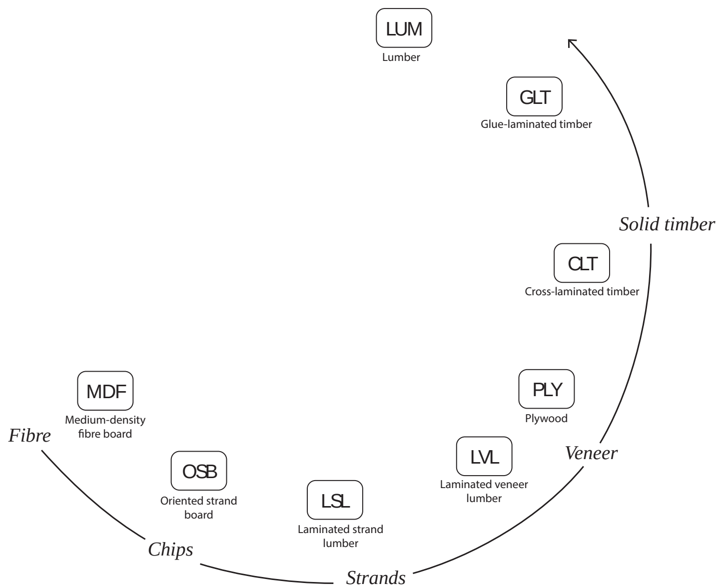


Fig. 3.12: The taxonomy of industrial wood fibre. Types of industrial wood fibre along with their corresponding engineered wood products.

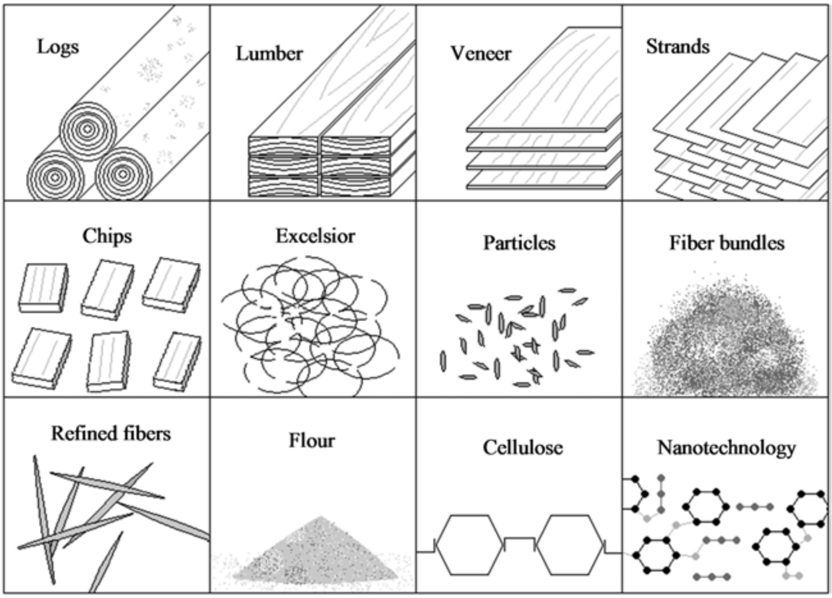


Fig. 3.13: George Marra's *Non-periodic table of wood elements* from Marra (1972).

while larger elements embody much more emergent complexity borne out of the accumulation of a large amount of material. The structural adhesive replaces the lignin as the interface between constituents. What this also highlights is the paradigm shift in construction that adhesives have wrought: the processing and use of timber moves from a subtractive, paring down of a highly variable input, towards a process of *aggregation*, *composition*, and *extension* of a highly controlled selection of inputs, on top of the existing subtractive steps.

Within this table of wood elements, Bowyer, Shmulsky, and Haygreen (2007, p. 321) also notes that "as the level of refinement increases, wood or bio-based raw material quality can decrease. Through application of composite products technology, low-value raw materials can be utilized to make high-value products". Harking back to Mumford's description of wood as a "cheaper model" for modern composite materials (Mumford 1934, p. 80), glue-lamination therefore offers an opportunity to turn wood itself into a modern, high-performing composite material. Therein lies the unique opportunity to surpass the limits of the tree through adhesion and aggregation. Indeed, the development of engineered wood products has permitted the scaling up of timber elements, the usage of lower-quality forest stock, and the much tighter quality control by being able to cut out any defects and patch them with more defect-free wood. The aggregation of wood - an added layer of separation of the finished product from the raw input material - also presents an opportunity for design intervention and for tailoring the composition and distribution of input elements towards some design objective.

3.4.3 Shaping wood

In *Unit Manufacturing Processes: Issues and Opportunities in Research*, any manufacturing process can be broken down into five main process families: mass-change, phase-change, structure-change, deformation, or consolidation processes (National Research Council 1995). In this framework, fabricating a glulam blank and machining it into its final form is a three-step process that involves a *consolidation* process, a *deformation* process, and a *mass-change* process. A similar categorization is presented by Veltkamp (2007), by which a glulam component would be a combination of *additive*, *formative*, and *subtractive* processes. The sum of these three processes is itself defined as an *integrated process*, one in which the final component is ”the product of this sequence and is the sum of the single manufacturing units” which means that ”the quality and the properties of the piece may be quantified by adding and subtracting the contributions of each unit process” (Caneparo and Cerrato 2014).

Subtractive processes

Subtractive processes in timber processing can be summarized into activities of cutting, drilling, machining, planing, and sanding. These use sharp blades or abrasives to remove material mass from the workpiece. The first subtractive process in the value chain is the chainsaw in the forest. Subsequent sawing and de-barking at the sawmill divides logs into rough units of lumber. Planers ensure an accurate dimensioning of lumber elements. Multi-axis machining and drilling further remove specific portions of the timber element.

Additive processes

A common association of the term *additive manufacturing* is with 3D printing. In the world of wood, 3D printing is typically explored through the extrusion of wood fibres embedded in some extrudable substrate. The other form of additive manufacturing - or consolidation process - is aggregating timber elements with adhesives: glue-lamination. This allows larger elements of timber to be joined while preserving more of their material integrity. This technique has led to the development of all manner of engineered wood products (EWPs). It can be argued that both 3D printing and glue-lamination are only different in proportion and type of inputs: the

Fig. 3.14: Richard Deacon's sculpture *UW84DC #8*, 2001. Photo: Richard Deacon (http://www.richarddeacon.net)

glue in EWPs serves the same role as the adhesive substrate in 3D printing, that is, to bond the pieces of wood together.

Forming processes

The forming of wood is made possible by its visco-elastic behaviour and is accomplished in two ways. The first is by relaxing the lignin matrix that holds the cellulose fibres together, allowing the fibres to assume a new form in relation to each other. The application of heat and moisture - through steaming, for example - softens the lignin and allows the wood to deform. Upon cooling, the lignin solidifies and the wood retains most of its deformation. Some residual stresses cause *springback*, which necessitates deforming the wood more than needed to compensate for this. With this technique it becomes possible to impose dramatic curvatures on even thick wood members, however this also comes at the cost of losing a good portion of its mechanical strength, as the integrity of the lignin bonds is disrupted. For this reason as well as issues of scalability, steam bending is not used for structural purposes, but the formal and sculptural possibilities of this technique are incredibly rich, as evidenced by the work of artists such as Richard Deacon (Fig. 3.14) and the furniture pieces of Michael Thonet (Fig. 3.15).

Fig. 3.15: Michael Thonet's Rocking Chair, Model 1, 1860. Photo: Brooklyn Museum

The second is through the active bending and glue-lamination of wood. Instead of softening the lignin, force is applied to two or more wood elements to introduce elastic bending. The interface between the wood elements - perpendicular to the bending direction - is glued. Upon curing, the glue resists the bending reactions and therefore holds the bent form. The bending reactions take the form of shear forces within the glue interface between the elements. As before, a measure of springback occurs because of the embedded bending forces in the glue-laminated element. This can be mitigated by lowering the amount of embedded forces or increasing the glue interface: using thinner wood elements which can be bent with less force in the former case, and using more layers of wood - the *lamellae* - to increase the amount of glue surface in the latter case. An added consequence of the visco-elastic nature of wood is that, over time, these internal stresses dissipate as the wood fibres relax into the new form, as in the case of creep. Curved glulam blanks are formed in this way.

A notable contemporary example of bending and laminating is in the work of Joseph Walsh, an Irish furniture maker who explores the formal possibilities offered by the natural bending and twisting tendencies of wood (Fig. 3.17). The work of Finnish architect Alvar Aalto is rife with experiments using laminated wood for both prototypes of architectural components, furniture

Fig. 3.16: Alvar Aalto's sculpture *The palette of the king*, 1955. Photo: Jacksons Design (jacksons.se)

pieces, and sculptures (Fig. 3.16). The pioneer of glue-laminated timber structures - Otto Hetzer - used this technique to produce his first glulam patent (Fig. 3.18), leading to the broader use of glue-laminated timber in construction.

3.4.4 Glue-laminated timber (GLT) and the glulam blank

The previous sections have identified the properties and complex behaviours of wood as well as the ingredients and processes involved in EWP production. If the former is a discussion of wood in its natural state, and the latter is a discussion of the transformations of wood into industrial timber elements and the types of processes involved, then what follows is a survey of the products of these transformations. This research is focused on a particular EWP: glue-laminated timber (GLT). In the chain of production - from the forest to the building site - glue-laminated timber is situated between the raw timber outputs of the sawmill and the fabricated architectural timber component.

The physical object that occupies this in-between space - between sawn lumber and the as-modelled architectural component with its fixings and finishes - is the central actor of this research. The *glulam blank* is the glue-laminated timber assembly after it leaves the press and before it is planed, surfaced, or otherwise machined to completion. If it is produced

Fig. 3.17: Joseph Walsh's *Enignum* shelves, 2016. Photo: Andrew Bradley

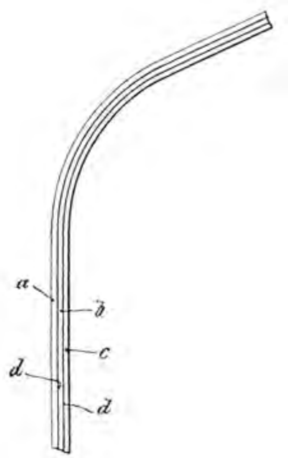


Fig. 3.18: Otto Hetzer's Patent Nr. 197773 from Müller (2000).

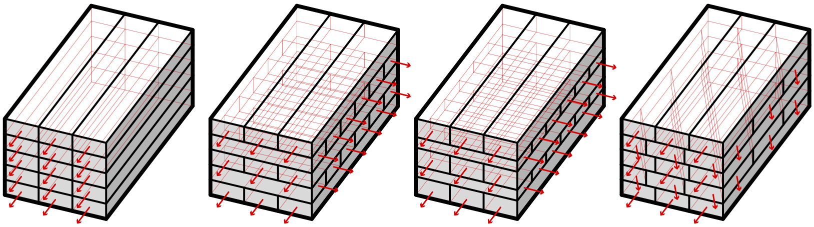


Fig. 3.19: The material orientation in (left to right) glulam, CLT, CLT with a dominant direction, CLT with non-perpendicular layers.

for a specifically shaped architectural element, it is the *near net shape* of that element, meaning that it approximates the form of the element, and is subsequently machined and processed to achieve the final form. Using the terms established previously, the glulam blank is the aggregate enabled by structural adhesives that changes the timber paradigm from one of subtraction to one of addition. In this way it offers to link the previously discussed material optimization, spatial variance of material properties, and harnessing of material behaviour in wood and trees with the processes and elemental products of industrial timber.

The design and production of glulams has to take into account the previously described properties and behaviours of wood: *grain orientation*, the *limits of elastic bending*, and *end-grain*.

Material orientation

Since glulams are typically slender, axial elements, their material orientation - the direction of the wood fibres - is aligned with the long axis of the glulam element. This is the strongest material orientation for beams and columns as they resist bending and axial forces better than with a perpendicular material orientation.

The material orientation of cross-laminated timber (CLT) panels provides a counterpoint to glulam material orientation. CLT panels - much like their plywood counterparts - are glue-laminated panels consisting of layers of lumber that are alternatively oriented in perpendicular directions (Fig. 3.19). This has the effect of minimizing dimensional distortions due to moisture fluctuations as well as homogenizing the directional strength of the panel, allowing the orientation of the panel to be of less importance.

This leads to a contrast between GLT and CLT: GLT remains anisotropic and unidirectional, while CLT becomes more isotropic and omnidirectional. If

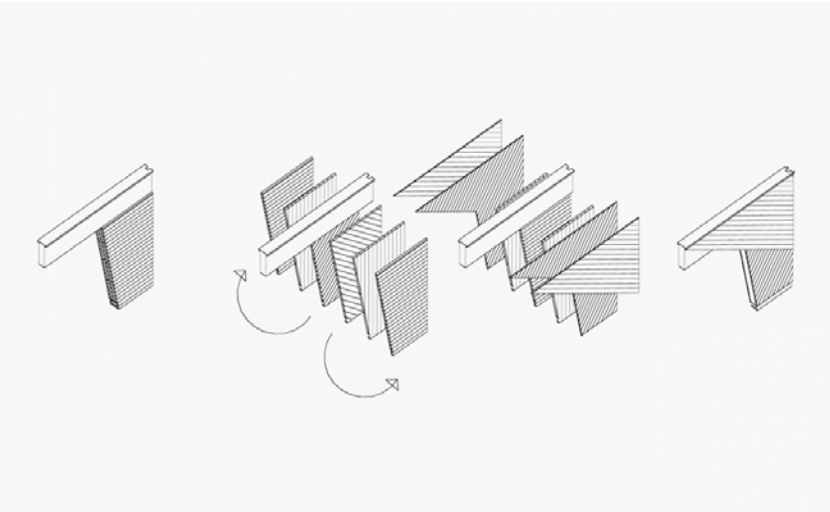


Fig. 3.20: The Pulpit Rock Mountain Lodge by Helen and Hard uses non-standard panel layups for the main structural frames. Image: Helen and Hard (www.helenhard.no)

these two EWPs present opposing ends of this contrast, then there arises a potential to investigate the gradient in-between, where the component might exhibit a general homogeneity with a bias towards a particular direction - such as in non-perpendicular CLT layer configurations (Buck et al. 2016) - or start to perform as something in between a beam and a panel. More interestingly - and referring back to the highly localized variations in fibre topology in trees and branches - this modulation of grain orientation could happen on a more localized scale, within the component. This raises interesting prospects for the functional grading and optimization of glue-laminated timber assemblies within the constraints of the industrial processes of timber, and invites speculation about what new kinds of timber morphologies could emerge from this way of thinking.

Bending limits

Curved glulam blanks need to confront the elastic bending limits of timber. Bending introduces stresses within the material which, if exceeded, lead to material failure. In principle, thinner sections of material require less force to impose a particular curvature through bending, meaning that a desired curvature is a function of material thickness. For curved glulams, this relationship is defined in Eurocode 5 as a ratio of 1:200 between the thickness of lamella and minimum radius of curvature (EN 1995-1-1 2004). This has a direct impact on the composition and complexity of manufacturing

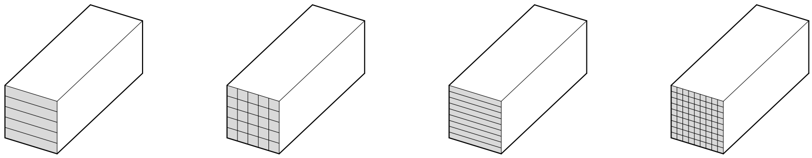


Fig. 3.21: Lamella size as a function of degree and magnitude of curvature (left to right): Single-curved with low curvature (a single stack of wide boards), double-curved with low curvature (large square pieces of lumber), single-curved with high curvature (thin, wide planks), double-curved with high curvature (very many small sticks).

curved glulam elements: smaller curvatures result in smaller lamella sections, which in turn result in a non-linear increase in number of lamellae.

Since double-curved glulams bend around both cross-sectional axes, they are particularly sensitive to this dimension change, as the lamella count increase both in width and height of the cross-section. This is a major challenge in current glulam production.

Fibre-cutting angle and end-grain

As discussed previously in terms of the effects of anisotropy on the strength of wood, the strength of a timber element decreases sharply as the material orientation changes from being aligned with the longitudinal material axis to being perpendicular to it. Hankinson (1921) illustrates how the ratio between a parallel and perpendicular strength can be up to 1:10 for spruce and similar species (Fig. 3.4). At a threshold of approximately five degrees from parallel, the material strength is greatly reduced.

This threshold is known as the *fibre-cutting angle*. This has an important impact on the choice and manufacturing of glulam blanks for free-form timber components. If the fibre-cutting angle is exceeded during the machining of the final free-form piece, the strength of the timber component suffers. This means that the form of the glulam blank and the form of the final timber component must be linked as closely as possible. This creates a relationship between the designed architectural element and the glulam blank that it is cut from.

This also creates a trade-off between the manufacturing complexity of the

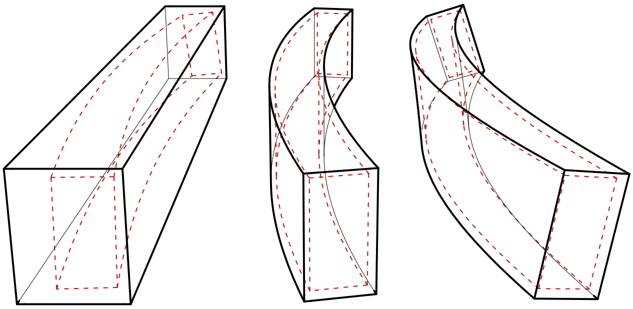


Fig. 3.22: The different types of glulam blanks (solid black line) for different curved elements (dashed red line): straight (left), single-curved (centre), double-curved (right). Image: Design-to-Production GmbH, redrawn by author

glulam blank and its performance demands. Higher curvatures introduce more manufacturing complexity and waste during the production of the glulam blank, however they have a higher strength because of the closer alignment between the free-form timber component and the material orientation of the glulam blank. Lower curvatures and straight glulam blanks are simpler to produce because they can use larger lamella dimensions, at the cost of a lower strength due to more fibre-cutting and more waste due to excess glulam blank volume.

Contemporary types of glulam blanks

These considerations of material orientation, bending limits, and the fibre-cutting angle have led to a classification of glulam blanks according to their curvature. This proceeds from no curvature - the *straight glulam blank* - to curvature in a plane - the *single-curved glulam blank* - to out-of-plane curvature - the *double-curved glulam blank* - to out-of-plane curvature with torsion - the *double-curved glulam blank with torsion* (Fig. 3.22). As described previously, the degree of curvature greatly impacts the number of constituent lamellae and, as a result, their handling and production (Fig. 3.21).

Fig. 3.23: A single-curved glulam press. Photo: Ledinek Polypress (https://www.ledinek.com/polypress)

Straight glulam blank Straight glulams are the simplest blanks to produce. Since there is no curvature, the timber boards can be of any convenient size that together makes up the desired dimensions of the finished timber component. Straight glulams are typically made by stacking dimensioned lumber vertically to achieve the desired depth.

Single-curved glulam blank Single-curved glulams are curved in-plane. That is, the curvature is confined to a single plane. This requires the use of a curved or variable press (Fig. 3.23). The timber boards are oriented such that their shortest dimension - the thickness - faces the direction of curvature. Because of the use of a curved press, the production of single-curved glulam is more demanding than straight glulams.

Double-curved glulam blank Double-curved glulams are curved out-of-plane, meaning that their curvature cannot be confined to a single plane. As such, both the width and thickness of the lamellae are affected by the degree of curvature. There are two methods of producing double-curved glulams, depending on the degree of curvature. For lower curvatures with larger lamellae dimensions, the glulam is assembled and pressed on a multi-axis glulam press. For higher curvatures that require much finer lamella sizes, the double-curvature is decomposed into two simpler process steps: the glulam is first formed as a single-curved glulam, then cut into slices that are parallel to its plane of curvature. It is subsequently bent out of plane in another process step.

Double-curved glulam blank with torsion Double-curved glulams with torsion are created in a similar manner as without torsion, however in addition to bending out-of-plane, the press also introduces twisting around the long axis of the glulam, rotating the cross-section.

Eurocode

Glulams are graded in Eurocode 5 (BS EN 1995-1-1) according to their bending stiffness. Common classes are GL24, GL28, GL32, and GL36. These correspond to bending strength of 24 N/mm², 28 N/mm², 32 N/mm², and 36 N/mm². The strength class of a glulam depends not only on the strength class of its lamellae but also their arrangement within the glulam. A *homogenous* glulam is made up of lamellae of the same strength class. A *combined* glulam contains laminations of differing strength classes: stronger lamellae on the outsides, weaker lamellae on the interior of the glulam (Blass et al. 1995).

In turn, lamellae are graded in two different ways: visual grading and machine strength grading (Blass et al. 1995), both of which are defined in Eurocode 5. The strength class system in EN 338 classifies lumber by its strength in N/mm². These are divided into coniferous (softwood) and deciduous (hardwood) species: C14 in varying increments up to C40 for coniferous, and D30 in varying increments up to D70 for deciduous species. Visual grading looks at two or all four sides of each plank, assessing the size and quantity of knots, checks, and other perceived defects in the wood (Swedish Wood 2016). The EN 1611-1 standard then classifies the lumber as G2 (two-sided grading) or G4 (four-sided grading) with a value between 0 and 4 to denote the grade quality - with 0 being the highest, with minimal defects and a high visual quality.

Wood species are also classified in Eurocode 5 in terms of durability, in 5 classes. Class 1 is described as ’very durable’ and includes very hardy species such as iroko and greenheart. Class 5 is described as ’not durable’ and includes species such as beech and birch (Structural Timber Association 2014). Spruce - the most common wood species for glulam and CLT - is graded as Class 4, ’slightly durable’.

The relationship between curvature of bending and the thickness of the lamella being bent is addressed in Eurocode 5 (EN 1995-1-1 2004), which sets a maximum ratio of 1:200 between the thickness of the lamella - the dimension that is bending - and the smallest radius of curvature of that lamella. This can be increased to a ratio of 1:150 or even 1:100 by the engineering calculations, depending on the anticipated stresses and amount

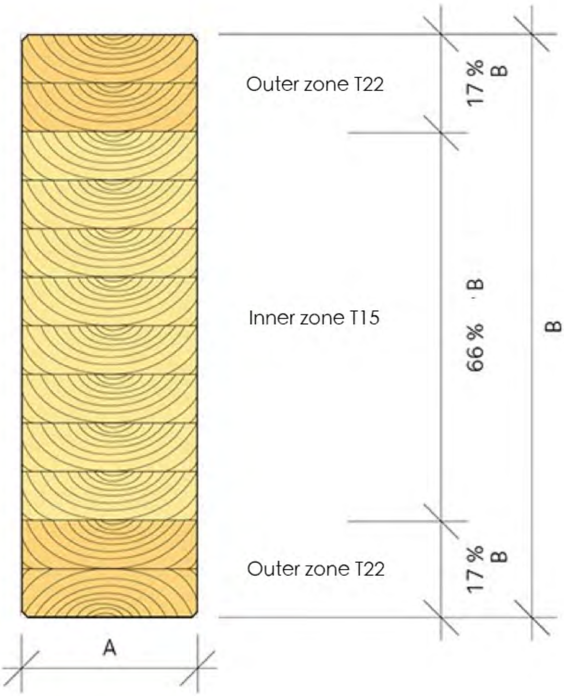


Fig. 3.24: Composition of a combined glulam beam, with higher grade lamellae on the top and bottom flanges. Image: Swedish Wood (www.swedishwood.com)

of bending.

This directly correlates curvature with the sizing of lamellas, and therefore means that a higher curvature results in more and thinner lamellas, which further results in more wood waste from the extra planing and cutting required. This has repercussions in the glulam production, as more lamellas need to be handled and accurately assembled into the glulam press. This becomes especially troublesome for highly double-curved glulams: with the exponential increase in lamellas, the production waste, complexity, and cost increase accordingly.

New developments in glulams

Current developments in glulams display efforts to utilize a larger diversity of wood species, new gluing techniques, and reinforcement of glulams with other materials.

Although historically all manner of wood species have been used for glue-laminated timber, spruce or similar species have been the most common in construction. Glulams using other wood species than spruce, such as beech, are appearing on the market in greater numbers, along with mixtures of beech and spruce (Dill-Langer and Aicher 2014). Although technically not a wood species, glue-laminated bamboo, or GluBam, is an attempt to utilize the fast-growing and abundant quantities of bamboo for large-scale, structural applications (Xiao et al. 2014) similar to glulam. This effort to diversify the species used for EWPs is driven by a desire to exploit a larger variety of forest stock and capitalize on more forest resources that have so far avoided exploitation.

New gluing techniques such as *block gluing* are increasing the scale of possible glulam elements (Aicher and Stapf 2014) by allowing large-scale glulams to be glued together on-site, thus avoiding transportation limitations.

Efforts to increase the bending stiffness and strength of glulams include the use of new developments in adhesives (Brunner et al. 2010) as well as through reinforcement of glulams with layers of synthetic materials such as glass-fibre reinforced polymers (GFRP) and carbon fibre (Fiorelli and Dias 2006; Romani and Blaß 2001).

Double-curved glulams are still very rare, with only a very few select manufacturers offering them as a product (Hess Timber GmbH). Much of the high technology in glulam production still resides in Central Europe: Germany, Switzerland, and Austria.

3.5 The roots of glue-laminated timber

The challenges in the industrial production of the glulam blank emerge from the material complexity of its raw source material - wood. The application of structural adhesives removed many limitations in terms of size and building complexity of large timber structures. The following charts the evolution of the built manifestations of the glulam and provides a short summary of new timber morphologies that have resulted in its innovative use today. To this aim, Christian Müller provides a good overview in *Holzleimbau (Laminated Timber Construction)*, where he traces the lineage of glulam structures from the work of Austrian pioneer Otto Hetzer at the start of the 20th century to developments in long-spanning, free-form glulam structures at its end (Müller 2000). In between then and the present, a series of notable structures have continued this lineage in innovative ways, in tandem with the rise of digital culture in design. These, therefore, illuminate current methods of designing, modelling, and producing complex free-form timber structures.

Müller explains that the birth of the glulam can be traced as far back as 1809, when Carl Friedrich Wiebeking first proposed glue-laminating curved timber for the construction of arch bridges, stairs, or any other application that required highly curved timber. Despite this early reference, the first glulam structure is generally accepted to be the assembly hall of King Edward College, Southampton, in 1860 (Müller 2000, p. 18). The method of laminating wide planks into curved members was a logical evolution of previous timber systems that were used for the construction of domes and long-spanning arches. Previous methods sought to increase the spanning distance of timber, while also taking advantage of the economy of using shorter timber pieces. Early composite beams used a toothed or jagged profile to connected multiple pieces together into a deeper cross-section and transfer shear loads from bending (Fig. 3.25). Several systems were proposed where larger beam or rafter cross-sections were built up by connecting smaller, shorter timber pieces. In particular, the *Emy system* (Emy 1828) by French Colonel Emy used multiple curved planks, fixed together with

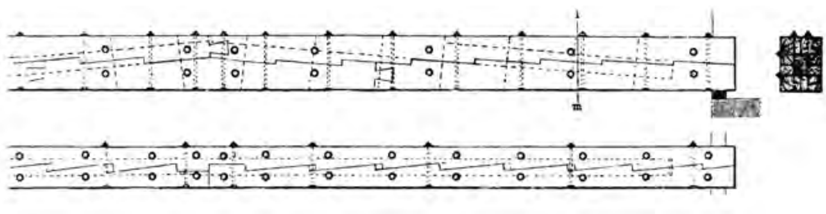


Fig. 3.25: Toothed composite beams. From Müller (2000).

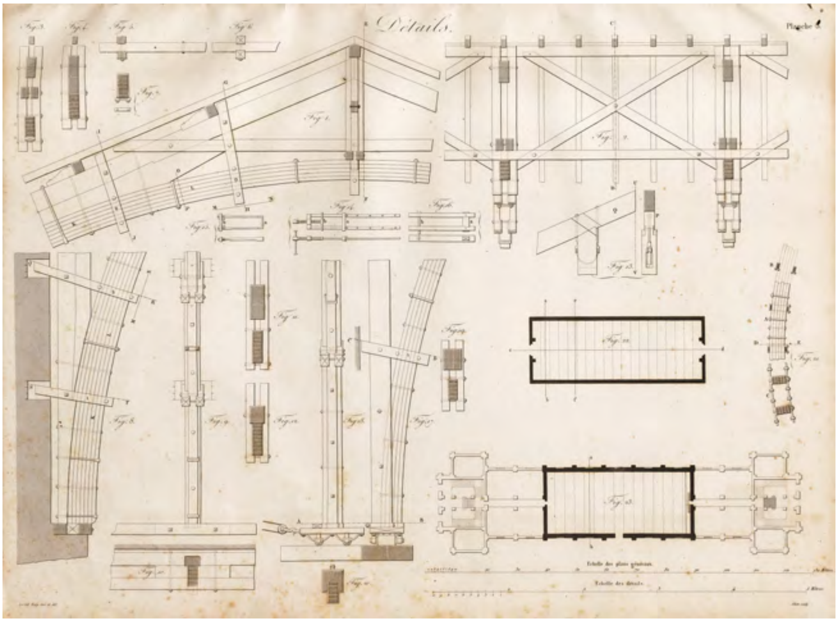
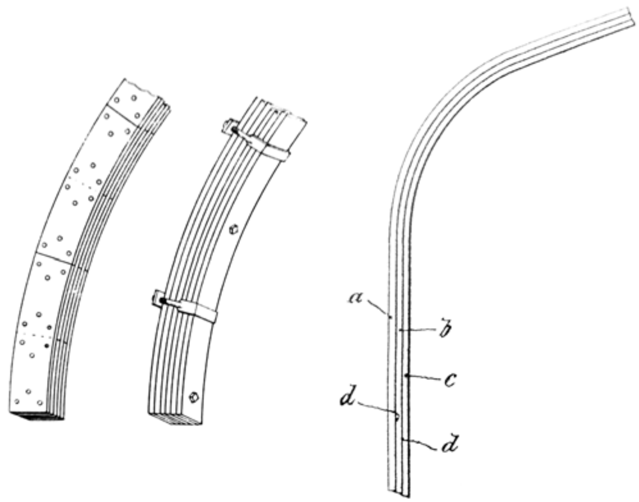


Fig. 3.26: The Emy system. From Emy (1828).

bolts and metal straps to hold their shape (Fig. 3.26). This itself was an improvement on a previous system by Philibert de l'Orme which combined timber boards oriented on their edge, cutting the outer curved profile out of each piece (Vandenabeele, Bertels, and Wouters 2016). The Emy system was able to better align the timber with the ideal stress line of the arch or dome, and avoided the laborious extra cutting of the outside edge to conform to the curvature.

3.5.1 Otto Hetzer's patents

Although not the inventor of glue-laminated timber, the work of Austrian carpenter and inventor Karl Friedrich Otto Hetzer is commonly attributed to developing it into practical and viable uses (Müller 2000, p. 19). Hetzer acquired a variety of patents for a series of innovations that attempted to optimize the use of timber in structural elements such as beams and trusses. A later one - patent DRP No. 197773 in 1907 - essentially replaced the bolts and metal straps of the Emy system with glue, and was intended as a combined element for roof posts and rafters (Fig. 3.27). This patent became the *Hetzer method* (Rug and Rug 1996) and essentially improved on the Emy system by replacing the mechanical fixings with adhesives. The Hetzer method formed the basis for subsequent developments in glulam



(a) The early de l'Orme system (left) and Emy system (right). From Müller (2000).

(b) Hetzer's patent no. 197773. From Müller (2000).

Fig. 3.27: Evolution from the older de l'Orme and Emy systems to the Hetzer method.

construction.

Driven by the need to optimize and make better use of timber stock that was growing more expensive, Hetzer acquired other patents which explored other methods of bending and laminating wood into optimized composite beams. Patent no. 125895 in 1900 mapped the bending diagram of a simply supported beam onto a composite timber box beam, which consisted of a pair of profiled web elements glued between a straight top flange and a curved bottom flange (Fig. 3.28). This was the first optimization of the cross-section of a laminated timber beam, where the cross-section varied in response to the load (Müller 2000, p. 23).

A subsequent patent - Patent DRP No. 1613144 in 1903 - used a similar principle to address a shortage in large timber sizes by cutting a timber element in half along a parabolic path, and laminating a curved timber element in between, thus creating a composite beam. The embedded curved element followed the principle lines of stress under bending as in patent no. 125895, although its strength improvements have been doubted (Müller 2000, p. 24).

Nevertheless, these two patents present an interesting approach that was

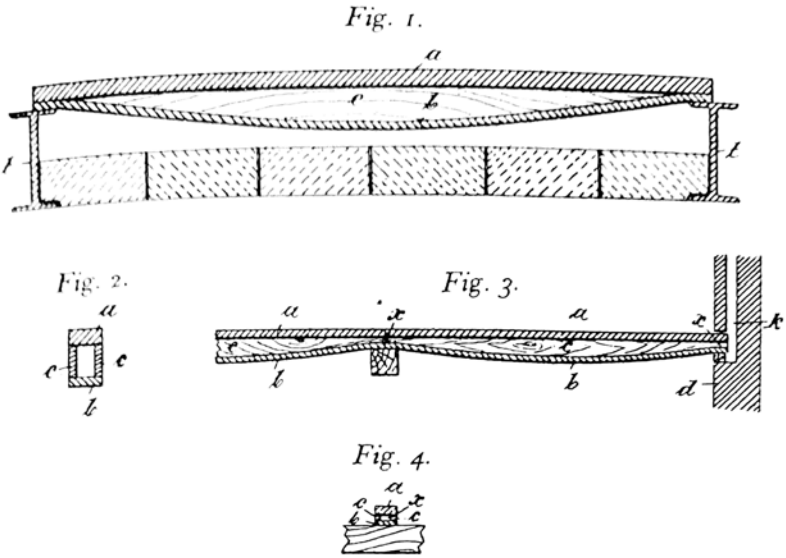


Fig. 3.28: Hetzer's patent no. 125895 for a composite, optimized beam.
From Müller (2000).

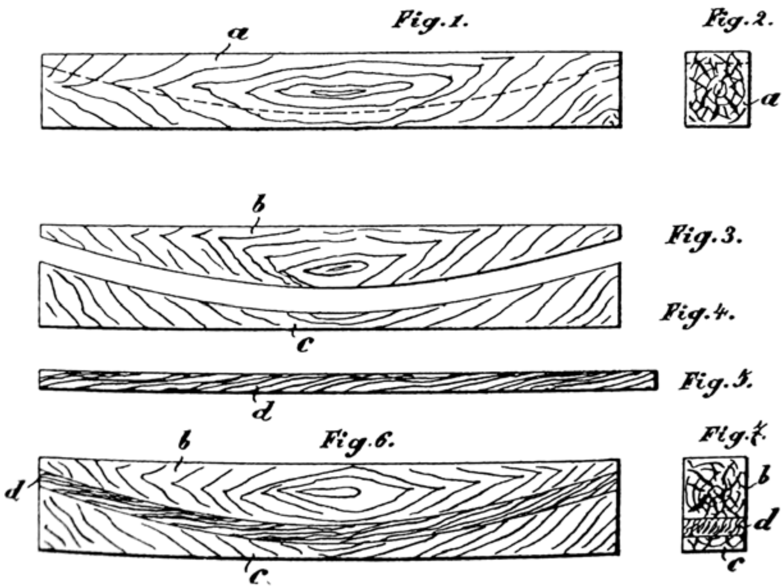


Fig. 3.29: Hetzer's patent no. 163144 for a composite, optimized beam.
From Müller (2000).

abandoned due to the higher labour involved in their production: cutting the parabolic profiles was not as economical at time as other means of gluing simple rectangular planks together. Referring back to the previous discussion about glulam production and material orientation, these two Hetzer patents are early specimens of a functionally-graded or optimized composite glue-laminated timber element, where the internal material orientation is non-uniformly varied using the anisotropic and elastic properties of wood in response to functional requirements. This provides an important underpinning to later experimental work in this research.

Hetzer's last patent - DRP No. 225687 in 1907 - consisted of a timber truss with a web composed of diagonal struts that were aligned with the main lines of stress. The main advantage was that it "avoided the problem of high shear stress parallel to the grain and the glue joint in solid timber sections" but it "does not seem to have been used for any practical applications" (Müller 2000, p. 25). These patents demonstrate the new possibilities, afforded by glue-lamination, for optimizing the use of timber by harnessing its inherent properties of anisotropy and elasticity. The main barrier for their widespread adoption seems to have been the increased labour in their production and inadequate methods of lamination.

Hetzer's patents were licensed to other producers, which expanded the use of glulam across Europe - from Italy to Scandinavia - and North America (Müller 2000, p. 25). This led to a world-wide embrace of glulam construction and the beginning of its international use.

3.5.2 Glulam typologies

Throughout Müller's account of the development of glulam structures, some basic generalizations become apparent. The first is that the use and development of glulam was driven by a need to span larger and larger distances with less material. The second generalization is that these spans were typically achieved through hierarchical one-way spanning structures, meaning structural layers were arranged such that a large primary structure supported a lighter secondary structure, which in turn sometimes supported a tertiary structure or roof panelling. This seems to have come out of the traditional roof organization of rafter, purlin, and batten, and has typically been an efficient way of organizing structures for calculation and construction (Lawrence 2014). The third generalization is that, up until the later surface-based structures such as at Bad Dürrheim, most glulam structures up until the 1980s were variants of either portal structures or radial arches. In the examples of portal structures, most individual portals were three-pinned arches: two curved glulams, one on either side, pinned in the centre of the span. Such structures would achieve spans up to 100 m in the 1960s with solid cross-sections (Müller 2000, p. 97).

Explorations into surfaces and shells by engineers such as Frei Otto during the mid-1900s also led to the development of *timber lattice shells* and *suspended shell structures*. This entailed two important differences compared to previous arch-based glulam structures: increased segmentation using smaller individual members, and more structural indeterminacy due to the membrane-like performance. In many cases, the ribs and segmented shells were stiffened by the surface panelling or layer of lathes such as in Bad Sulza and Bad Dürrheim. The segmentation of domes and surfaces was challenged by the difficulty of suitable node connections between converging elements: these were typically multi-axis steel connectors.

A particularly interesting development began with the construction of suspended timber shell structures. In this typology, a primary structure - an arch or a column - is erected and a secondary structure is draped or hung from this. Müller explains that ”this form of construction was made popular in Germany mainly through the publication of Frei Otto’s *Das hängende Dach*” (The Hanging Roof) (Müller 2000, p. 150). An example of it is the double-curved suspended shell structure of the Festival Hall for the Swiss National Exhibition EXPO 1964 in Lausanne. Frei Otto used the same principle for the Wilkhahn production plant in Bad Münder-Einbeckhausen in 1987, except with a double three-pinned arch as the primary structure and using the open web of the double-truss to insert skylights (Fig. 3.30). Another example - this time using a concrete column as the primary structure - is the recycling plant in Vienna, Austria, built in 1982. This example is organized radially around the column, with the timber elements hanging from the top of the column to anchor points on the ground.

The roof of *the Solemar baths* in Bad Dürrheim by Geier and Geier uses a similar principle - a ”very liberal interpretation of this idea” (Müller 2000, p. 166) - except with set of distributed radial columns composed of branching glulams - tree-like assemblies - that suspend a free-form lattice structure of glulam elements (Fig. 3.31). This project is important due to its use of digital simulation tools and free-form double-curved glulams. Instead of the single-curved production and grid-like logic of previous glulam structures, the design of the bath roof used the principal stress lines of the hanging surface to organize the glulam elements and derive their form, simulated digitally. The double-curved glulams were produced by bending them in-plane as single-curved glulams, slicing them into layers, and then bending them out-of-plane. This freedom from radial or linear organisation was a precursor to more current examples of free-form glulam lattice structures.

Fig. 3.30: The Wilkhahn production plant. Photos: Wilkahn

Fig. 3.31: The Solemar baths, Bad Dürrheim.

A notable omission in the exploration of the roots of glulam construction is the production and processing between the lamination and assembly of glulam structures. Müller does not describe this process over the course of the evolution of glulam construction, save to briefly mention it later on when describing the construction of the thermal baths in Bad Sulza: ”Fabrication was carried out on a CNC assembly plant.” (Müller 2000, p. 145). While cutting and planing operations were relatively straight-forward for the single-curved glulam elements for arched and simple lattice structures, the increasingly complex double-curved elements that followed necessitated more attention to the digital modelling and processing of free-form glulam structures.

3.5.3 Recent free-form surface-based timber structures

Developments in more contemporary examples of curved glulam construction need to be prefaced by the mention of another, parallel development throughout the second half of the 20th century: the development of timber lattice structures and grid shells. In his work with three-dimensional hanging chain models, engineer Frei Otto continued the work of Antoni Gaudi to develop a flexible system for erecting a double-curved lattice shell structure from straight, elastic elements (Happold and Liddell 1975). Hanging chain models allowed the form-finding of ”direct force” structures that ”can theoretically be extremely thin” but whose thickness is ”determined by the stiffness required to withstand buckling and asymmetrical loading” (Happold and Liddell 1975). Otto’s development of these principles allowed him to construct several examples of light-weight, large-spanning structures using straight laths, culminating in the *Mannheim Multihalle* in 1975. A major issue with covering such large spans with very thin elements was the problem of buckling and the lowered stiffness of the elements. To solve this, the Multihalle construction system used a double-layer grid, whereby the bending stiffness of the elements was increased by offsetting parallel laths to increase the total bending depth of the structure.

Jumping ahead in time, the *Centre Pompidou-Metz* - designed by Shigeru Ban and finished in 2010 - shows a remarkably similar approach with its double-layer structure, however with key differences. Firstly, the weave-like lattice of the Pompidou-Metz has no relationship to the structural form-finding and material optimization of the Mannheim grid shell. Instead, the hexagonal pattern of the structural lattice is derived from references to basket weaving, vertically projected onto a continuous, free-form surface. The reliance on fixed boundary edges is also absent: instead, the edges of the Pompidou-Metz lattice are free and the lattice is supported by six funicular boundaries on the interior of the lattice surface.

Fig. 3.32: The interior of the Mannheim Multihalle. Photo: Daniel Lukac

The structural system demonstrates a similar increase in bending stiffness through a double-layer of members, separated by timber shear blocks (Fig. 3.33). This also allows the opposing directions of the "basket weave" to interpenetrate and pass through each other, thus avoiding node points. Instead of flexible, straight, and light-weight timber laths, however, each weave strip is a prefabricated, free-form glulam element, assembled on-site. As with the roof of the Solemar baths, this necessitated much more pre-planning and focused more on the prefabrication of the individual, formally-complex elements.

Fig. 3.33: Centre Pompidou-Metz. Photo: Didier Boy de la Tour

Fig. 3.34: Centre Pompidou-Metz. Photo: Didier Boy de la Tour

The comparison between the Centre Pompidou-Metz and the Mannheim Multihalle - and between the glulam lattice roof of the Solemar baths and preceding suspended timber shell structures - highlights a shift in process and exploitation of material behaviour. Whereas the timber grid shells use the elastic behaviour of wood to simplify the production of individual elements and relies on their deformation during assembly to achieve the double-curved form, the glulam lattice structures use the elastic behaviour of wood within a more complex process of prefabrication - bending, laminating, machining - which simplifies the assembly process. These two glulam lattice structures - displaying vestiges of their light-weight predecessors - therefore mark a displacement of the use of material behaviour from the process of form-finding and assembly to the process of prefabrication. While drawing from the organizational techniques of their predecessors, they depart into new directions occupied more with the prefabrication of bespoke, individual elements.

Through the use of prefabricated glulam elements, the elastic behaviour of the timber is ”frozen” and transported to the construction site as a static building element. This effectively uncouples the design of the form of the lattice surface from the intrinsic material behaviours, meaning the form is once again designed and not found.

As with the roof of the Solemar baths, the modelling of the Pompidou-Metz was driven by a free-form surface upon which the hexagonal weaving pattern was projected. This ensured that continuity between glulam elements was maintained, and that adjustments to the surface would be reflected in the form and detailing of each individual glulam element: a parametric approach to generating the individual free-form geometries. As the building process relied entirely on the accurate prefabrication of the glulam elements, production constraints and processing limitations had to be reflected in the development of the ”master surface” and derived glulam geometries (Scheurer 2012).

Fig. 3.35: Nine Bridges Golf and Country Club. Photo: Hiroyuki Hirai

Fig. 3.36: Nine Bridges Golf and Country Club. Photo: Hiroyuki Hirai

The *Nine Bridges Golf and Country Club* in Yeoju-gun, Gyeonggi-do, South Korea - designed by Shigeru Ban in partnership with NACI International and completed in 2010 - uses the same hexagonal basket-weaving motif as the Centre Pompidou-Metz (Fig. 3.35). In this case, however, the structural system is composed of a single layer of interlocking glulam elements. This approach flattens the ”weave”: the intersecting glulam strips are flush with one another, instead of the interpenetrating layers of the Pompidou-Metz.

The Nine Bridges structure was produced by *Blumer Lehmann AG* in their factory in Gossau, Switzerland: entirely prefabricated out of single- and double-curved spruce glulams and shipped to Korea. The design of the lattice structure was a modular grid - another departure from the Pompidou-Metz - which allowed the structure to be pre-assembled away from the construction site in smaller units, which were then lifted into place and fixed. The modularity also allowed the machining of repeated elements, simplifying the production by re-introducing aspects of serial production into an otherwise completely bespoke process.

The modelling of the lattice structure was again driven by a free-form surface, which was modularized by mirroring in two axes around the centre of each ”tree” or ”leg”. As in the Pompidou-Metz, the hexagonal weaving pattern was projected onto this surface module so that data such as the glulam curvature and cross-section orientation could be derived from the surface.

Fig. 3.37: Nine Bridges Golf and Country Club. Photo: Hiroyuki Hirai

Fig. 3.38: Swatch-Omega. Photo: Didier Boy de la Tour

Fig. 3.39: Swatch-Omega. Photo: Didier Boy de la Tour

The *Omega Swatch Headquarters* in Biel, Switzerland - designed by Shigeru Ban, once again, and completed in 2019 - utilized a simpler, square lattice pattern though at a larger scale and extent. However, the curving snake-like plan of the building - as well as its tapering - introduced constant variations in the lattice geometry, resulting in almost all of the glulam elements being entirely unique. Further disruptions to the lattice pattern around the openings for balconies increased the geometric complexity, requiring double-curved glulam members that were difficult to handle and process. The extreme curvatures relative to the member sections in these areas meant that in some cases, lamella thicknesses were only a few millimetres. From a production standpoint, this project almost entirely embodied the principles of mass-customization and bespoke production.

The production of the Omega Swatch building was led and coordinated by *Blumer Lehmann AG*, which resulted in the opportunity to directly observe the processing of these complex elements over the course of this research. As with the previous two examples, a surface-based approach was used: a ”master surface” which drove the positioning and orientation of the glulam elements.

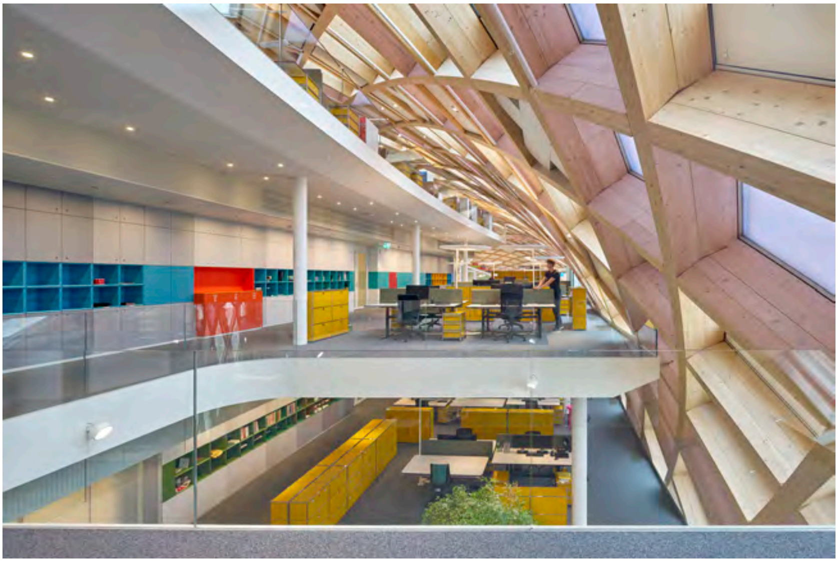


Fig. 3.40: Swatch-Omega. Photo: Didier Boy de la Tour

Fig. 3.41: Cambridge Mosque.

Fig. 3.42: Cambridge Mosque.

The most recent example in this lineage of glulam lattice structures is the *Cambridge Mosque* in Cambridge, UK - designed by Marks Barfield Architects and finished in 2019 (Fig. 3.41). Although in terms of design and modelling it is very similar to the previous projects - a two-dimensional pattern projected onto a modular free-form surface to produce a free-form timber lattice structure - the production of the Mosque presented some optimizations. In particular, the diversity and uniqueness of the glulam blanks was minimized such that only a number of unique blanks had to be prepared, in contrast to the total uniqueness of blanks in the Omega Swatch building. Where possible, single-curved glulam blanks were employed. For the 2746 total beams in the Cambridge Mosque, there were 145 unique types of elements, and only 23 unique types of glulam blank, meaning the advantages of serial production could be re-introduced into the production process once again.

In this case, the design of the lattice pattern was not based off of a weaving pattern or simple geometric tessellation, but was rather developed through research into Islamic patterns. This once again underscores the separation between the lattice pattern, the free-form surface, and the optimization and utilization of inherent material behaviour.

3.5.4 Trends in recent free-form timber structures

The built examples previously described expose particular similarities and trends that can be challenged by a new material practice. The developments from the first glulam structures to the recent free-form examples show an increased complexity in the individual glulam component and accompanying focus on prefabrication. The conceptualization of long-span timber structures as networks of filigree elements is belied by the scale of large glulam components and their substantial carving with machining tools. The surface-based design approach in recent glulam structures hides alternative possibilities that could arise from other, perhaps more volumetric, strategies.

A shift towards piecemeal indeterminate structures

The development of glulam structures began with efforts to increase the spanning capacity of structural systems using short timber elements. The replacement of metal straps and mechanical fixings with adhesives in the Emy system resulted in the glulam, which was employed as a hybrid column-beam element for domes and roofs. Further development led to increases in scale and span. Parallel developments in light-weight structures and the use of elastic materials resulted in the use of free-form glulams in indeterminate and non-hierarchical structures such as contemporary glulam lattice structures. As the geometric complexity of the glulam increased, more focus was placed on processes of prefabrication and production of the glulam blank.

Filigree strand to stereotomic block

The comparison to light-weight grid shells helps to differentiate glulams from previous conceptions of filigree timber structures. Glulams enable the construction of much larger structures, due to the lack of size limits on their cross-section. This bulkiness is combined with the displacement of bending and material behaviour to the prefabrication process of the glulam blank, instead of within the assembly and dynamic performance of the structure. Instead of the flexible timber laths that are dynamically activated on the grid shell building site, glulam elements are static aggregations of frozen bending that are assembled piecemeal. In this way, the glulam is more *stereotomic block* than *filigree strand*. The continuity of woven strand and flowing changes in curvature in the preceding examples of contemporary glulam lattice structures are belied by the segmentation of the strand into constrained lengths of glue-laminated timber, carved from different types of glulam blanks, lifted into place as rigid puzzle pieces.

Surfaces to branches

The surface-based approach to modelling glulam lattice structures finds a conceptual grounding in ideas of *macroweaving* (Simmonds, Self, and Bosia 2006) and *textile logics* for construction (Ramsgaard Thomsen, Bech, and Sigurðardóttir 2012). The weave features prominently: Simmonds, Self, and Bosia describe the application of Chinese hat weaving topology to the structural system of the Centre Pompidou-Metz; Ramsgaard Thomsen, Bech, and Sigurðardóttir look at assembly from the point of view of textiles and systems based on redundancy. Phil Ayres, Alison Grace Martin (2018) point out the benefits of *kagome* weaving topology for increased production efficiency of glulam structures, referencing the distorted weaving patterns in both the Centre Pompidou-Metz and the Nine Bridges Golf and Country Club, which necessitated complex double-curved glulams and multi-axis machining.

Weaving aside, the surface-based approach - evident even in the drawings of Colonel Emy - seems consistent with a wish to span large spaces with a single, thin skin. This ambition is realized in Otto's grid shell structures such as the Multihalle and perhaps in the Omega-Swatch building, where the single, convex surface allows a shell-like solution without additional structural elements. The columnar or tree-like projects - beginning with the Solemar baths, and including Pompidou-Metz, Nine Bridges, and Cambridge Mosque - require additional prosthetics: steel tension rings inside the branching "tree trunks". This demonstrates a shortcoming with the purely surface-based approach: at critical points it still needs to be spatially reinforced off the surface (Fig. 3.37).

As a parting thought along this thread, perhaps the surface-based approach and textile logics can be typologically contrasted with a more volumetric approach such as the work of Konrad Wachsmann and his spatial frames. This invites speculation about what kind of other glulam structures could arise from a more relaxed adherence to the ”master surface”. In particular, notions of branching, peeling, and bifurcating arise as potential architectural moves that could arrive at new glulam typologies. As contemporary free-form glulam structures seem to be held captive by the *surface*, a question while moving forward is: what kind of new glulam blanks could introduce more spatial topologies by branching or splitting, and what kind of structures could result?

3.6 Developing the digital timber continuum

This section concludes the chapter by connecting the previous discussions about the material complexity of timber, the industrial processes behind glue-laminated timber, and the evolution of glue-laminated timber structures with current discourses about architectural design, material practice, and digital technology. Of particular importance are the consequences of the digital shift in architecture for glue-laminated timber construction, and how that offers an opportunity for a deeper engagement with the material and process complexities of the glulam blank. *Prefabrication* shifts the operating arena from the construction site to the factory-workshop. The resulting gains in precision and quality control as well as a shift in focus towards information transfer and process design enable a confluence of the designer-maker and accompanying notions of *digital craftsmanship* to be applied even to large-scale timber construction. The modelling and information-generating that is used by such a practice therefore also shifts from ways of communicating information between designer and maker to functional models that convey material- and fabrication-specific information to the designer-maker throughout the design process. These models employ digital simulation in different forms to integrate material performance and behaviour into a reflexive design process.

3.6.1 The digital shift in architecture and construction

Architectural design has undergone fundamental shifts through the introduction of digital tools. These have permeated all aspects of the design-to-production chain - the design, development, fabrication, and assembly of buildings. Integration of modelling tools from the aeronautics, automobile, and engineering domains have led to a closer relationship between the methods used to design and represent buildings and the methods used to fabricate them. Computer-aided design (CAD), engineering (CAE), and manufacturing (CAM) methods have placed the data used to design and represent a building in the same space as the data used to manufacture it. Kolarevic characterises this rapprochement of design and production tools as the ”digital continuum” (Kolarevic 2003) - the seamless flow of design intent into automated tools of production. Although CADCAM has been a staple of manufacturing since the mid-20th century, it has only become standardized in architectural practice and construction relatively recently, mostly due to the development of CAD interfaces and their availability for designers and architects (Callicott 2001). The merging of digital design with digital production, aided by computationally-driven parametric and procedural modelling paradigms, has led to new logics of building design and construction. This has led to concepts such as ”the digital chain” and ”file-to-factory” workflows (Larsen and Schindler 2008). These developments have left previous processes behind: Kocaturk and Veltkamp (2005) note that the digital revolution in architecture has made conventional - here read as pre-digital - processes incapable of confronting the new complexity in constraints and interdisciplinary relations involved in the design and production of buildings. While conventional design and production processes could be managed somewhat intuitively by designers, based on their familiarity with and understanding of standardized construction systems, digitisation and specialization of the involved knowledge domains has made this much more complex and difficult (Kocaturk and Veltkamp 2005).

This new condition is also described by Schindler (2007) in the context of timber construction. Schindler argues that the current state of timber processing technology is the latest in a series of ”waves” of development which focus on the relationships between energy, material, and information. The characterising feature of the present wave of timber processing is the use of information technology to relieve intellectual human operations and to instruct machines - what Schindler calls *information-tool-technology* (Schindler 2007). Although this is made possible by digital technologies and CADCAM systems, he contextualizes this against the preceding waves: hand-tool-technology being ”the use of energy, material and information processing by a human hand-tool operator” where the ”design of the tool is the crucial intellectual performance” and, subsequently, machine-tool-technology, which is ”the use of energy and material processing by a machine to substitute repetitive physical human operations, while a human machine-tool operator processes information” wherein the role of the operator shifts from ”labor to process design”. The gradual replacement of labour and intellect by machines is not seen as a devaluation of the human designer, but rather a change in role: the introduction of parametric and procedural modelling shifts the role of the human designer from ”processor to process designer”. Schindler continues that this leads to effects on production - the universality of G-code, increasing genericness of processing machines, increased complexity of machine movements, and a ”formalized flexibility” which enables mass-customization - and effects on timber architecture - obsolescence of the grid, the shift to using panel elements instead of beam elements, and the enhancement and revival of timber joints. He concludes that contemporary timber construction focuses on the design of the fabrication process rather than the process itself, that the symbols for labelling elements - metadata - are *operative* and *algorithmic* instead of merely *descriptive*, that the density of information is increased to handle the unambiguous description of complex elements, and that contemporary timber architecture ”is about skillfully combining these three kinds of knowledge”: material knowledge, product knowledge, and process knowledge.

While initially digitalisation in the timber industry was occupied with the automation of existing processes to meet large-scale demand, the rise of computation and parametric design methods has meant that a new focus on element variability and complexity are possible, while retaining the benefits of automation (Schwinn 2016). However, as Schwinn points out, even today the additional complexity of planning and handling involved in digitisation and automation must be justified by complexity or volume: the processes can be an economic overkill and more of an organizational burden for more straight-forward projects. Larsen and Schindler propose two main points of intervention or opportunity to utilize this capacity for complexity: the *detail* and the *variated element* (Larsen and Schindler 2008). Both derive from the capacity of the digitally-driven machine to make geometrically complex cuts, as much as the capacity of the parametric model to define and model them.

As made obvious by the *Centre Pompidou-Metz* and the *Omega Swatch Headquarters*, the variated element is a characterizing feature of free-form timber structures, made possible only by a digitalisation of the design, modelling, planning, and production processes behind their realization.

Beyond the detail and the variated element, what Larsen and Schindler (2008) and Kolarevic (2003) leave out in their focus on the production opportunities provided by digitalisation is the further opportunity for exploiting material specification, composition, and performance through digital means. Including the material complexity of timber and the possibilities afforded by the industrial glulam process, the digital shift in architecture hence requires a closer look at how the material composition - or design - of the glulam blank can be challenged, even before it is met by the computer-driven saws and cutters. In this way, Kolarevic's digital continuum is expanded to a more materially-aware *digital timber continuum*.

3.6.2 Prefabrication

The shift towards prefabrication in timber construction outlines the operating context of a material practice seeking to engage with the glulam blank. The move away from the coordination of the construction site towards the controlled factory environment creates a closer relationship between the design and fabrication of timber elements, both out of opportunity and necessity.

As a general strategy for the procurement of buildings, prefabrication results in ”better quality, shorter build times, lower cost and special solutions for difficult or unusual problems” (Aitchison et al. 2018). Factory-made buildings offer an increase in control, flexibility, and customizability, and are indicative of the concept of ”mass customization”. This is markedly different from conventional construction which is a ”service-oriented, client initiated, labor-intensive approach” where every building is built ”as if it was a prototype” Richard (2017). The shift of construction from on-site to factory-based allows buildings to be prototyped and tested *before* their assembly on-site. For Stacey, ”the prototype is the key feedback loop informing both the design outcomes and critically the quality of construction” which, because of prefabrication, allows a ”potential elegance of architecture assembled from prefabricated elements” by ”thinking through the architecture before it has been built” (Stacey 2012). The opportunity here arises from the closer dialogue between design and fabrication, which facilitates experimentation and iterative prototyping away from the construction site.

However, Stacey also notes that ”vitally this requires investment in design time and early collaboration with the makers of the components and systems” or, in other words, a front-loading of the design process that integrates fabrication knowledge and the various stakeholders at the outset of a project. Scheurer et al. (2013) echo this in relation to the detailing of timber buildings: ”The development of suitable connection detailing is one - if not *the* - key to a successful project. Requirements of all involved disciplines have to be integrated into one solution, most of them reciprocally affecting each other.” and, because of these challenges, the required effort for this collaboration is currently limiting the potential of mass-customized and digitally-fabricated timber buildings. Along with the difficulty of involving all parties at the outset, a rigorous monitoring of the process is crucial: ”Extensive quality control on this conceptual stage greatly helps spotting possible problems early and solving them before even the first bit of material has been touched”. That is to say: prefabrication demands a tighter integration between design and fabrication, which necessitates tools and methods of achieving this integration.

What is required for the success of these strategies is ”clearly defined interfaces and bidirectional data flow” between stakeholders as well as between CAD, CAM, and physical reality (Scheurer et al. 2013). Developing a material practice around the glulam blank therefore requires early and constant feedback between stakeholders such as fabricators and designers, between information models and physical material workpieces, and between design models and fabrication models. This points to differing notions of feedback: feedback between stakeholders is markedly different from feedback from physical reality.

Further, the intertwining of design and fabrication allows a move of more design effort into the space of fabrication: complexity can be embedded in the component; tests and prototypes can be fabricated off-site under controlled conditions. Not only can new types of glulam blanks be designed in this way but, most importantly, the gathering of experts at the beginning of the design process opens up the possibility of designing glulam blanks from the outset of the project - not only later on - and more fully engaging with the material properties and behaviours in a more craftsman-like approach.

3.6.3 Digital craftsmanship

Aided by the digital shift in the timber fabrication and the move towards prefabrication, a concurrent discourse about craft and material engagement evolves in the context of the architect’s role in the design and prototyping of buildings. The key attributes of the new craftsmanship are interdisciplinarity; an integration of stakeholders and expertises; a reflexivity between modelling and making; and an active agency of digital models due to simulation.

Scheurer et al. propose that the early interaction and pervasiveness of collaboration and design throughout the whole planning and construction process is indicative of a ”digital craftsmanship”, based on thinking, modelling, and building in large timber structures. Using the Centre Pompidou-Metz as a case study, Scheurer et al. reveal that the very capacity of preplanning and prefabricating permits this to occur. The defining characteristics of this digital craftsmanship is an integration of different domains of knowledge, collaboration, and a persistence of both of these attributes throughout the entire project timeline.

Another view of craftsmanship is that of ”design through making”, an approach in which the emergence of digital tools of fabrication has merged the spaces of drawing and making: ”As the distinctions between both disciplines become blurred, design will be understood as neither drawing nor making, but both. Design will transgress rather than merely translate the conversion of ideas into matter, and architects will design through making.” (Sheil 2005). This reflexivity between drawing and making is described as being performed by a ”Jack of all trades” or interdisciplinary architect and taking place in the workshop.

These two examples further reiterate the primary operating environment of a new material practice - the workshop-factory - and its nature - a blurring of expertises and a multi-disciplinary oscillation between design and making. The implications for the material practice centred around the glulam blank are that it is integrative and bound to interrelated domains of modelling and materialization.

Harrop (2004) focuses on the point of contact between maker and material: ”When we make, instead of predetermining action, we discover a map of engagement. We play by challenging and resisting material. It in turn, reveals an intentional resistance that provokes yet another challenge, and on and on and on” and ”when we make something, we engage in a playful challenge to the limits of the material”. Although Harrop is suspicious of digital tools, asserting that they ”are conditional on the complete subjugation of materiality” and ”are only compliant with material realism at a representational level”, this playfulness and back-and-forth engagement is similar to Ayres’s later concept of *persistent modelling* (Ayres 2012), which instead embraces the digital and proposes the intertwining of digital modelling with material behaviour. Here the link between the model and material reality is persistent, constantly kept up-to-date with real-time information about the physical state of the material product, much like contemporary notions of the *digital twin* (El Saddik 2018).

Indeed, while Sheil and Scheurer et al. are driven by the potential of digital technology in the design and manufacture of architecture, they approach it from the point of view from production and prototyping. Tamke and Ramsgaard Thomsen (2009) develop a similar notion of craft and material practice, however they focus on the potential of digital technology for the simulation of complex material behaviour. Simulation tools take up the engagement with the material by ”introducing feedback and cyclical thinking in a process that is otherwise characterised by an ideal of linear progression and division of labour separating design generation and analysis” (Ramsgaard Thomsen, Tamke, et al. 2017). The digital revival of this type of material feedback and agency is necessary, because ”the development of architectural design and its material practices is impeded by our inability to comprehend and capture the complexity of more hybrid and more bespoke material systems.”

The inclusion of digital simulation in the material practice as another method by which to engage with material reality creates the questions of what material behaviours, properties, and affordances are required to be simulated in order to facilitate the crafting of the glulam blank and its resultant free-form assemblies. The development of digital models that allow this is therefore a fundamental starting point.

3.6.4 Functional models

On top of recognizing the value of architects interfacing with the means of digital production, Tamke and Ramsgaard Thomsen and Ayres show that the role of the digital model has the potential to graduate from being primarily representational to that of an active participant in the crafting process through the means of digital simulation.

A similar development by Hensel and Menges asserts that modelling with material performance - or ”performance-oriented design” - requires a shift from representational models to *functional models* (Hensel and Menges 2006, p. 34). Indeed, the tight integration of simulation tools presented by Tamke and Ramsgaard Thomsen allows the cyclical feedback loops to re-inform the designer at every iteration in much the same ways as Hensel and Menges describe. This results in design elements that are ”defined by behaviour rather than shape” and which allow a ”performative capacity and material resourcefulness while at the same time [expand] the design space towards hitherto unexplored architectural possibilities” (Fleischmann et al. 2012). A similar concept - *material computation* - is proposed by Oxman (2012) which seeks to shift design from ”homogeneous modular design driven by the logic of material assembly to heterogeneous differentiated design driven by material distribution”.

While Hensel and Menges, Fleischmann et al., and Oxman steer these concepts towards a generative and morphological end-result - models that generate forms through the simulation of behaviour - there is also value in a more ”back-seat” interpretation of the functional model that can have just as big of an impact on the realization of materially-driven architecture: a model that simulates the material and fabrication implications of particular design decisions; reveals challenges, constraints, and barriers; and thereby stimulates form generation or alteration through the reaction of the designer to these revelations. In a context of multiple stakeholders and a variety of design drivers and influences such as described by Scheurer et al. before, this reactionary type of functional model serves less as a dominant driver of design but as an embedded set of material-based rules to engage with in lieu of the physical material, and is thus better suited to a material practice that engages with such a diverse context.

3.6.5 Between model and material

The cyclical engagement with material in a digitally-augmented material practice therefore relies on interfacing with physical material and simulated material. In order for the practice to be fruitful in opening up opportunities in new types of glulam components and assemblies, both of these methods of engagement need to be implemented.

Material to model

While the simulation returns a measure of materiality to the digital environment, it ”is not a generic tool but an environment that needs calibration to real-world behavior through measurements specific to the area of application” (Tamke, Hernández, et al. 2012). This ”calibration to real-world behaviour” or validation of the simulation model is necessary to ensure the accuracy of designs that are based on this simulation model. A reaffirming through sensors therefore enables a cyclical relationship not just with analysis and simulated material performance but with physical material behaviour, especially during fabrication.

This type of material practice is demonstrated by Nicholas, Zwierzycki, Nørgaard, et al. (2017) in an incremental sheet forming process, where each production pass is 3D scanned and used to inform consecutive tool paths. A similar thinking is proposed by Duro-Royo, Mogas-Soldevila, and Oxman in the form of their Fabrication Information Modeling (FIM) framework (Duro-Royo, Mogas-Soldevila, and Oxman 2015). The FIM approach integrates multi-scale trans-disciplinary data - including form generation, digital fabrication, and material computation - by ”starting from the physical and arriving at the virtual environment”. It is a bottom-up approach that references biological precedents, which is similar in spirit to the biomimetic approach espoused by Menges (2012). These approaches require a sensor-based fabrication strategy to inform the design model.

Other practices - such as that of the AA Design Make programme at Hooke Park - use scanned feedback to design the next intervention in an iterative fabrication process (Fig. 3.43). This particular practice also demonstrates some of the possibilities of tailored glulam blanks for the construction of a bespoke timber frame.

Fig. 3.43: Bespoke glue-laminated timber frame for the Hooke Park library. Photo: AA Design Make.

In terms of the tools used for these feedback-based approaches, the use of 3D scanning to capture the geometry of existing objects and environments is becoming an integral and commonplace component of the design workflow (Fig. 3.44). LiDAR scanners are used to digitize intricate physical sites at resolutions down to a millimetre or less. This technology is used to capture irregular, non-orientable forms such as trees and tree trunks: Schindler et al. (2014) capture the irregular form of natural tree branches and explore their use in various designs as a way of challenging existing design and production processes; and the *Woodchip Barn* project in Hooke Park, Dorset employs a similar technique of 3D scanning the forest, building a library of tree forks, and using a heuristic algorithm to map the library of forks onto a structural diagram (Mollica and Self 2016; Self and Vercruysse 2017; Self 2016).

Other technologies, such as real-time motion capture used in the film and video game industries, also show promise in material applications. The *OptiTrack* system, developed by NaturalPoint Inc., is an optical motion tracking system used in motion sciences, virtual reality, and robotics. The installation piece *Phantom (kingdom of all the animals and all the beasts is my name)* by artist Daniel Steegmann Mangrané and ScanLAB Projects (2015) demonstrates its use in merging physical movement and a digitally-scanned environment. The same system is used in the author's prior unpublished work for tracking the form of a free-form laminated timber element while being manipulated by a robotic arm.

The key difference between the two reality capture approaches is that LiDAR creates high-density datasets of unmoving environments, whereas optical motion tracking records only a few specific points but over a period of time and at high frame rates. Achieving direct feedback from the production and material processes in free-form glulam fabrication therefore involves discovering the applicability of these systems and how they might interact. Other, more basic feedback systems such as contact probes, laser projection, and simple industrial laser distance sensors also need to be considered. Merging the physical space of production with the digital information model and aligning material with model necessitates methods and workflows that integrate these feedback systems within the design and fabrication of free-form glulam components.

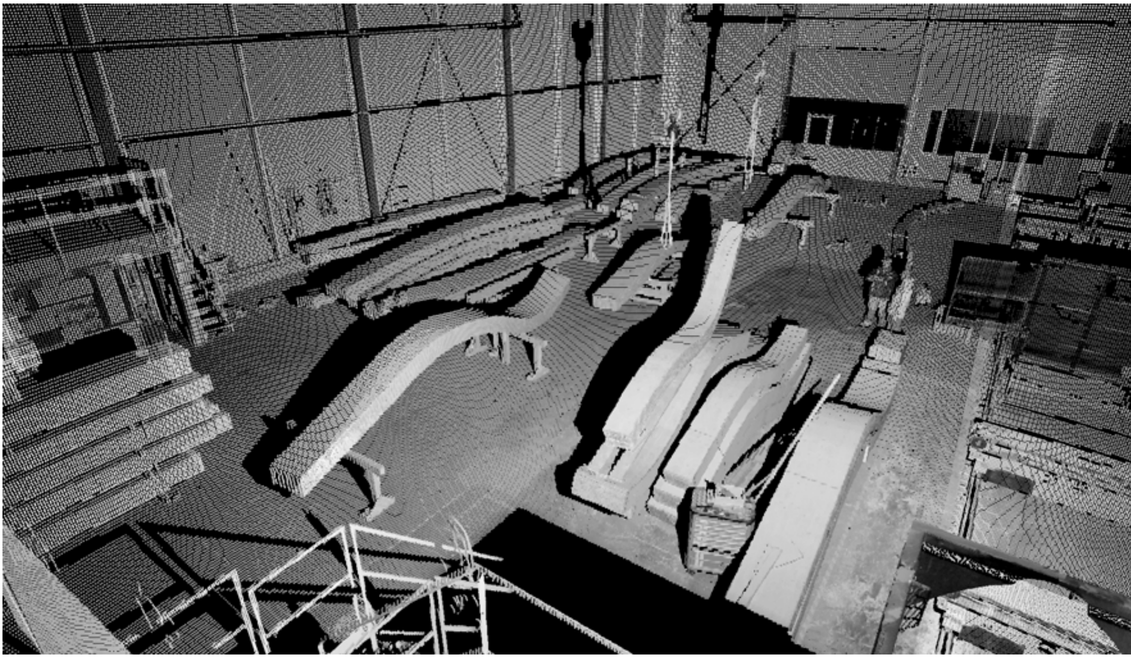


Fig. 3.44: A 3D scanned point cloud of the production hall at *Blumer Lehmann AG*.

Material model

The heterogeneity of wood impacts the ways in which its material behaviours are simulated. Timber displays variations at the cellular and grain scales, which affect is behaviours and performance at an element scale. Simulating the effects of grain and cell variation is therefore different from simulating the bending behaviour of multiple interacting timber elements in a structure. As described in the methodology of this research, a multi-scalar approach that interfaces different types of models is deployed to confront this challenge. This requires a look at what kinds of simulation frameworks are applicable at the various scales of intervention.

One of the most-used simulation methods for a wide range of physical phenomena is the *finite element method* (FEM). This involves the discretization of a problem domain into simple subdomains - the finite elements - whose interaction can be simulated in a straight-forward and divisible manner (Reddy 1993). The simulation converges to an approximate solution within a margin of error which is in a large part dictated by the resolution of discretization - the relative size of the elements compared to the scale of the phenomena being simulated. This leads to the problem of determining the optimal discretization and resolution of elements for a particular problem - the finer the discretization, the more accurate the simulation results will be, however at a greater computational cost. Below a certain margin of error, further discretization has very little effect on the converged solution.

Finite element analysis (FEA) is the use of the FEM to simulate and analyse phenomena in this way. At the micro-scale, high-resolution FEA is used to simulate everything from growth stresses in trees to the effects of moisture and drying on glue-laminated timber elements (Ormarsson 1999). These studies take into account very specific process steps such as the cutting, gluing, and splitting of timber, as well as the layout and orientation of each lamella in glued composites - the influence of the lamellas position within the log on the overall performance of the finished glued product. The drawback is that, due to the large amount of parameters and quantity of finite elements, it is particularly computationally expensive.

A related simulation method that is particularly useful for architectural form-finding and has seen much use and popularization is the *dynamic relaxation method* (DRM). This method similarly breaks down a problem into finite elements and converges to an approximate solution where the forces and deflections are in equilibrium. It differs by beginning with the model in an unloaded state and subsequently following the development of internal forces (Day 1965). This method has been implemented into architectural design software as a popular plug-in by Piker (2013). The interactivity and responsiveness afforded by this method is also what allows it to be embedded within fast, iterative design processes for architectural structures (Senatore and Piker 2014). This approach is particularly applicable to the overall form-finding of meso-scale architectural components, such as in the design of timber grid shells (Quinn 2018) and other bending active assemblies such as described by Bauer et al. (2018).

When modelling architectural components, the problem becomes one of how to move between the continuous surfaces that describe their geometrical boundaries and the discretized and volumetric element models used to analyse them. Meshing - turning a continuous surface model into a polygon mesh - is a typical way of generating finite elements from surfaces. Volumetrically, closed geometric forms can be divided into a 3D grid of voxels or into other such primitives such as tetrahedra through volumetric discretization.

The recent development of a technique called *isogeometric analysis* (IGA) avoids this requirement and allows simulating within the continuous domain of surfaces and curves. As with the DRM, an interface with architectural software allows its use within the comfortable computational modelling environment of architects and designers (Längst et al. 2018). Bauer et al. present a comparison between the DRM and IGA methods, and expand on the unique strengths of each within the context of modelling bending-active structures.

The difference in the applicability of these simulation methods to particular scales illustrates the difficulty in developing a useful design model that incorporates material-level changes at architectural scales. Simulations performed at higher resolutions generally yield more accurate results - better approximations of the problem being analysed - yet they incur a heavier computational cost and are slower as a result. The quick and iterative design explorations required at the beginning of a design project therefore lend themselves to lighter and faster simulations, at the cost of accurate approximations. This trade-off between responsiveness and accuracy is touched upon by Ramsgaard Thomsen, Tamke, et al. (2017) in discussing the integration of different types of simulation in the Complex Modelling project. Although initially considered as a difference between *lightweight* and *heavyweight* models, they argue that it is instead a matter of fidelity and using appropriate degrees of resolution to simulate the behaviour at hand: different models will require different resolutions, and the focus is on how the models link to each other.

What the modelling methods in the new material practice require, then, is ways of interfacing with these methods of simulation at the different scales. Local material differentiation in laminated timber components needs methods of translating geometric definitions of design models into element models suitable for FEA. Similarly, at the meso-scale, glulam geometry, orientation, and cross-sectional composition need methods of interfacing with the DRM and IGA, perhaps through centreline models that are materially-informed.

3.7 Summary

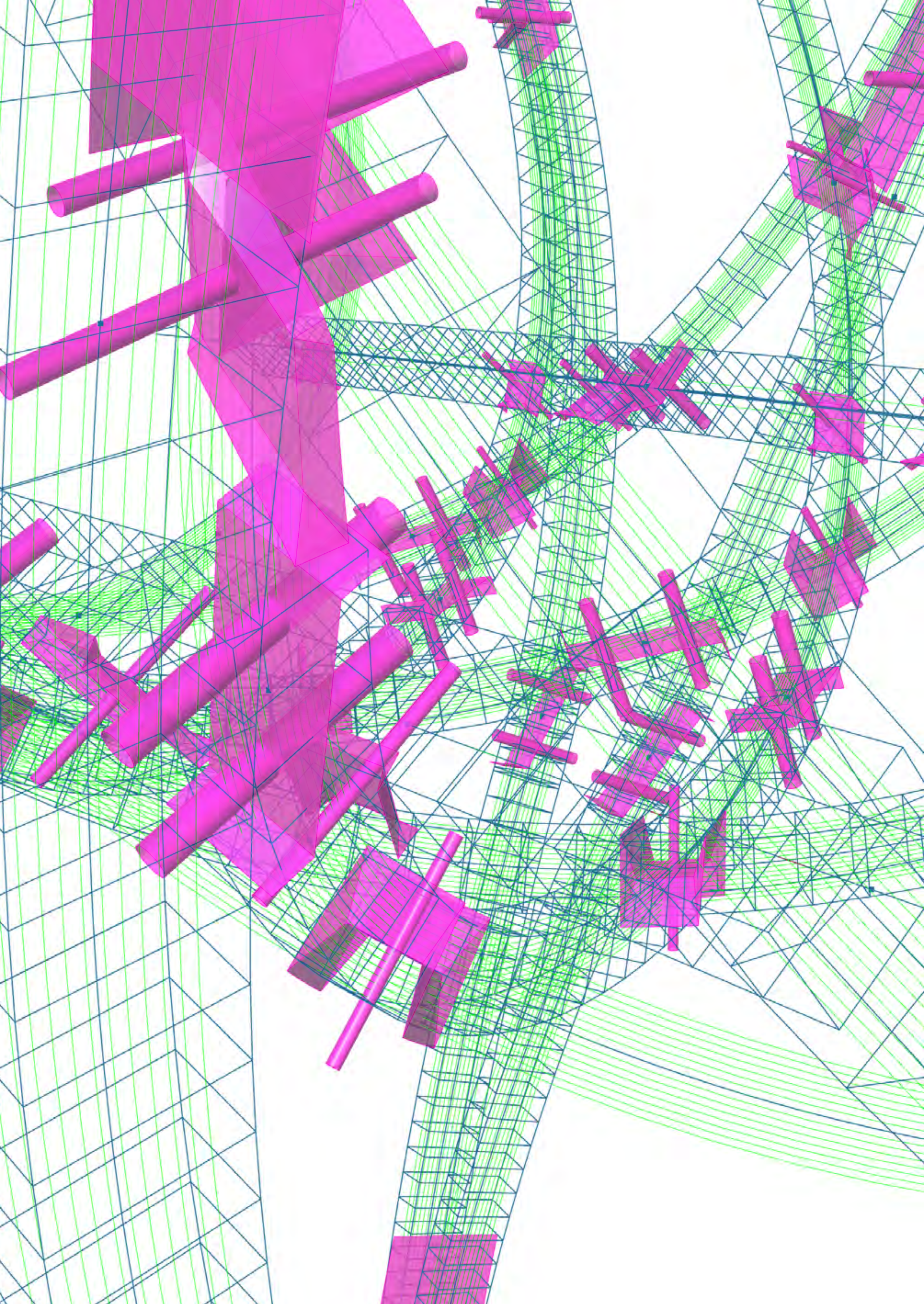
This chapter describes the relevance of timber today and the challenges posed by its material complexity. Material properties - elasticity, strength, durability - are identified as being largely driven by material orientation - the anisotropy of wood. The industrialization of wood and the transformation of trees into timber products, along with the associated manufacturing processes, creates a palette of industrialized ingredients and methods that can be interfaced with design. The development of the glulam blank into its contemporary built examples shows an increase in scale, geometric complexity, and associated shifts towards prefabrication and automation, and also reveal trends that can be challenged. These shifts run in parallel to discourses about the changing role of the architect in the face of digital tools of production and simulation: a new definition of craftsmanship and material practice that is digitally-augmented. This sets the stage for creating a new material practice around the free-form glulam blank, that can leverage automation, prefabrication, and digital simulation to mitigate the challenges posed by the material complexity of wood and expand the space of design into the creation of the blank.

The role of the model transforms from being one of representation to one of function and feedback, complementing the engagement with physical material with an engagement with simulated material. The move between digital model and physical material requires both an application of sensor systems to synchronize the model with material reality as well as interfaces to different simulation frameworks at the micro and meso scales. This sets out the two main experimental starting points: the multi-scalar modelling of glue-laminated timber components, and their materialization and merging with the digital model.

The following chapter describes the computational basis for the new material practice by developing a series of modelling experiments that together create a multi-scalar modelling framework. It focuses on the *representation* of timber and timber process properties at different scales and *simulated feedback* that displays the consequences of design decisions through geometric analysis and the encoding of material and process limitations.

4

COMPUTING TIMBER



4.1 Overview

This chapter focuses on the domain of glue-laminated timber modelling and representation. The heterogeneity of timber at a material level, the varying composition of the glulam blank, and the distribution of different types of glulam blanks across a timber structure make it challenging to construct models that fully take into account these factors across all scales. A multi-scalar modelling approach is therefore used to confront these challenges, using a differentiation between micro, meso, and macro scales proposed by Faircloth et al. (2018). This approach confronts the distribution of timber material properties at a micro scale, fabrication and material constraints at a meso scale, and component interrelation in structural assemblies at a macro scale (Fig. 4.1). The chapter therefore is structured along the corresponding modelling frameworks of meshing and discretization at a material scale, mapping of curved coordinate systems at an element scale, and graph-based modelling at a structural scale.

At the material scale, fibre orientation is the primary point of interest since this impacts other important factors in the use of timber components, such as bending and end-grain exposure. The encoding and digital representation of fibre direction in 3D geometric models is explored in Probe 1: Modelling wood properties through the discretization of design models and the use of colour to show differences in fibre direction. The probe results in techniques for encoding and visualizing these concerns in a *fibre direction map* and a *fibre deviation map*.

At the element scale, a *glulam blank model* - developed as Prototype 1: Glulam blank model - is presented which incorporates characteristics and constraints of glulam production such as bending limits, lamella sizing, and type of glulam blank. This offers a fast creation of glulam blank geometries in familiar design modelling environments, which incorporate fabrication constraints and therefore allow an indication of production complexity within early-stage design workflows. The application of this glulam blank model is demonstrated in Probe 5: Branching Probe, Prototype 2: Grove, Prototype 5: Magelungen Park Bridge, as well as in the final Demonstrator: MBridge. The use of this glulam blank model is also presented in relation to the experimental glulam blank types in Probe 4: CITAstudio glulam workshop. The modelling of more iterative and compound glulam assemblies such as those in Probe 4: CITAstudio glulam workshop is determined to require further considerations of production sequencing and a tree-like organization of process steps.

At the macro scale, the glulam blank model is extended into graph-based modelling techniques which allow the management and linking of structural assemblies with a large number of components. The application of these graph-based modelling techniques is demonstrated in Prototype 2: Grove and Demonstrator: MBridge.

Although the exploration of modelling and representing glulam components and structures involves most of the experimental work, this chapter focuses particularly on the development of Probe 1: Modelling wood properties and Prototype 1: Glulam blank model, since these reside primarily in the computational domain. The other experiments mentioned above are discussed only with regard to how the methods developed in Probe 1: Modelling wood properties and Prototype 1: Glulam blank model are refined and applied.

The central goal of this investigation into modelling and representing glue-laminated timber components is the imbuing of digital models with a notion of materiality: the provision of ”capabilities that afford or constrain action” (Leonardi 2010). Digital models - the kind that are used to describe forms and physical objects in architectural design - are by nature material-less. In many cases, it might be sufficient to simply designate a geometric model as being made of a particular, homogenous material. However, the heterogeneity and anisotropy of timber demands more. The orientation of wood fibres has a profound effect on the material's response to forces, moisture, and processing and therefore the model requires an additional indication of how the material is oriented. The variable properties of wood as well as the change in material orientation due to actions such as bending further require a way that these variations are encoded in the model. The resultant model becomes *functional* (Hensel and Menges 2006, p. 34) by simulating the constraints and capabilities of timber and the glulam blank. This creates a *simulated feedback* where the designer can gauge the material consequences of design decisions without actually interfacing with the physical material. This constitutes the computational foundation for the integrated material practice that this research pursues by embedding materiality and late-stage production constraints into early-stage

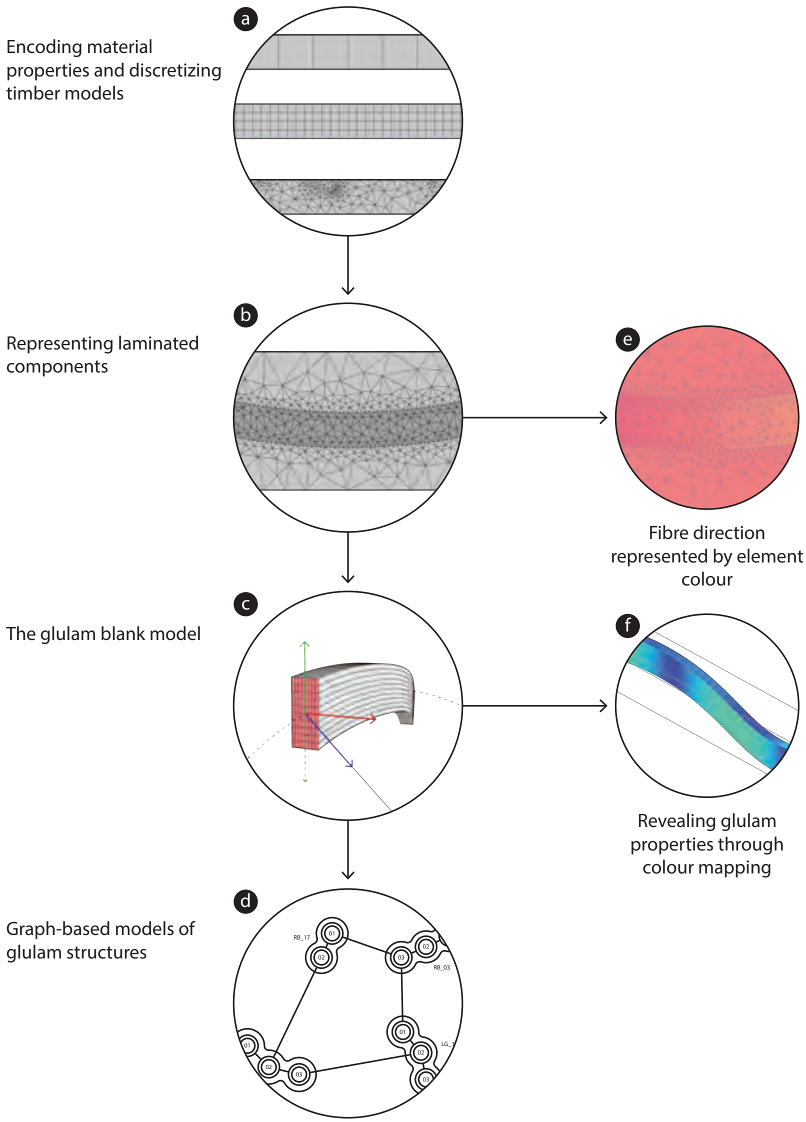


Fig. 4.1: An overview of the experimental work described in this chapter. The development moves from modelling challenges at the level of an individual wood component and its fibre distribution (a), to a method of modelling and representing fibre changing fibre directions in glue-laminated composites (b), to a lightweight model of a glulam blank (c), and to an overall strategy for organizing and analysing complex timber structures through graph-based methods (d). The experiments include how fibre direction is represented as an additional layer of information on discretized element models (e) as well as its impact on glulam blanks (f).

digital design environments. The development of this simulated feedback therefore relies on the translation of material constraints and behaviours into algorithms and functions.

Software

These experiments are primarily based in the McNeel Rhinoceros 3D modelling environment (Rhino3D), as well as its graph-based parametric modelling plug-in, Grasshopper. These are both popular platforms in the architectural and computational design community, because they cost much less than competing packages, are supported by an enthusiastic and active community of users and developers, and possess a powerful yet straight-forward API, exposed in 3 popular programming languages: C++ (Stroustrup 2000), C# (Hejlsberg, Wiltamuth, and Golde 2003), and Python (Van Rossum and Drake 2009). These languages each have different characteristics: Python is a dynamically-typed scripting language with a simple and clean syntax, and is very often used as a programmatic ”glue” between different software libraries and pieces of software since many software packages have Python APIs. The dynamic typing and simple syntax make it especially easy to ”sketch” with, as scripts can be quickly set up and run. C++ is a low-level strongly-typed language that is more demanding on the user, requiring much more attention to memory management and how data is laid out and passed around. Although this demand, as well as the need to compile the program before running it, make fast, iterative development slower than writing and running a script, the low-level control of data and machine performance can also make it extremely powerful and high-performing. C# is a strongly-typed language in the Microsoft .NET ecosystem and could be thought of as occupying a space somewhere in between the high-level scripting of Python and the low-level pointer math of C++. The relatively clear syntax and garbage collection in .NET, as well as the ability to compile small programs quickly, make it a balanced alternative to the previous two. Most of these experiments make extensive use of RhinoCommon, the .NET API for Rhino3D (Baer 2019), and are often ”sketched” or prototyped in the Grasshopper environment. To form a more cohesive and stable codebase - since script snippets and Grasshopper definitions often get misplaced or buried within projects - the scripts, objects, and methods prototyped within the Grasshopper environment are graduated to a collection of .NET assemblies - also written in C# - once they have been tested and fleshed out. These assemblies - together forming a software library - form the main code-based contribution of this thesis and serve as a continually evolving toolkit and playground. The details of the contents, organization, and ambitions for this software library will be discussed later on.

4.2 Encoding material heterogeneity

This section describes the effort to effectively integrate material properties within data and model formats that are most common in architectural design and modelling. As the first computational design probe, Probe 1: Modelling wood properties is the initial foray into encoding heterogeneous material properties within design workflows for the purposes of *representation* for feedback and *interfacing* with other domains of expertise, such as material engineering.

4.2.1 Meshing and discretization

Texture mapping has long existed as a means of augmenting 3D surface data with additional detail (Heckbert 1986; Blinn 1978). This additional detail takes the form of arbitrary multi-dimensional parameters: surface color, specular reflection, normal vector perturbation, and so on. The mapping of these parameters onto arbitrary 3D surfaces demonstrates a useful characteristic for multi-scalar modelling: that of decoupled models and datasets. Texture maps can be of arbitrary resolution, irrespective of the target 3D geometry that they are being mapped onto. Similarly, this makes them interchangeable.

Although the use of texture maps for encoding additional parameters on modelled timber surfaces is useful, discretization of the 3D model into elements allows a similar encoding of parameters which embeds their distribution into the topology of the model. Discretization also is not constrained by the grid-like topology of image maps - a common way of mapping texture data. Further, this division of the 3D model into discrete elements allows an almost one-to-one interfacing with material and structural simulation techniques, such as the *finite element method* (FEM) (Larson and Bengzon 2013).

In a more general sense, discretization can be used as a method for moving in-between different scales of modelling in a multi-scalar approach. Discretizing a model at one scale represents a refinement of information at a lower scale, such as described by Nicholas, Zwierzycki, and Ramsgaard Thomsen (2015), along with increasing the amount of data being considered and processed. Thus meshing is only one form of discretization that is conveniently applicable to the encoding of heterogeneous properties in 3D surface models. Beyond the individual timber plank, the glulam blank can be discretized into its constituent lamellae, and the glulam structure can be discretized into its constituent glulam components. The discretization of the glulam blank is presented later on as an extension of this approach.

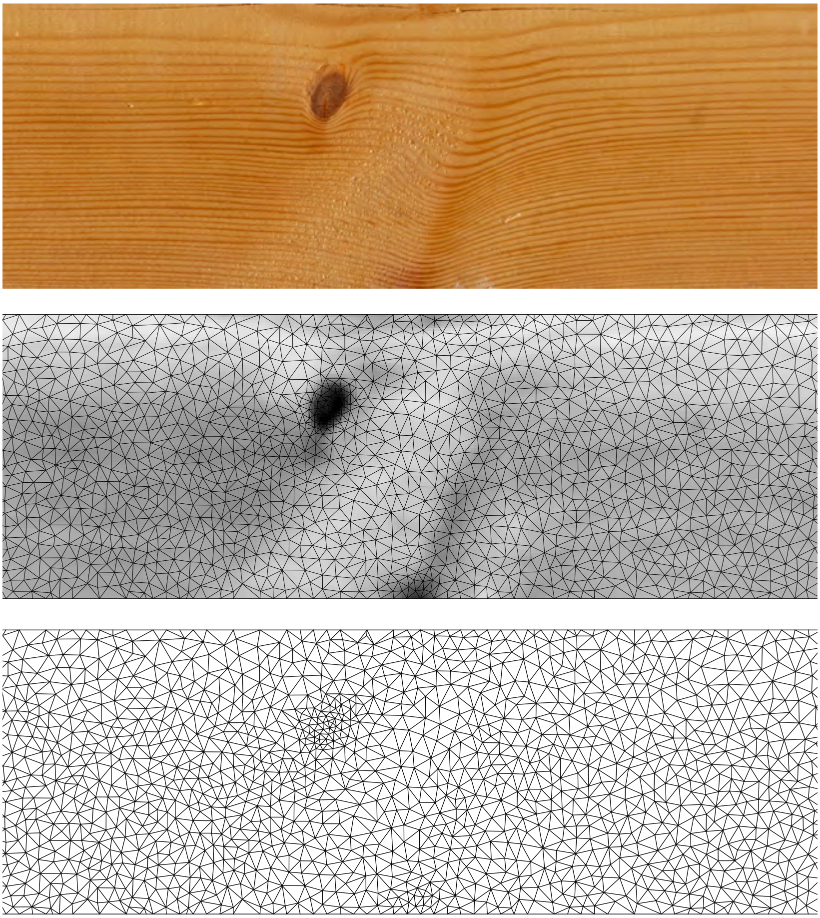


Fig. 4.2: Discretizing a timber component. A timber surface with highly varying properties (top). A discretization technique decomposes the rectangular boundary into triangle elements based on a variance map (middle). Element density corresponds to areas of higher material variability (bottom).

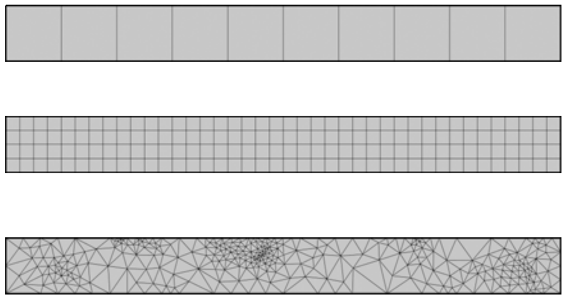


Fig. 4.3: A proportional subdivision (top), grid-like subdivision (middle), and an adaptive triangle subdivision (bottom) of a 2-dimensional timber plank.

Since timber is made up of individual wood cells and fibres, a complete discretization of a timber plank model would result in an element for each cell and fibre: an increase in resolution that matches the material resolution. In typical use cases, however, local properties can only be inferred at lower resolutions, meaning microscopic properties are averaged into more abstracted indications of local material property.

Types of meshing

This probe took the timber plank as its starting point due to its simplicity: projected to two dimensions, the plank is a simple rectangle and can be represented as a mesh with a single face. As planks are linear elements, the proportion of the rectangle is several times wider as it is high (Fig. 4.3).

Proceeding from this, the most basic discretization consists of dividing the rectangle into smaller faces with roughly equal proportions. This first and coarsest technique creates a differentiation of properties along the length of the plank.

Next, the resolution of this discretization in increased by further subdividing the faces in both dimensions: a grid-like discretization. Again, this is well-suited to a rectangular plank because it is orthogonal to begin with and is topologically trivial. A problem arises once the plank is no longer purely rectangular - such as when it is cut at an angle or has cut-outs. Further, a grid-like discretization yields elements that are all similarly sized and evenly spaced. This can misrepresent the underlying timber surface which can have large areas of even properties (clearwood) interspersed with small areas of large property deviations (knots). These small interruptions nevertheless have a large impact on the performance and behaviour of the plank. However, subdividing the whole plank to a much higher resolution to capture these small areas also means that the large and even areas have a mass of redundant data.

A third method of discretization is therefore triangle-based and adaptive which allows an uneven distribution of model elements across a timber surface. Higher-resolution elements can be applied to areas of the timber plank that are varying the most and, conversely, lower-resolution elements can be applied to larger areas of more even properties. This comes at the cost of the uniform and easily traversable topology generated by the preceding two methods, since the triangle elements are not organized in a grid.

To implement this third method, the probe uses a modified implementation of the Poisson disk sampling method by Bridson (2007) and a Delaunay triangulation of the resulting points (Fig. 4.2). The sampling disk radius is driven by a processed image map of the timber surface, which makes it possible to relate the sample density with the specific timber surface. For this probe, the intensities of the image values are used, blurred to remove high-frequency information below the minimum sampling distance, and normalized. The resultant values drive the disk radii between a specified minimum and maximum distance, arbitrarily chosen to illustrate the effect. Although the image gradient would be a better candidate to use for driving the disk radii, this method still correctly allocates finer elements around areas of high variation such as knots, and thus demonstrates the adaptivity of this method.

Glue-laminated components

Extending this meshing approach to glue-laminated components requires the definition of different regions of mesh elements that correspond to the constituent lamellae or timber planks that are glued together. A similar method is used as before, however with the addition of a property per resultant mesh element that identifies which part of the glue-laminated component it belongs to. A laminated component can be therefore construed as distinct groupings of mesh elements that represent the separate timber elements within the laminated assembly.

This probe uses Otto Hetzer’s patent no. 163144 as a test case (Fig. 4.5) since it presents the simple case of a bent plank laminated in-between two halves of an un-bent block of timber. An exploratory physical prototype illustrates the principle (Fig. 4.4).

To implement this case study, the .NET implementation of the Triangle library

Fig. 4.4: A physical probe similar to Otto Hetzer’s patent no. 163144.

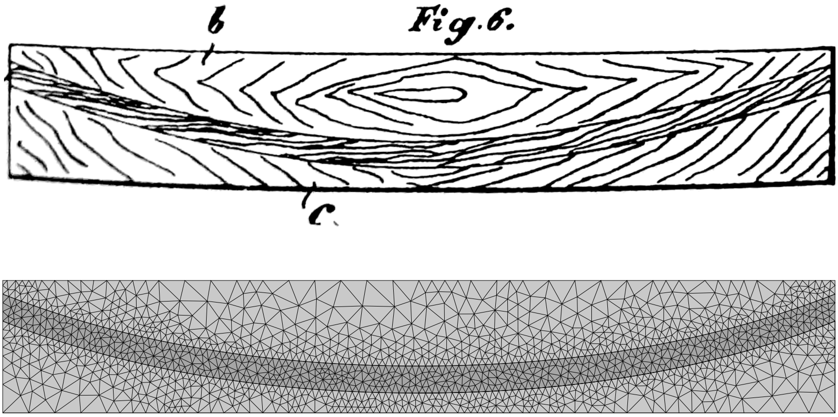


Fig. 4.5: Adaptive meshing of Otto Hetzer's patent no. 163144. Each zone or group of elements represents a different constituent element. The boundaries between zones represent the glue boundaries.

by Shewchuk (1996) was adapted for use with the RhinoCommon API. The Triangle library creates constrained Delaunay triangulations from arbitrary point or segment input, while respecting boundaries of input polygons or regions. This allows different regions to be defined as polygons with shared boundaries - corresponding to the glue-line interfaces between laminated components - which, after meshing, can be recovered as groupings of mesh elements. The constrained Delaunay method has the added advantage of responding to a variable distribution of input points and segments. This means that the thinner centre piece in Fig. 4.5 is discretized to a finer degree than the two surrounding pieces.

Fibre interfaces

Of particular interest in this move from individual timber plank to a glue-laminated component are the boundaries between the regions of mesh elements (interior) and between the mesh elements and the outside of the model (exterior) (Fig. 4.6). The interior boundaries between regions of mesh elements represent glue-line boundaries, where the fibre directions of two separate timber pieces meet. Comparing the material direction of mesh elements on either side of this boundary yields important information about the quality of the glue-line, since this is dependent on the orientation of fibres: effectiveness of adhesion is higher when the wood grains are parallel.

The exterior boundary - between the mesh elements and the outside of the model - yield useful information about the end-grain exposure of the model, which, in turn, has important repercussions for the durability and structural

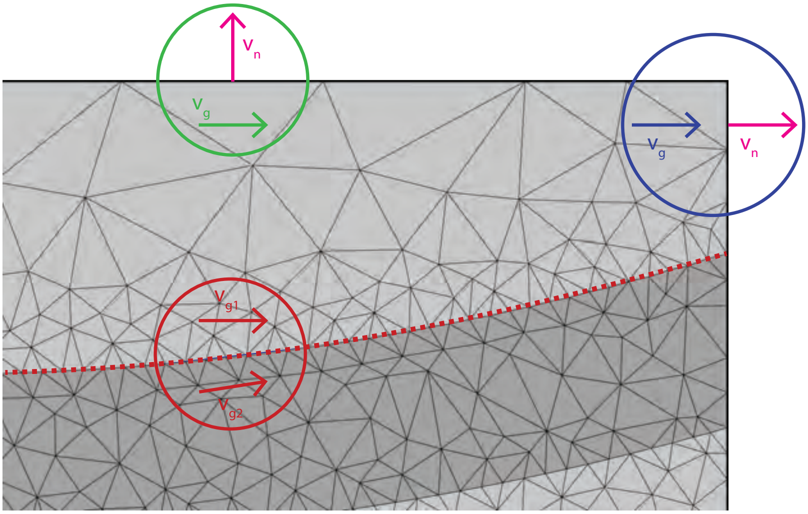


Fig. 4.6: Fibre boundaries in the discretized wood model. The green area shows where the surface normal $\vec{v_n}$ is perpendicular to the wood grain vector $\vec{v_g}$, meaning the surface is parallel to the grain direction - an ideal scenario from a structural and durability perspective. The blue area shows the opposite case, where the surface normal $\vec{v_n}$ and grain vector $\vec{v_g}$ are parallel, meaning the surface is cutting across the wood fibres. The red area shows a glue-line boundary (red dashed line) and the two wood grain vectors ($\vec{v_{g1}}$ and $\vec{v_{g2}}$) on either side of it. Comparing these two can give an indication of the effective adhesion between the two laminated regions.

performance of the timber component. Comparing the normal vector of this exterior boundary with the material direction in the neighbouring mesh element gives the amount of end-grain present: if the normal is perpendicular to the material direction, then the fibres are parallel to the boundary and there is no end-grain; if the normal is parallel to the material direction, then the fibres are orthogonal to the boundary and there is full end-grain exposure.

Representing end-grain and fibre direction on the model boundary can therefore give an insight at a glance about issues of durability and structural performance, without even considering the fully discretized interior of the model.

4.2.2 Representing heterogeneity

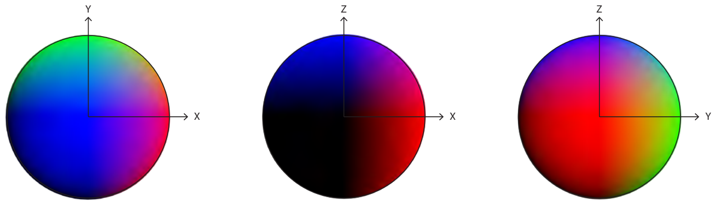
The importance of visually representing varying wood properties such as grain direction is made clearer when considering that two architectural timber components might be identical in form, yet might be machined out of a different glulam blank. Recalling the differences between a straight and double-curved glulam blank, differentiating them would be important. The geometrical model of both would not reveal this difference, however a geometric model augmented by a representation of these properties would clearly illustrate the difference in a qualitative way. Although arbitrary data can be encoded within - or linked to - 3D model data structures, making it visually differentiable makes it useful as a feedback tool for the designer. Such a visual representation might not communicate precise numeric values, however it can still reveal variations in properties and their relative magnitude. Other efforts such as those by Heinrich and Ayres (2016) have similarly looked towards encoding additional dimensional data in colour to increase the density of information in architectural representations.

This probe augments the discretized glue-laminated timber model with a *fibre orientation map* which relates orientation of the longitudinal timber axis to colour. The precedent for encoding vector data using colour lies in *normal mapping* - a standardized method used to encode surface normal deviations in an image texture in computer graphics. The beginnings of this technique lie in the preservation of detail - such as colour, high-resolution shape detail, arbitrary scalar fields, and so on - on meshes of reduced complexity (Cignoni et al. 2002) and the simulation of realistic surface wrinkles (Blinn 1978) by storing this extra, higher-resolution data in texture maps. These techniques are focused on preserving the appearance of heavy and complex models whilst actually using reduced or decimated models (Cohen, Olano, and Manocha 2005). Normal maps store 3D vector data - *x, y, z* coordinates - in RGB (red, green, blue) colour channels.

This mapping creates a *colour sphere* of all possible vector directions, where each vector axis is aligned with a primary RGB colour (Fig. 4.7). The problem with this is that, being centred on the origin (0,0,0), the values of direction vectors can be negative, while typical display colours require values between 0 and 1 - or 0 and 255 for 8-bit encodings. If the direction vectors are clamped to 0 and 1, all directions that point along any of the negative axes are displayed as black and therefore cannot be differentiated.

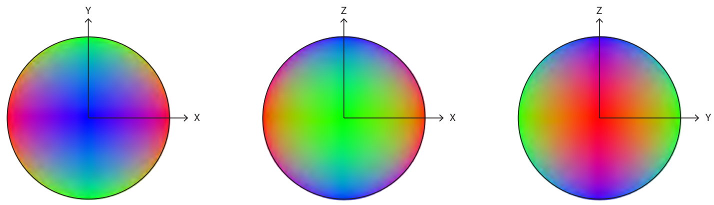
One solution is to use the absolute value of the direction vector values (Fig. 4.8), which ensures that all values are between 0 and 1. However, this presents another problem where different vectors are represented with the same colour because of the symmetry that is induced in the colour sphere.

The third approach is that used in most normal mapping techniques, where



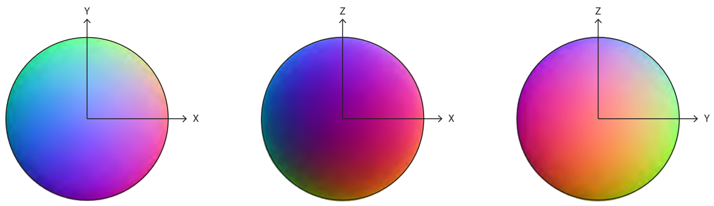
(a) XY plane **(b)** XZ plane **(c)** YZ plane

Fig. 4.7: Mapping direction vectors onto colours.



(a) XY plane **(b)** XZ plane **(c)** YZ plane

Fig. 4.8: Using the absolute value of the direction vector results in ambiguities because of symmetry.



(a) XY plane **(b)** XZ plane **(c)** YZ plane

Fig. 4.9: Normalizing the direction vector (shifting the zero-point to 0.5) creates a unique colour for every vector.

the zero-point is shifted. The vector is moved to (0.5, 0.5, 0.5) and its components are halved:

$$\vec{v_{rgb}} = \frac{\vec{v_f}}{2} + (0.5, 0.5, 0.5)$$

This creates a unique colour for every direction vector, thus allowing the full direction sphere to be mapped. Negative values are confined between 0 and 0.5, and positive values are similarly mapped between 0.5 and 1 (Fig. 4.9).

When considering the fibre direction of wood, its growth direction - upwards from the roots - can be thought of as ”forward”. When harvested and processed into timber, the ”forwards” and ”backwards” of this fibre direction are less important, as the strength and behaviours of timber act the same in both directions. The fibre direction is therefore, in a sense, bidirectional. This has repercussions for the fibre orientation map in this probe. Because of this bidirectionality, it can be assumed that a particular fibre direction vector is equivalent to its reverse:

$$\vec{v_f} = -\vec{v}_f$$

This means that fibre direction vectors which are equivalent are represented by two contrasting colours, which implies a large difference between them when, in fact, there is no practical difference (Fig. 4.10).

A hemispherical mapping succeeds in mapping the same colour for a vector and its reverse. Direction vectors that have a negative Z-component are reversed, creating a *colour hemisphere*, similar to cutting the previous colour sphere in half along the XY plane. This results in a single colour for a vector and its reverse, however it presents a problem close to its equator.

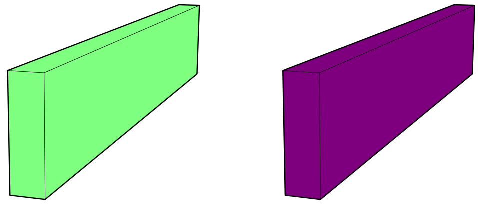


Fig. 4.10: Reversing the direction vector (0,1,0) (left) to (0,-1,0) maps to a very contrasting colour.

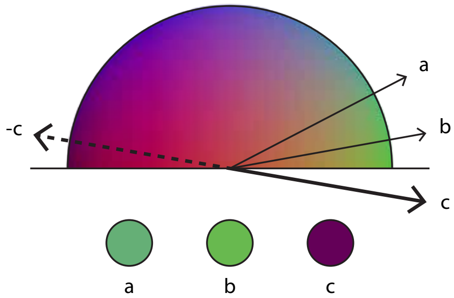


Fig. 4.11: The problem of constraining vectors to a hemisphere by flipping them. Vector $\vec{b}$ is close to $\vec{c}$ however, in order to keep its Z-value from being negative, it is reversed ($-\vec{c}$), putting it on the other side of the hemisphere and thus resulting in a dramatically different colour.

Given a direction vector that lies on or close to the XY plane (on the equator of the colour hemisphere), a small deviation in the positive Z-direction is represented as a small deviation in colour. However, a small deviation in the negative Z-direction is represented as a large deviation in colour, because the vector is flipped to the other side of the hemisphere (Fig. 4.11). Once again, this can result in the misrepresentation of varying fibre directions between very similar timber components.

Two strategies for mitigating these misrepresentations arise: finding a frame of reference that minimizes these ”flips” around the colour hemisphere or alternating between a fibre direction map and its reverse. The first involves ”rotating” the colour hemisphere such that as few as possible direction vectors are below its equator. This works when fibre directions are generally

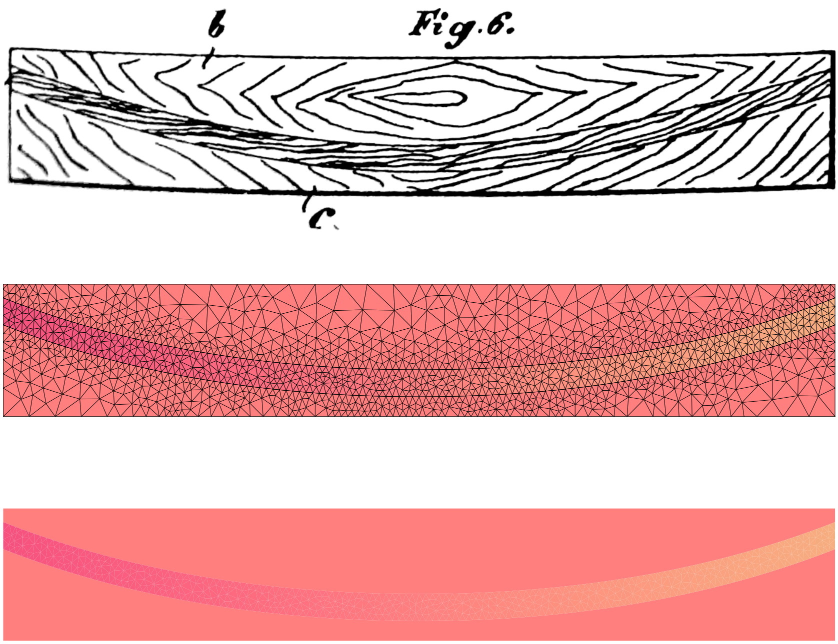


Fig. 4.12: Discretizing a model of Otto Hetzer's patent no. 163144 (top), mapping grain direction vector (XYZ) onto the colour (RGB) of the elements (bottom).

less than perpendicular. The second strategy is to alternate between two different representations: the original fibre direction map and the map of the reversed direction vectors.

Setting aside the shortcomings of these colour mappings, the probe explores their application to some digital case studies. Following the discretization of Otto Hetzer's patent no. 163144, its fibre orientation map allows the principle behind its invention to become more obvious (Fig. 4.12). The outer two regions display a constant colour, which corresponds to the constant (straight) fibre direction in the outer laminated members. The middle region displays a subtle gradient, corresponding to the varying (bent) fibre direction in the middle laminated member.

Apart from the mapping of grain direction onto colour, the mapping of how much a surface deviates from the grain direction can reveal important performance considerations on models of timber components. This *fibre deviation map* can reveal areas where end-grain is exposed - which can impact the durability of the timber component - or where the deviation from the fibre direction is large enough to cause a significant degradation in structural strength - the fibre-cutting angle.

As discussed before, comparing the normal of the surface to the fibre direction at that point gives an indication of this deviation. In terms of implementation, this simply involves taking the dot product of the surface normal and the fibre direction vector to give the cosine of the angle between the vectors:

$$deviation = \vec{n} \cdot \vec{v_f}$$

Since the result is a scalar value, it can be represented as a greyscale gradient or heat map across the model, avoiding the difficulties of mapping vectors to colour described previously. Although the dot product between two unit vectors is a value between -1 and 1, in this case using the absolute value - between 0 and 1 - is sufficient, since the fibre direction can be assumed to be bidirectional. Between the representations of fibre *direction* and *deviation*, the varying properties of glue-laminated timber components and their implications can be visualized.

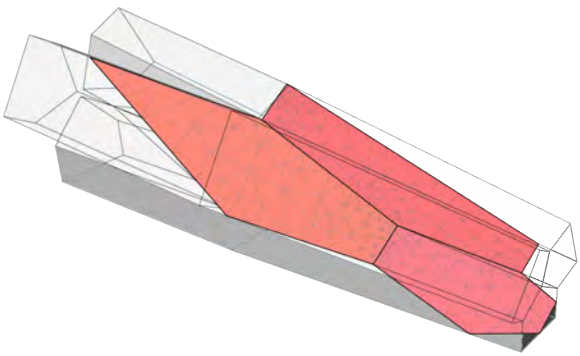
4.2.3 From surface to volume

Since geometric models of architectural components are typically surface-based, mapping heterogeneous properties onto 2D surfaces is sufficient to communicate differences between geometrically identical components. However, certain applications can make full use of the volumetric distribution of heterogeneous material properties, such as *finite element analysis* (FEA) of material behaviour and structural engineering. A volumetric representation and mapping of properties also opens up the potential to model glue-laminated timber elements that have a varying internal organization which might be invisible from the outside.

This requires corresponding methods of discretizing 3D models into elements. This development therefore extends the initial 2D triangulation methods with a 3D tetrahedralization and follows a similar approach for mapping properties. To implement this, the TetGen library by Si (2015) was integrated into a plug-in for the RhinoCommon API. TetGen is written in C++, which meant that several steps were required: exposing the functionality of TetGen as a shared library in C++, writing a wrapper in C# to expose the functionality of this shared library in the .NET framework, and writing a plug-in for both Rhino and Grasshopper in C# using the RhinoCommon API.

The results are much the same as the previous discussion with the 2D discretization and mapping of heterogeneity, except in a volumetric sense (Fig. 4.13). The benefit of both 2D and 3D methods is that they yield simplex

(a) A physical prototype of a diverging glue-laminated component.



(b) A cutaway of the laminated element, revealing the different regions inside, each with its own fibre direction.

Fig. 4.13: The model discretization in 3D, with wood fibre direction encoded as colour.

elements - triangles and tetrahedra - which can be interfaced with FEA models in domains of material science or engineering. The simulation of wood in FEA software such as Abaqus relies on the generation of individual elements and a designation of their material properties, as explained by Mirianon, Fortino, and Toratti (2008), building on the work of Ormarsson (1999). Engineering values are available for a large variety of wood types and species (Obara 2018), meaning that a design interface to these domains can begin to extend the realm of the architectural designer towards the specification and control of properties and performance at a material level, through digital simulation.

Finally, Probe 1: Modelling wood properties prioritizes the longitudinal material axis in its explorations, since this aligns with the fibre direction of the timber. This privileges the strongest material axis and serves to illustrate the focus of the probe, especially in two dimensions. Detailed behaviour simulations of timber and more in-depth models no doubt would require the full orthotropic frame, which includes the radial and tangential vectors. The encoding of direction vectors as colour remains valid, however, because the rest of the frame can be derived from the addition of just one of these vectors. This means that the fibre direction map must be supplanted by an addition *radial map* or *tangent map*. The precedent for this again comes from the computer graphics field: a technique called ”frame mapping” is presented by Kajiya (1985) for the representation of anisotropic lighting models in computer graphics. This uses both a normal map and a tangent map to derive the orthonormal local coordinate system, used to modulate lighting effects and simulate anisotropic surfaces. The derivation of a full orthonormal frame can therefore be borrowed for the encoding of the orthonormal material frame of timber in the same way.

This has a particular consequence for the representation of a glulam beam. As an assembly of lumber that is generally pointing in the same direction, a fibre orientation map would not show much deviation. However, depending on where each lamella is cut from in relation to the tree trunk, the radial and tangential directions could greatly vary. Using a tangent or radial map as described above, the amount of variation or crowning in the glulam cross-section could be thus communicated (Fig. 4.15).

Probe 1: Modelling wood properties concludes with the question of how these lower-level material distributions and associated datasets can be integrated into models of glulam components and structures at meso and macro scales, respectively. Further, generating and controlling fibre orientation data through higher-level models would allow the presented methods of *representing* timber properties and *interfacing* with other domains of simulation to be deployed at a wider architectural scale (Fig. 4.14). A significant component of that is how local properties - such as

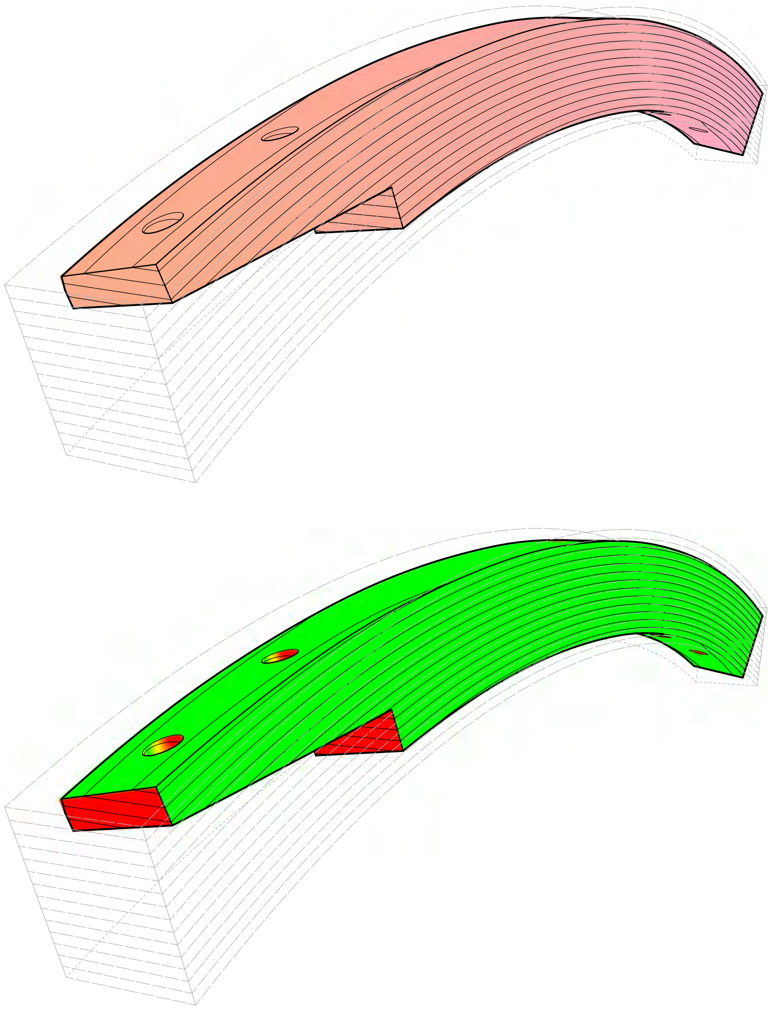


Fig. 4.14: Representing fibre direction (top) as colour and deviation (bottom) as a green-to-red heat map on an architecturally scaled component - RB_4_0 - from Demonstrator: MBridge.

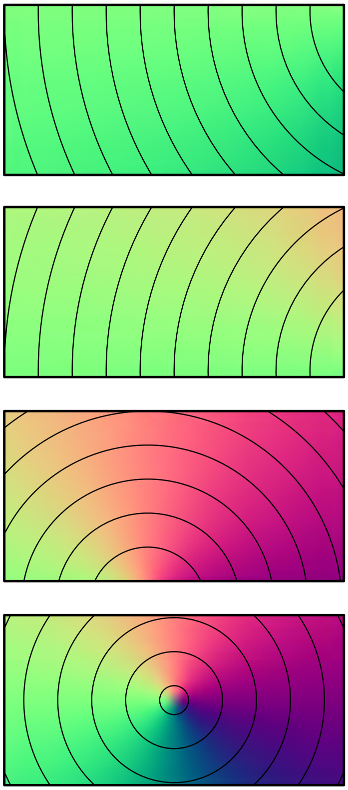
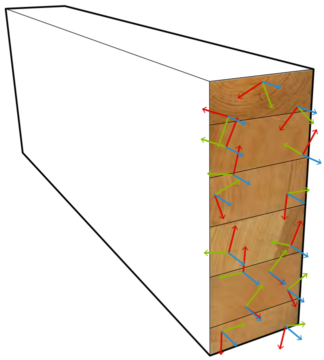
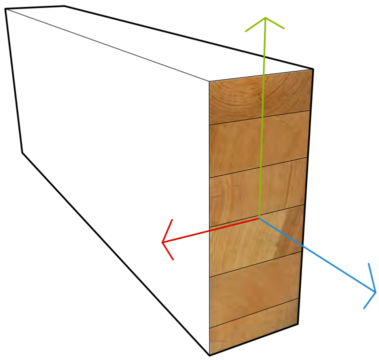


Fig. 4.15: Using the fibre direction mapping to visualize differences in the radial material direction on a timber cross-section. The concentric circles show growth rings. The top two cross-sections show less colour variation due to being cut further away from the centre of the log. The bottom two cross-sections show much variation due to being cut around the centre of the log.



(a) The orthonormal wood axes vary between lamellae and within each lamella cross-section. The longitudinal direction (blue) represents the fibre growth direction, along which the wood is strongest. Radial (green) and tangential (red) directions vary strongly depend on their distance to the centre of the tree and the orientation of the lamella in the cross-section.



(b) The main axes in a glulam beam section become the averaged longitudinal fibre direction (blue) and the width (red) and height (green) directions.

Fig. 4.16: Moving from a material scale to a component scale requires the abstracting of properties.

the longitudinal material direction or fibre orientation - can be abstracted into a larger-scale, simplified property more suitable for assemblies with more numerous components (Fig. 4.16).

4.3 The blank model

4.3.1 Modelling glulams

The Prototype 1: Glulam blank model project takes the embedding of timber properties to the scale of architectural components and glulam blanks. As such, the embedded information in the models changes from one of being purely material properties to also encompassing fabrication data and material specifications such as wood quality and type of manufacturing process. The established production processes of glulam blanks provide useful constraints that allow the glulam blank model to be abstracted into a lightweight geometric model with associated functions. The blank model incorporates a data structure that allows the referencing of individual lamellae, meaning that a link between light-weight, architecturally scaled models and the lower-level, discretized element models of individual timber planks is made possible.

Because of the production processes involved in the creation of a glulam blank, certain 3D modelling assumptions can be made. Sawing logs into lumber results in timber elements that resemble rectangular extrusions. Indeed, the planar and parallel cuts in the sawmill ”crop” the log into nominally straight sections of rectangular profiles. Cut along the trunk of the tree, the longitudinal axis of the lumber element corresponds to the approximate longitudinal material orientation throughout its volume. As beams or columns, glulams follow a similar process: longitudinal extrusions of a rectangular cross-section, with the longitudinal material orientation roughly parallel to the central axis of extrusion - the *centreline curve*. This is a convenient starting point for developing a constrained and light-weight model of free-form glulam blanks: a straight or curved extrusion axis, swept by a rectangular cross-section that is, in turn, composed of smaller rectangular sections corresponding to the cross-sections of the individual constituent lamellae.

The initial exploration into the modelling of free-form glulam blanks takes place in Probe 2: IBT glulam workshop. Through a combination of digital modelling and physical prototyping, the bending limits of timber lamellae and overall fabrication feasibility of free-form blanks is linked to computational rules and procedures. This leads to the first 3D models in this research that focus on the relationship between curvature and material specification, issues of orientation and consistency, and key aspects of the 3D model that distinguished free-form glulams from other free-form digital elements. In transferring the principles of glulam production to 3D modelling, the probe draws on advice from industrial partners *Blumer Lehmann AG* and *Design-to-Production GmbH*.

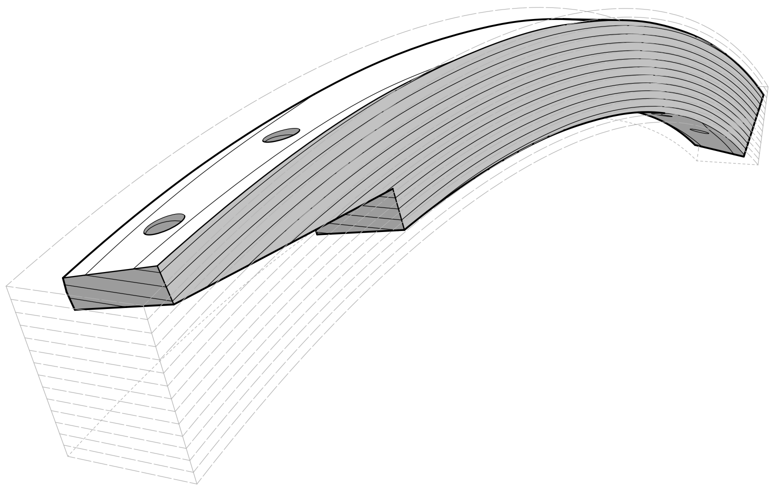


Fig. 4.17: A free-form element cut out of a single-curved glulam blank. The glulam blank (dashed outline) envelopes component RB_4_0 from Demonstrator: MBridge. Traces of each lamella leave their imprint on the final design geometry.

To begin with, free-form curves are projected onto an undulating surface. A rectangular cross-section is aligned with the start of the curves, and oriented so that it stands normal to the surface. Sweeping the cross-section in this way results in a free-form rectangular extrusion that is oriented on the surface. However, this does not result in consistent cross-section dimensions along the sweep. A subsequent method instead distributes the cross-section onto a series of planes perpendicular to the free-form curves, which are then lofted together. This ensures that, at each cross-section along the curve, the cross-sectional dimensions are true.

Relating the material specification of the glulam to its centreline curve requires the translation of Eurocode bending limits into algebraic and modelling procedures. Referring back to Eurocode 5, the maximum allowable thickness for a timber lamella in a glulam is $1/200^{th}$ of the minimum radius of its curvature. Implementing this rule consists of finding the largest curvature vector of the centreline curve by sampling the curve at regular, user-specified intervals. The magnitude of this curvature vector ($\vec{v_k}$) is the maximum curvature (k_{max}) of the curve. Since the curvature and radius of curvature are inversely related, the maximum thickness (t_{max}) of the glulam lamella is easily found:

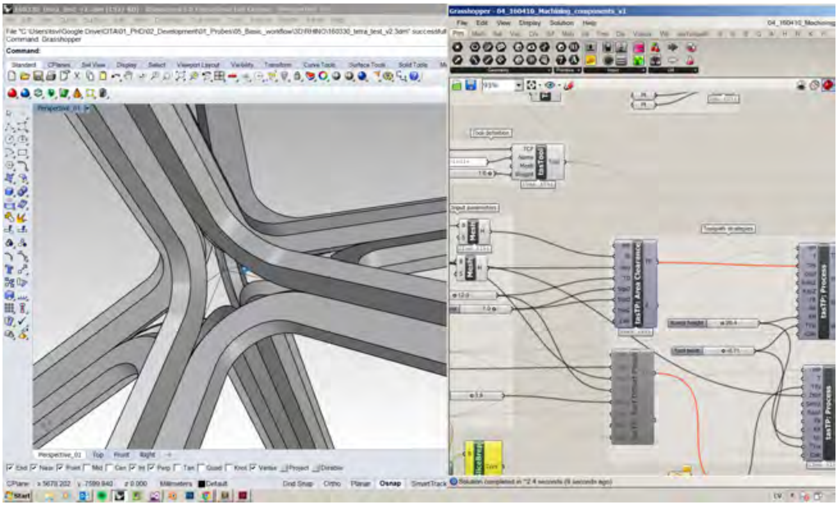
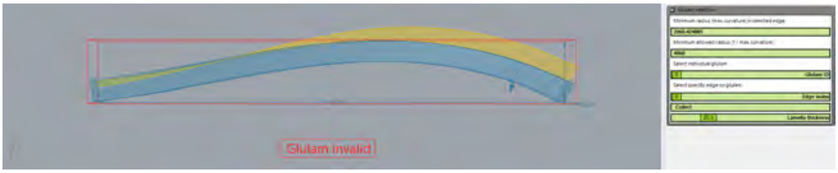
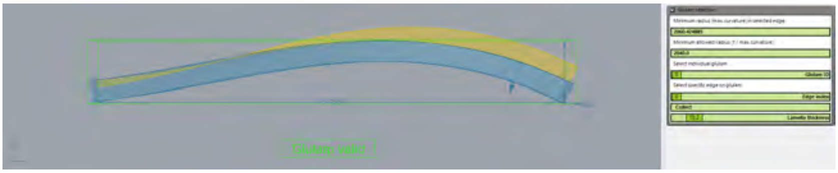


Fig. 4.18: An introduction to modelling 3D glulams in Probe 2: IBT glulam workshop.



(a) The lamella thickness (20.3mm)exceeds the curvature limits of the glulam.



(b) The lamella thickness (10.2mm) is within the curvature limits of the glulam.

Fig. 4.19: Integrating fabrication and material bending constraints into 3D glulam modelling. A curvature graph (yellow) identifies the areas of greatest curvature on the glulam, allowing the minimum radius of curvature to be calculated (2060.4mm).

$$t_{max} = \frac{200}{\|\vec{v_k}\|}$$

Or, put another way:

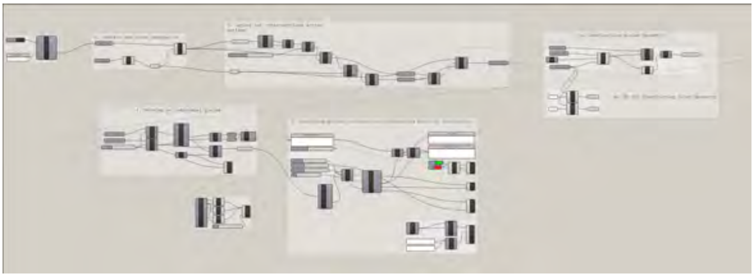
$$t_{max} = \frac{r_{min}}{200}$$

where r_{min} is the minimum radius of curvature of the glulam centreline curve. This radius must also be adjusted to account for half of the width or height of the glulam cross-section, since the glulam face on the inside of the curve has a higher curvature than the centreline.

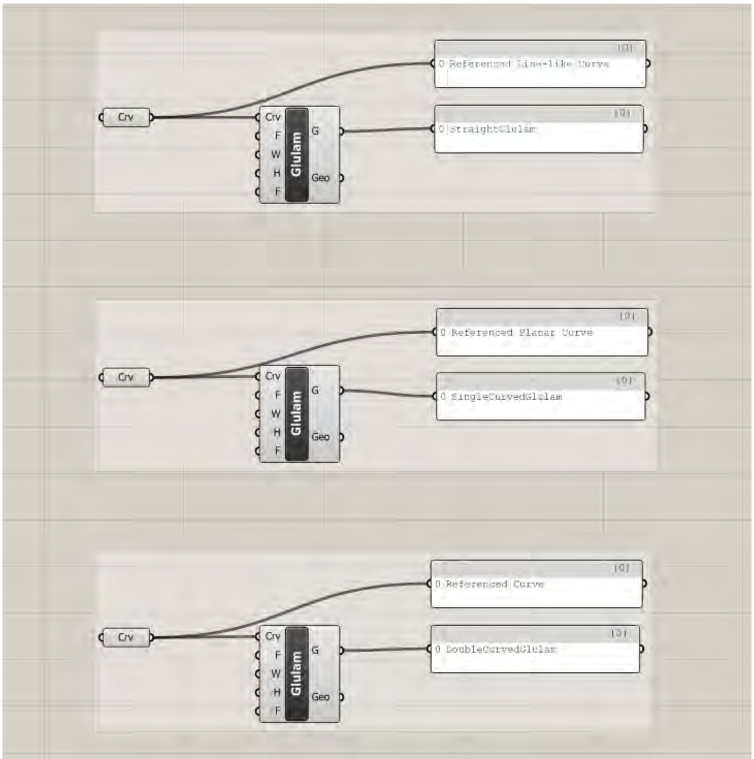
These two considerations - the alignment and consistency of orientation cross-sections on a free-form centreline curve and the relationship between the maximum curvature of the centreline curve and the maximum allowable thickness of its lamellae - are the primary modelling distillations from Probe 2: IBT glulam workshop. In addition, the straightness and planarity of the centreline curve - not only as a driver of curvature but of fabrication complexity - becomes a key ingredient in the glulam model. To explore how they can be deployed, the workshop uses these relationships to model four free-form glulam blanks and fabricate them using hand tools, clamps, and simple jigs. These initial explorations help to identify key modelling principles that form the basis of the *glulam blank model* which is further developed into Prototype 1: Glulam blank model.

One particular driver for moving from an implementation of existing modelling tools to dedicated plug-ins for modelling free-form glulams is the high degree of involvement and organisational clutter in the modelling environment during Probe 2: IBT glulam workshop. This entails a large amount of repetition of labour and increase in visual density within the modelling environment. Also, by having every modelling step explicitly exposed, it results in frequent errors and inconsistencies, especially when used by different designers in an ad hoc manner.

The implementation of these modelling principles - cross-section orientation along a free-form centreline curve and the relationship of cross-section specification to bending limits - is therefore encapsulated in a software library (Fig. 4.20). The cross-section specification dictates the sizing and count of lamellae and is therefore dependent on the curvature and type of centreline curve. This positions the modelling of different types of glulam blanks as a convergence of the *centreline curve*, *cross-section orientation*, and *cross-section material specification*.



(a) The node layout for modelling a glulam blank in Probe 2: IBT glulam workshop.



(b) Encapsulating of the procedures into a software library simplifies the modelling environment.

Fig. 4.20: Encapsulating a complex modelling process (a) by creating custom plug-in components for modelling different types of glulams blanks (b).

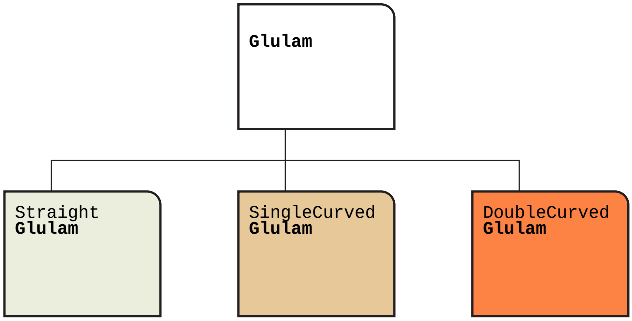


Fig. 4.21: The different glulam types derive from the same generic base class.

4.3.2 The centreline curve

The type of centreline curve that is used to drive a glulam model directly impacts what kind of glulam it models. Using the categorization of straight, single-curved, and double-curved glulam blanks, drawing a parallel between the type of glulam blank and the type of centreline curve used to model it is straightforward. A straight line is a curve with zero curvature. As such, a centreline curve that is a straight line results in a straight glulam blank, with the caveat that its cross-section is not twisted. A planar curve possesses curvature vectors that lie in the same plane. This is analogous to a single-curved glulam blank, which curves only in a single plane, with a similar caveat that the cross-section is also aligned with the plane of curvature. A free-form curve which curves out-of-plane is therefore analogous to a double-curved glulam blank.

These relationships between centreline curve types and glulam blank types are significant because they have important implications for the fabrication process - in terms of cost, material waste, and fabrication complexity. Analysing the centreline curve of a glulam blank model therefore reveals crucial implications for fabrication.

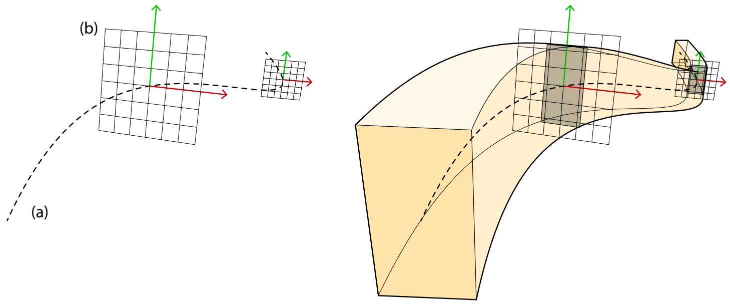
The glulam blank model implements these relationships as a subclassing of a generic `Glulam` base class. Upon creation, a `Glulam` factory method analyses the type of input centreline curve and outputs the appropriate subclass: `StraightGlulam`, `SingleCurvedGlulam`, `DoubleCurvedGlulam` (Fig. 4.21). Using object inheritance between the base `Glulam` class and its subclasses allows the establishment of common functions and outputs for all glulam types, while speciating particular functions and outputs for specific glulam types. For example, querying the cross-section plane of a glulam is simpler for a straight glulam than for a double-curved glulam, where the precise orientation at a specified point has to be interpolated due to the out-of-plane curvature. How the cross-section is oriented around the centreline curve has further implications for fabrication.

4.3.3 Orienting free-form glulams

Given a 3D glulam centreline curve, the orientation of the glulam cross-section is the other crucial variable necessary to unambiguously define a glulam geometry. Orienting an object on this curve requires calculating a frame of reference on the curve that the object is mapped to from its own frame of reference. This has particular applications in computer graphics, robotics, the study of particle motion, and other fields that study the motion of objects in 3D space. The Frenet-Serret frame - independently discovered by French mathematicians Jean Frédéric Frenet (Frenet 1852) and Joseph Alfred Serret in 1851 - uses the curve's tangent and curvature vectors to construct an orthonormal reference frame at any point on a differentiable curve, however this has discontinuities on sections where there is no curvature or where the curvature vector abruptly flips. This is improved upon by the Bishop frame (Bishop 1975) and the Beta frame, which combines the best aspects of the Frenet and Bishop frames (Carroll, Kose, and Sterling 2013).

Another, similar, technique that is widely used in computer graphics is the computation of the *rotation minimizing frame (RMF)* which has the characteristic of minimizing twist around the curve, and therefore results in more continuous interpolations of frames along a 3D curve than the previous types of frames (Wang et al. 2008). In the glulam model, the calculation of an orthonormal frame of reference on the 3D glulam centreline curve is important for mapping the cross-section along its length. By mapping the cross-section at intervals along the centreline curve, the outer geometry boundary of the glulam can be modelled - similar to how ”sweeping” and ”lofting” operations work. This makes it possible to derive the precise position and orientation of the cross-section at any given point along the glulam, using only its centreline curve, and thus get a non-ambiguous free-form glulam geometry.

However, the alignment of the cross-section with the centreline's RMF is not always desirable in the design of glulam components, and it also depends on the specific implementation of calculating the RMF. In the design and modelling of free-form glulam structures, the orientation of the cross-section along the glulam can be driven by a variety of other parameters, such as a global direction vector, a reference surface - such as in the process of



(a) The main components for modelling a double-curved glulam blank: a centreline curve (a) and a method to calculate reference frames (b) that define cross-section orientations.

(b) The geometric boundary of the glulam is generated using the centreline curve as a guide and frames to orient the cross-sections (grey, shaded areas).

Fig. 4.22: Constructing a glulam model using a guide curve and guide planes.

modelling Centre Pompidou-Metz, Nine Bridges Golf and Country Club, Omega Swatch Headquarters (Scheurer et al. 2013), and others - or some other points of alignment from other design features.

The glulam blank model therefore implements this variety in a modular way. As with the glulam types before, the orientation of a glulam model is defined as a base `GlulamOrientation` class, from which several subclasses are derived. A common method to all orientation types is the querying of the orientation at a particular point on the glulam centreline, which yields a direction vector. Combining this direction vector with the centreline tangent at the same query point results in an unambiguous orthonormal frame of reference at that point on the centreline. The types of orientation subclasses are:

- `KCurveOrientation`, which simply constructs the Frenet frame of the curve using the curve tangent and the curvature vector;
- `RmfOrientation`, which uses the RMF of the curve as described above and as implemented in the RhinoCommon API;
- `PlanarOrientation`, which aligns all cross-sections with a vector perpendicular to a planar curve tangent and the normal vector (Z-axis) of its plane;
- `VectorOrientation`, which aligns all cross-sections with a single user-defined vector, while ensuring that the resultant direction vector is perpendicular to the centreline curve;

- `SurfaceOrientation`, which queries a user-defined surface at the point closest to the centreline query point and returns the surface normal at that point, while, again, ensuring that the resultant vector is perpendicular to the curve;

- `RailCurveOrientation`, which returns a vector from the query point on the centreline to a corresponding point on another user-defined curve;

- `VectorListOrientation`, which uses an internal list of vectors and corresponding curve parameters that defines specific user-defined direction vectors at user-defined points on the centreline curve. These are converted and stored as angular offsets from the RMF, where the RMF is rotated along the curve tangent by a specified amount. This allows the robustness of the RMF to be combined with a user-defined modulation of its rotation along the centreline. At a query point in between the user-defined points, the angular offset is interpolated between the surrounding values, and the RMF is rotated accordingly.

Using this modular approach allows a combination of different glulam centreline types with different orientation strategies. However, as mentioned before, there are caveats. The production of simple, straight glulam blanks does not involve the twisting of the cross-section. This means that for a glulam model to be a `StraightGlulam`, its orientation must be a `VectorOrientation` which provides a single, consistent orientation for its cross-section. Similarly, the cross-section of a single-curved glulam is typically aligned with its plane of curvature: this corresponds to the way it is pressed and the use of wide, thin planks that can only bend around their thin section. Therefore, this means that a `SingleCurvedGlulam` can also only have an orientation that results in vectors that lie in the same plane of curvature.

While these are limitations that arise out of the production process of these glulams, they can be overlooked if the model is used not to model the glulam blank, but if it instead is used to model the glulam component that is machined out of the blank. For example, a `SingleCurvedGlulam` with a free orientation can describe a double-curved component that is following some surface using a `SurfaceOrientation`. This means that the component as-is cannot be fabricated using a standard single-curved glulam press due to the twisting cross-section. However, since the centreline is planar, the centreline curve can be re-used to model a single-curved blank that envelopes the designed component, with the appropriate cross-section orientation constraint in place. The double-curved component can then be machined out of the single-curved blank. This shows a bifurcation in the application of the glulam blank model, where it can be used to model constrained glulam blank models, or can be used more freely to design glulam-like geometries that have a relationship to specific types of glulam blanks.

Much like the first spline curves in computer graphics derived from real bands of wood or metal, pinned by ”ducks” Farin 2007, p. 4-7, a similar analogous model needs to be determined or found, which takes into account the bending and twisting of free-form glulams.

4.3.4 Bending and the glulam cross-section

The material specification of the cross-section is linked to both its orientation and the characteristics of the glulam centreline curve. As the results from Probe 2: IBT glulam workshop showed, the appropriate thickness of lamellae to use in a glulam is directly related to the maximum curvature of the centreline and can be calculated by sampling the curve. For double-curved glulams, the glulam blank model assumes a typical grid-like cross-section arrangement of lamellae. Since the orientation of the cross-section is not necessarily aligned with the curvature vector, this impacts both the width and height of each lamella. Deriving the width and height of the lamella is therefore done by projecting the curvature vector of the centreline curve onto the X- and Y-axes of the oriented cross-section plane. This gives the proportional curvature vector along the width and the height of the cross-section, meaning their values can be solved using the previously described lamella thickness formula (Fig. 4.25).

This illustrates how double-curved glulams require exponentially more lamellae than single-curved or straight glulams, leading to a much higher labour cost and fabrication complexity (Fig. 4.23). The calculation of lamella sizes in the glulam cross-section can therefore be used to estimate differences of cost or material usage: by associating an amount or percentage of material waste per lamella - for example, from planing and cutting operations - the use of different glulam blanks can be compared and evaluated.

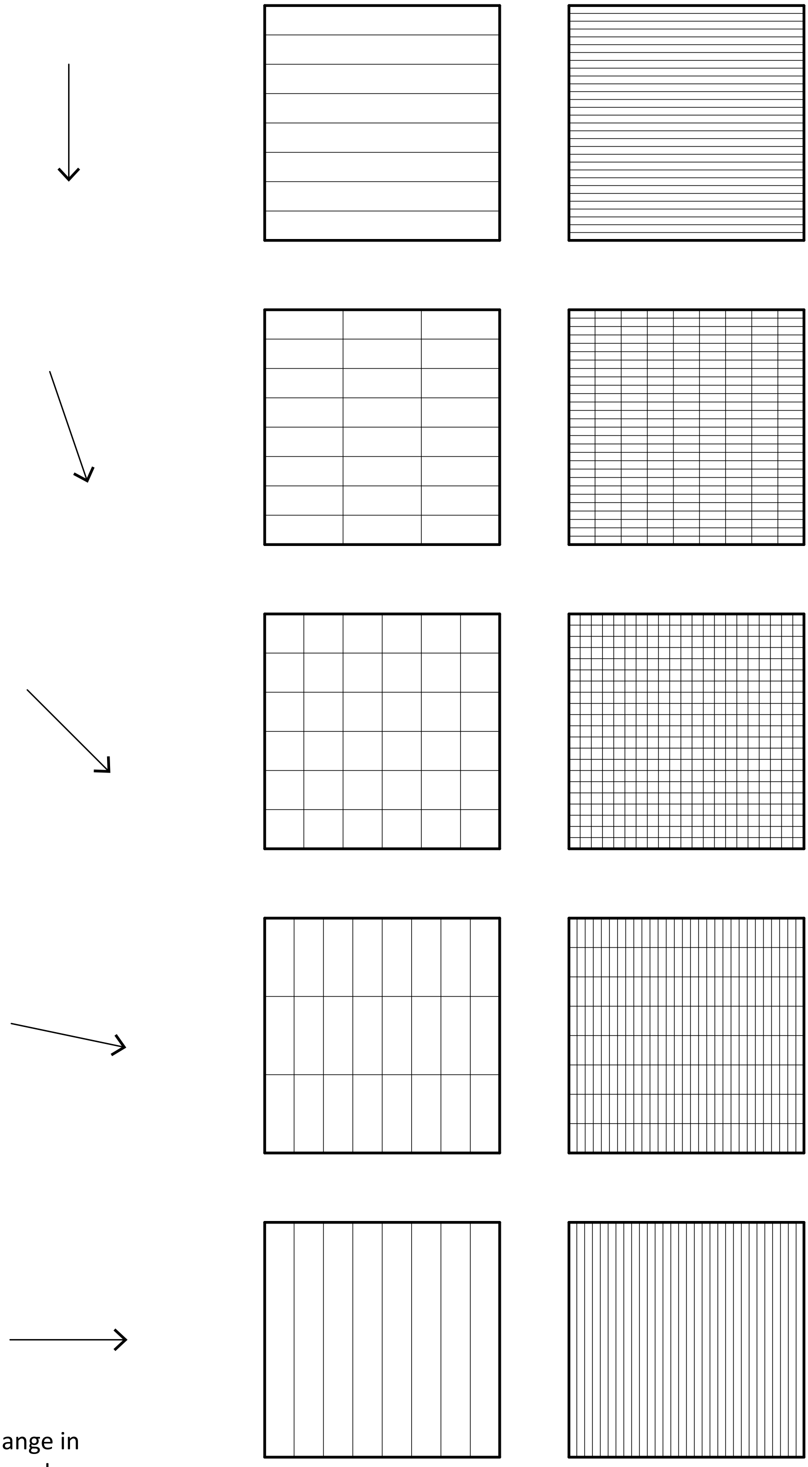


Fig. 4.23: The change in lamella dimensions due to different curvature vectors (left) for lower curvatures (centre) and higher curvatures (right).

Fig. 4.24: Visualizing the bending performance of each lamella in Probe 5: Branching Probe. Localized areas of the lamellae that exceed bending limits are red.

In much the same way as the maximum lamella dimensions can be derived from sampling the glulam centreline curve, the centreline for each lamella can be extracted from the glulam blank model. This gives an overview of bending and material limits on a per-lamella basis, meaning that particularly performance-intensive portions of the glulam blank can be identified (Fig. 4.24). Comparing the curvature of the lamella along its lamella centreline curve to its dimensions shows how close it is to its bending limits. This can be used to identify areas for optimization within an individual glulam. For example, if most of the bending of a glulam is concentrated in one particular area of the glulam, and therefore is constraining the lamella dimensions to impractical values, it creates the possibility of identifying this area and relaxing the curvature or changing to a different glulam blank type that still satisfies the performance demands.

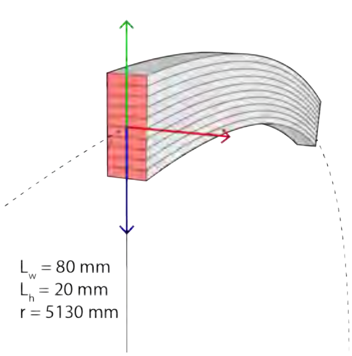
The glulam blank further provides an interface between the meso-scale glulam and the micro-scale material mapping from Probe 1: Modelling wood properties. The cross-section of the `Glulam` contains an array of reference GUIDs (Globally Unique Identifiers) as well as a designation of the wood species for each lamella. The GUIDs can therefore be associated with the more dense datasets for individual timber elements. This suggests that a detailed element analysis of a glulam blank can be assembled by combining the referenced material datasets using the glulam blank model. Even without the inclusion of the material scale datasets, being able to specify a wood species for each lamella adds another aspect to the material specification of the model.

4.3.5 Free-form glulam coordinate space

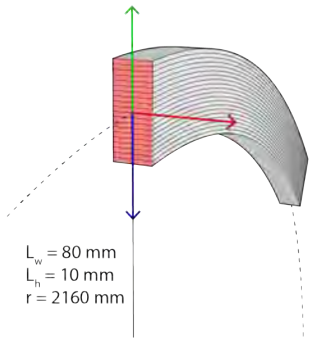
The generation of oriented cross-section frames for free-form glulams raises an interesting prospect: the local *glulam coordinate system*. Using the tangent of the centreline curve as the Z-axis of an oriented frame creates a particular type of coordinate system: if the centreline curve is linear and the cross-section frames have a constant orientation, this glulam coordinate system is much like an ordinary Cartesian coordinate system, whose origin is centred on either the start or end point of the centreline curve and whose axes are aligned with the centreline direction and oriented cross-section. If the centreline is curving, however, it creates a coordinate system whose Z-axis is curved, while its XY plane stays aligned with the glulam cross-section. Limiting the Z-dimension to the extents of the centreline curve, and the other two dimensions to the width and height of the glulam cross-section makes it a finite coordinate system that can describe any point within the boundary of the free-form glulam blank.

Within this free-form glulam coordinate system, coordinates are defined using the oriented cross-section plane and its distance along the centreline curve. Due to the curved Z-axis, it creates the possibility of the same point in global Cartesian space mapping to more than one set of coordinates in the local glulam coordinate system. However, this can only occur where the width of the glulam is greater than the radius of curvature at that point: something which is materially not possible if the lack of material discontinuities in the glulam is assumed.

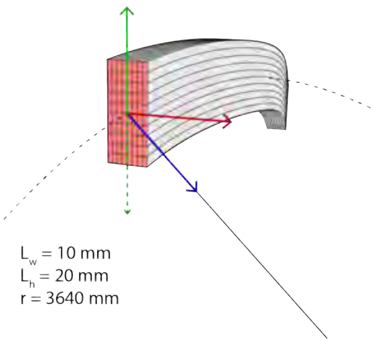
The glulam coordinate space allows the evaluation of properties of the glulam in its local space, which is analogous to the glulam in its unbent state. This allows the mapping of data to the free-form glulam space, and another means to connect micro-scale material models to the meso-scale glulam blank model: sampling a point within the glulam yields its position in glulam space, which can subsequently be used to sample a finger-grained material dataset at that particular position in the glulam. This avoids the need to transform the potentially heavy datasets associated with detailed material models. Querying the points within the free-form glulam can therefore map onto separate material performance or quality data - such as CT scans of individual lamellae, for example.



(a) Single-curved glulam.



(b) Single-curved glulam with greater curvature.



(c) Double-curved glulam.

Fig. 4.25: Sampling the glulam centreline curve gives the curvature vector (blue) and the cross-section plane (red and green axes). Finding the maximum curvature of the glulam - or minimum radius of curvature (r_{min}) from these samples allows appropriate lamella sizes - lamella width (L_w) and lamella height (L_h) - to be calculated. This gives a direct relationship between modelled curve, material specification, and fabrication process.

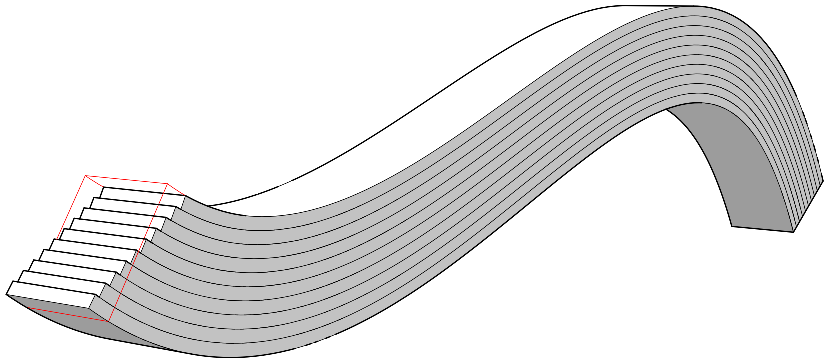


Fig. 4.26: Bending results in different edge lengths, meaning that lamella lengths need to be compensated during fabrication.

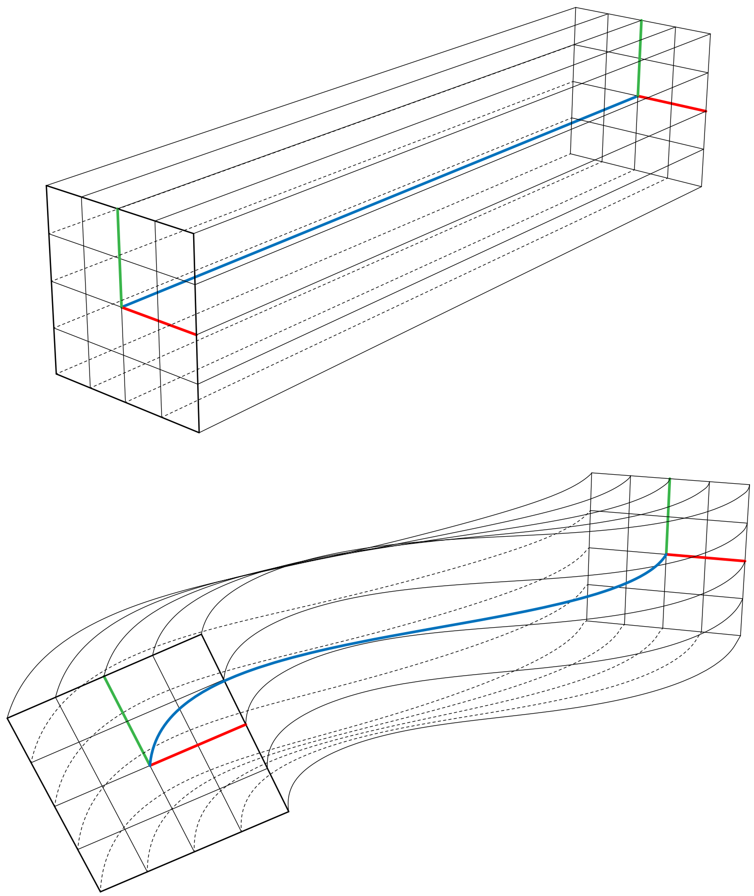


Fig. 4.27: The glulam coordinate system of a straight glulam (top) and a double-curved glulam (bottom). The X (red) and Y (green) axes define the cross-section plane. The Z (blue) axis follows the glulam centreline curve.

4.4 Workpieces and assemblies

The model thus described demonstrates the application of material and fabrication principles to the constrained modelling of glulam blanks and reveals key considerations for their use. Prototype 1: Glulam blank model proceeds further to address the context of fabrication *after* the lamination of the glulam blank as well as the aggregation of glulam blanks into novel glue-laminated assemblies. This section describes the development of the fabrication-related modelling in Prototype 1: Glulam blank model, especially how it relates to other experiments such as Probe 4: CITAstudio glulam workshop, Prototype 2: Grove, and Demonstrator: MBridge. In particular, Probe 4: CITAstudio glulam workshop presents five speculative glulam assemblies:

- the *Voxel Blank*
- the *Finger-joint Blank*
- the *Cross-laminated Joint Blank*
- the *Branching Blank*
- the *Kinky Blank*

These are introduced and described in more detail within the domain of materialization in the next chapter. However, deploying the glulam blank model for modelling these assemblies required a further expansion and development of Prototype 1: Glulam blank model. Further, going beyond the individual glulam blank to develop glulam models for structures requires the generation of fabrication data for joints and other details. The non-orientable geometries of free-form glulams make aligning this data correctly an important necessity. The glulam blank model therefore is expanded to accommodate the generation and organization of fabrication data - a `GlulamWorkpiece` class - and the aggregation of the established glulam types into more complex assemblies using a `GlulamAssembly` class.

4.4.1 The glulam assembly

The speculation about new glulam types in Probe 4: CITAstudio glulam workshop challenges the glulam blank model in Prototype 1: Glulam blank model because the principles that constrained the modelling of typical glulam blanks no longer hold. This entails a departure from the usual consideration of a glulam blank as the parallel arrangement of similarly-sized rectangular wood lamellae and an introduction of alternative wood distributions and lamination strategies. For example, creating a

Finger-joint Blank results in a glulam centreline that is a series of straight lines, and whose lamella dimensions are not dependent on the original centreline curve. Similarly, the outer flanges of the Voxel Blank are, in effect, double-curved glulams, but they are laminated onto a straight glulam - the voxelized web - that has been previously machined. The Branching Blank can be broken down into two free-form glulams - the two ”branches” - with some extra components for the cross-laminated bracing layer.

This requirs the breaking down of each speculative glulam blank type into constituent parts, while also including the processing steps in-between. This results in a process diagramming which seeks to link the speculative glulam blank designing with the sequencing of process steps and operations of gluing and machining, beginning with an application of this diagramming to the already established glulam types (Fig. 4.28). Each process diagram begins with dimensioned lumber as an input, followed by gluing or machining operations which result in one of the established glulam types and, potentially, another iterative gluing / machining operation. Each diagram ends with the final machining of surfaces and joints, marking the end of the fabrication process.

The `GlulamAssembly` class formalizes these types through sub-classing, as with the `Glulam` and `GlulamOrientation` classes before. This formalization allows them to be integrated into design models and explore their parametric variability. Each of the five speculative blank types is broken down into its constituent process steps and glulams (Fig. 4.29). The Voxel Blank shows different orientations of the voxelized ”web” - placing the lamellae parallel or perpendicular to the overall direction of the blank (Fig. 5.7). The Finger-joint Blank shows the assembly of several straight glulams using finger joints (Fig. 5.12). The Cross-laminated Joint Blank shows how interleaving the lamellae between intersecting glulams can take the place of crossing joints (Fig. 5.17). The Branching Blank also suggests multi-ended glulam components by splitting a free-form glulam (Fig. 5.20). The Kinky Blank addresses discontinuities or corners in the glulam centreline curve with a similar cross-lamination approach (Fig. 5.25).

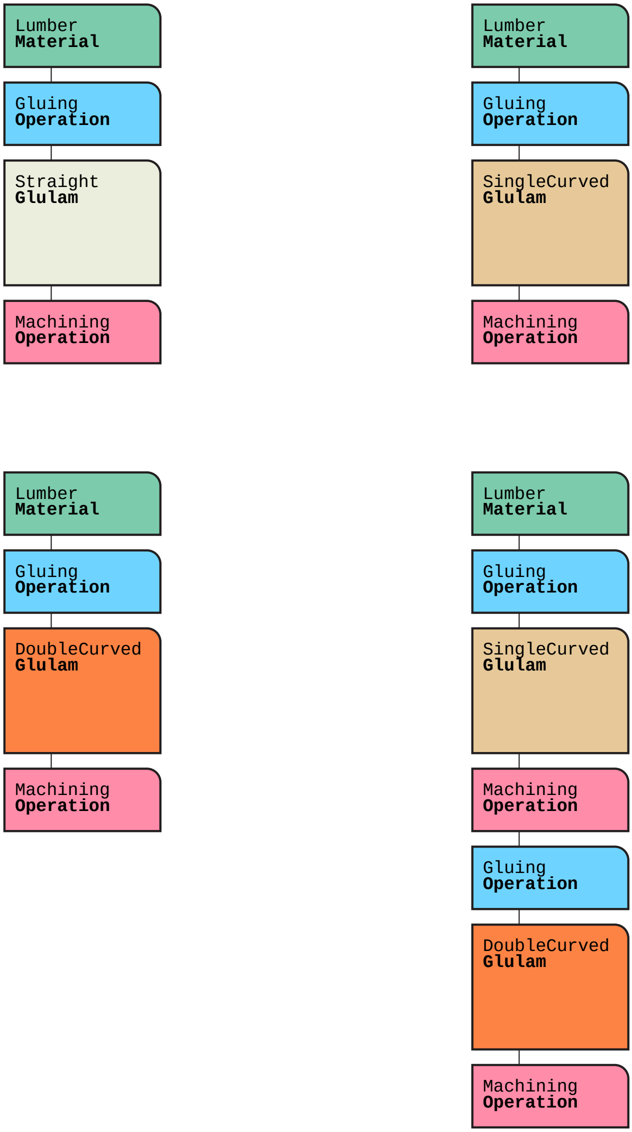


Fig. 4.28: Process diagrams of the basic glulam types and their production. The process for gluing a straight glulam is simple (top left). Gluing a single-curved glulam uses essentially the same steps, just with a different type of press (top right). Depending on the complexity and required size of lamellae, a double-curved blank is either formed all at once in free-form press (bottom left) or first as a single-curved glulam which is subsequently sliced into thin layers and formed again into a double-curved glulam (bottom right).

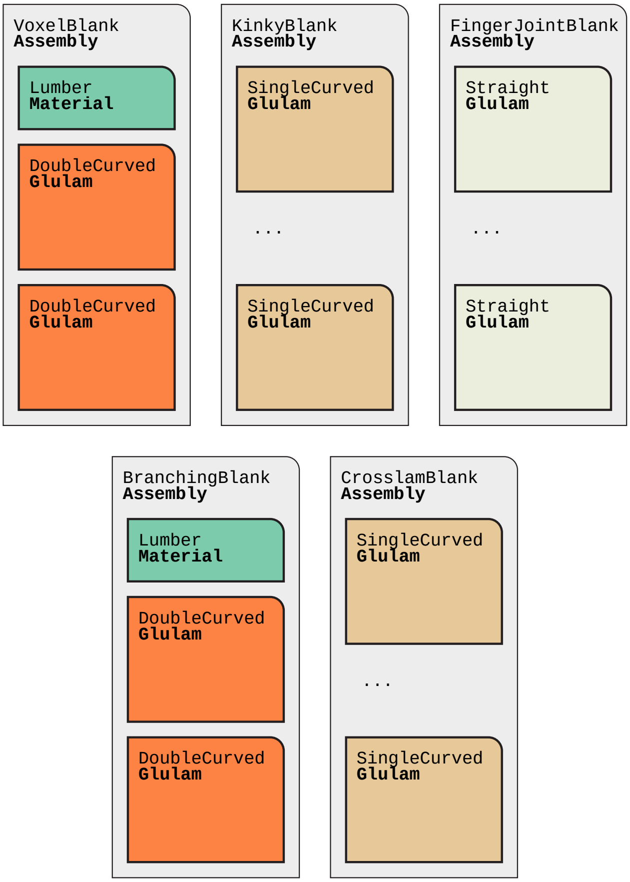


Fig. 4.29: The Assembly types, based on the experimental glulam blank types explored in Probe 4: CITAstudio glulam workshop. The "..." denotes potential repetition or expansion of the number of elements. For example, a Finger-joint Blank could have 2 individual segments or 10.

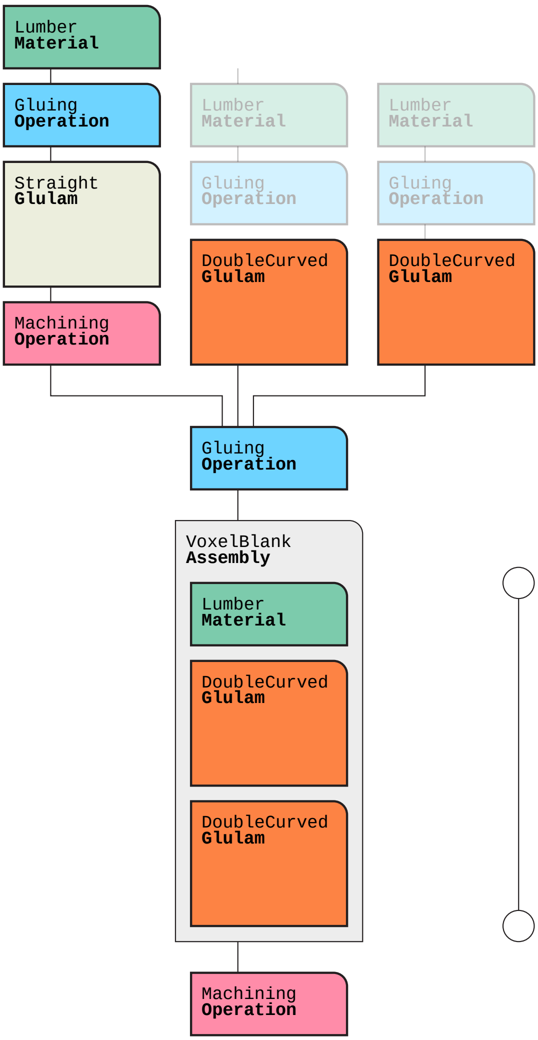


Fig. 4.30: The process tree for the Voxel Blank assembly. The symbol on the bottom right describes this blank as a beam-like element (line) with two end-points (circles).

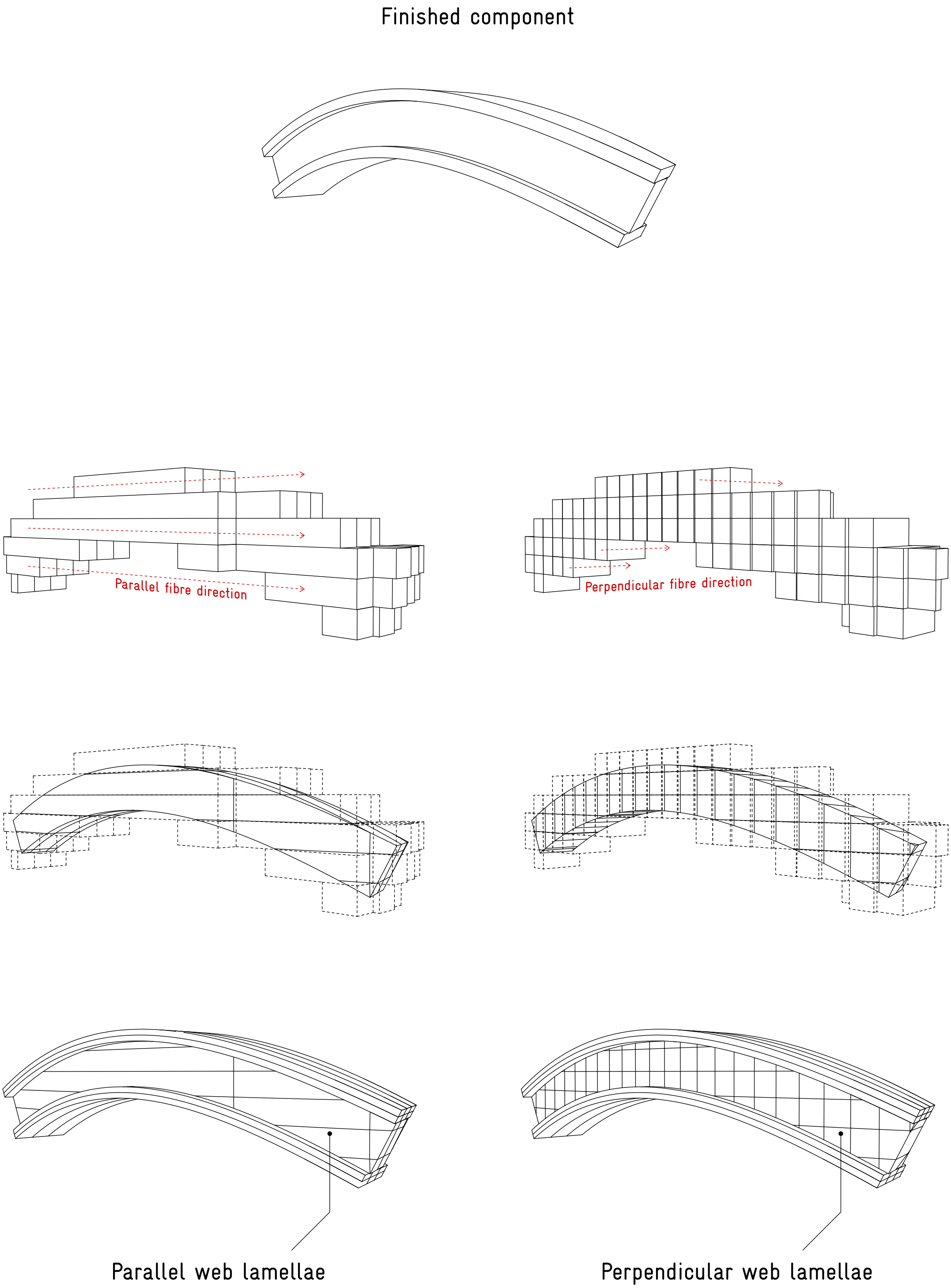


Fig. 4.31: The process of creating a Voxel Blank. A free-form glulam blank (top) is made by "voxelizing" it using parallel lamellae (left side) or perpendicular lamellae (right side).

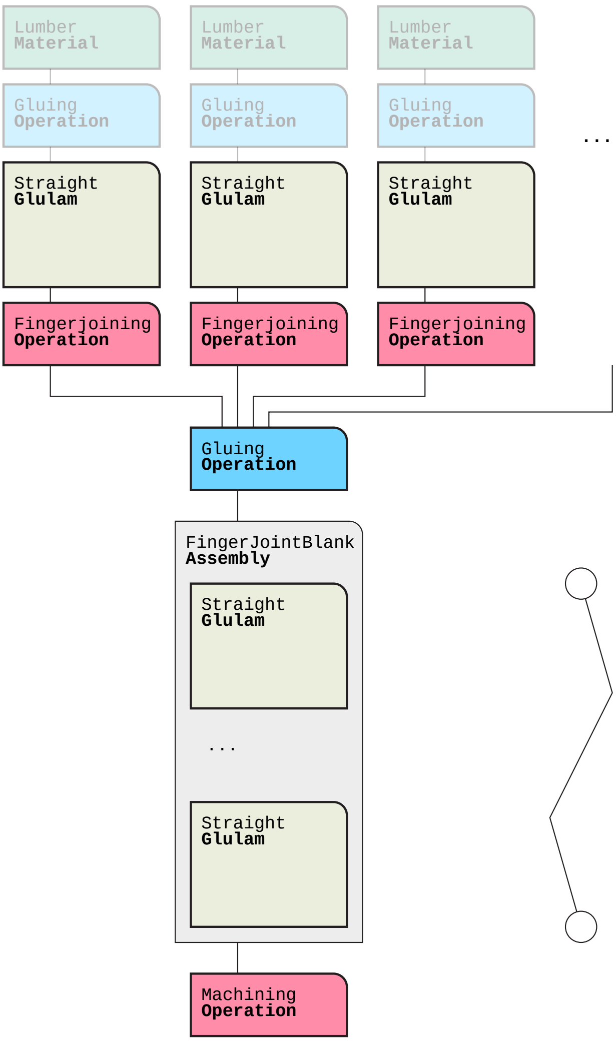


Fig. 4.32: The process tree for the Finger-joint Blank assembly.

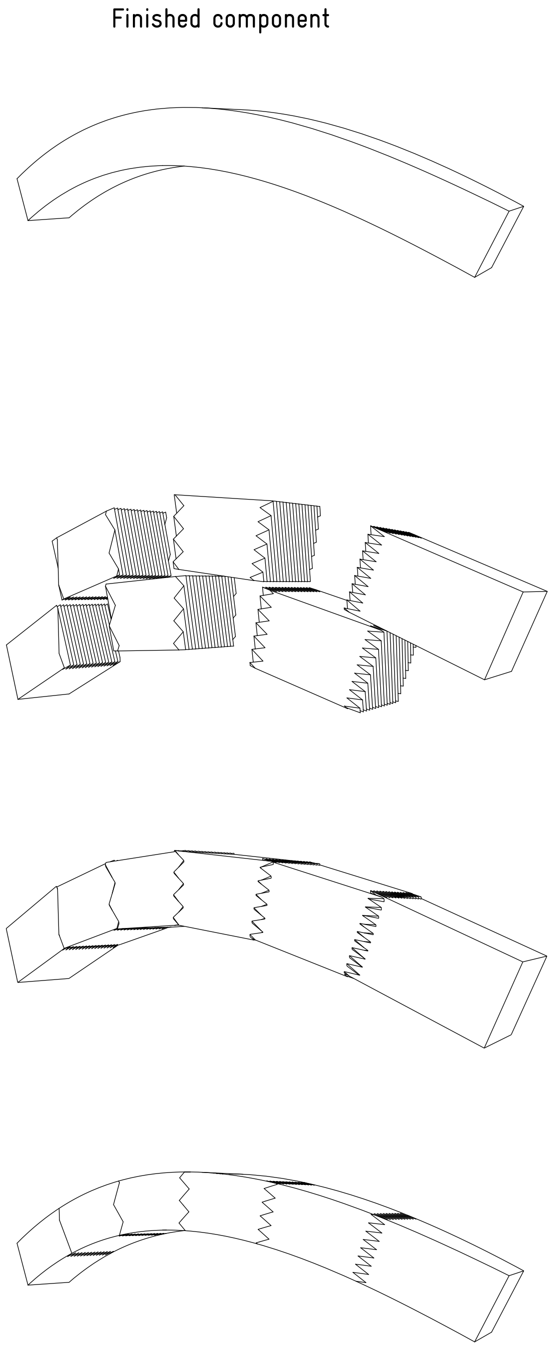


Fig. 4.33: The process of creating a Finger-joint Blank.

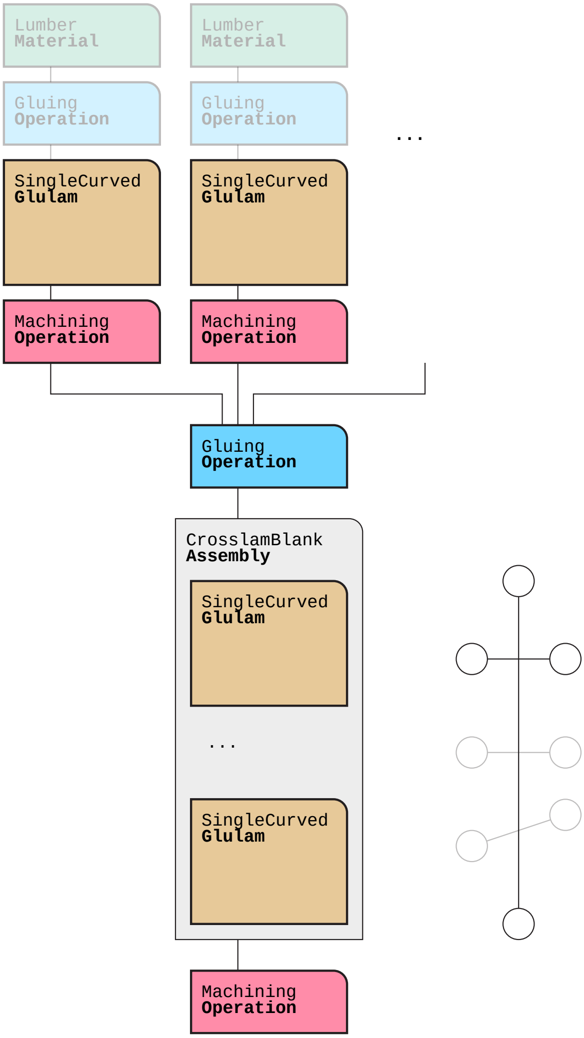


Fig. 4.34: The process tree for the Cross-laminated Joint Blank assembly.

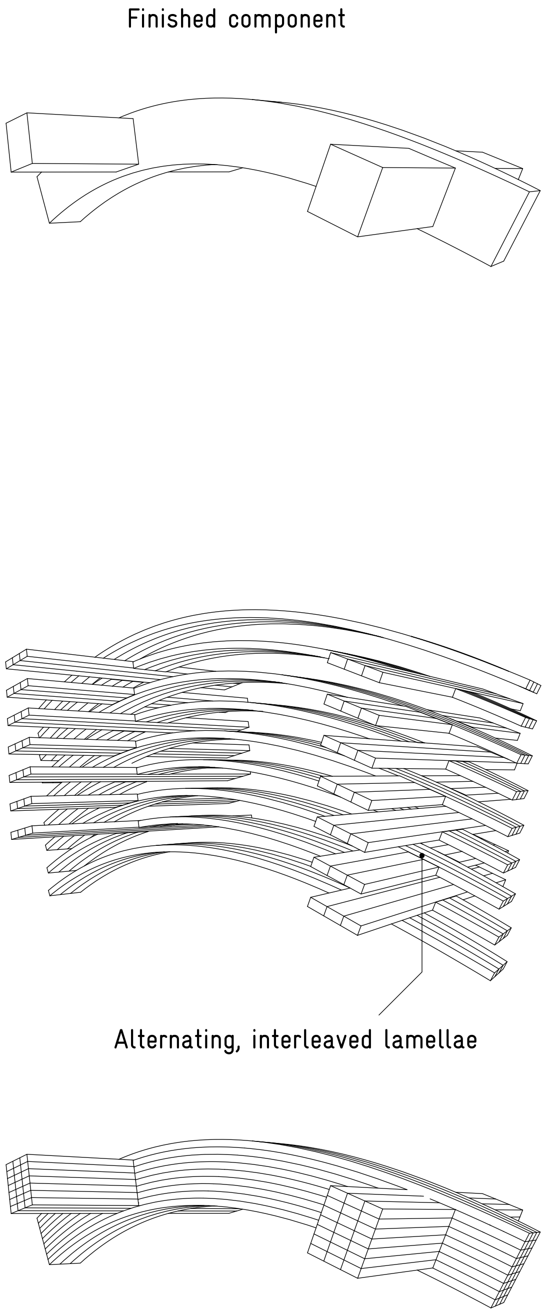


Fig. 4.35: The process of creating a Cross-laminated Joint Blank.

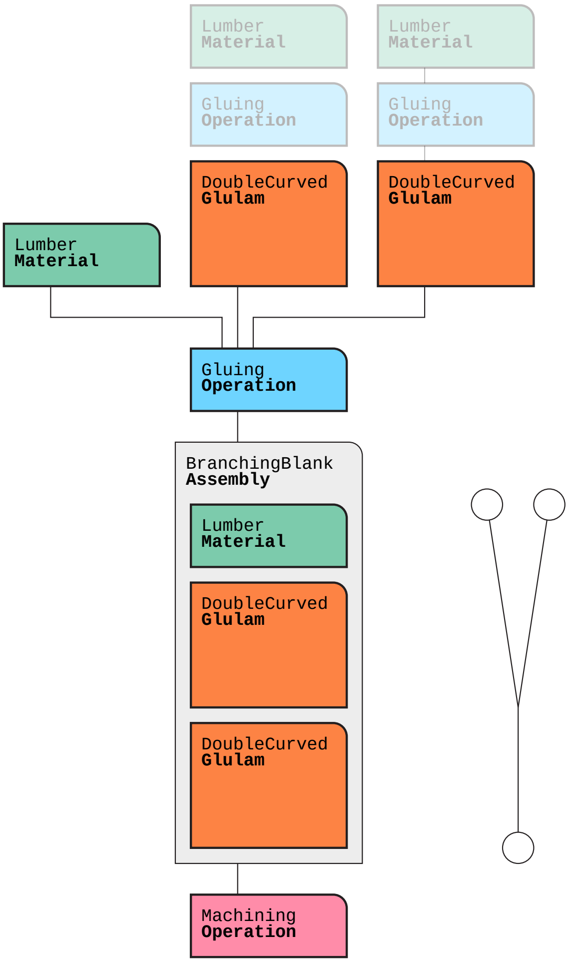


Fig. 4.36: The process tree for the Branching Blank assembly.

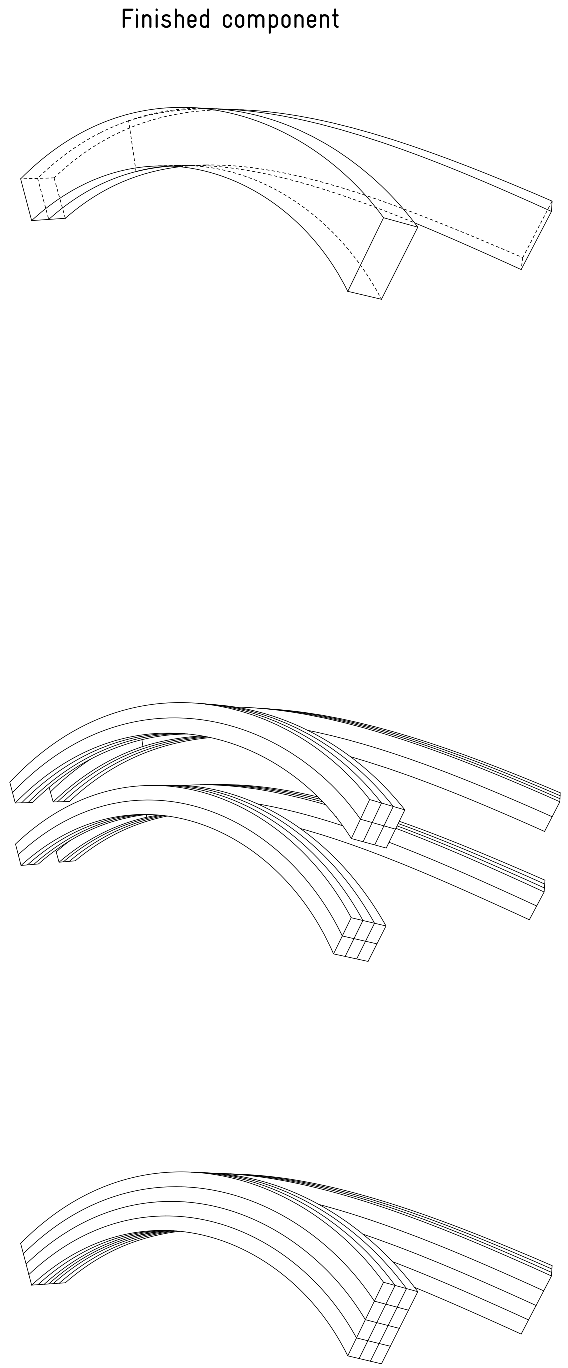


Fig. 4.37: The process of creating a Branching Blank.

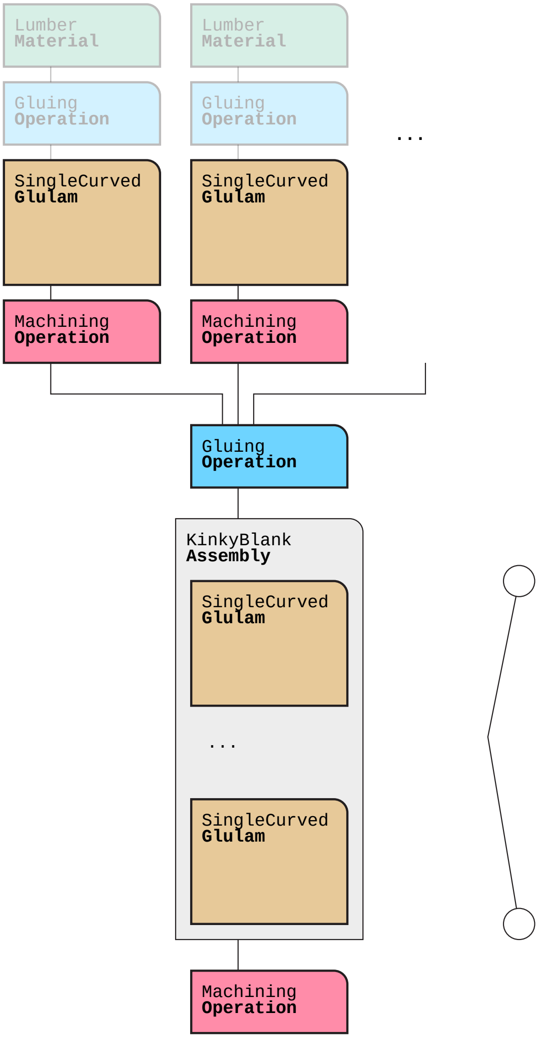


Fig. 4.38: The process tree for the Kinky Blank assembly.

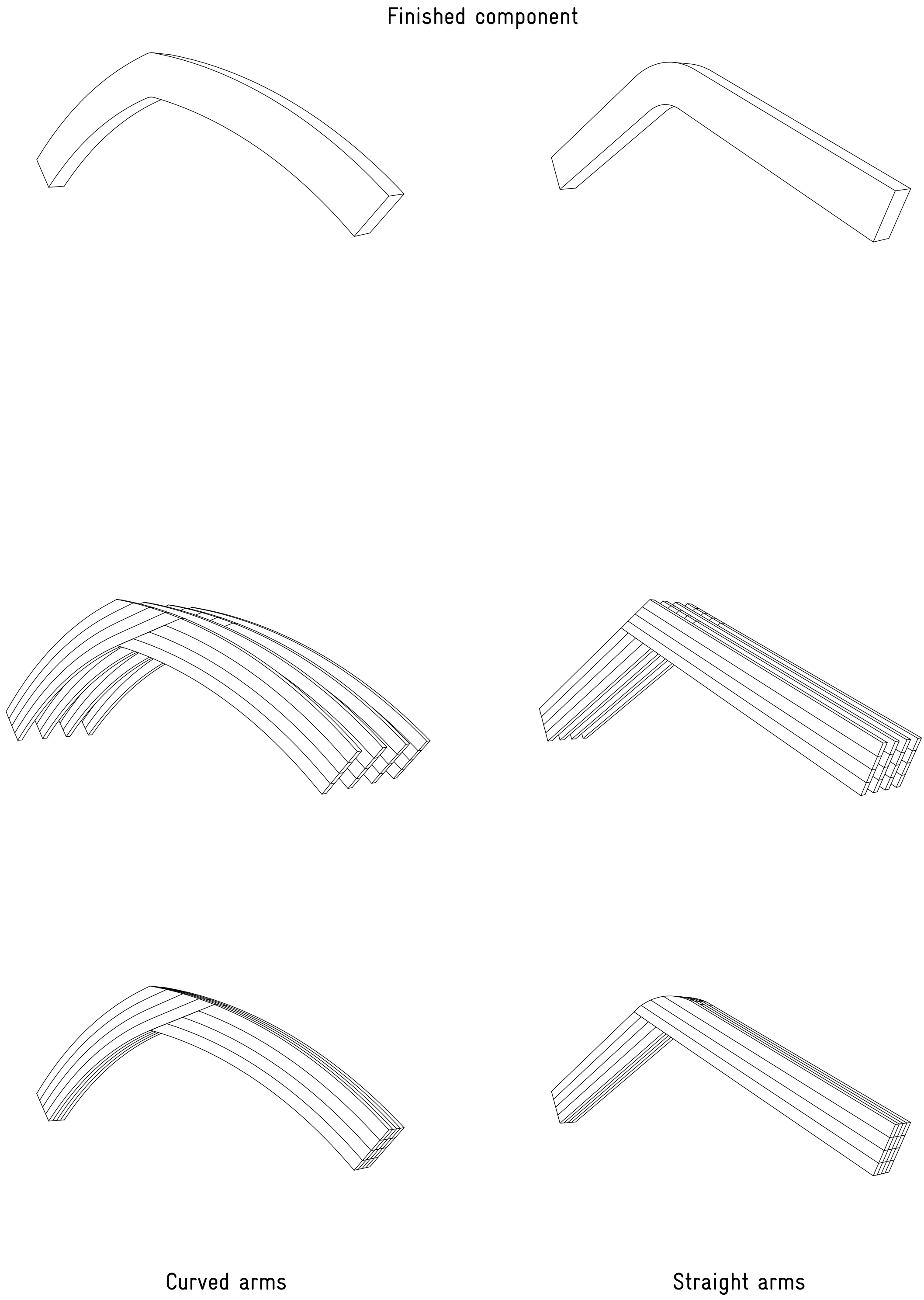


Fig. 4.39: The process of creating a Kinky Blank.

While this method allows the five speculative blank types from the Probe 4: CITAstudio glulam workshop to be programmatically described in terms of their constituent glulam elements, the specification of a new sub-class for each assembly turns out to be too rigid of an approach, since it requires programmatically defining a new assembly and implementing its functions before being used. Variations of the assemblies would require the writing of a new sub-class, and the use of an assembly as an input element into another assembly would be inhibited, limiting the flexibility of this approach.

Taking the process tree diagrams as a precedent, a more flexible approach is to implement each glulam assembly as a dependency graph made up of the elements and operations required to form and shape it (Fig. 4.40). This requires that both the `Glulam` and `GlulamAssembly` classes share a common base class so that they can be interchanged and made more generic. The root of the process tree is the finished glue-laminated component, and the branches of the tree represent the different constituent glulams and glulam assemblies that constitute the final piece. Differentiating different assembly types - such as those presented previously and in Probe 4: CITAstudio glulam workshop - is consequently a matter of differentiating their process tree topologies. This points towards a topological approach to designing new glulam morphologies, based on a limited set of initial production processes and basic glulam types.

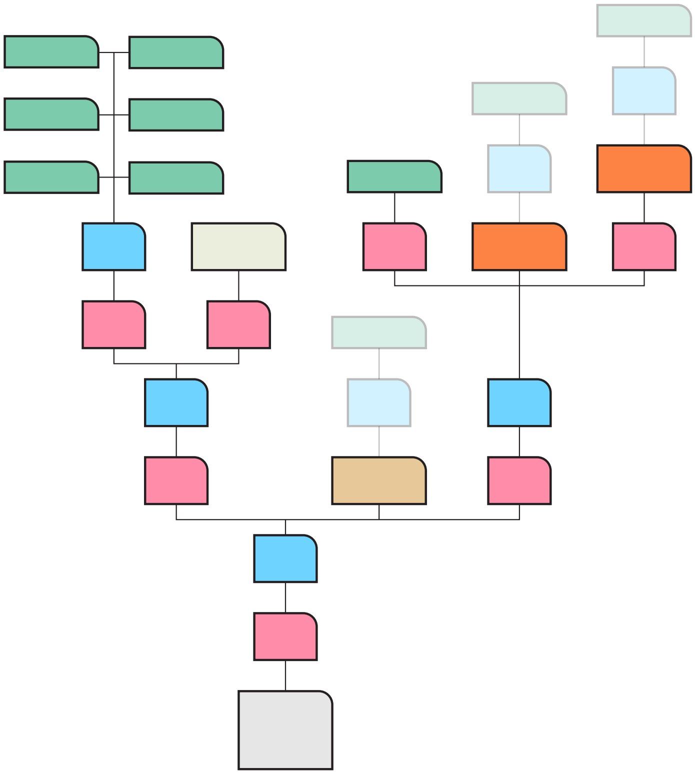


Fig. 4.40: Generalizing the specific assembly types into a more generic process tree model for glue-laminated timber elements allows more elaborate and flexible compositions of assembly types.

4.4.2 The workpiece

The `GlulamWorkpiece` class provides two main fabrication-related pieces of information on top of the glulam blank model: feature descriptions for generating fabrication data and a reference frame for moving and orienting the workpiece data within the fabrication environment. As such, it wraps the previously described `Glulam` and `GlulamAssembly` models in a layer of fabrication-specific data.

Features

A `Feature` class describes geometries that are used to drive machining strategies and cutting. When they are used to describe joints and connections, they also provide a reference to the other `GlulamWorkpiece` object that is being joined. This bidirectional referencing provides a link between the two `GlulamWorkpiece` objects that are to be joined, which means that the information used to drive the cutting of joints is always synchronized between the pieces being joined.

The `Feature` class is further sub-classed to specific joint types - much like the speciation of specific glulam types from the `Glulam` base class. Being linked to both models allows the joint models to extract necessary information for creating the relevant joint geometry. The joint details therefore are parametrically driven by the specific glulam models that are interacting - the simplest cases being the crossing lap joint (Fig. 4.43) and the end-to-end splice lap joint (Fig. 4.45).

Reference frame

The reference frame provided by the `GlulamWorkpiece` provides a handle with which to orient the fabrication data, primarily for aligning it to the specific fabrication space - in front of the robot or on the CNC machine bed - independently of its constituent material data. The transformation from the reference frame of the `GlulamWorkpiece` to the production space work plane is therefore freely adjustable without impacting the integrity of the `GlulamWorkpiece` and its contained `GlulamAssembly` and `Glulam` models. This transformation also makes it possible to easily integrate methods of automatically aligning the Workpiece model to physical material - for example, using 3D scanning. Registration algorithms, such as those used in Prototype 3: Four methods of digital feedback, return a transformation that best fits the model data to the acquired sensor readings or point clouds. This transformation is used to map the fabrication data of the `GlulamWorkpiece` to the fabrication environment employed for production (Fig. 4.42).

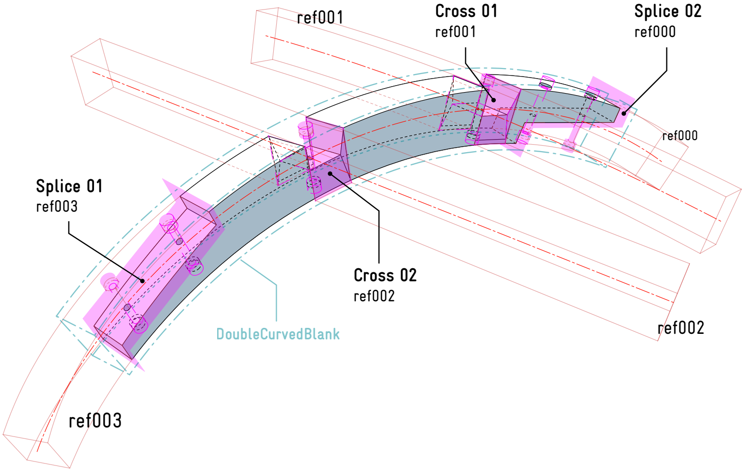


Fig. 4.41: The `GlulamWorkpiece` model incorporates both material and fabrication data.

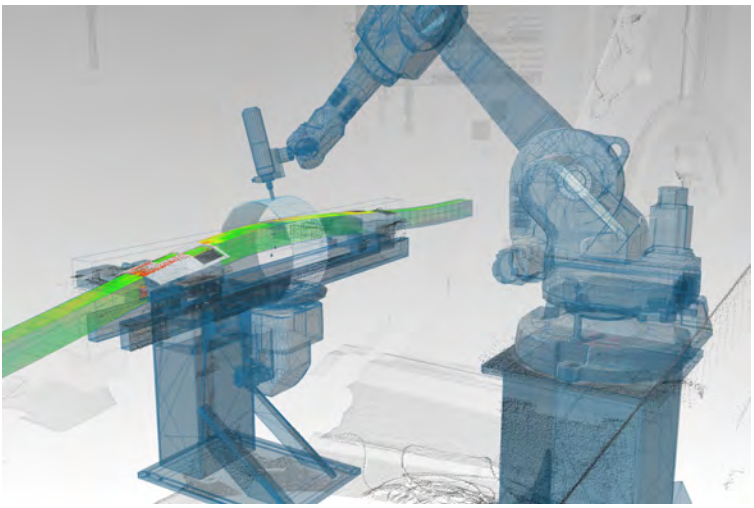


Fig. 4.42: The `GlulamWorkpiece` model allows the glulam data to be positioned within the fabrication space using registration algorithms.

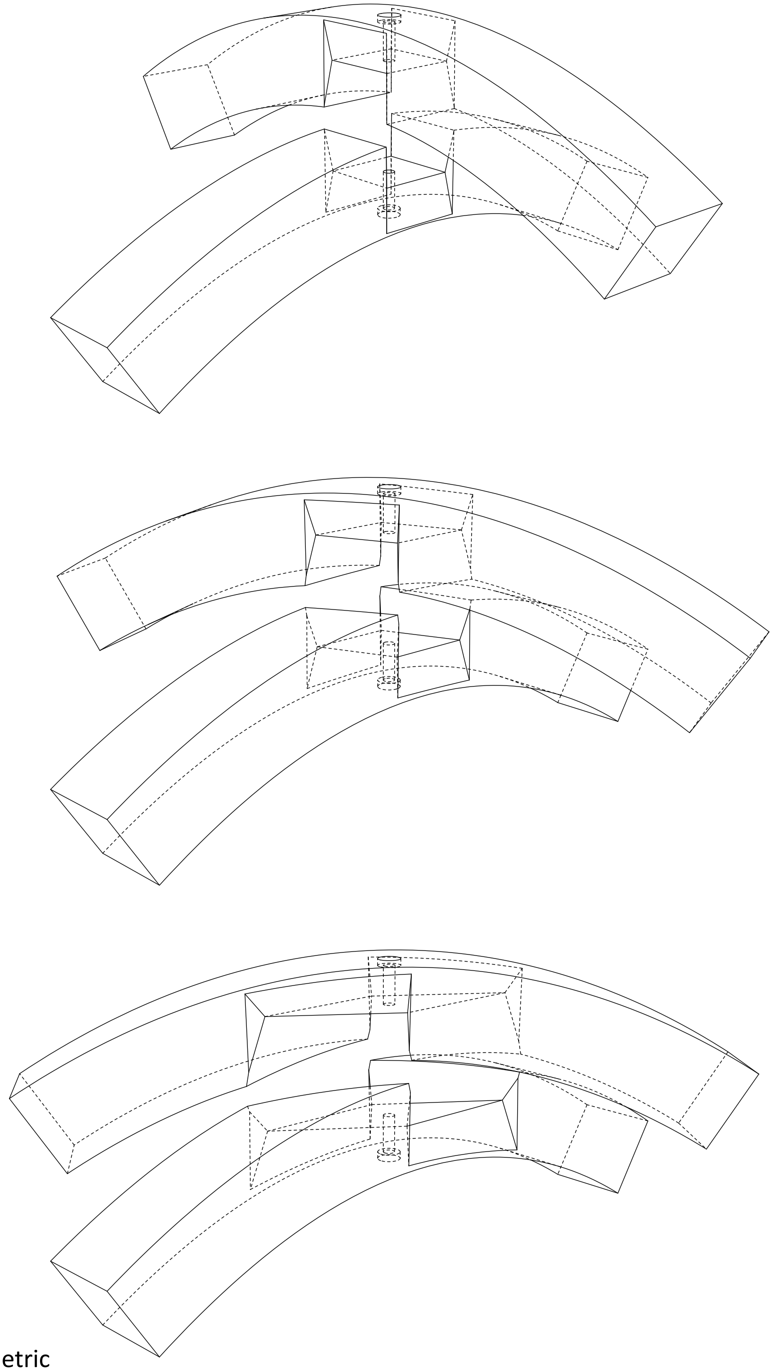


Fig. 4.43: A parametric crossing joint - `CrossLapJoint`.

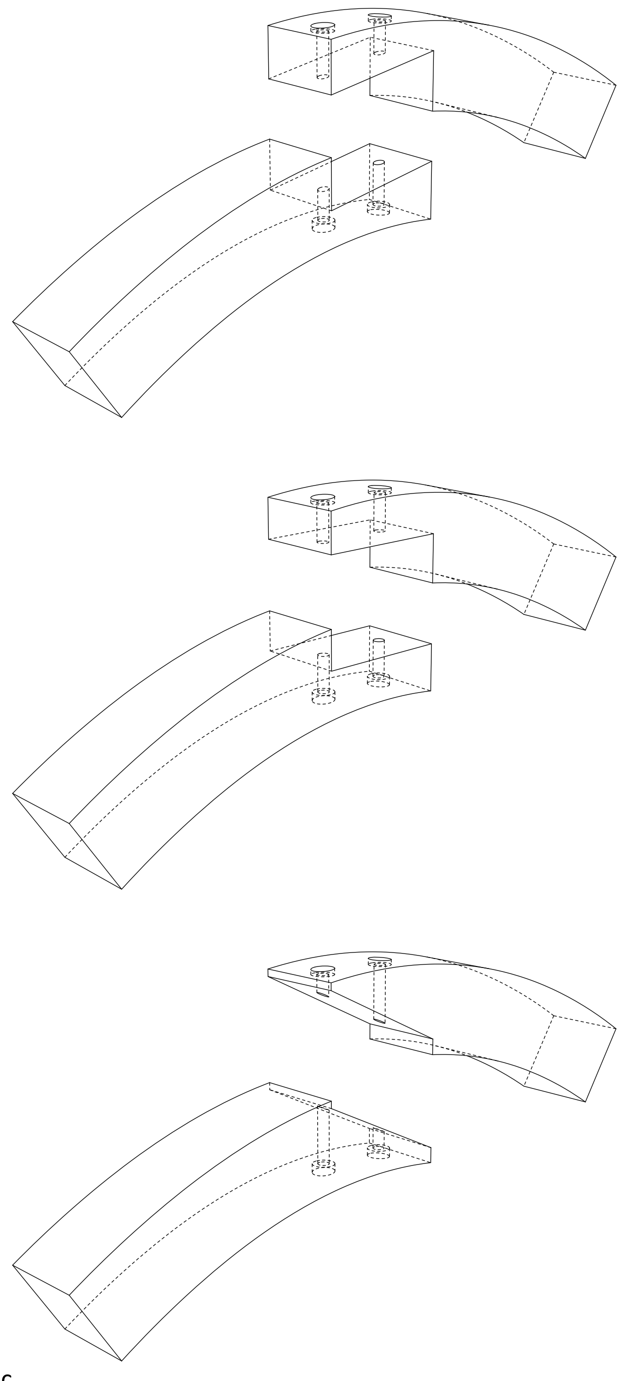


Fig. 4.44: A parametric splice joint - `EndLapJoint`.

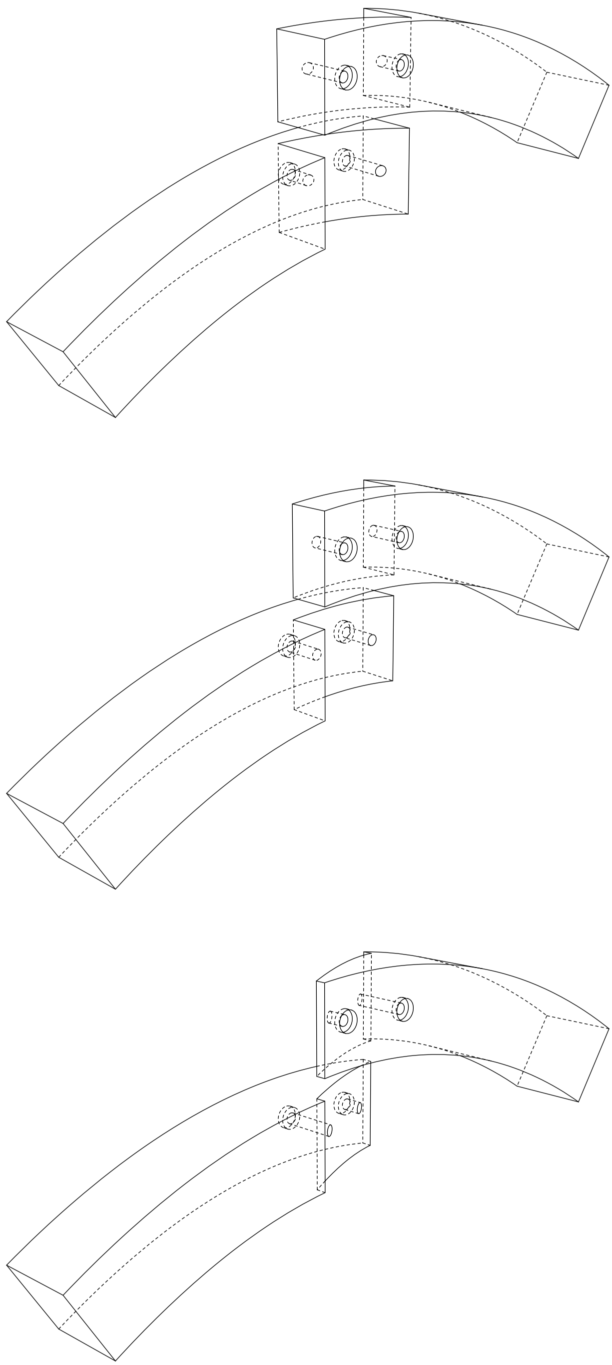


Fig. 4.45: A sideways parametric splice joint - `EndLapJoint`.

The `GlulamWorkpiece` and associated fabrication data are deployed extensively during Demonstrator: MBridge (Figs. 4.46, 4.47, 4.48). Here the model links together glulam-specific attributes such as material specification and blank geometry with data that is important for the assembly of the individual glulam elements into the structure: joint geometries and references frames that describe the spatial relationship between individual components. This creates the trans-scalar link between the meso-scale glulam blank model and the macro-scale model of the entire bridge demonstrator.

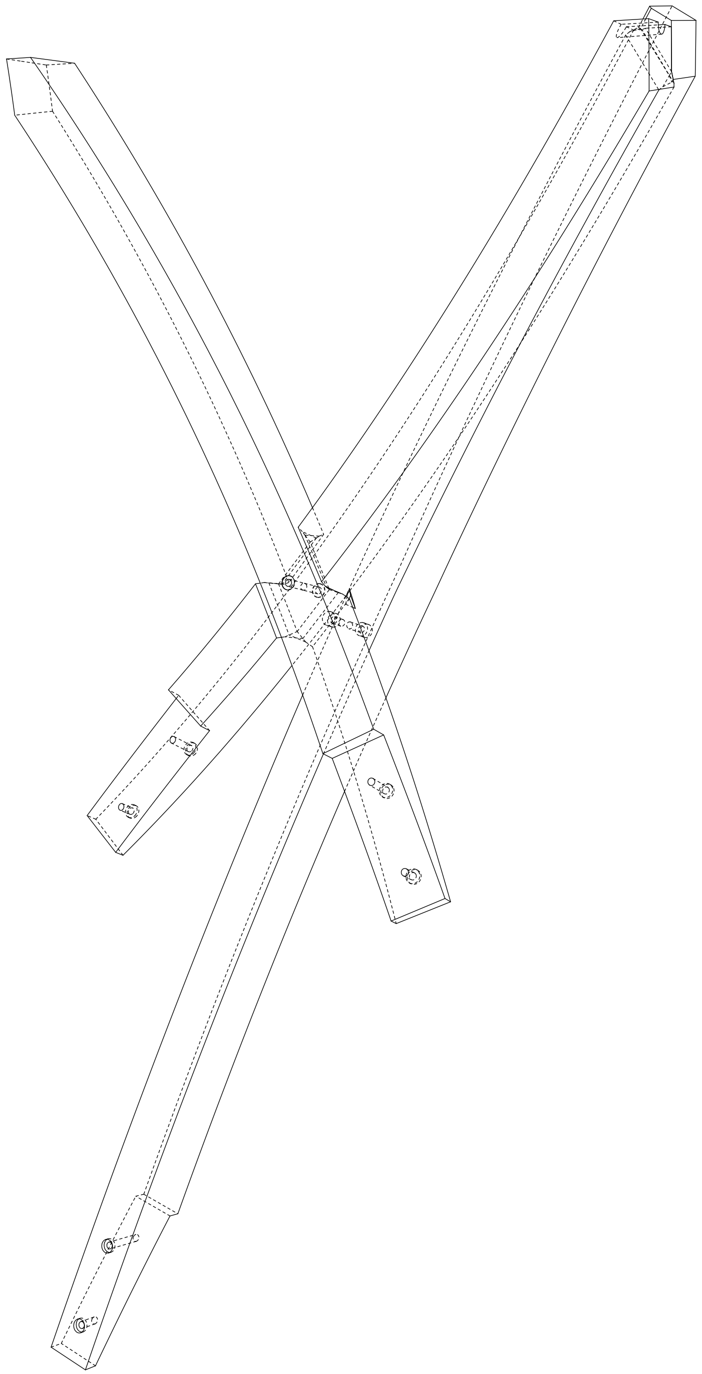


Fig. 4.46: Fragment 1. A section of the fabrication model for Demonstrator: MBridge.

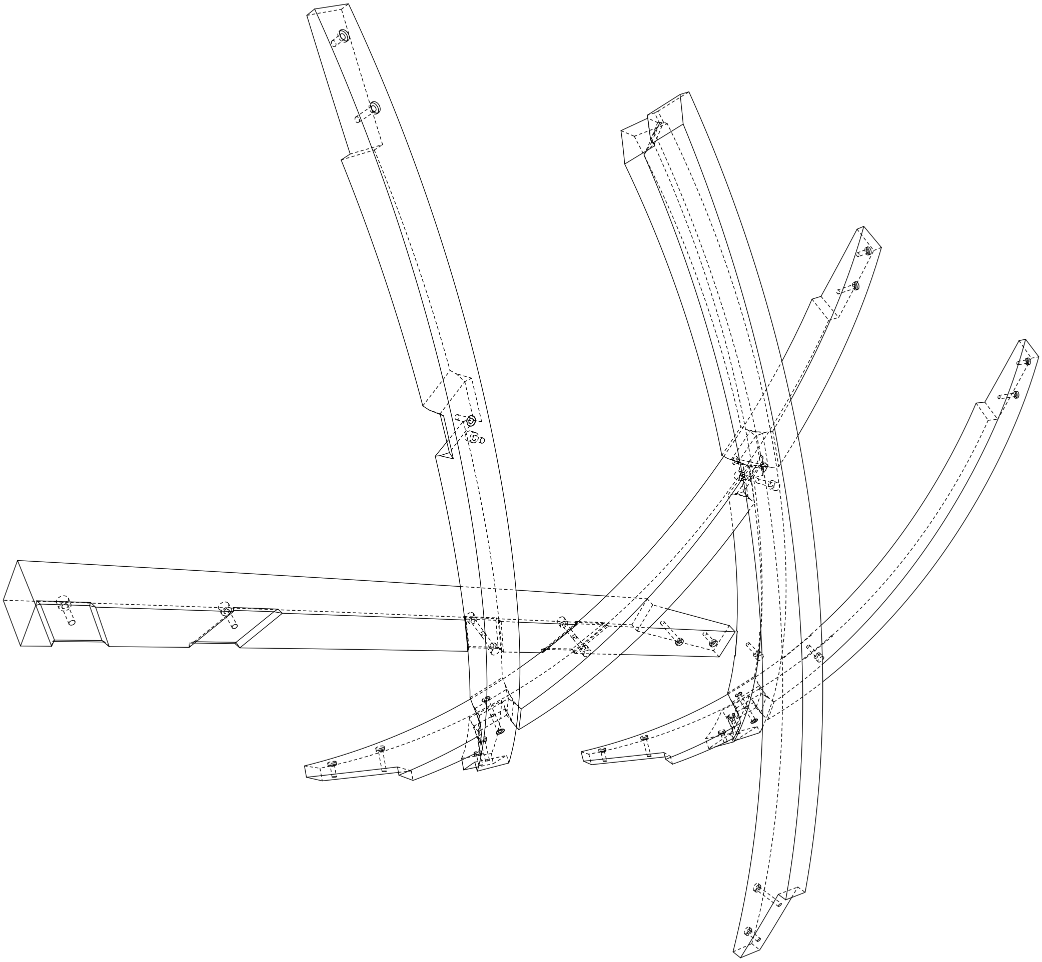


Fig. 4.47: Fragment 2. A section of the fabrication model for Demonstrator: MBridge.

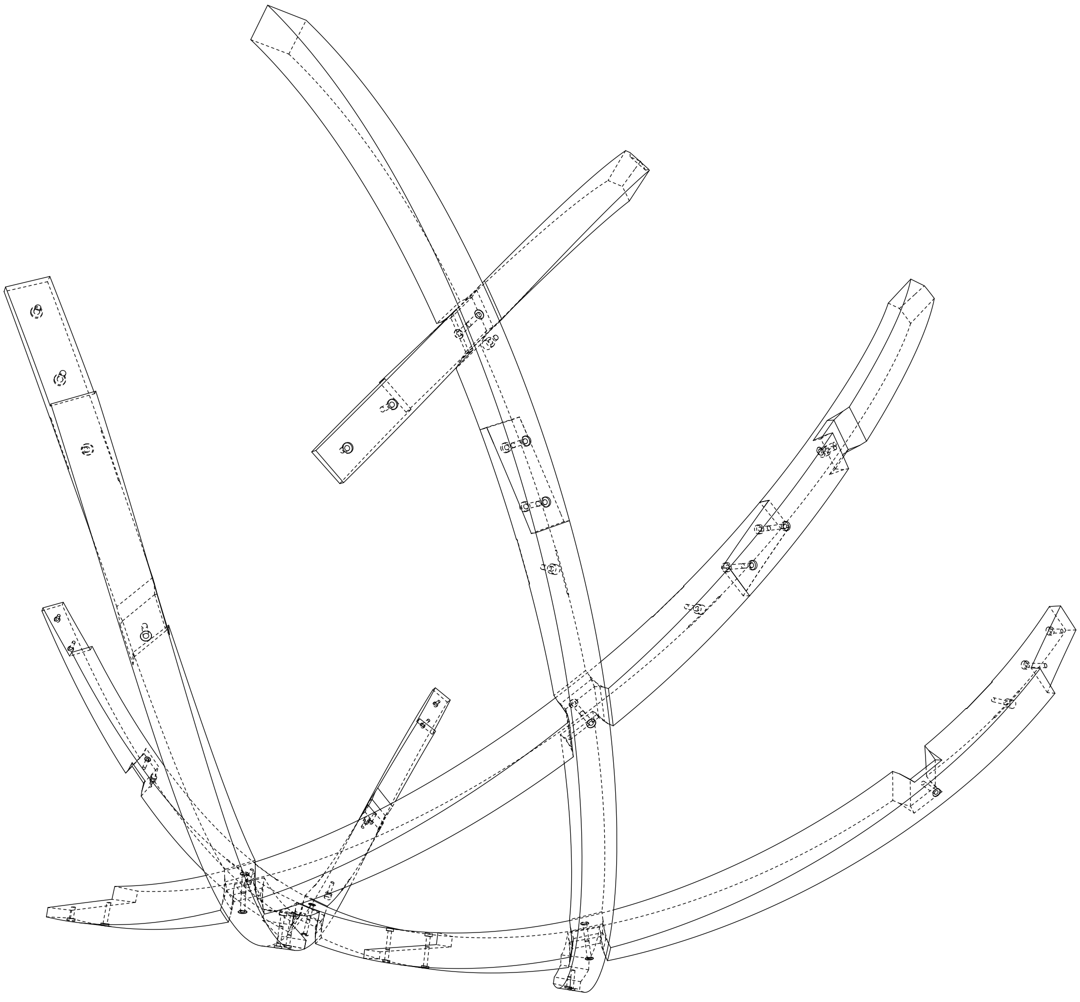


Fig. 4.48: Fragment 4. A section of the fabrication model for Demonstrator: MBridge.

4.4.3 Fibre mapping in glulam assemblies

Expanding upon the previously described strategy of analysing fibre orientation with colour, the glulam blank model allows the application of this technique to larger, more abstracted elements. Of particular importance for models at the scale of a glulam blank or the corresponding architectural component is fibre orientation in relation to structural strength and material durability. This is particularly important when there are multiple options for different types of glulam blanks for a glulam component: straight glulams are cheaper and easier to make, however cutting curved forms out of them exposes the most amount of end-grain, while double-curved glulams are stronger and minimize end-grain exposure if they are used to closely approximate a curved component but are expensive and wasteful to fabricate. Being able to visualize the impact of glulam choice across a design model therefore presents an opportunity to engage with the material consequences of design decisions. The visual mapping of a component that uses a straight glulam blank (Fig. 4.49) can be compared to a component that uses a curved glulam blank (Fig. 4.50). The mapping of fibre direction and deviation therefore provides simulated, qualitative feedback also at the meso-scale - for each glulam component and workpiece. Extending this also to the speculative glulam blank types reveals their heterogeneous makeup and strategic lamination which is discussed in further detail in the next chapter (Fig. 5.8).

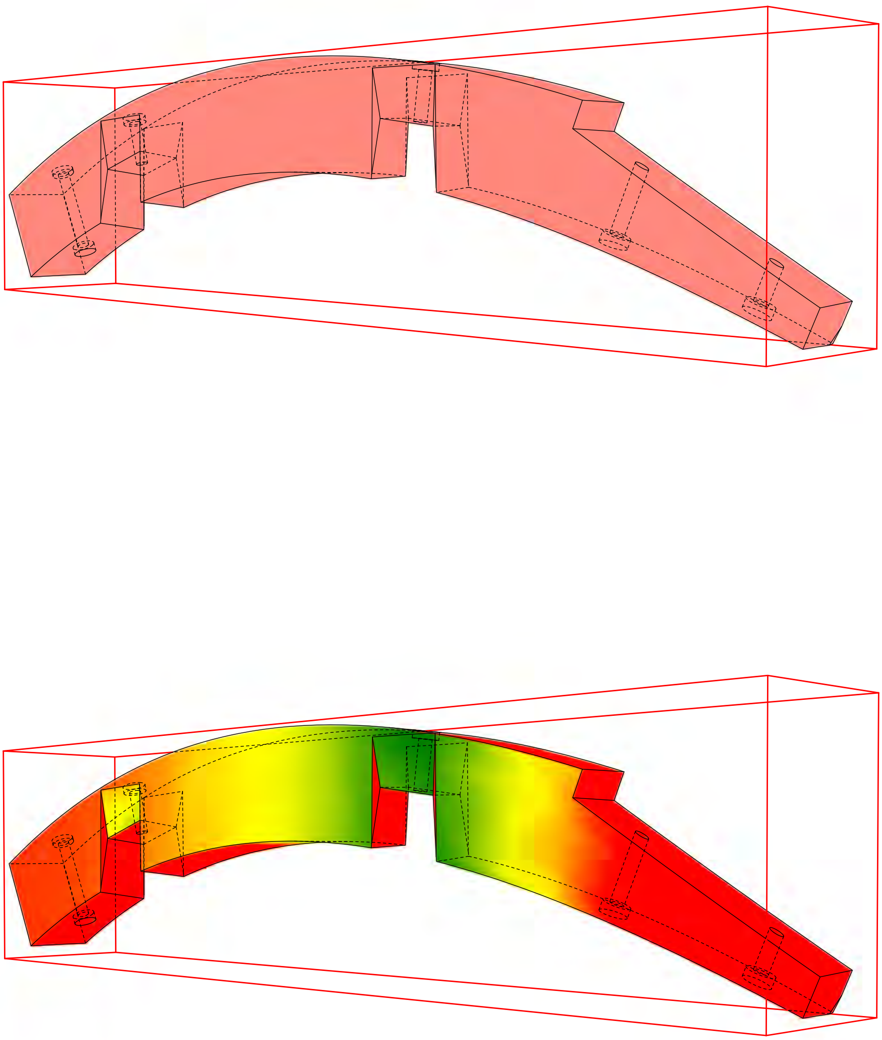


Fig. 4.49: A curved component cut out of a straight glulam (red outline). The constant shade of in the fibre direction map (top) means a constant fibre direction. The red zones in the fibre deviation map (bottom) show many areas that exceed the 5-degree fibre-cutting angle.

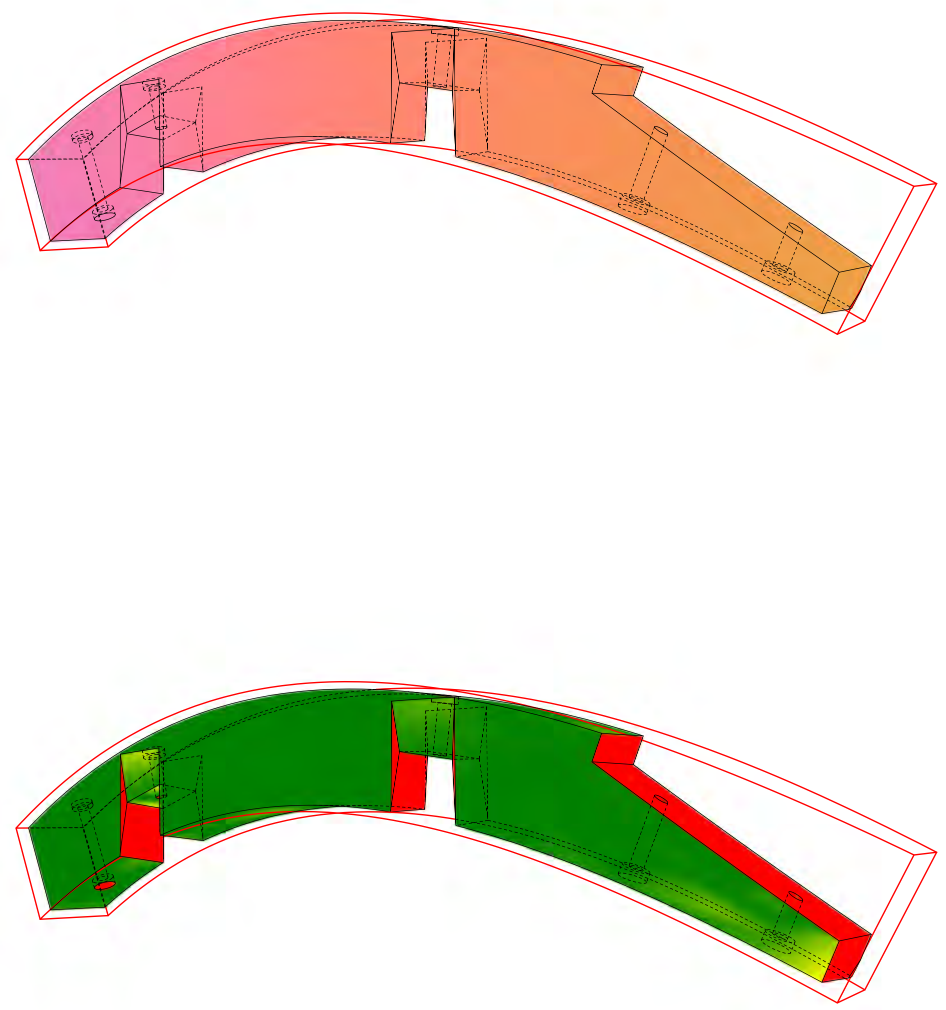


Fig. 4.50: A curved component cut out of a double-curved glulam (red outline). The fibre direction map (top) reflects the curving fibre direction. The fibre deviation map (bottom) shows less areas that exceed the fibre-cutting angle.

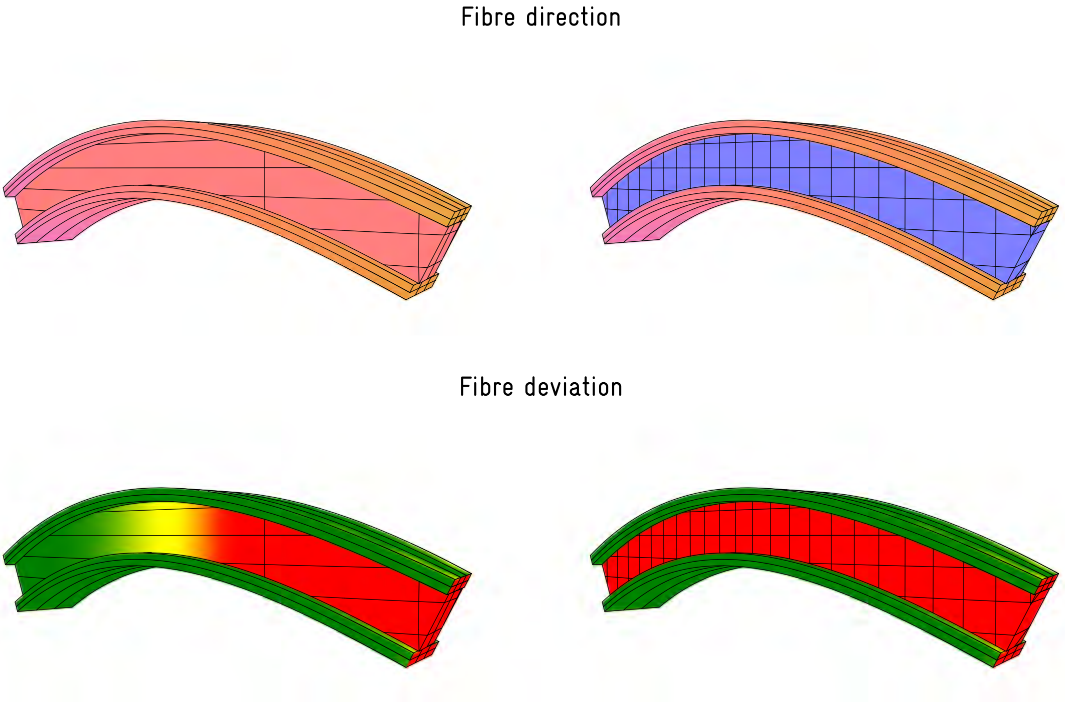


Fig. 4.51: The fibre mapping of the Voxel Blank. Fibre deviation map, showing the areas that exceed the 5-degree fibre-cutting angle (red) for a parallel web (top left) and a perpendicular web (top right). The fibre direction map clearly shows the difference between the parallel web (bottom left) and the perpendicular web (bottom right).

4.5 Glulam structures and graph-based models

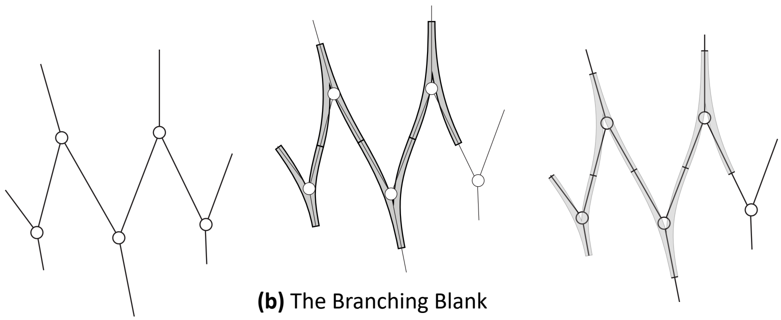
4.5.1 Joints and connectivity

The use of the `Feature` class as a method for coordinating joint geometry between two glulam components suggests a method by which a glulam structure can be described by traversing its constituent cross-referenced components and joints. Considering that a single glulam component can have multiple connections to other glulam components, and that each connection holds a reference to the glulam component that it is joined to, a connectivity graph naturally emerges. Beginning with a single glulam component, and by following each of the references provided by its connections, the entire inter-connected glulam structure can be discovered. Modelling a glulam structure at a macro scale as a connectivity graph is therefore an non-geometric method of managing the interrelations of its components. In such a graph, each glulam is a node, and each connection or joint detail is an edge that connects two nodes.

The use of graphs to describe spatial relations and architectural constructions is not novel: Christopher Alexander applied graph theory to the design and analysis of cities (Alexander 1965) in the 1960s and inspired subsequent development in other fields such as computer science. Using relational diagrams and graphs to analyse connectivity between rooms in buildings is similarly deployed in early-stage architectural design processes, as described by Thurow, Langenhan, and Petzold (2016). The problem of top-down graphs and topology in early-stage design is discussed by Harding et al. (2012), and similar problems of flexibility in the face of topological complexity are explored by the work of Daniel Davis (Davis 2013). Several projects at CITA have explored the application of graph theory and graph-based modelling to architectural structures and assemblies such as Deleuran et al. (2016), Quinn et al. (2016), and Ramsgaard Thomsen, Tamke, et al. (2017).

4.5.2 Managing complexity through graphs

The emergence of a connectivity graph from the bidirectional referencing of glulam joints is first explored in Probe 5: Branching Probe and Prototype 2: Grove to organize and manage the high number of individual elements. In both of these projects, a coarse mesh formed the basis for a spatial graph, which provided information for element positions and end-points. Each node and edge contains minimal data about the components and joints they represent, such as a frame of reference and a unique ID which corresponds to the glulam component. Keeping the glulam blank and component models separated from the graph model means that the graph remains lightweight



(a) The mesh graph consisting only of vertices and edges.

(b) The Branching Blank overlaid onto the graph, resulting in a 3-way module whose ends are located along the mesh edges.

(c) The resultant locations of the end-to-end splice joints between the branching modules.

Fig. 4.52: The use of a mesh-based graph as a basis for a structure using the Branching Blank.

and agile.

In Prototype 2: Grove, the structure was composed of many bifurcating and interconnected Branching Blank components. A coarse reference mesh drove the distribution of the components and the location of all necessary joints in-between (Fig. 4.52). The spatial location as well as the configuration of each Branching Blank component - such as the angle in between the branches and length of each branch - were thus derived from the mesh vertices and edges. The angle of the branches and the overall length of each unit drove the maximum curvature of the individual glulams, and therefore could relate the mesh topology to the sizing of glulam lamellae and type of glulam. The inverse of this relationship was also true: constraining the size of lamellae or relaxing the curvature of the Branching Blank modules affects the positions of the mesh vertices. A relationship between the coarse mesh graph and the individual fabrication data of each glulam element was therefore created and maintained - a demonstration of the multi-scalar approach described in Svilans, Poinet, et al. 2017.

This allowed a fast iteration and overview of fabrication consequences from a simple manipulation of the base mesh and a checking of the fabrication parameters of each component.

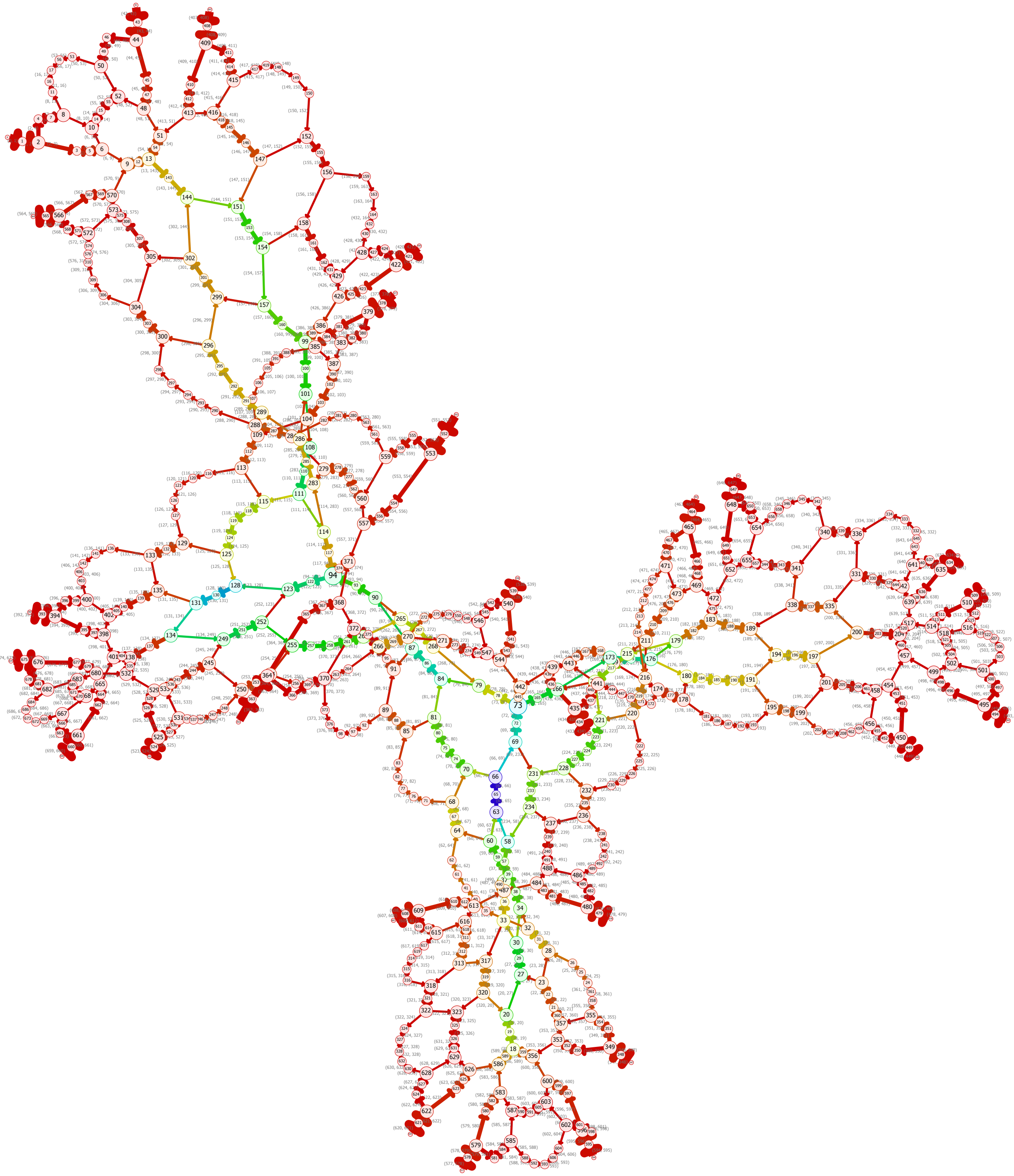


Fig. 4.53: The graph of the Prototype 2: Grove proposal. Image credit: Paul Poinet

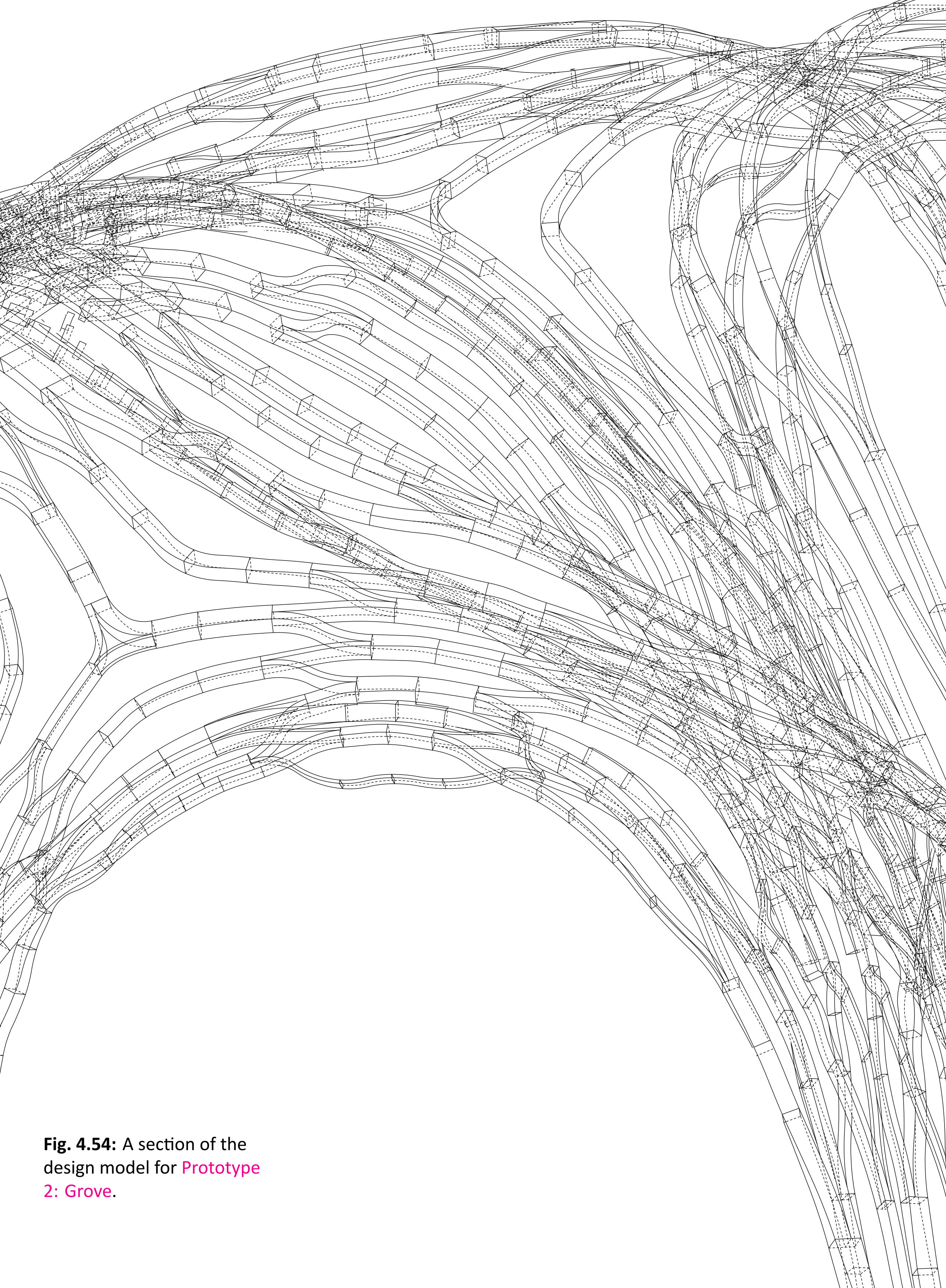


Fig. 4.54: A section of the design model for Prototype 2: Grove.

This imbues the reference mesh in Probe 5: Branching Probe and Prototype 2: Grove with a dual function: as a graph for organizing the component data as well as a driver or reference for the positions, orientations, and sizes of the components. While this dual function successfully allows the organization of a large number of individual components and their fabrication data as well as the reciprocal relationship between the overall design of the structure and the specific material specification, the design and modelling of Demonstrator: MBridge presents other challenges. In this case, the geometry of the components and their spatial organization comes from a pre-established design model and a graph is only used as a tool for organization the relationships between elements, not controlling their spatial location. The bridge design also calls for long glulam ribs that have to be segmented whereas the previous projects assume a highly segmented, discretized, and module-based design. The bridge elements are not limited to end-to-end connections, but also integrate multiple crossing joints with other elements. Some of the bridge elements are adaptations of the Branching Blank with additional joint details while others are double-curved glulam components with up to six joints - encoded as `Feature` objects.

The solution for this is to create a graph from the main design elements - the long glulams that form the ”grid lines” (Fig. 6.43) - and subsequently subdivide this graph according to the segmentation of these (Fig. 6.47). This solution is described further in the *Chapter 6: DESIGN IMPLEMENTATION* and shows how, even within an overall - or global - graph model at the scale of the whole structure, sub-graphs and groupings are necessary to describe relationships between larger cohesive elements and their constituent parts.

Taking this further, the process dependency tree described previously for the glulam assembly can therefore be considered as part of this overall graph: each node, representing a glulam workpiece or architectural element, can be unpacked into the process tree which describes its manufacturing process.

4.5.3 Graphs and trees

Graph-based representations of glulam structures can represent their connectivity topology at a given point in time, typically the projected ”end result”. Another prospect arises, which seeks to merge the process diagramming of the glulam assembly with these graphs. The process diagram inevitably has a tree-like topology: multiple inputs result in a single end-result component that is delivered at the end of the process diagram. The process diagrams of the speculative glulam blanks presented in Probe 4: CITAstudio glulam workshop result in a single material output. This is contrasted with the undirected character of the topological graph of the entire structure, which does not have a clear progression from one end to another. Given that the process tree of each element also has a time element to it, the merging of these two strategies requires the reconciliation of the idea of the ”end result” with the notion that actions performed on some material input results in a material output in a series of time-based steps.

Such a train of thought necessitates a reconsideration of such notions as ”final output” or ”final design”. A connectivity graph that describes the relationship between multiple glulam components therefore only describes a certain point in time when all of those components are joined together. If the assumption that the process tree occurs before the connectivity graph is eschewed, then the undirected connectivity graph becomes a structure that only appears intermittently between different processes of manufacture and assembly. Extending this logic further, such a graph must also be extended to consider the post-assembly life of the components as well as their disassembly.

The idea that a glulam component can also be split into several parts, each of which subsequently follows its own process tree, deserves further consideration. The process tree strategy for designing novel glulam morphologies needs to take into account cases where both processes of materialization and topological linkages diverge or split throughout the temporal dimension of production and assembly. More and more this points towards a hereditary charting of process genealogies: splits and merges whose outputs are extracted snapshots of an evolving process rather than finite end-products. This points towards perspectives in the fields of design-for-assembly, operation, maintenance, and design-for-disassembly.

This hints at a further inquiry into combining this type of process tree with the organizational graph of the whole project. The process tree has a time dimension: operations are performed on objects in a sequence, transforming those objects along the way. The organizational graph describes the spatial positions, orientations, and joints between elements in the final structure. Both describe the assembly of smaller elements into wholes, meaning that aspects of both could be described by a common assembly model - however this assembly model would have to also include processes of transformation and manufacturing. This aspect remains speculative in this research.

4.6 Summary

This chapter presents a multi-scalar approach for the modelling and representation of glue-laminated timber components and structures. The three scales are addressed by three different modelling frameworks: the micro scale employs a discretization of individual timber fragments or glue-laminated assemblies and a mapping of heterogeneous material properties; the meso scale uses a constrained glulam blank model which integrates fabrication considerations and material limits; and the macro scale deploys graph-based modelling techniques to manage a large amount of interrelated glulam components and connections. The scales are traversed through bidirectional referencing, centred on the glulam blank model: the glulam blank cross-section holds references to each lamella which is a discretized dataset at the micro scale, and the interplay between graph, component model, and glulam blank is negotiated by storing references to the components models within the graph structure.

Together, this approach integrates the material properties of timber into a design modelling environment that can be deployed throughout the design process to achieve a measure of *simulated feedback*. The flexibility of this approach is augmented by the sub-classing of base models, creating an expandable object-oriented ecosystem of different types of glulam models such as the `Glulam`, `GlulamAssembly`, `GlulamWorkpiece`, and `Feature` models. At a material scale, the discretization of timber models and assignment of heterogeneous properties creates an interface with simulation tools for other domains such as material engineering and CAE. At a component scale, the encoded material limits and fabrication constraints create an interface with production capacities and manufacturing affordances.

This constitutes the computational foundation for the proposed material practice in free-form timber structures. The use of these models and workflows is described further on in *Chapter 6: DESIGN IMPLEMENTATION* through their application to design projects. The making of the speculative blank types briefly described here for the purposes of highlighting their process tree diagrams and fibre direction and deviation mapping are explored in the next chapter.

5

GLULAM PROVOCATIONS

5.1 Overview

This chapter focuses on the domain of glue-laminated timber materialization. Whereas the previous chapter discusses a multi-scalar approach to mapping and representing heterogeneous material properties through computational models - from individual pieces of timber to free-form glulam structures with many parts - this chapter explores the processes involved in the production of architecturally-scaled glue-laminated components. The two main objectives are to explore the design territory offered up by considering the glulam blank as an intermediate space between raw lumber and finished architectural component, and to explore how the integration of computation and digital sensing can augment existing timber processes, making them more receptive to handling non-standard glue-laminated timber elements and thus expanding the scope of feasibility in industrial timber production. Both objectives introduce cyclical thinking into the production process: moving from a linear gluing and machining process to iterative gluing and machining steps, and integrating direct sensor feedback into the production workflow to shift the outcome of the machining process. The chapter encompasses the physical prototyping experiments performed during the PhD as well as the industry secondment with *Blumer Lehmann AG*.

By introducing a deeper *engagement* with the processes of materializing glulam components, an iterative dialogue is opened up between designer and the glulam blank, constituting a *process feedback* that integrates the design of the glulam blank into the architectural design space. By measuring and recording the evolving workpiece, and locating it within the virtual space of toolpaths and fabrication models, an increased *awareness* of the material processes is achieved, leading to *direct feedback*, where digitized knowledge of the material reality during production merges the space of the model with the space of the material.

Much like the last chapter initially probed the principles behind modelling

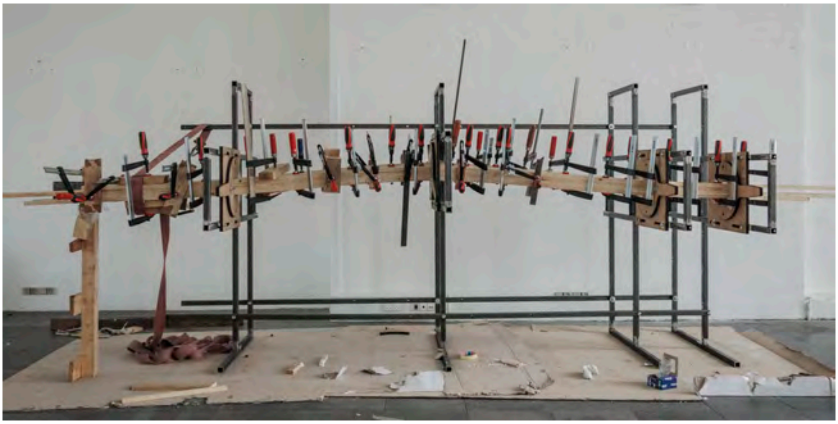


Fig. 5.1: The steel jig created for bending a double-curved glulam. Four adjustable frames allow different curves to be formed. The lasercut MDF portals hold the glulam and allow twisting the cross-section.

glulam members, the domain of materialization begins with a preliminary exploration of glue-lamination and bending, then speculates about the possibilities of morphing, modulating, or re-arranging established timber processes. Five speculative glue-laminated timber assemblies are drawn from a reflection on specific strategies, tools, and operations in industrial timber processing. In all of them, the role of the fibre direction is paramount, as is the choreography between lamination and machining, which results in multi-headed and irregular physical forms that depart from established glulam blank types. These require methods of mapping the physical artefact back into the digital modelling environment. To this end, four methods of digital feedback in the industrial production of a large free-form glulam building are prototyped and put forward as possibilities for integrating model and material.

5.2 A tactile exploration of glue-lamination

Just as Probe 2: IBT glulam workshop is the first exploration of digitally modelling glulam components, it is also an opportunity to delve into constraints and methods involved in laminating timber components. The workshop - run over the course of one week with twenty undergraduate architecture students - is in equal measures an inquiry in how glulam components can be digitally modelled, and how they can be materialized. As such, this initial exploration is an ad-hoc, intuitive, and hands-on introduction to the world of bending and laminating wood. The tactility of this exploration serves as a way to ”size up” the wood: feeling how much

Fig. 5.2: The bending performance and elastica of the 20 x 20 mm lamella are explored intuitively in Probe 2: IBT glulam workshop.

force it takes to bend a lamella of a certain size, how hard the clamps need to be tightened to achieve an effective glue joint during bending, negotiating the complexity of arranging dozens of lamellae at the same time, and so on. The goal is to identify the challenges that arise from a direct confrontation with material behaviour and its limits.

The subject matter is approached naively, with very few specialized tools. Hand clamps are used for pressing the components. Shipping pallets and improvised timber jigs are used as the forming and pressing framework: the frame which resists the bending that is imposed on the timber. An adaptive steel jig is fabricated to attempt to make a double-curved glulam without costly form-work (Fig. 5.1). Timber lamellae of different thicknesses are bent around jigs of varying curvature: beginning with the natural elastica curve that a bent lamella takes when bent between two points, additional support pieces are screwed down to attempt to even out the curvature and thus prevent material failure at points of concentrated curvature (Fig. 5.2). The curved shape of each test piece is traced on the shipping pallet backing, identifying shapes that break and shapes that manage to be bent further. The relationship between the lamella thickness and the radius of bending - encoded in the Eurocode 5 specification as a ratio of 1:200 - is tested with high quality spruce laths. The alternating orientation of the lamellae crowns is heeded: in principle, changing the crown direction of each lamella is import to minimize the form distortion of the whole glulam caused by the

Fig. 5.3: A glulam section from the Probe 2: IBT glulam workshop.

anisotropic swelling and shrinking of the wood (Fig. 5.3).

These efforts demonstrate a first-hand ”coming to terms” with the glulam materialization. The workshop confirms the substantial difference in effort between laminating simple, straight timber elements and attempting to craft double-curved glulams. As shown previously, these have a corresponding difference in cost and production complexity in large-scale industrial contexts. The simple difficulty of accurately managing 3D curvature, twisting, and the larger count of necessary lamellae makes it tricky work. Using hand-tools such as parallel clamps requires surfaces for the clamps to grip. A double-curved element is also clamped from all sides of the cross-section, leading to difficulties in applying enough pressure at all necessary points to result in a sturdy lamination.

The glulam members that result are between two and three meters long, with a square cross-section of eighty millimetres. They are formed out of square lamellae that are twenty millimetres thick, resulting in a total of sixteen lamellae per glulam. The difficulties that are encountered in bending even only this many lamellae highlights the appeal of rationalizing glulam structures so that they use straight or single-curved glulams, and avoid double-curvature. The glulam members reflect the established categorization of straight, single-curved, and double-curved glulam blanks.

Apart from confirming the complexity of forming free-form glulam blanks, the workshop shows the importance of smaller, less exciting details, such as the importance of a good contact surface for gluing, methods of applying appropriate clamping pressure, and the logistics of applying glue and assembling the glulam within the open (wet) time of the glue. Indeed, the whole process of glue-lamination is performed under a strict time limit, beyond which the glue is not effective any more and the exercise fails. The main challenge is therefore found to be an appropriate *pressing framework* which involves the management of material, pressure, forming accuracy, and time. The corresponding processes for shaping the resultant glulam - the *machining framework* - are explored in subsequent prototyping work.

5.2.1 Frameworks of production

The experimental apparatus of glue-laminated fabrication therefore consists of the material ingredients - the timber lamellae and the adhesive - the pressing framework, and the machining framework. The physical prototypes are a result of the interaction of these three elements in different arrangements and variations.

The pressing framework in Probe 2: IBT glulam workshop consists of store-bought PVA wood glue, Bessey hand clamps, and a steel jig. There is no machining framework, except the minimal surface finishing of the glulam members using electric sanders by hand. The lamellae are square-section spruce sticks purchased from a lath factory. The steel jig is an effort to create a pressing framework that is adaptable and somewhat modular, but it requires a much larger investment of time and material to produce successful glulam members.

Another approach is attempted during the prototyping for Probe 5: Branching Probe and Prototype 2: Grove: form-work for each branching and double-curved glulam component is constructed out of laser-cut MDF sheets (Fig. 5.4). They are assembled in a waffle-like structure that allows the wood to be bent into double-curved configurations. This method is labour-intensive and materially wasteful: the increase in number of glulam components means a corresponding increase in form-work. The rigidity of the form-work becomes a key factor in a successful result, since it needs to effectively resist the bending forces that are induced into the lamellae while they are being glued. Failure to do so results in springback in the form-work and therefore a geometry that is different from that which is designed. MDF waffle structures - though cheap and easy to process - fail in this regard and must be reinforced by steel members and ad-hoc additions to the form-work. Scanning the outcome of this method during prototyping for Probe 5: Branching Probe reveals sizeable deviations from the design geometry because of this.

(a) Laser-cut MDF moulds used for the Probe 5: Branching Probe and Prototype 2: Grove prototypes.

(b) 3D scanning the formed prototype for testing the quality.

Fig. 5.4: Forming the branching prototypes in MDF formwork and subsequently 3D scanning them to compare against the intended outcome.

A third approach is used for the production of Demonstrator: MBridge: vacuum lamination using a polyurethane bag and a compressor - or ”bag press”. The advantage of using such a pneumatic system is that the pressing mechanism is soft and compliant, and that pressure is evenly distributed across a pneumatic surface. This means that the entire surface of the bag that is in contact with the wood imparts a uniform ”clamping”, as opposed to the piece-meal and localized jaws of mechanical clamps. This reduces the chances of marking the wood surface with the clamp jaws and avoids the need for clamp spacing.

In this pressing framework, the pressing together of the lamellae is separated from the forming of the glulam blank. The vacuum bag takes care of pressing the glued lamellae against one another. Because the bag is soft and compliant, the whole glued assembly can still be manipulated and bent. A secondary system of adjustable steel arms is used to bend and hold the vacuum bagged assembly into its designed form. In this sense, it is much like the first steel jig that is used in Probe 2: IBT glulam workshop except it replaces the large amount of clamps with a single vacuum bag.

The machining framework is introduced in the physical prototyping in Probe 5: Branching Probe and Prototype 2: Grove. These experiments consider the glulam in the context of a structure or assembly, and therefore necessitate the cutting of joint details and surfacing the glulam blanks to reveal the designed glulam component. The three-dimensional nature of the branching components require multi-axis machining and therefore employ an industrial robotic arm at *CITA* - an ABB IRB1600 - with a mounted high-speed spindle. This mimics the multi-axis machining framework used in the industrial production of free-form glulam members with the added convenience of a portable and modular setup: the robotic arm is not a tool that is specific to timber machining but has a open interface and exchangeable end-effector that permits it to perform different tasks. The genericness of robotic actuation is therefore conducive to exploratory prototyping at a smaller scale than the industrial processes it imitates. However, the robotic arm is an aggregation of six rotary axes, which present more challenges in calibration and accuracy than typical CNC machining centres with linear axes. This anatomical difference affects the shadowing of the industrial timber machining process by changing the limitations of machinability and the setup of the machining framework.

The production of Demonstrator: MBridge employs a dedicated five-axis timber machining centre - a CMS Antares CNC machine - which has a much greater similarity to the machining centre employed by *Blumer Lehmann AG*. As opposed to the robotic arm at *CITA*, the CMS machine has an anatomy that better reflects the industrial machining framework: a closed and inward-facing machining volume and a spindle that is mounted on a vertical aggregate that moves on three linear axes. The difference in programming the robotic arm and the CMS machining centre also differs: the robotic arm is commanded by an ABB-specific robotic programming language (ABB Robotics 2014) whereas the CMS uses industry standard G-code. These differences make the CMS machine a better alternative for the *mirroring* of the machining framework at *Blumer Lehmann AG*.

Although the pressing and machining frameworks are central to the production of glulam components, other processes within the timber processing chain deserve equal attention. The finger-joining of lamellae is used to remove defects and to extend their limited length to arbitrary extents. The machining of this joint using a special finger-joint cutter occurs within the processes that prepare the lamellae for lamination into a glulam blank: each lamella is cut around a perceived defect, the cut ends are machined with a finger-joint cutter, and the ends are glued together in an entirely automated process. The opportunity arises to consider how this process could be considered as an active ingredient in the glulam production apparatus and deployed in other areas of the machining framework. A similar consideration is drawn from the lamination of other, related engineered wood products such as cross-laminated timber (CLT): the lamination of alternating layers of timber can be extracted from the production of CLT and re-deployed elsewhere as a way to advance a localized variation in fibre direction within non-standard glulam blanks. This re-deployment of timber processes suggests an opportunity to use established industrial methods to achieve glulam blanks that use a varying internal fibre orientation in their laminated volume for specific, designed, and functional purposes.

5.2.2 Functionally-graded glulam assemblies

The production of glue-laminated timber components can be thought of as a series of distinct process steps: the pressing framework demonstrates an *aggregation* through the use of adhesive and a *deformation* through the use of form-work and presses. The machining framework represents the subsequent process step of *substraction* through the cutting, planing, drilling, and machining of the glued timber mass. Examining the established family of straight, single-curved, and double-curved glulams therefore shows that they are products of a specific arrangement of these process steps. Glulams have parallel rows and columns of lumber lamellae, glued along their faces. This is both a product of the input material - rectangular sections of lumber - and expediency - it is simple and fast. The result is glue-laminated timber components which are beam-like and direct the fibre direction along the main, linear axis of its form.

Non-homogeneous glulams introduce a variation in the quality of timber for the purpose of increased material and structural efficiency. The inferior grades of lamellae on the inside of the glulam cross-section have lower performance demands than the superior grades of lamellae on the outsides of the section. This mapping of superior material where demand is highest, and inferior material where demand is lowest forms the basis of a *functional grading of glue-laminated components*. Looking towards related engineered timber products such as plywood or CLT also show a similar modulation in fibre quality and direction: the alternating fibre directions of a plywood sheet or CLT panel are distributed evenly to increase the overall form stability of the sheet or panel.

Referring back to the topological fibre variation in living trees, these ingredients - lamination strategies and individual processes within the timber processing chain - offer new potentials for exploring glue-laminated components which respond to specific functional demands through a strategic lamination and distribution of processed timber lamellae. Combined with the genericness of robotic or five-axis CNC machining, tailored arrangements of glue-laminated timber can be produced. Otto Hetzer explored a similar line of reasoning such as in patent no. 163144: a curved lamella laminated between two machined members with a straight fibre direction with the intent of achieving a greater structural efficiency. This moves the functional grading of glulam blanks from being one of material specification - specifying different grades of wood for the constituent lamellae - to one of a larger geometric and organisational complexity which involves cutting and bending to alter the internal fibre organisation of the glulam blank, involving a wider range of process steps. This results in a functional organization or distribution of differing fibre orientations and properties throughout a glue-laminated component.

Further, considering the initial steps of aggregation, deformation, and subtraction, the introduction of cyclical thinking and iteration re-introduces the laminated glulam blank as an input into another glue-lamination and machining process. This detaches the glulam blank from the established and linear procedures of lamination-machining-assembly and recasts it as a product of the interaction of a *constellation* of processes. This line of thinking eschews the linearity found in glulam production, opens up the possibility space of glue-laminated timber morphologies, and challenges the dichotomy between glulam blank and finished glulam component.

5.3 Speculative glulam blanks

This departure from the initial forays into glulam production is explored through five speculative glue-laminated blank types in Probe 4: CITAstudio glulam workshop. The workshop is used as an opportunity to speculate about new glulam blank types that result from a reorganization or reconfiguration of current glulam production processes as well as to find how these new blanks can be modelled and materialized. Each blank is driven by a particular question drawn from an overview of established glulam types and the array of timber processes that are involved from the production of timber lamellae to the assembly of glulam structures. The criteria for their design is only that they describe a glue-laminated component that is double-curved or that they eschew the two-ended beam-like form of established glulam types. This allows a way to look for solutions to the difficulties in forming the curved glulam blanks in Probe 2: IBT glulam workshop and a wider exploration of formal potential. A further criteria for their materializing is that they challenge the linearity of lamination-machining-assembly by including at least one recursive step such as laminating *after* machining.

5.3.1 Overview of the blanks

The five speculative blank types each explores a different aspect of industrialized timber production and proposes an alteration, deviance, or iteration to generate a novel glulam blank type:

- The *Voxel Blank* uses short elements - possibly off-cuts from other processes - to compose a rough mass which is then machined into a free-form beam. This machined wood mass then acts as formwork for gluing continuous lathes of higher-quality wood along the top and bottom flanges of the beam.
- The *Finger-joint Blank* creates a segmented, free-form blank from large sections of lumber by gradually changing the orientation of a finger joint between consecutive segments.
- The *Cross-laminated Joint Blank* departs from the crossing lap joint which removes half of the elements' cross-sections to a multi-ended glulam blank that integrates crossing connections through the interleaving of lamellae.
- The *Branching Blank* creates a three-ended glulam blank that divides its *trunk* into two *branches*, with an integrated cross-laminated layer to provide bracing and resistance to splitting forces.
- The *Kinky Blank* addresses elements with sporadic and sharp bends or kinks by interleaving and cross-laminating the lamellae at these points, allowing the use of larger lamellae and therefore a more economic production.

Fig. 5.5: A physical prototype of the Voxel Blank.

5.3.2 Voxel Blank

The Voxel Blank asks two questions:

- How can the production of double-curved glulam blank be made easier by integrating its form-work into its own body?
- How can the use of continuous and bent lamellae be relegated to the outer flanges of the blank, where the structural performance demands are greatest, while using larger and less-curved lamellae for the interior web of the blank, where the structural performance demands are lower?

It proposes an iterative process where a rough, near-net shape - or ”voxelized” version of the final blank - is glued from short, straight pieces. The voxel size is driven by the use of larger sections of lumber. The voxelized approximation - the *core* - is machined back to the double-curved surface, and then laminated with continuous, bent lamellae on the top and bottom surfaces - the *flanges* of the beam (Fig. 5.6). The machined surface is offset from the final blank surface in order to accommodate the secondary lamination of these continuous lamellae. The resultant ”core” or web that is made from the simply laminated straight pieces therefore becomes the form-work for the double-curved ”flanges” or outside surfaces (Fig. 5.7).

It is a principle similar to wooden I-joists, which have an OSB web that is bonded to solid wood flanges. In this sense, the Voxel Blank is akin to a ”free-form wooden I-beam”. The core displays large areas of fibre-cutting due to being a free-form surface cut from straight wood pieces, however the outer flanges are continuous and orient the wood fibre closely along the double-curved form.

The effect is two-fold: allocating continuous fibre to the parts of the blank that would be under the highest stress in simple bending - in this case the flanges - while allowing a lower grade of material to be used in the core, and simplifying the double-curved forming process by having the mould or form-work of the complex curvature be part of the final blank. Another effect of this is that material usage is improved, as shorter pieces and off-cuts of sizeable dimensions can be used for the weaker core, while only using high-quality but wasteful thin lamellae on the flanges. Machining the double-curved core nevertheless generates a large amount of material waste, however this is a function both of the resolution of the voxelization and, if using off-cuts, allows the salvaging of material that would anyway be discarded as waste.

Since laminating the core only involves straight elements, the resolution of the ”voxelization” can be varied depending on the size of the available material. Having a more coarse voxelization means more machining and material waste, however it also means laminating fewer pieces and less material waste beforehand from planing down smaller pieces of lumber. The lamination of straight elements for the core also increases its stability, as it does not have to take into account any springback or bending stresses. This simplifies the creation of accurate, double-curved elements, since their accuracy is limited only by the precision of the machining framework rather than the precision of the pressing framework.

The reliance on special double-curved glulam presses is also avoided, however the voxelized lay-up presents its own challenges. A regular straight glulam can be pressed easily because it has 6 facets, of which only 2 need to be pressed - the top and the bottom. The sides simply need to be aligned to avoid too much wasteful planing afterwards to even out the misaligned lamellae. This means that the press simply needs two parallel jaws that run the length of the glulam. These are often broken down into sections, either allowing several shorter glulams of different depths to be pressed at once, or the creation of a *stepped glulam*, where the ends or the middle might have extra layers of lamellae. The core of the Voxel Blank can therefore be considered as a stepped glulam extended to three dimensions - stepped in width as well as in height.

In Probe 4: CITAstudio glulam workshop, this problem is addressed by first laminating each ”slice” of the Voxel Blank as a stepped, straight glulam, then subsequently cleaning up the flat faces of each slice and gluing those together. This divide-and-conquer technique allows each slice to be

Fig. 5.6: Robotic machining of the Voxel Blank.

controlled independently for quality at the cost of an increase in the time required to glue the core together.

Another cause for concern with the Voxel Blank is the large amount of exposed end-grain on the flanks which results from machining the core into the double-curved form. While the outside flanges show very little end-grain because they are able to lie so close to the final element form due to the precise form-work, the exposed portion of the core can show only end-grain, depending on how it is laminated (Fig. 5.8).

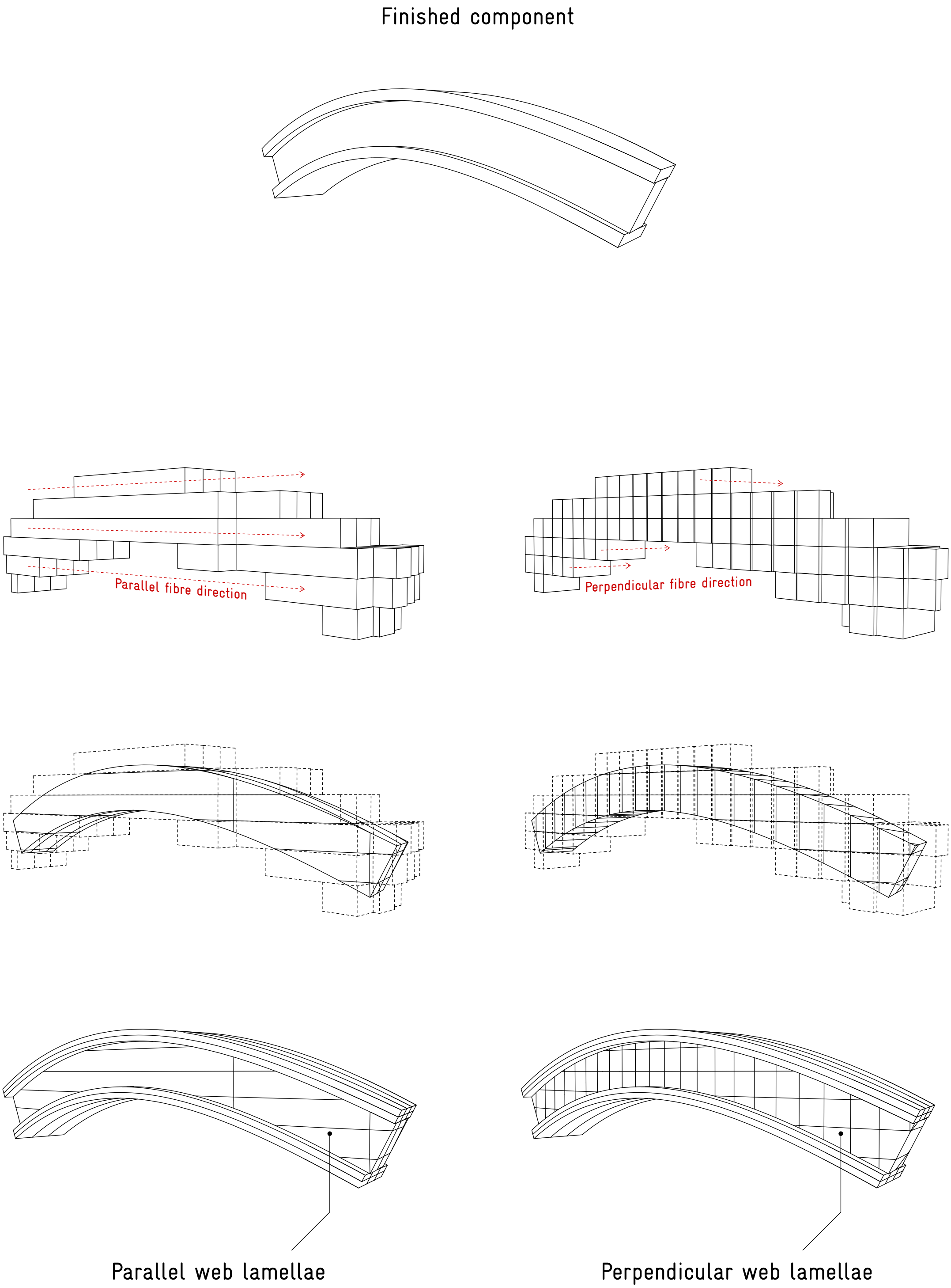


Fig. 5.7: The process of creating a Voxel Blank. A free-form glulam blank (top) is made by ”voxelizing” it using parallel lamellae (left 5side) or perpendicular lamellae (right side).

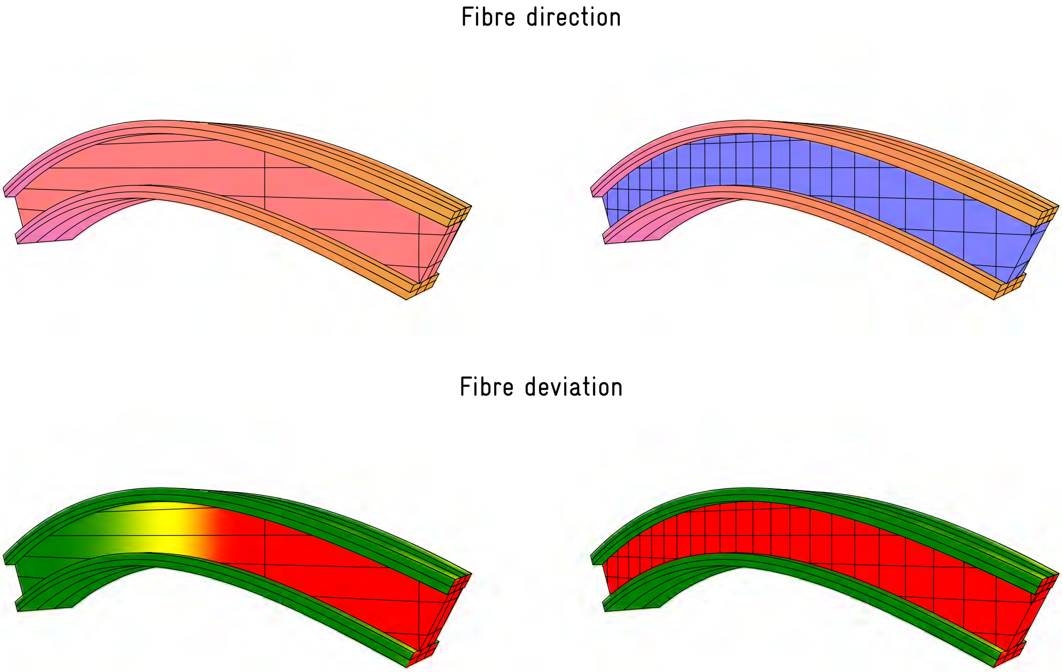


Fig. 5.8: The fibre analysis of the Voxel Blank. Fibre deviation, clamped to a 5-degree deviation for a parallel web (top left) and a perpendicular web (top right). The fibre direction analysis clearly shows the difference between the parallel web (bottom left) and the perpendicular web (bottom right).

Fig. 5.9: A physical prototype of the Finger-joint Blank.

5.3.3 Finger-joint Blank

The Finger-joint Blank asks:

- Can a small, angular modulation of finger-joining allow the lamination of a segmented blank that approximates a double-curved component while avoiding the use of thin lamellae?

The Finger-joint Blank avoids the use of complex double-curved pressing and small lamellae required for producing free-form glulam elements. Instead, it propose a small variation to a commonplace process - finger-joining - which is used throughout the timber industry, and very commonly in glulam production for cutting out defects and composing lamellae longer than the available input lumber. Finger joining is an automated and high-speed process where, after marking defects on incoming lumber, the whole section of lumber with imperfections is cut out, the cut ends are cut with a profiled cutter with many thin blades - the fingers - and the ends are pressed together using a fast-curing, RF-activated glue. The elongated fingers of the cutter - typically inclined at a few degrees - make deep incisions, which means that the wood boards are bonding mostly along the grain, rather than along their end-grain. This results in a strong joint that is often stronger than a clear section of the same board.

Although this is typically used to remove defects and extend wood boards - thereby allowing the use of lower-quality wood for high-performance applications - the piecemeal aggregation of short pieces of straight wood raises an interesting possibility if the cutting plane can be controlled and modulated. Similar to how continuous curves can be approximated piecemeal linear segments - such as polylines - the incremental adjustment of the cutting plane of the finger-joiner means that such a piecemeal glulam blank could be built up to approximate a double-curved element (Fig. 5.12). The amount of modulation of the cutting plane changes at what angle two connecting pieces are bonded together: having a small angle means that the joint is stronger as the pieces are being glued more in-line with their fibre direction, while having a larger angle is more similar to cross-lamination. Afterwards, a continuous double-curved piece can be machined out of the segmented blank, smoothing out the inflection points. The segmented nature of the blank is revealed as areas of constant fibre direction and a fibre deviation that fluctuates around the edges of each segment (Fig. 5.13).

Once more, the main advantages of this blank is that double-curved components can be fabricated from an aggregation of simple, straight lamellae of a large size, and that lack of bending means that there is no springback or issues of precision due to bending. The material waste saved by using large lamellae is offset by the larger amount of machining the final form out of the blank, however this is dependent on the geometry of the particular component.

This approach has been demonstrated previously in the construction of the Z-Plus Pavilion (Fig. 5.10) and the Kreisel Waldstatt (Fig. 5.11) by *Blumer Lehmann AG* and others, who also have conducted experiments with a radial finger joint. The complexity of producing these segmented blanks has, however, prevented them from being used more widely in the industry.

The main difficulty encountered during the Probe 4: CITAstudio glulam workshop is the problem of how to effectively clamp and glue the segments together. Since the cutting plane between them varies and is intentionally not perpendicular to the axes of the segments, a clamping method is needed which can somehow grip the sides of the segments while applying pressure into the finger joint. A solution is found where bespoke steel parallel clamps are clamped around each segment, providing a gripping surface for another set of clamps that pull the segments together. Although this succeeds within the prototyping context of Probe 4: CITAstudio glulam workshop, further development points towards automated assembly and pressing of the Finger-joint Blank using a robotic arm, which can manipulate and apply force along any orientation.

Fig. 5.10: The Z-Plus Pavilion by Création Holz, Blumer Lehmann AG, Design-to-Production GmbH, and SJB Kempter Fitze. Photo: Design-to-Production GmbH

Fig. 5.11: The Kreisel Waldstatt by Création Holz, Blumer Lehmann AG, and Design-to-Production GmbH. Photo: Design-to-Production GmbH

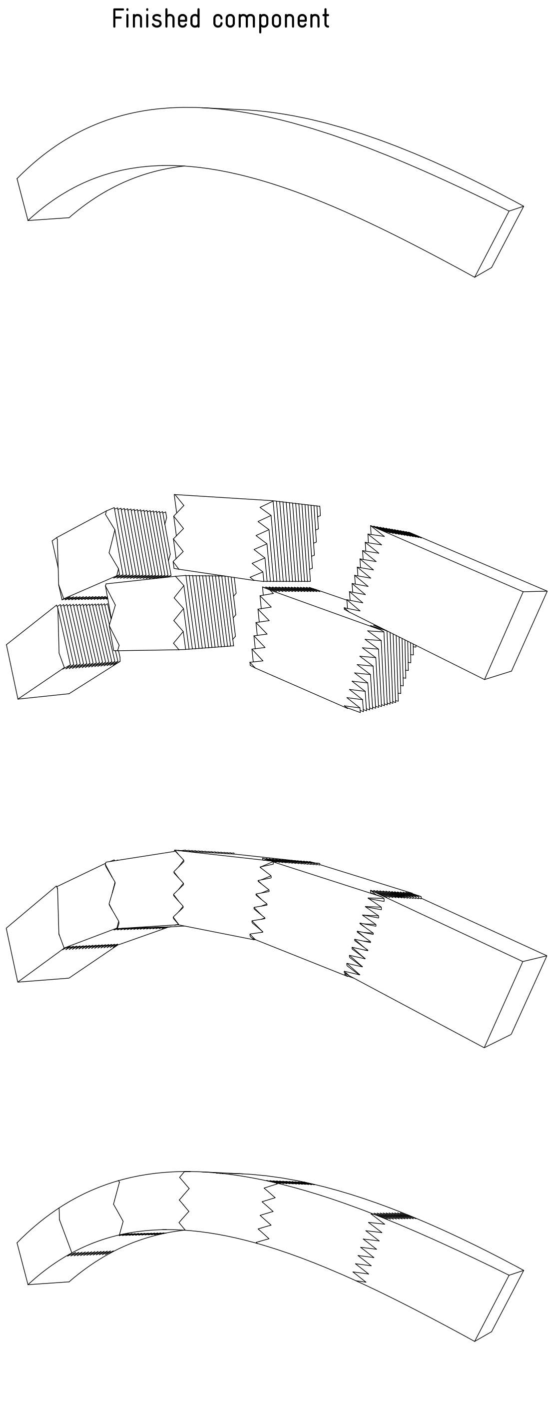


Fig. 5.12: The process of creating a Finger-joint Blank.

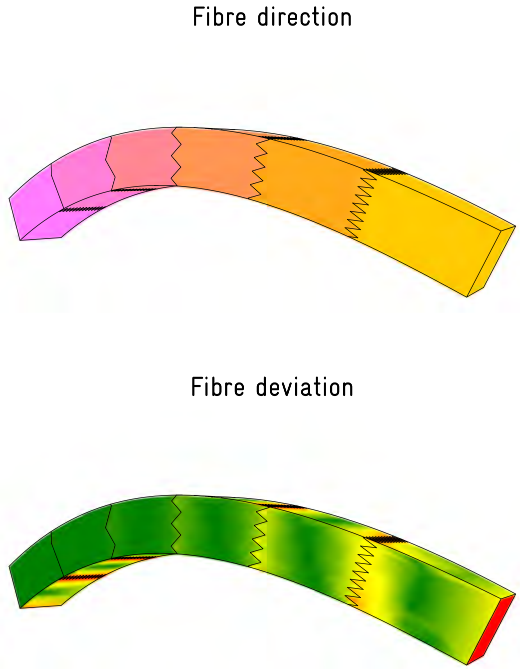


Fig. 5.13: The fibre analysis of the Finger-joint Blank.

Fig. 5.14: A physical prototype of the Cross-laminated Joint Blank.

5.3.4 Cross-laminated Joint Blank

The Cross-laminated Joint Blank asks:

- How can crossing joints - such as lap joints, which remove a large portion of the beam cross-section - be integrated into the lamination of the glulam blank, thereby leading to glulam components that only have end-to-end connections?

The Cross-laminated Joint Blank considers the linearity of glulam beams and the problem of making effective crossing connections between beam elements in lattice and grid structures. Crossing lap joints typically involve the removal of a substantial portion of the glulam cross-section from one side so that the joint can mate with its complementary joint on the other element (Fig. 5.15). While this is not as big of an issue in lap joints that are acting in compression - the sides of the lap joint are being squeezed shut around the receiving element - it becomes a concern when there is tension across the joint, especially over the open side. Further, when an element contains multiple lap joints and lies on a non-planar surface, inserting the element during assembly requires special considerations of insertion angles and clearances in the design of each joint.

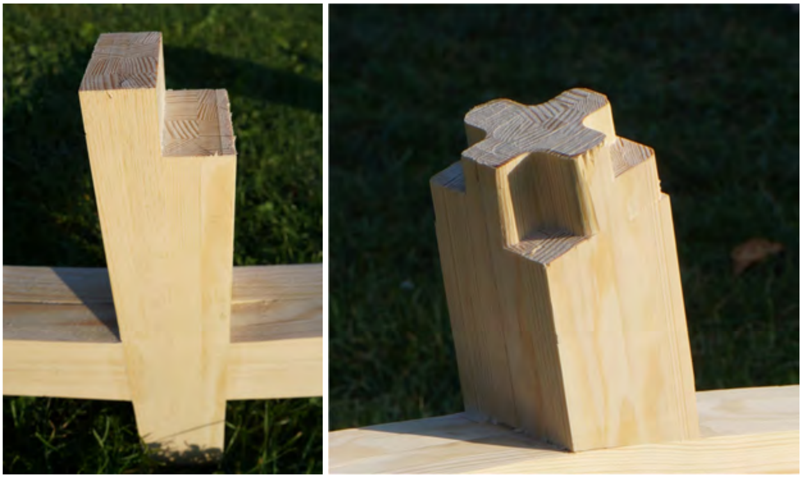
This blank proposes a method by which to overcome both issues by employing the principle of cross-lamination - borrowed from neighbouring wood products such as CLT or plywood - to create multi-directional glulam blanks and structural modules that only have end-to-end joints - avoiding crossing lap joints. At junctions where ordinarily a crossing lap joint would be used, the crossing glulam is instead interleaved with the main glulam. Lamellae are interleaved and ”woven” at oblique or perpendicular angles such as in the alternating wood layers in a CLT panel, in effect distributing a continuous grain orientation throughout the cross-section of

Fig. 5.15: Crossing lap joints require the removal of a large portion of the glulam cross-section.

the joined area (Fig. 5.17). This avoids the problem of having an abrupt fibre discontinuity where the crossing lap joint is cut out, and instead distributes this discontinuity over the whole cross-section. The advantage of this is that the fibre stays continuous along the outside surfaces of the blank, especially if the crossing arms are made one layer smaller on the top and the bottom. In simple bending cases, this continuity along the outer flanges means that fibre direction is aligned with the higher structural performance demands in those areas.

Because of the interleaving of lamellae and integration of crossing joints into the gluing of the blank, connecting multiple blanks together is done using only end-to-end connections, which contributes to an easier assembly strategy, as multiple crossing lap joints with different insertion angles can be avoided.

The main challenge with the Cross-laminated Joint Blank is the large amount of iteration between lamination and machining. The interleaving of the lamellae needs to be done for each layer and the precise alignment is paramount. This increases production time and assembly of the glulam blank. However, as a prototype for new timber morphologies, the Cross-laminated Joint Blank points to multi-ended glulam components that are optimized through an interleaved lamination (Fig. 5.18).



(a) An end-to-end lap joint on one of the branches.

(b) A tenon joint on another branch designed by the students.

Fig. 5.16: The Cross-laminated Joint Blank results in all joints being end-to-end connections since crossing members are integrated into the blank.

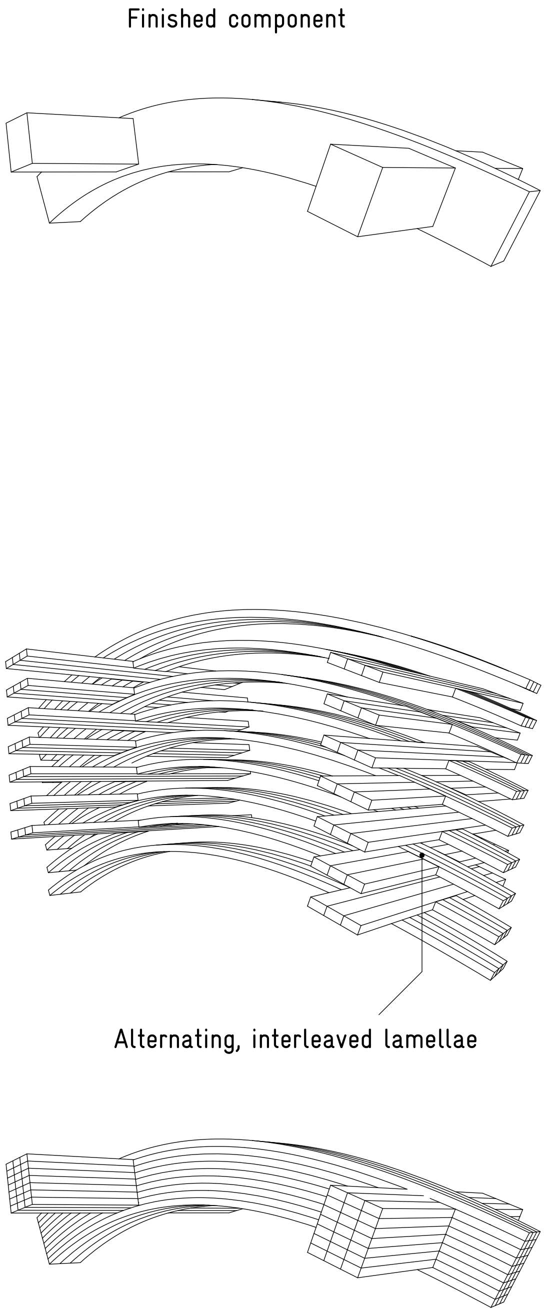
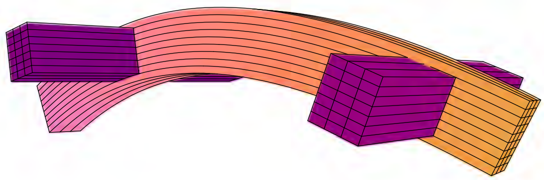


Fig. 5.17: The process of creating a Cross-laminated Joint Blank.

Fibre direction



Fibre deviation

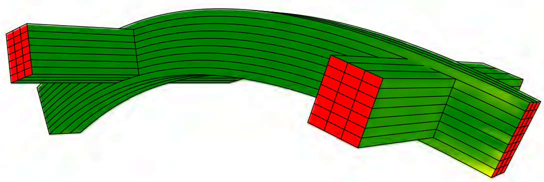


Fig. 5.18: The fibre analysis of the Cross-laminated Joint Blank.

Fig. 5.19: A physical prototype of the Branching Blank.

5.3.5 Branching Blank

The Branching Blank asks:

- Can notions of *splicing*, *peeling*, and *branching* be applied to the glulam blank instead of the joining of two glulam elements through traditional wood joints or mechanical fixings?

- Can a glulam component begin to occupy the design space between beam-like and panel-like geometries?

The Branching Blank takes its cue from the strategy of block gluing - laminating two prefabricated glulam elements together on site, commonly used in large-scale bridge construction - and cross-lamination to propose a bifurcating component.

It also challenges the typical beam-panel dichotomy by proposing a glulam element that is somewhere in between a beam and a panel. By integrating the splitting connection into the blank, assembly time and effort on site can be decreased. The Branching Blank is composed of two free-form glulam blanks that share one end and are interleaved with a cross-laminated layer, forming a 3-ended architectural element.

The main principle explored in this blank is the branching or bifurcation of a free-form glulam blank with continuous fibre along its length. Drawing inspiration from the branching and bifurcation of trees, and the intertwining of fibres at those critical junctions at the crotches of a branch or split, the blank includes a middle layer that runs perpendicular to the direction of the splitting members. The seam between two branches can become a point of critical stress, leading to large forces that try to split the seam. Since the fibres are aligned with the seam, this introduces splitting forces along the fibres which can easily lead to a failure along that seam. The cross-laminated layer counteracts this splitting by tying the branching arms together. The cross-laminated layer takes the splitting forces across its fibres, meaning it is much less susceptible to splitting.

In terms of production, the blank is composed of two free-form glulams that are glued together at one end, and iteratively built up to accommodate the cross-laminated central layer. In Probe 4: CITAstudio glulam workshop, form-work is made to attempt to glue both glulams and the cross-laminated layer at the same time. This proves to be extremely challenging, as two double-curved glulams have to be kept in shape and sufficiently clamped, while the middle layer also needs to be fixed and glued. The limited access on the inside of the branching also caused difficulties, as room for clamps decreases sharply towards the inside of the split.

The Branching Blank is used as a modular element in the design of Probe 5: Branching Probe and Prototype 2: Grove. A structure is formed by propagating the triple-ended Branching Blank across a mesh, with simple scarf joint connections between their ends.

Physical prototyping during these experiments uses a more complex MDF and steel form-work with a varying degree of success. The additional MDF form-work is wasteful and the issue of finding clamping access within the split leads to insufficient clamping distribution and resultant delamination. This approach also introduces an unwelcome constraint where the width of the joined end - the *trunk* - has to equal the sum of the width of both diverging ends - the *branches*. This presents difficulties in modelling the entire structures of Probe 5: Branching Probe and Prototype 2: Grove because changes to the width of one component have to be propagated and solved for all other interconnected components.

In Demonstrator: MBridge, the bottom section of the legs - where two columns meet the ground - and the top section of the legs - where the columns meet the rib structure - utilize the Branching Blank. In this case, a different approach is attempted: each branch is fabricated separately as a single element and joined together afterwards in another lamination step. This makes the production easier because the complexity of the whole module does not have to be addressed at once; each branch can be fabricated separately. The interface between the branches, where they merge into the trunk, is also considered differently: it is a machined surface which doesn't rely on the summing of the lamellae of the two branches. Instead of the integrated cross-laminated layer, a series of beech dowels are glued in between the merging branches in the trunk to provide this cross-bracing layer. Once again, this decouples the fabrication of each branch from the fabrication and assembly of the whole Branching Blank, and demonstrates the iterative lamination and machining process. The laminated and machined branches are used as inputs into a secondary lamination process - laminating the branches together, including the cross-bracing dowels - and subsequently a secondary machining process for the final joints in the trunk.

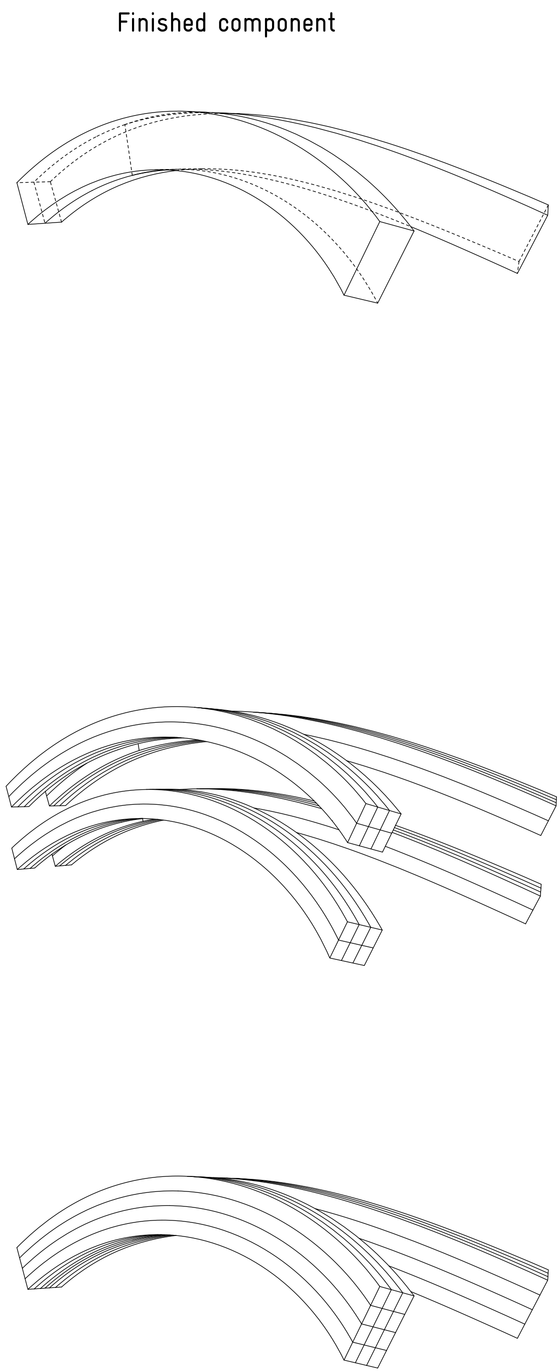
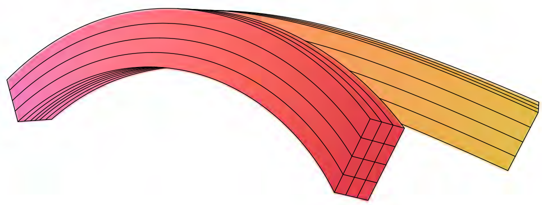


Fig. 5.20: The process of creating a Branching Blank.

Fibre direction



Fibre deviation

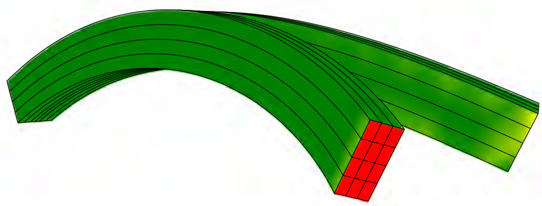


Fig. 5.21: The fibre analysis of the Branching Blank.

5.3.6 Kinky Blank

The Kinky Blank asks:

- How can the production complexity and material usage be reduced for curving elements with only local areas of high curvature or discontinuities?

Free-form or curved glulams typically require a continuous centreline curve. Kinks and sharp corners present discontinuities where the material physically would not be able to turn as sharply - especially kinks or corners, which represent abstract points of infinite curvature. The Kinky Blank proposes a different interpretation of centreline curves that contain kinks. The discontinuities caused by kinks are instead taken to be areas of lamella interleaving and cross-lamination, not bending. This means that, where a curve has a corner, this corner is composed of an overlapping section where alternating layers of lamellae follow the curve tangents on either side of the corner, similar to the way in which the Cross-laminated Joint Blank handles crossing lap joints. This is also expanded to tightly curved areas, where the extreme curvature would make paper-thin, continuous lamellae impractical. As in the Finger-joint Blank, the inflection points can be smoothed out afterwards during the machining of the final form.

Two built examples demonstrate a similar approach. The library in Hooke Park, Dorset, UK - designed and fabricated by the students of the Design Make course at the Architectural Association - is composed of large glue-laminated portal frames that are cross-laminated or interleaved at the corners. These corners are subsequently sculpted with a robotic band saw to their final geometry. The Jowat Loop by Urs-P. Twellmann, fabricated by *Blumer Lehmann AG*, also demonstrates this technique for its tightly curved corners, which are assembled out of large planks of cross-laminated wood and then machined back to their smooth final form (Fig. 5.22).

This method has three shortcomings focused on the inflection points: the larger amount of wood necessary to built up the inflection points, the lower structural strength due to the discontinuous fibre direction, and the large areas of exposed end-grain (Fig. 5.26). The first shortcoming has to be balanced between the ability to use larger lamellae which are less wasteful to produce in the first place while machining more wood volume for the final form, and the use of thinner lamellae who incur much more material waste in their production and planing but then don't require as much machining for their final form. The lower structural strength of the cross-laminated area of the blank has concerns for the engineering of structures that use this method, especially when the area is acting in bending as the fibre continuity is interrupted around a critical part of the glulam. The cross-laminating of the inflection points also exposes a large amount of end-grain, similar to the

Fig. 5.22: The Jowat Loop by Urs-P. Twellmann. Photo: Jowat Adhesives

Voxel Blank and Finger-joint Blank which, again, creates issues for durability if exposed to the elements.

This approach is used for the Prototype 4: Slussen benches proposal (Fig. 5.23). The main structure and envelope of the free-form benches are designed as an inflected timber surface. Where the surface folds sharply, this method of the cross-laminating the structure is proposed instead of bending extremely thin lamellae or veneers. To solve the issue of exposed end-grain at the cross-laminated inflection, a thin laminated timber skin is proposed that sheaths the surface, much like the flanges of the Voxel Blank (Fig. 5.24). Since the structural mass is taken up by the thicker timber layer and the cross-laminated folds, the thin skin does not have to be so thick and can use the underlying Kinky Blank as form-work. This presents other durability issues due to the thinness of the proposed skin such as cracking due to the hygroscopic expansion and contraction of the wood when placed in an extreme outdoor environment.

Fig. 5.23: The cross-laminated material prototype of Prototype 4: Slussen benches without the laminated skin.

Fig. 5.24: The cross-laminated material prototype of Prototype 4: Slussen benches with the laminated skin.

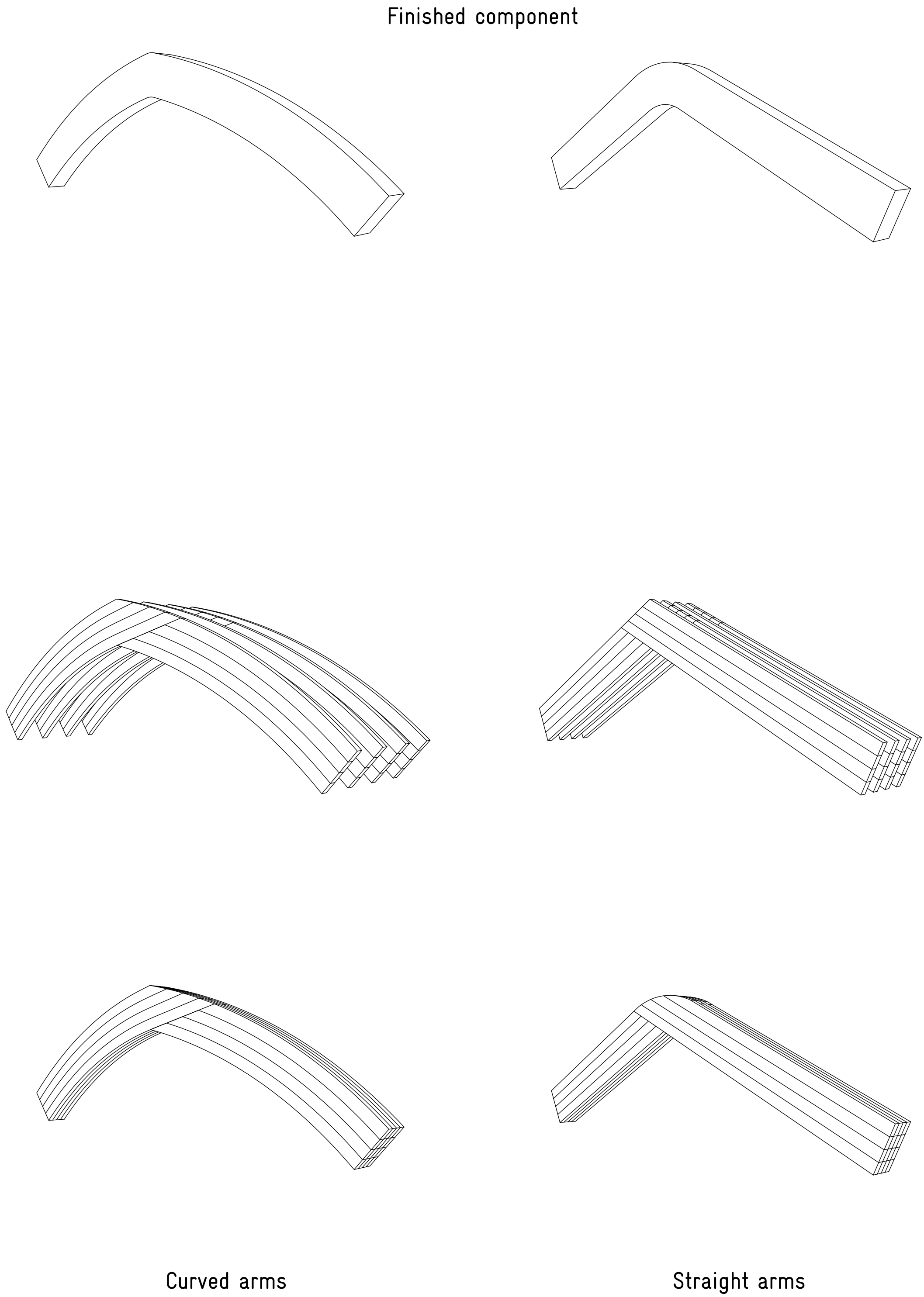


Fig. 5.25: The process of creating a Kinky Blank.

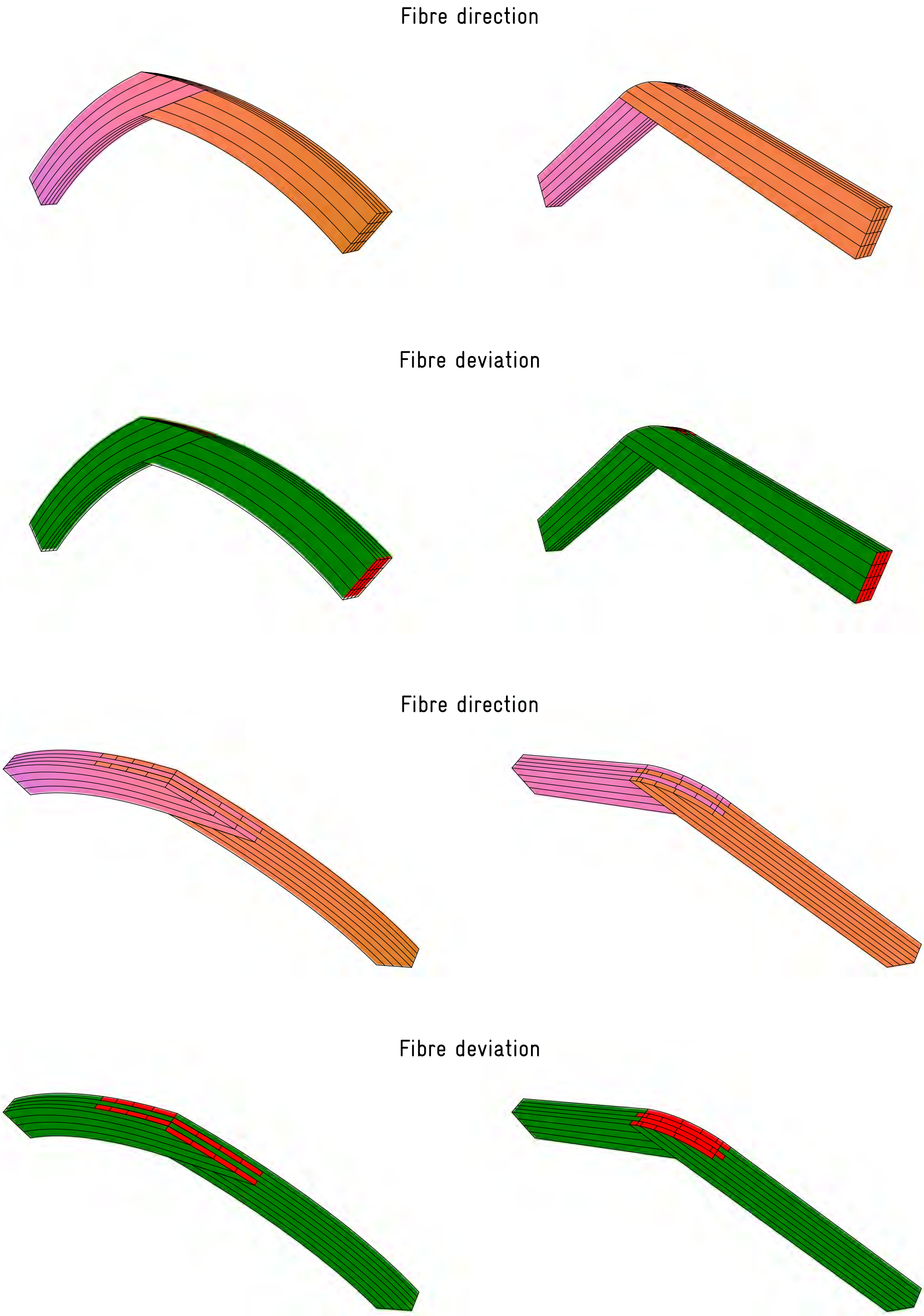


Fig. 5.26: The fibre analysis of the Kinky Blank.

5.4 Direct material feedback in a digital production environment

The secondary objective of the Probe 4: CITAstudio glulam workshop - apart from planning and fabricating the five speculative blank types - is to explore how the non-standard blank geometries are reconciled with the machining framework. As with single-curved and double-curved glulam blanks, the alignment of these speculative blanks with the coordinate system of the machining framework is not straightforward. Straight glulam blanks can be aligned orthogonally within the machining coordinate system using one of their straight edges and flat faces. Single-curved glulams can be aligned with one plane in the machining coordinate system due to their planarity. Double-curved glulams require the use of jigs or precise measurements at known locations to effectively align them to the machining space. Since the speculative glulam blanks present even more complex geometries that also diverge from the beam-like property of established glulam blanks, their positioning and orientation within the machining framework become even more of an important issue.

In Probe 4: CITAstudio glulam workshop, this challenge is first explored through the application of 3D scanning within the machining framework (Fig. 5.27). The coordinate system of the robotic arm is aligned with the coordinate system of a LiDAR scanner through common points of reference. Placing the physical prototypes within the machining volume and 3D scanning them therefore allows the fabrication model and machining data to be re-oriented and aligned with the material reality of the blank. This enables the accurate machining of surfaces and joints on non-standard glulam geometries. In Probe 4: CITAstudio glulam workshop, the fabrication data and tool paths are manually aligned to the resultant point cloud generated by the scanner. Measuring the distance from the surface of the model geometry and the point cloud records the discrepancy between model and material. Representing this measurement as intensity or colour gives direct visual feedback about how closely aligned the model is to the material.

This is further expanded into an exploration of how this *direct feedback* could be applied to the industrial machining framework at *Blumer Lehmann AG*. Deploying it in an industrial production context requires different considerations than in the experimental prototyping context: the scale is larger, there is more urgency in terms of time, and the relationship between the digital feedback technology and the machine operators needs to be taken into account.

The production of a free-form glulam structure at *Blumer Lehmann AG*

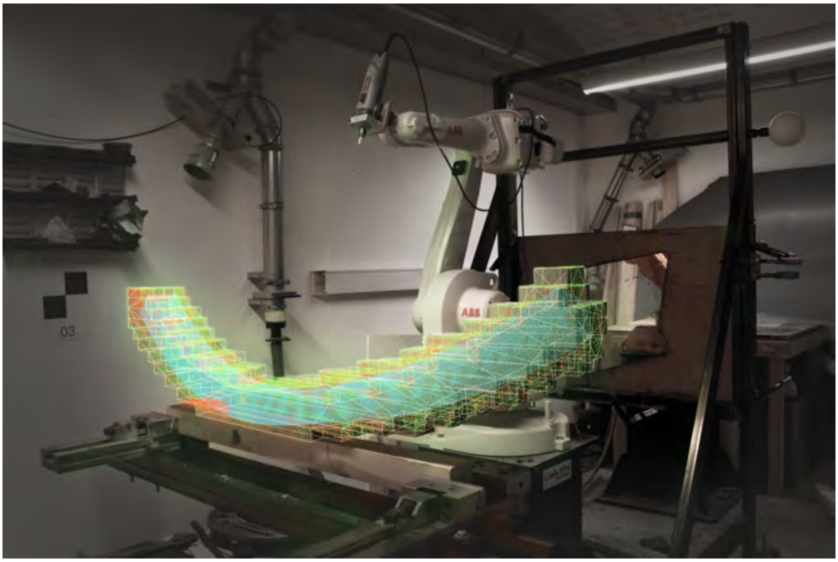


Fig. 5.27: The integration of 3D scanning in the glulam prototyping workflow in Probe 4: CITAstudio glulam workshop. The Voxel Blank is scanned so that it can be accurately machined. Image: Stian Vestly Holte, Luca Breseghello, Leonardo Castaman, Johan Lund Pedersen

presents similar challenges of aligning double-curved glulam beams with the machining framework (Fig. 5.28). These alignments are due to the dimensional variability of the glulam blank both because of production variations in the pressing framework as well as geometric variations caused by material behaviour (Fig. 5.29). Long beam members are particularly susceptible to the hygroscopic distortion of timber, since small variations across long lengths result in sizeable local deviations. These result in a loss of productivity and quality, and an increase in risk because of these uncertainties. Misalignments between the fabrication model and the glulam blank require additional time to take measurements and, in many cases, a series of ”best guesses” to shift the fabrication model or the glulam blank into the correct place. Previous efforts at *Blumer Lehmann AG* used a spindle-mounted contact probe to measure points on glulam blanks, however this is a slow process and involves the risk of breaking the probe since it has to physically touch the material for every sample. Developing optical and laser-based feedback techniques avoids these pitfalls.

Although the glulam blank is larger than the finished component, the tolerances are still small enough to necessitate a high precision of alignment: in most cases the blanks are larger than the component only by approximately ten millimetres on each side. This means that the alignment

(a) Tracing the production data on the material to measure the alignment deviation.

(b) Comparison of where the production data is (drawn green outline) versus where the material is.

Fig. 5.28: Free-form glulam blanks are difficult to align correctly with the production data, resulting in much time lost.

Fig. 5.29: The non-orientable free-form glulam blanks increase uncertainty and risk.

tolerance has to be within this safety tolerance. Increasing this tolerance results in a higher machining time because more material needs to be removed, and a corresponding increase in material usage in the production of the glulam blanks. The goal of the experiments during the secondment at *Blumer Lehmann AG* is therefore twofold: to explore methods by which this safety tolerance can be minimized through more accurate measurement methods that are integrated with the digital fabrication model, and, in parallel, to explore techniques that allow a quick visualization of any discrepancies between the glulam blank and the fabrication model.

This development comprises Prototype 3: Four methods of digital feedback, performed over the course of a three-month secondment at *Blumer Lehmann AG* during the production of the Omega Swatch Headquarters building by Shigeru Ban Architects. The experiments focus on the machining of glulam blanks into finished components but also find applications elsewhere in the industrial production environment.

5.4.1 Four methods of feedback in industrial timber production

The integration of direct material feedback into an industrial timber context requires the consideration of technical issues such as hardware interfacing and software development to create the necessary infrastructures to link the sensor data to the fabrication model as well as a strategy to minimize disruption to the active production process. Prototype 3: Four methods of digital feedback presents four types of direct feedback methods which use different technologies. The methods are organized in a succession that begins with the least complex and transformative method and ends with the most technologically complex one. This means that development begins with small changes to the machining framework that are incrementally expanded. Tests of each method are conducted during points in the production when the glulam blanks are being loaded or the machine is otherwise inactive. The incremental strategy of conducting the tests lets successful tests be retained and integrated into the production framework at *Blumer Lehmann AG* and unsuccessful tests can be easily rolled back. This minimizes disruptions to the production line and allows the research to be conducted in parallel to the production in a shadowing role.

5.4.2 Overview of the four methods

The four feedback methods thus begin with the mounting of a laser pointer in the machining spindle and conclude with the coordinated integration of LiDAR scanning in multiple areas of the factory:

- *Spindle-mounted laser pointer* employs a laser pointer to give quick and simple visual feedback to compare a tool path to the boundaries of the glulam blank.
- *Spindle-mounted rangefinder* exchanges the laser pointer for a laser rangefinder in a custom housing to measure precise points on the glulam blank and relay them to the digital fabrication model via a custom software interface.
- *Real-time optical motion tracking* uses a system commonly used in the film and VFX industries for capturing the real-time motion of many individual points to create a ”3D tape measure” that can be used within the machining framework as well as in other parts of the factory.
- *Terrestrial LiDAR scanning* generates high-density point-clouds of glulam blanks for alignment with the machining framework, for quality control after machining, and for quality control during the arrival of

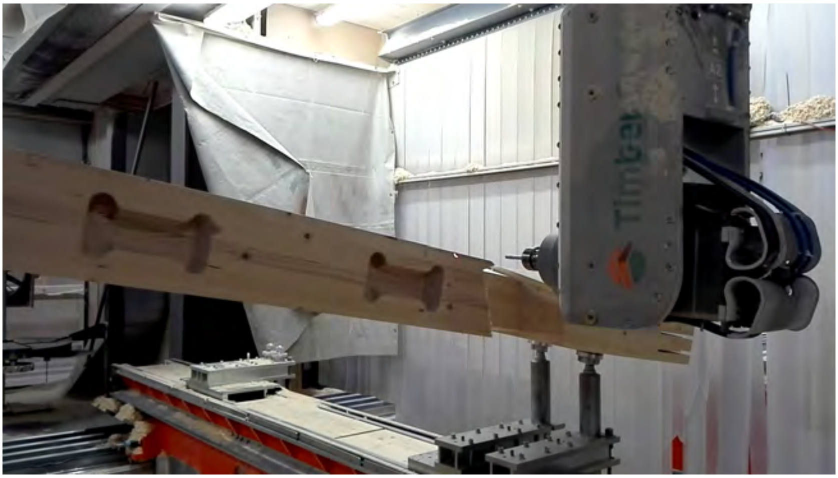


Fig. 5.30: The spindle-mounted laser pointer traces a pre-programmed path onto the glulam blank.

glulam blanks to the factory.

5.4.3 Spindle-mounted laser pointer

The first method is the simplest and fastest in terms of implementation. It consists of inserting an off-the-shelf laser pointer into one of the main spindles of the production mill at *Blumer Lehmann AG*. The purpose of this method is to arrive at a quick way to visually evaluate the alignment of the production data with the glulam blank before machining. This is to check that the positioning is correct and that the production data fits inside the glulam blank. The operator can see the projected laser beam on the glulam blank and verify that each point on the tool path is contained within it (Fig. 5.30).

Implementing the laser pointer is trivial: since it has a cylindrical chassis, it can be mounted directly into the spindle using a tool collet of appropriate size. Because the laser pointer is not made to any sort of industrial performance specifications, the alignment of the laser beam is not calibrated to the alignment of the plastic chassis, meaning the laser beam cannot be assumed to be linearly aligned with the axis of the spindle. This results in an offset from where the spindle is pointing and where the laser beam strikes the surface. This problem is solved by running the spindle at a slow speed so that the laser beam offset is rotated around the axis of the spindle. This traces a circle of light onto the material surface which changes diameter according to how far the spindle is from the surface. The centre of this circle lies on the spindle axis and can be approximately inferred by moving the spindle closer to the material.

To compare the production data with the glulam blank, two types of tool path are extracted from the fabrication model: one which traces the projection of the free-form blank onto the top and side planes of the glulam bounding box, and one which traces the edges of the final component on the glulam blank. Both give indications of whether or not the glulam blank is large enough to contain the model data, however tracing the final component is more useful: because of the margin of extra material on the glulam blank, the model data can fit inside the blank with some leeway for positioning. This means that, although the blank may not be precisely where it is supposed to be, the model data can still fit inside of it and can therefore be accurately machined. Both types of tool paths allow a useful estimation of the three-dimensional positioning and orientation of the production model within the mounted glulam blank.

This first method is the simplest because it uses the existing fabrication model data to create visual feedback for the machine operator.

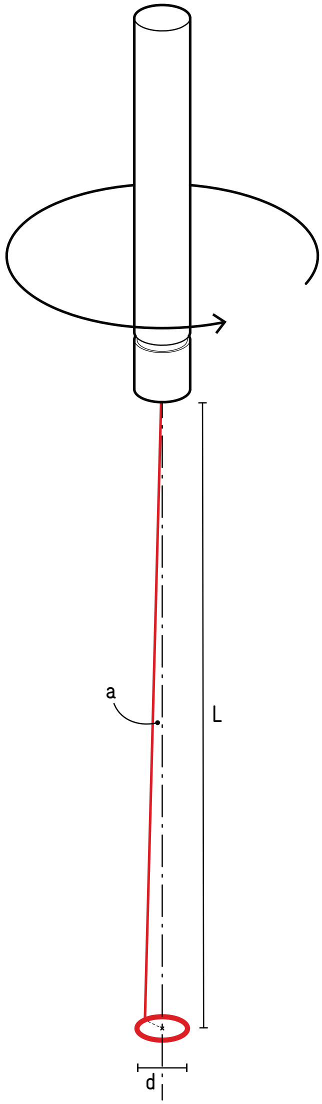


Fig. 5.31: Spinning the cylindrical laser pointer in the spindle traces a circle of light due to the angular imperfection (a) of the laser beam. The diameter of this circle (d) decreases as the distance to the material (L) is shortened.

Fig. 5.32: Prototyping a spindle-mounted laser scanner at Blumer Lehmann AG.

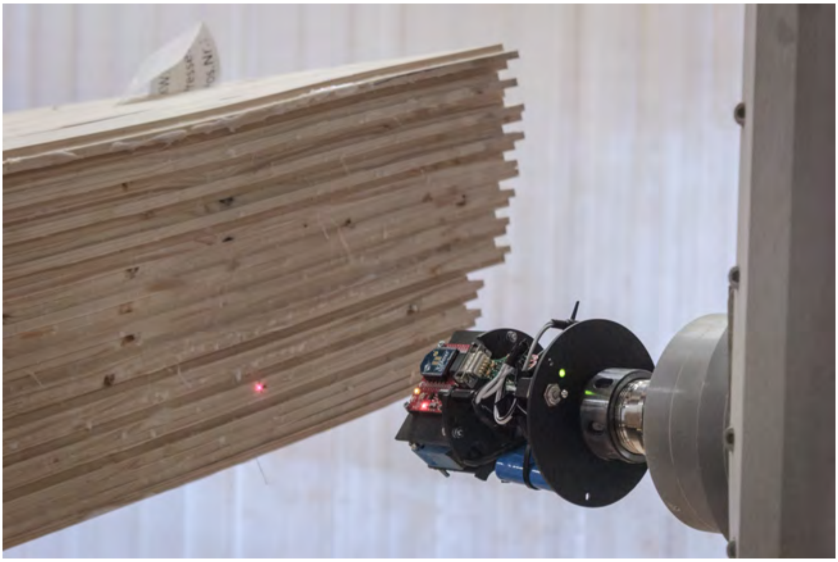
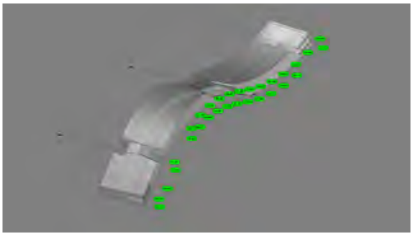


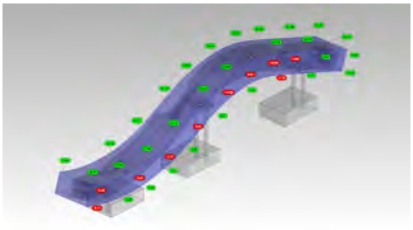
Fig. 5.33: Prototyping a spindle-mounted laser scanner at Blumer Lehmann AG.

5.4.4 Spindle-mounted rangefinder

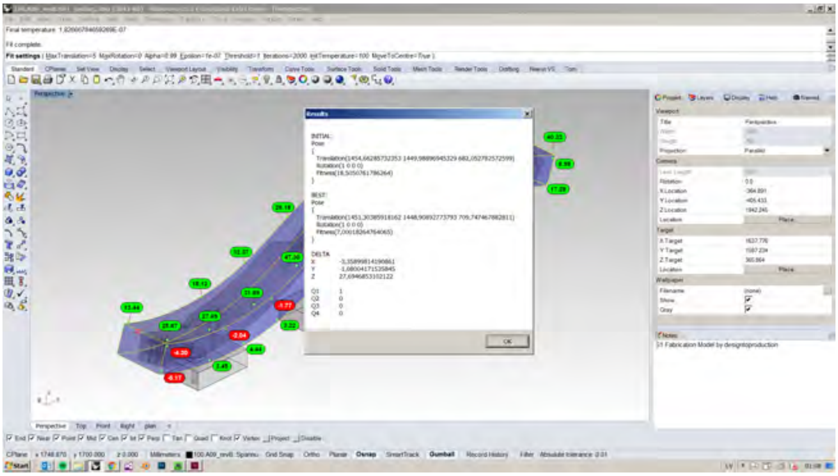
The second method builds upon the first method by exchanging the off-the-shelf laser pointer with a bespoke laser rangefinder and software interface. The rangefinder is equipped with a wireless module and is housed in a sturdy chassis that has an adjustable armature, enabling the calibration of the laser beam alignment with the spindle axis. The wireless module communicates with the operator's workstation to measure samples and respond to changes in the distance readings. The adjustable armature allows the rangefinder laser axis to be precisely aligned with the spindle axis, avoiding the need for spinning the device as before. Because the spindle's position is known, and the offset of the rangefinder from the spindle is measured, the distance reading can be translated into a 3D point within the coordinate system of the machine, down to the accuracy of the rangefinder - well within the tolerances of production and the surface relief of the glulam blank. The wireless communication avoids the need for any wiring from the rangefinder to the spindle and allows the operator's workstation to sit comfortably outside of the machining volume. The conversion from distance readings and machine coordinates to 3D points is done through a custom software interface and a script transfers these points to the Rhinoceros 3D modelling environment, which is also used by *Blumer Lehmann AG*. The gathering of numerical sample data moved beyond visual feedback into a more integrated digital feedback between material and model.



(a) Measured sensor samples from the rangefinder on the production model.



(b) Comparison of the sensor samples against the glulam blank model.

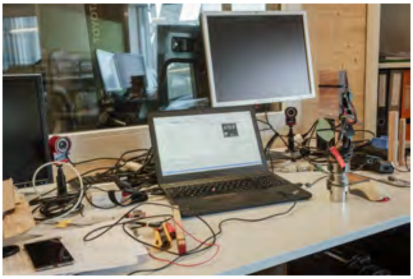


(c) The output of the fitting process is a transformation that creates a better fit between the production data and the sensor samples.

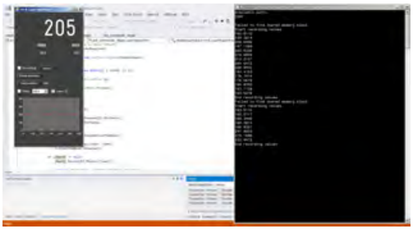
Fig. 5.34: The gathered point samples from the rangefinder are used to indicate the degree of variation between the fabrication model and the physical glulam blank.

The rangefinder itself is a SICK laser distance sensor housed in a 3D-printed ABS cover and mounted on a waterjet-cut and welded steel armature, itself fixed to a steel rod that is machined to fit in a standard tool collet. The steel armature also holds the XBee wireless module, a rechargeable Li-ion battery for powering the rangefinder and wireless module, an RS-485 to RS-232 serial converter for translating the signal from the rangefinder to the XBee module, an on-off switch, and an indicator LED to show when the device is powered on. The ABS cover prevents dust from affecting the electronics while remaining transparent to the wireless signal. The adjustable mounting plate for the rangefinder unit uses split rings and compressible rubber washers to finely adjust the alignment of the laser beam axis with the spindle axis. The steel frame and armature are fabricated in Copenhagen, the cover is 3D printed in Zurich.

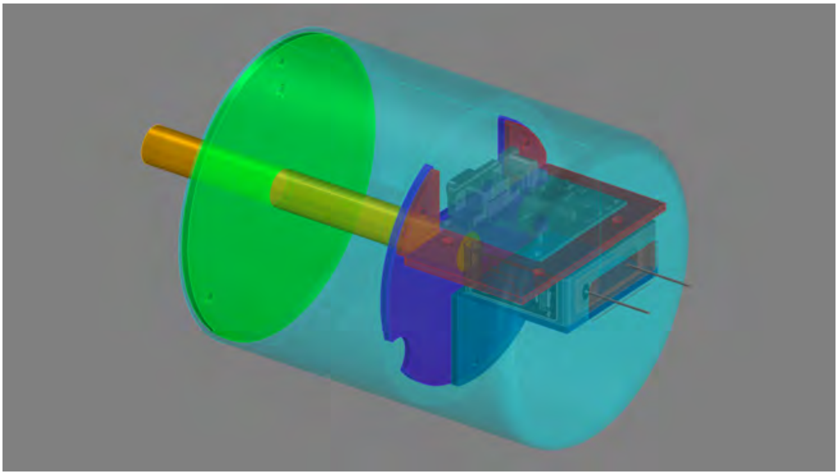
While the second method allows a clear, numerical sampling of material position throughout the machining volume - an improvement over the purely visual feedback in the first method - both methods are only employable when the glulam blank is already mounted on the carriers for machining, meaning time spent measuring is time taken away from production. If the glulam blank is found to be invalid or positioned inadequately, more time is lost unloading the defective blank and loading the next one. The next method therefore considers digital measurement off the machine and within the wider context of the factory.



(a) The workspace at Blumer-Lehmann AG.



(b) The software interface for communicating with the rangefinder wirelessly.



(c) The 3D model of the rangefinder assembly.

Fig. 5.35: Prototyping the rangefinder involves fabricating the hardware and programming the hardware-software interfaces.

Fig. 5.36: The OptiTrack system setup at *Blumer Lehmann AG*.

5.4.5 Real-time optical motion tracking

The third method employs equipment usually used in the visual effects and film industries, and the movement sciences. Real-time optical motion tracking uses a distributed array of cameras to detect reflective or high-contrast markers on a moving body. The cameras are calibrated so that their intrinsic parameters and poses relative to each other are known. This allows each detected ”blob” - the pixel cluster that represents the detected marker - to be triangulated by correlating corresponding marker blobs between the cameras. To capture the motion of humans or animals, markers are placed on actors’ bodies at key locations such as joints and extremities. This allows their movement to be captured and transferred to a 3D skeleton to drive animated characters or study their movement.

For this experiment, Naturalpoint’s OptiTrack system is used with a set of six Flex 13 cameras. These are setup in an area of the production hall at *Blumer Lehmann AG* that is used for storing glulam blanks awaiting machining. A plug-in is developed for Rhinoceros 3D that displays the detected markers as 3D points in the 3D viewport in real-time. This is done by using the NatNet SDK of the tracking system to harvest the real-time data from the cameras and convert them into points using the RhinoCommon API. Since this feeds real-time data into the display pipeline, it requires the implementation of display callbacks and mechanisms to prevent the user interface from lagging or slowing down. Once the real-time points are displayed in Rhino, they can

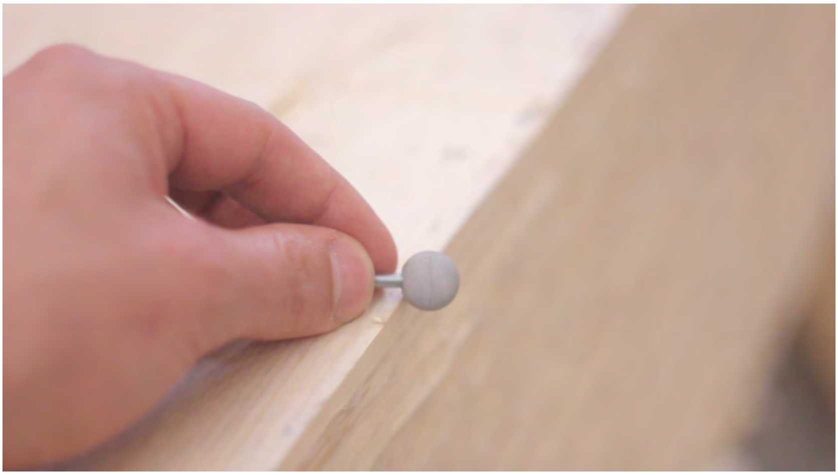
Fig. 5.37: The view from each of the OptiTrack cameras.

be "baked" or turned into fixed, static points, and measured.

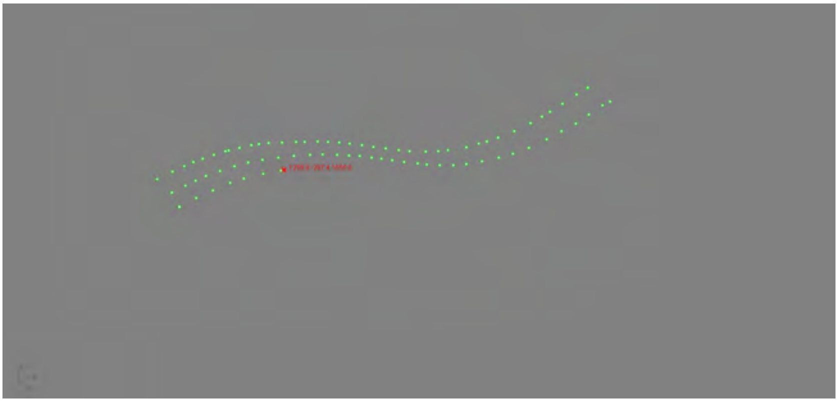
The primary benefit of this system is the ability to quickly and interactively measure multiple point samples at once, to a similar resolution and accuracy as the preceding method. The markers are used in two ways. The first is to distribute them over a glulam blank, much like point measurements are taken across the blank in the second method. This can be used to track the glulam blank through the space of the production hall, and make its alignment with the carriers during loading more precise. Also, much like the previous method, the constellation of marker points can be used to optimize the alignment of the glulam blank with the fabrication model, or vice versa. The problem with this is that the markers need to be physically fixed onto the blank, which means that they may be destroyed during machining. Another issue is that the coordinate system of the camera system needs to be aligned with the coordinate system of the production mill - an added layer of calibration and potential source of error. A future solution to this would be to place tracking markers on the machine spindle as well, meaning that the precise location and orientation of the spindle can be tracked within the same coordinate system as the markers on the glulam blank.

The second way in which the tracking markers are used is as a "3D tape measure". Once again, one of the challenges with free-form glulams is that they do not have clear geometry, therefore it is difficult to obtain precise dimensions with traditional means. A single marker can be handheld by the operator and touched to various points of interest. While holding the marker to the point of interest, the point is baked in Rhino. Thus, by measuring multiple points across the glulam, fast and accurate 3D measurements can be taken. The benefit of this technique is that it brings in a haptic dimension to the digital sensing, and is therefore more intuitive to understand and use.

An added advantage of this method over the first two is its ability to be used both within the machining volume as well as within the wider factory space. While the two previous methods rely on the machine spindle and the machine coordinate system, the camera system can be setup throughout the whole production hall, implying a future prospect where elements of the entire production hall are monitored and tracked in real-time. The mobility of this setup means that it can be applied to other processes: to measure blanks that have just arrived at the factory to ensure that they comply with the fabrication data before they are loaded, blanks that are being loaded onto the carriers for machining to precisely align their position and orientation, and finished glulam components that are leaving the factory to verify dimensional accuracy.



(a) A hand-held reflective marker is held against the glulam blank.



(b) The marker is tracked in the Rhinoceros 3D environment by the OptiTrack system.

Fig. 5.38: The real-time tracking of discrete markers using the OptiTrack system.

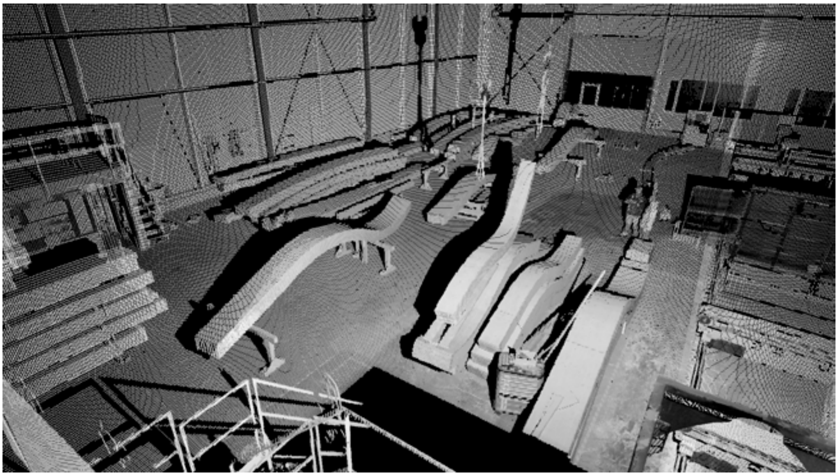


Fig. 5.39: A LiDAR scan of the production environment at *Blumer Lehmann AG* yields a detailed but heavy point-cloud dataset.

5.4.6 Terrestrial LiDAR scanning

The last method explores at *Blumer Lehmann AG* is the integration of 3D LiDAR scanning in the fabrication environment. Terrestrial LiDAR scanning is a form of laser scanning which captures entire environments in the form of high-resolution point-cloud datasets, often to a resolution below a millimetre. This method uses the same Faro Focus 3D scanner used in the initial scanning exploration in Probe 4: CITAstudio glulam workshop due to its familiarity and portability. This scanner is capable of measuring individual points up to a range of about 150 metres, with a variable accuracy depending on the distance of the sample - typically a few millimetres at long ranges, but within a millimetre for close ranges. Compared to the data collected using the previous three methods, this method can generate tens or even hundreds of millions of points per scan. This large volume of data creates a redundancy of information that can be both beneficial and challenging due its technical nature and large data storage requirements. Such large datasets require selective filtering, interpretation, and extraction of useful data which makes their usage a much more specialist and technical task.

In this method, the 3D scanning is used throughout the factory for a multitude of applications: for glulam blanks that have arrived from the glulam factory, for glulam blanks in the staging area where they are prepared and mounted for machining, and within the production area where they are aligned with the fabrication model. Scanning in the staging area is used for the same reason as the real-time motion tracking system: for quality

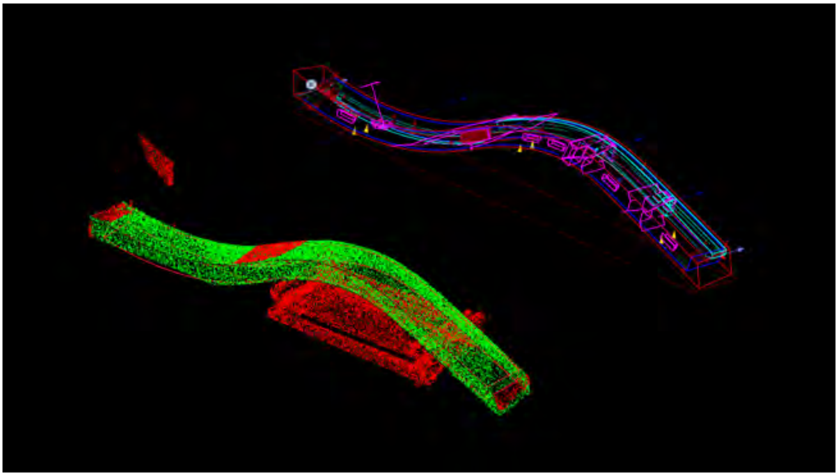


Fig. 5.40: The production model (right) is compared to the point cloud (left).

control of the incoming glulam blanks and for verifying whether or not the glulam blanks are appropriate for the production geometry that is meant to be machined out of them. The larger amount of point samples and the lack of tracking markers mean that this process yields a more complete and finer-grained image of the scanned glulam blank. This allows the registration algorithms to use more point samples to generate a more complete and robust fit between the production data and the glulam blank (Fig. 5.40). During the pre-machining stage when the glulam blank is mounted on the machining carriers, the 3D scanning is used again to align the production data with the material. As with the previous method, this requires that the coordinate system of the scanner is aligned with the coordinate system of the machining workspace.

This alignment can be accomplished in three ways: setting up static registration targets within the machining volume to align the scans to, using a "master scan" of the machining volume and aligning subsequent scans to that, or mounting the scanner in a fixed and known location in the factory, relative to the production mill. All of these ways require a calibration step in the beginning: to determine the spatial relationship between the registration targets and the machine coordinate system, to align the master scan with the machine coordinate system, and to determine the spatial relationship between the static scanner and the machine coordinate system. The first two ways have the advantage of allowing the scanner to be moved around the factory as necessary to achieve the best scan coverage for any particular glulam blank, as long as they remain in sight of the static registration targets or overlap the master scan well enough to be confidently aligned. The static scanner, once calibrated, involves the least amount of subsequent

Fig. 5.41: The Faro Focus 3D LiDAR scanner in the *Blumer Lehmann AG* production environment.

processing work, as the transformation between the gathered data and the machining volume is already known.

This method is the least intuitive and most technically complex of the four, however it also offers the most potential in extracting useful and complete information from the production environment, alongside the potential of the third method to capture real-time tool and deformation data. This method is employed further in the production of Demonstrator: MBridge where it is used to position and calibrate the glulam blanks into the machine coordinate system and verify their geometry.

5.4.7 Finding the blank

The gathered measurements are used in two ways: to document the fabrication process and to find a best-fit position and orientation of the production model that aligns it with the material. Documenting the fabrication process with discrete point samples means that discrepancies can be tracked and analysed for patterns or trends across multiple glulam blanks.

The alignment of the production model to the sampled point data is tested with several iterative algorithms that seek the best pose - position and orientation - of the fabrication model of the glulam blank by attempting to minimize the distance between the point samples and the surface of the glulam blank model (Fig. 5.42). Preference is given to keeping the point samples on the outside of the model, as this ensures that there is more available material rather than less.

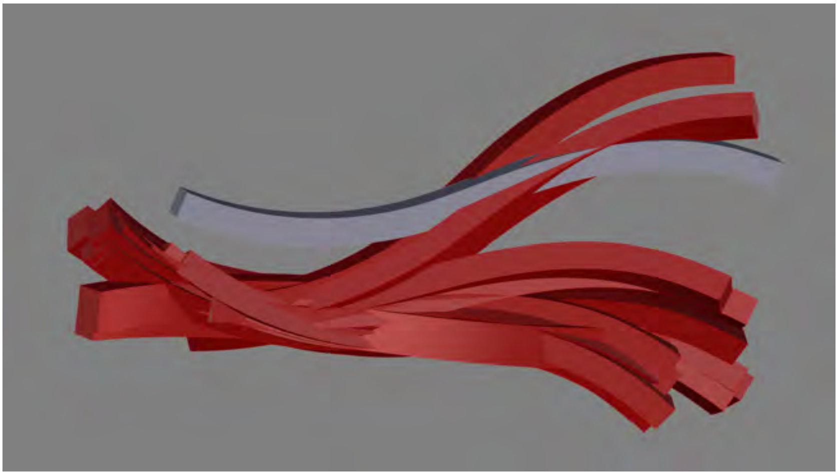


Fig. 5.42: Showing the many iterations of alignment as the algorithm converges on an acceptable solution.

The main algorithms used to this effect are a basic adaptation of the iterative closest point (ICP) algorithm from the Point Cloud Library (PCL) (Rusu and Cousins 2011), a basic implementation of the Metropolis-Hastings algorithm (MH), and a basic implementation of the Simulated Annealing (SA) algorithm. The PCL version of the ICP algorithm is implemented as a wrapped C++ library, called from a C# wrapper, while the other two algorithms are implemented in C# for compatibility with the RhinoCommon API. The MH and SA algorithms allow position and orientation to be treated separately, as this can help to shorten the running times and sometimes even results in a better alignment outcome. Position is encoded as a normal three-dimensional vector; orientation as a quaternion. Variations in orientation are given by perturbing the orientation quaternion.

Each algorithm works in a similar way: the initial starting pose of the glulam blank is perturbed and the new pose is evaluated against the fitting criteria - in this case, the minimization of the distance from the measured samples to the bounding surface of the glulam blank model. If it is an improvement, the new pose is accepted and the process iterates; if it is not, then the process iterates using the initial pose. This results in an iterative search through a multi-dimensional space until some stopping criteria is met: either a maximum number of iterations or a acceptability threshold below which the algorithm stops.

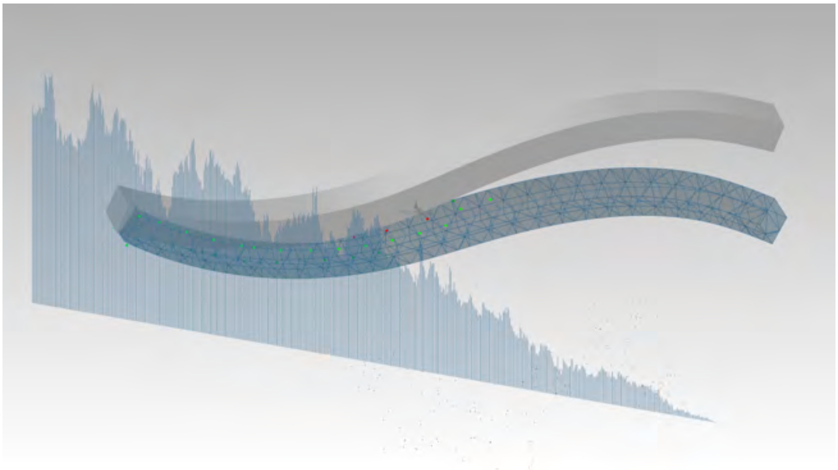


Fig. 5.43: The registration process attempts to minimize the distance between the sampled points (green and red) and the model of the glulam blank. The background graph shows the decrease of the sum of the distances over time (left to right).

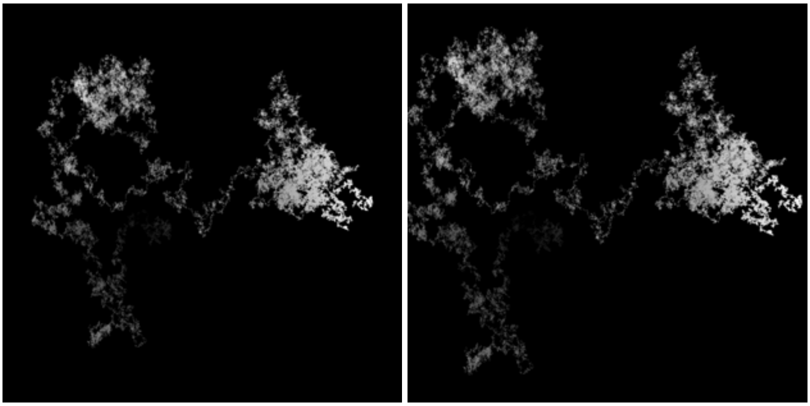


Fig. 5.44: A visualization of the progress of a registration algorithm. Each point is a possible solution, and the brightness of each point represents how fit the solution is. The meandering path of the solutions is made visible as the algorithm seeks better solutions.

5.5 Summary

The work described in this chapter - the domain of materialization - demonstrates how an engagement and challenging of a constellation of timber production processes expand the space of design into the realm of the glulam blank, and how a feedback link between processes of materialization and the digital model can be established through the integration of digital sensor systems - a synchronized awareness between model and material. These two outcomes form the notion of *process feedback* and *direct feedback* respectively.

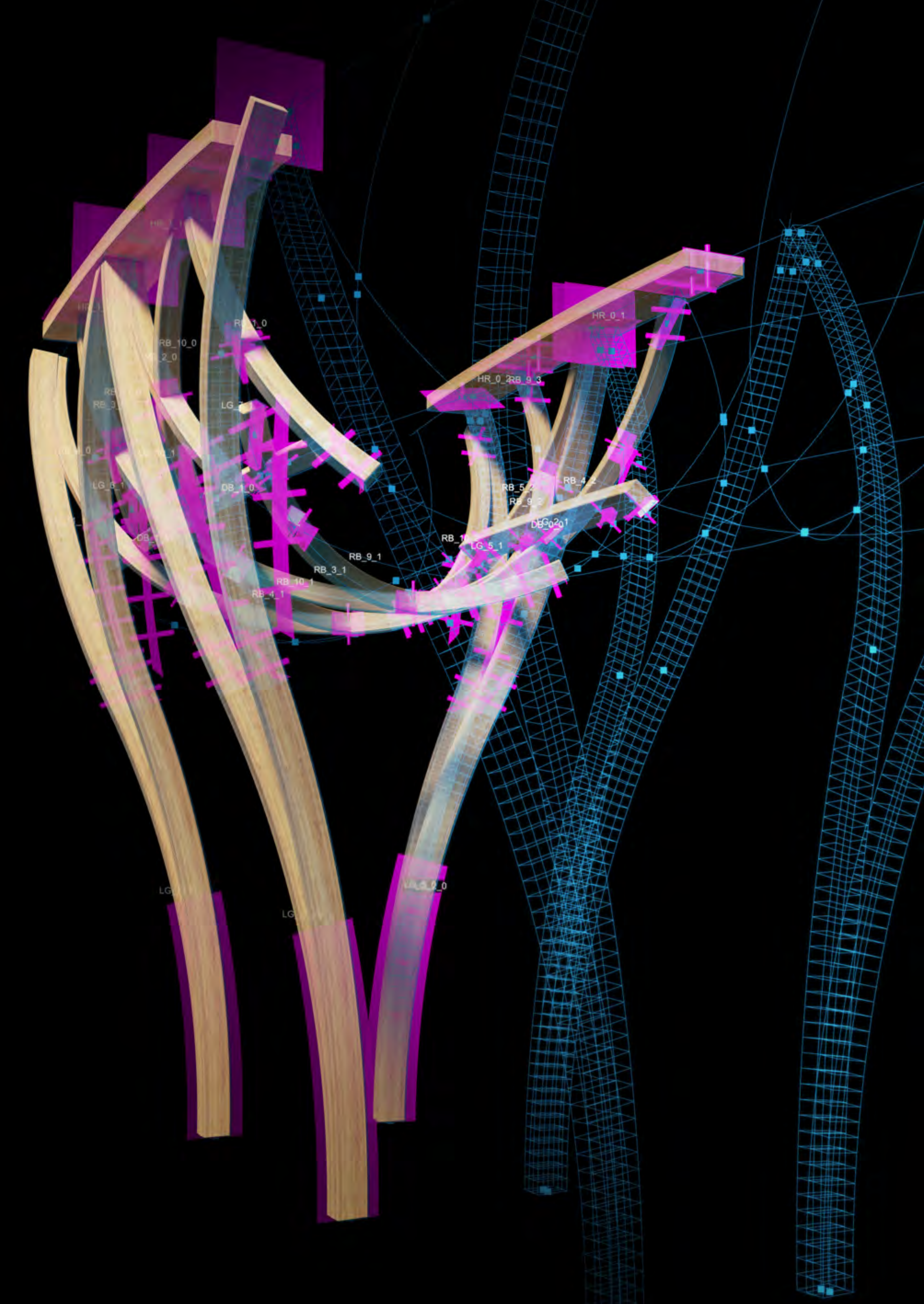
The speculative glulam blanks are prototyped and deployed in further projects: the Kinky Blank finds an application in the free-form timber benches in Prototype 4: Slussen benches and the Branching Blank is the design driver for Probe 5: Branching Probe and Prototype 2: Grove, while also appearing in a modified form in Demonstrator: MBridge. The implementation of these new timber morphologies comes from a haptic introduction to the principles of glue-lamination and bending as well as an overview of the various process steps in glulam manufacturing.

Integrating the higher geometric complexity that results into multi-axis production workflows is demonstrated through the digital sensing experiments. These show that, in order to confront morphologically novel timber components, the domains of modelling and materializing need to be synchronized throughout the whole production process.

Altogether, the work here presented establishes the design domain of the new material practice as well as the digital link that relates it to the computational foundation described in the previous chapter. How both of these are further intertwined and deployed is demonstrated in the next chapter - the domain of design implementation - which concludes with the integrated computational modelling, physical prototyping, and material-model synchronization in the production of Demonstrator: MBridge.

6

DESIGN IMPLEMENTATION



RB_10_0
HR_0_1
HR_0_2
RB_9_3
LG_3_1
DB_1_0
RB_5_2
RB_4_2
RB_9_2
LG_5_1
RB_9_1
RB_3_1
RB_10_1
RB_4_1

6.1 Overview

The previous two chapters explore the domain of glue-laminated timber modelling and the domain of glue-laminated timber materialization through the lens of digital tools, computation, and physical prototyping. Both introduce notions of cyclical thinking: the computational models seek to link together the various scales necessary to translate material behaviour from a local property into an architectural design opportunity while the speculative glulam blanks introduce iterative processing techniques, and the digital feedback experiments enable a tighter link between material and model through digital sensing. This chapter discusses how these two domains are brought together into architectural experiments and design propositions to form a new material practice.

This chapter describes several projects that move beyond being simple prototypes or experiments into being larger demonstrations of technique with an overarching design intent. Architectural concerns such as structure, space, and function are design drivers, and the models and prototypical production methods are used as methods to enact and deliver on these. In effect, these architectural propositions are developed as a series of inquiries about what an integrated material practice with glue-laminated timber looks like, when it is augmented by the previously established forms of feedback.

The first design project - Probe 3: Future Wood workshop - is a playful exploration of the speculative design space opened up by large-scale glulam structures and the emerging glulam blank modelling tools.

The the next two design projects - Probe 5: Branching Probe, Prototype 2: Grove - bring the computational and prototyping experiments from the last two chapters into an architectural context and serve as platforms for fleshing out their architectural applications and feasibility. These demonstrate an integrative approach, where the design, modelling, and prototyping of the projects is holistically managed and executed. They also seek to broaden the scope of the research by collaborating with other research projects within the InnoChain network and responding to an external design brief. The Prototype 4: Slussen benches and Prototype 5: Magelungen Park Bridge projects further contextualize the developed tools and methods within a broader design environment. These are collaborations with the industry partners and integrate the research into a multi-disciplinary architectural practice setting. They require a negotiation between a wider range of stakeholders, parameters, and partners. Here the transfer of knowledge between the two preceding domains through models, physical prototypes, and principles of timber behaviour and processing constitute a *brokering feedback* which shifts the project development to more integrated and materially-aware timber proposals at the early design stages.

The last project - Demonstrator: MBridge - synthesizes the integrative approach and Prototype 5: Magelungen Park Bridge by focusing on the material potential of free-form glulam, using Prototype 5: Magelungen Park Bridge project as a foundation. This creates a divergence of Prototype 5: Magelungen Park Bridge into two tracks: the *practice track* which is developed further at *White Arkitekter* and rationalizes and constrains some of the complex geometry, and the *research track*. The research track avoids rationalizations due to cost or fabrication complexity, and instead pushes the limit of material capacity and integrates the computational design tools, the glulam prototyping, and the direct feedback in glulam production into a holistic demonstration of a digitally-augmented material practice in free-form timber structures.

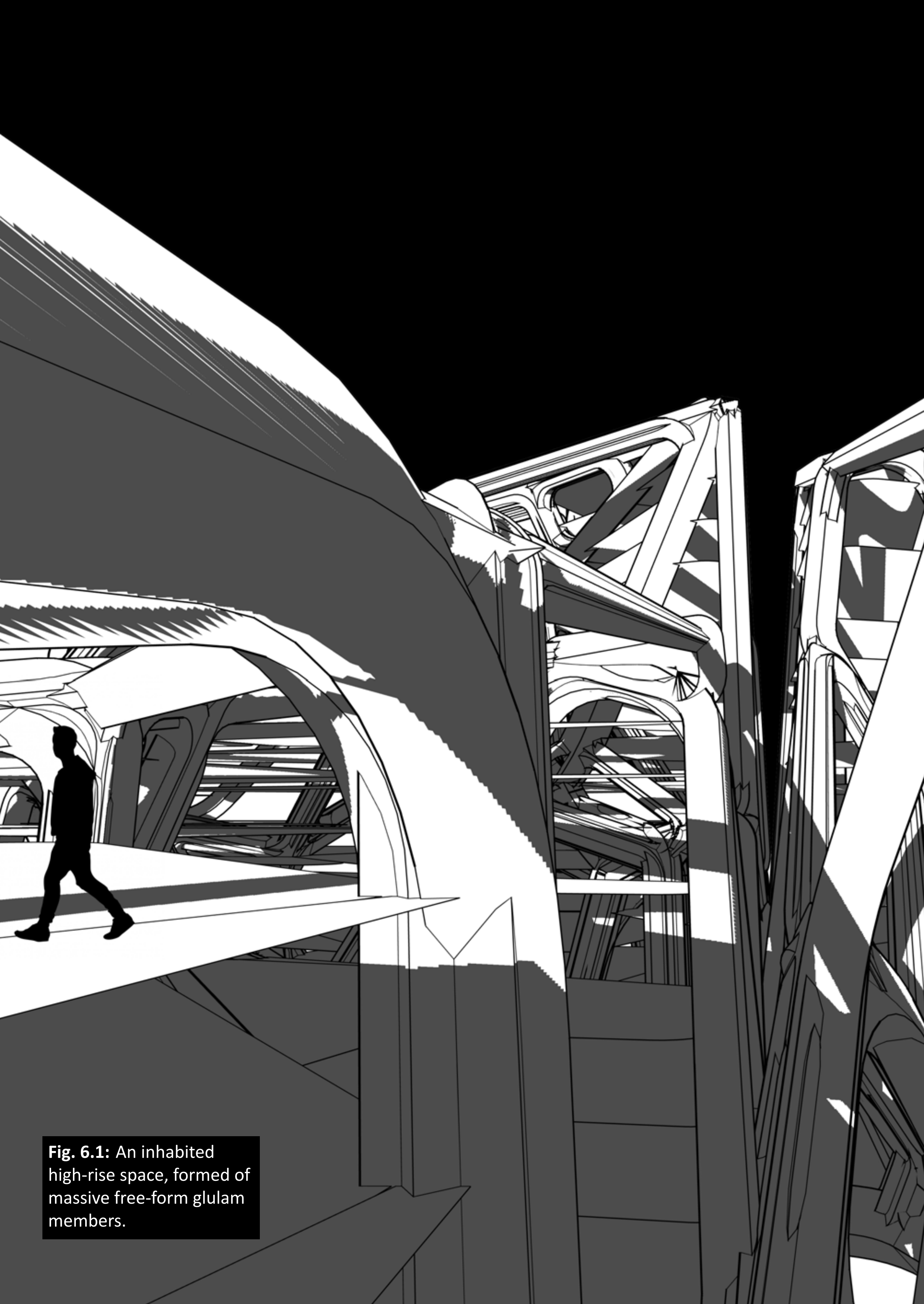


Fig. 6.1: An inhabited high-rise space, formed of massive free-form glulam members.

6.2 Exploratory spaces

The domain of design implementation focuses on how the preceding domains of modelling and materialization are applied to architectural design schemes. Much like the preceding domains, it begins with a speculative and intuitive exploration of the subject matter and a visionary outlook on what large-scale, free-form timber architecture could be. This is therefore an open-ended probing of the design space of glulam structures, which seeks to move away from existing glulam structures and wonder about what other forms could timber architecture take.

The Probe 3: Future Wood workshop is an InnoChain training course that brings together early-stage researchers (ESRs) from the Communicating Design work package. It is an opportunity to investigate the architectural consequences of each research project, develop new collaborations, and speculate about the visionary applications of the research at larger scales. For this project, it provides a useful platform to bring the first modelling experiments from Probe 2: IBT glulam workshop and Prototype 1: Glulam blank model into an architectural context and begin the dialogue between material experimentation and architectural design proposals that incorporate a site, context, and programme. The work that develops over the three-day workshop is a collaboration with Paul Poinet (ESR 6) and Kasper Ax (ESR 14) from the InnoChain network.

The work in this workshop focuses on the spatial qualities and possible architectural morphologies that could come about by using only free-form - single- and double-curved - glulams at a very large scale. This is to counteract the prior small-scale material investigations that hide some of the spatial potential of glue-laminated timber assemblies, and to begin to engage with the potential for inhabitation. The design follows a couple of simple rules: it employs only curved glulams; it attempts to avoid standard glulam connections by instead using the bending of glulams to peel, splice, and branch glulam elements; and it stays away from the grid- and lattice-based structural morphologies - exemplified by projects such as the Centre Pompidou-Metz and Solemar Baths - and instead explores volumetric structures more akin to space frames.

Fig. 6.2: Exploring the spatial qualities of large-scale glulam spaces with light and material.

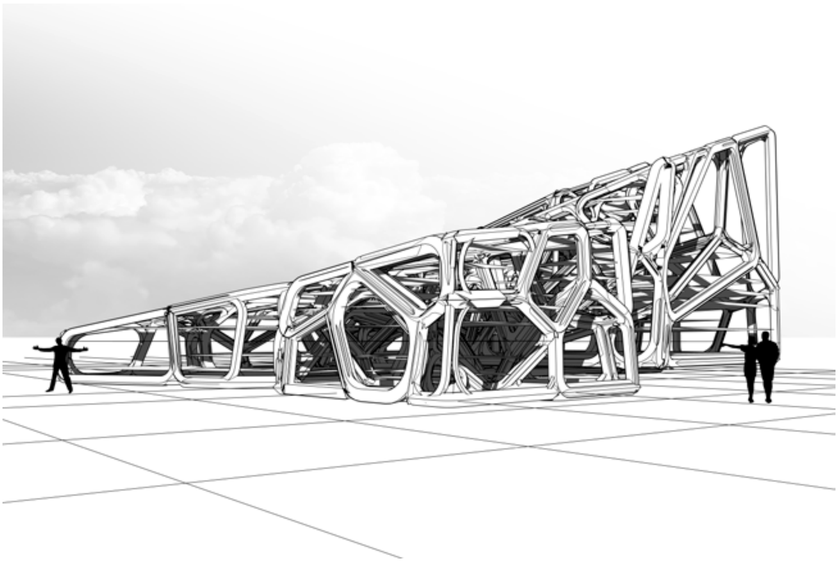


Fig. 6.3: A speculative free-form building proposal, exploring the formal possibilities of joined timber frames.

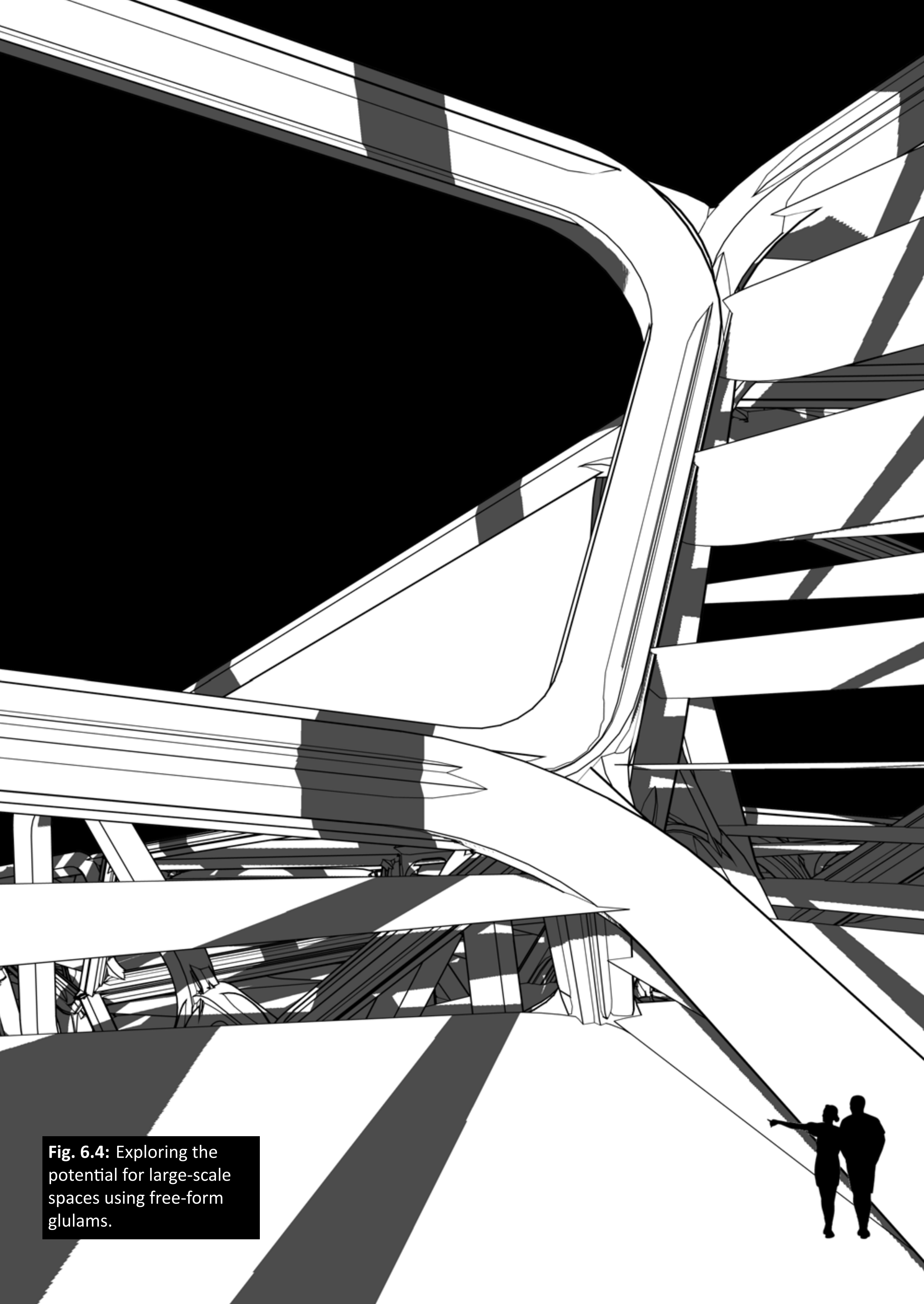


Fig. 6.4: Exploring the potential for large-scale spaces using free-form glulams.

Fig. 6.5: Aggregating free-form glulam members through architectural notions of splicing, peeling, and bending.

The workshop results in a series of drawings that illustrate structures and spaces that follow these rules. The insertion of figures for a sense of scale changes the perception of the glulam elements from the small components explored in Probe 2: IBT glulam workshop to more urban and architectural girders. This recasts their role from being glulam objects that investigate production processes to spatial devices capable of defining notions of enclosure, frame, and structure.

Fig. 6.6: Exploring branching and peeling strategies in architectural propositions.

6.3 From components to structures

This shift of the physical glulam prototypes - such as those in Probe 2: IBT glulam workshop and Probe 4: CITAstudio glulam workshop - as well as the development of the glulam blank modelling library - encompassing the developments in Probe 1: Modelling wood properties and Prototype 1: Glulam blank model - to their spatial implications addresses new issues of connectivity, programme, and the structural morphologies suggested by both the computational modelling and physical experimentation. By deploying the tools and processes developed in the prior domains in a collaborative effort with other research partners and design briefs, a particular, glulam-centric design practice begins to emerge.

6.3.1 Branching Probe

The Probe 5: Branching Probe is an effort to consolidate the material output of Probe 4: CITAstudio glulam workshop into a buildable architectural proposition. It draws on the formal language and design logic first explored in Probe 3: Future Wood workshop by proposing a structure that is only composed of free-form glulam elements with end-to-end splice connections, and a volumetric distribution of elements - keeping a distance from single-surface-based lattice structures. The Branching Blank from Probe 4: CITAstudio glulam workshop - with its architectural notion of peeling and branching - is taken as a structural module and ”building block” for the design (Fig. 6.6).

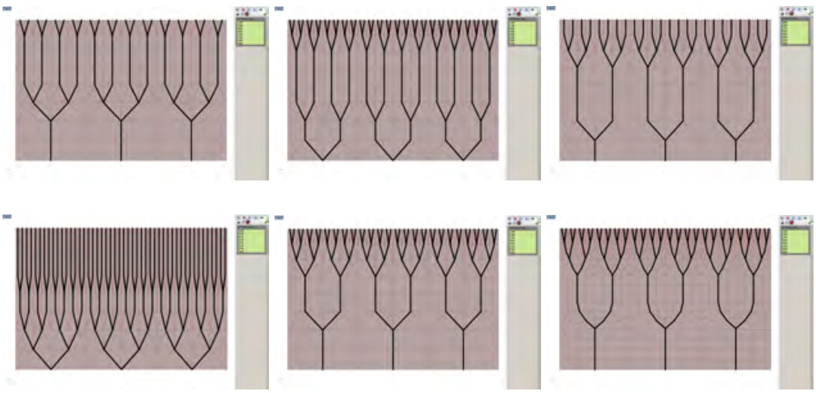
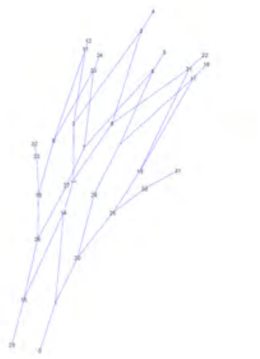
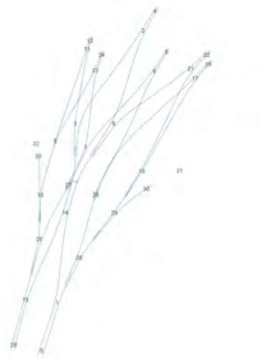


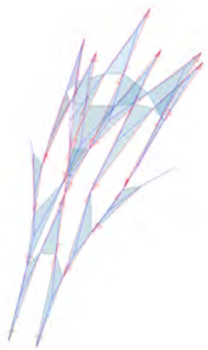
Fig. 6.7: Evolution of the branching pattern. Image: Paul Poinet



(a) The original mesh-based graph model.



(b) Generating smooth centreline curves with offsets for the branching modules.



(c) Deriving the branching modules.

(d) Dimensioned glulam blank models including overlaps for cutting joints.

(e) Solid models of each module.

Fig. 6.8: The process of turning mesh-based spatial graph into a production model for the demonstrator.

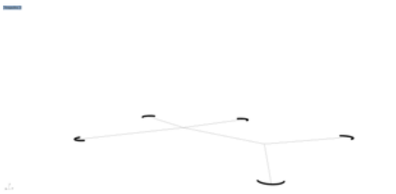
Collaborative research

The exploration of the Branching Blank as a structural module and spatial device therefore necessitates a method of modelling its assembly into a greater whole and re-examining its individual instances need to change in response to larger-scale design moves. This introduces the collaboration with the multi-scalar modelling research developed by CITA colleague Paul Poinet (InnoChain ESR 2). The multi-scalar and graph-based developments from that research are integrated with the early development of the glulam blank model in Prototype 1: Glulam blank model as well as the production parameters derived from the Branching Blank's prototyping in Probe 4: CITAstudio glulam workshop. The combination of multi-scalar modelling concepts with the glulam blank model constitute a modelling architecture or workflow that embodies ideas of multi-scalar modelling from the overall design strategy down to the individual fabrication of components. This is organized as a set of interconnected models shared between the researchers that each addresses the micro-, meso-, and macro-scales. In this instance, however, the micro-scale is not one of timber fibre and material orientation but rather the details and data of fabrication, such as tool path strategies and the constraints of the machining framework.

In this way, shortcomings in the glulam blank model that pose barriers for design exchanges and fabrication feedback are identified and earmarked for further development. Similarly, the solution space of the Branching Blank is explored through a larger variety of overall design elements that reveal its limitations. For example, prototyping the Branching Blank in Probe 4: CITAstudio glulam workshop reveals the challenges of a particular instance, whereas within Probe 5: Branching Probe variations that increase or decrease its production complexity are represented.

Design of the Branching Probe

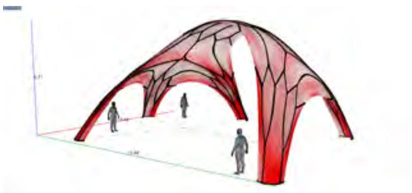
The demonstrator is conceived as a vaulted structure with a number of foot conditions. The Branching Blank modules provide a way for these foot conditions - comprised of thick cross-sections - to dissolve into a lighter canopy of thinner elements. A branching pattern is designed and imposed at the global level to allow this logic of branching and dissolving to propagate across the vaulted surface. This branching pattern is represented as a undirected graph based on a coarse *driver mesh*. The graph guides the design by giving minimal yet important data about the spatial orientation and location of each structural member and the connectivity relationships between them. Such a lightweight representation allows analyses of the design topology and configuration through the driver mesh, as well as the application of simulation tools on the mesh itself. Dynamic relaxation techniques are deployed to shape the driver mesh into an inverse catenary



(a) Foot points are established on the site.

(b) The two-dimensional branching pattern is laid out to connect the anchor points.

(c) The vaulting form is generated.



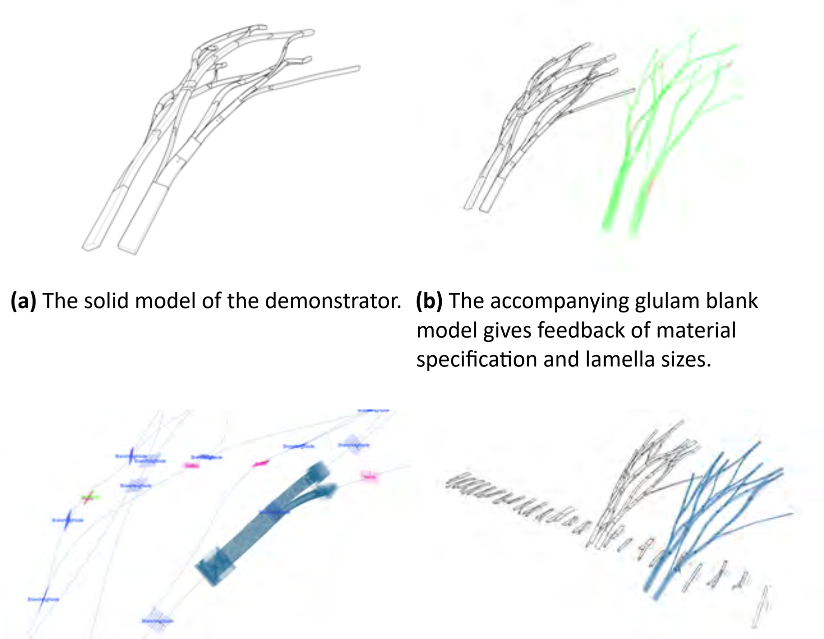
(d) The resultant 3D branching pattern serves as a basis for spatially organizing the structural scheme.

Fig. 6.9: The modelling process of the spatial graph and global design. Image: Paul Poinet

structure, and rough structural analysis based on the mesh edges and nodes give an overall indication of areas of stress.

The linking of this global "skeleton" to the glulam blank model creates a multi-scalar relationship where the branching modules in these areas respond to changes in the skeleton by increasing or decreasing their cross-section sizes or by altering their overall curvature. This negotiation between the overall branching pattern at the global level and the material reality of each branching module creates a central feedback and cyclical process: design moves and changes at the global level create demands on the individual branching modules, however these also demand changes from the global organization due to material constraints such as bending limits. For example, branching modules that require extremely thin lamellae are avoided by adjusting the global graph accordingly. The combination of an organizational graph with the glulam blank model therefore allow global design changes to be effected, while also yielding important fabrication parameters and specifications at a glance and motivating adjustments at the global level.

The design is construed as a global mesh model and then interrogated through the lower-level glulam and fabrication models for information



(a) The solid model of the demonstrator.

(b) The accompanying glulam blank model gives feedback of material specification and lamella sizes.

(c) Extracting specific elements from the light-weight model to generate fabrication data.

(d) Using the demonstrator model to create production data for every element.

Fig. 6.10: The process of turning mesh-based spatial graph into a production model for the demonstrator.

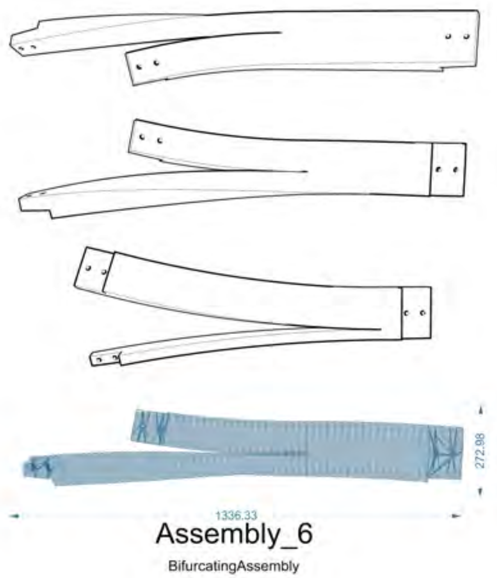
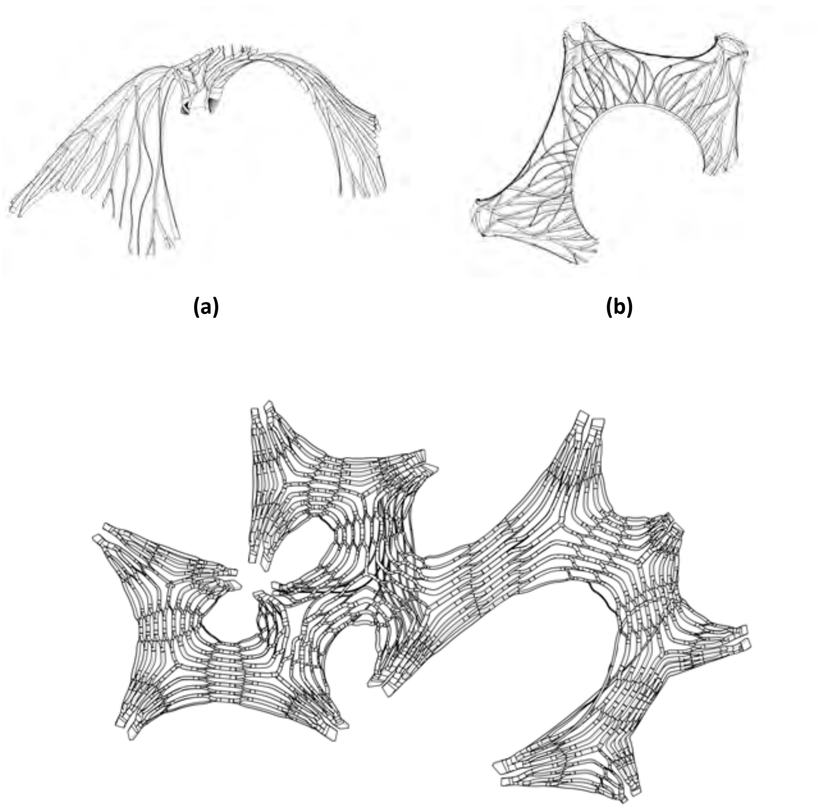


Fig. 6.11: Each element is extracted with relevant connection details and documented.

about material requirements, production implications, and joint details. The connections between the Branching Blank modules are simple end-to-end lap joints. Because of the integrated split, one module can connect to two others without the use of crossing joints.

A number of these elements are prototyped to test the fabrication workflow, with mixed results. The initial strategy takes Probe 4: CITAstudio glulam workshop as a precedent and produces laser-cut MDF moulds with which to laminate the double-curved branching modules. These proves extremely difficult to laminate effectively, owing both to the large amount of lamellae needed for the double-curved modules, as well as the limited space for clamping the elements together. Despite this shortcoming in the prototyping of the elements, the established multi-scalar feedback process succeeds in connecting the glulam modelling experiments to a broader scope of design modelling. The production of the Branching Blank is reconsidered in later prototyping efforts during Demonstrator: MBridge.

Fig. 6.12: The competition proposal for the Tallinn Architecture Biennale 2017 folly competition.



(a) (b)

(c)

Fig. 6.13: Early sketches for the Grove proposal.

6.3.2 Grove

Prototype 2: Grove is an evolution of the multi-scalar modelling and design investigation developed during the Probe 5: Branching Probe and a further test of the application of the tools and workflows to an architectural context. It is a competition entry for the Tallinn Architecture Biennale 2017 folly competition, continuing the collaboration with researcher Paul Poinet (Fig. 6.12). The key difference with the previous work is the addition of a specific site, context, client (the jury), and external partners. These added aspects move the design project from being internal and self-reflecting to responding more to external inputs.

Design brief and context

The requirements of the competition brief are simple: to propose an installation or architectural folly that would sit in front of the Estonian Museum of Architecture for two years, made out of wood, and in collaboration with local Estonian timber producers. The brief is therefore highly aligned with the evolving design implementation developments: as a temporary structure for a celebratory and provocative festival of architecture, it is encouraged to be experimental and daring, and does not have severely restrictive programmatic requirements. Working with local timber producers also means that the modelling tools and workflows can be tested in a more ”real-world” context in terms of the type of data and models that could be communicated to the producer, as well as in terms of how the production and logistical constraints of the producer can be integrated into the workflow and design process.

The site for the installation is a grassy knoll in front of the Estonian Museum of Architecture, between two major roads into the city of Tallinn and just on the outskirts of the Old City. It provides an elevated earthen platform with views to the Old City, the Museum, the harbour, and the new adjacent urban development, bounded by road traffic. Being such a visible site, the engagement with these surroundings is a priority, also demanding a strong visual presence from the folly.

Design modelling strategy

The main organizational strategy of the Prototype 2: Grove proposal is similar to that of Probe 5: Branching Probe: a series of interconnected vaulting spaces composed of branching modules that stem from a collection of footings. Where Probe 5: Branching Probe is composed of a single vault with several feet, Prototype 2: Grove seeks more spatial complexity by interconnecting and branching multiple vaults. These follow a similar strategy as before, of thick trunks at the footings which bifurcate and dissolved into a screen-like surface. The dissolution of the main supports introduces a fluidity to the form and structure which blurs the distinction between beam, panel, and column. The inspiration for this move is the intertwining of tree canopies in a forest grove - relating the branching modules to the figurative splitting and branching trees. This tectonic possibility is driven directly by the Branching Blank, relating the architectural language of the whole Prototype 2: Grove proposal to the formulation of an alternative glulam blank type.

The multi-scalar workflow from Probe 5: Branching Probe and the further deployment of the glulam blank modelling tools are pivotal in managing the complexity of the design and building a strong case for the proposal, both for the Estonian producer that was brought on board - Arcwood - as well as the competition jury. Graph-based modelling and the integration of glulam blank model and joints with the `GlulamWorkpiece` models prove instrumental in developing and tracking the large number of elements and connection details: over one thousand individual pieces and their interrelations have to be kept intact and up-to-date.

The graph-based organization model proves extremely useful in this respect, by providing a light-weight representation of the whole proposal and a means to quickly navigate the model and access the finer-grained glulam blank and fabrication models attached to each graph element. The flexibility of this approach mitigates the daunting complexity of the project in conversations with the local producer and the competition jury. Although on the surface the proposal appears too complex, the ability to move across scales and organize all relevant material and fabrication data provides reassurance and makes the proposal a serious contender.

Although the competition entry achieves second place and is not chosen for construction, it demonstrates the efficacy of a multi-scalar approach that combines high-level graph-based organization with low-level material and fabrication modelling. Further, the physical prototyping of the Branching Blank is iterated and the difficulties of forming it as initially conceived are discovered. These point to alternative strategies for producing the Branching Blank in future development.

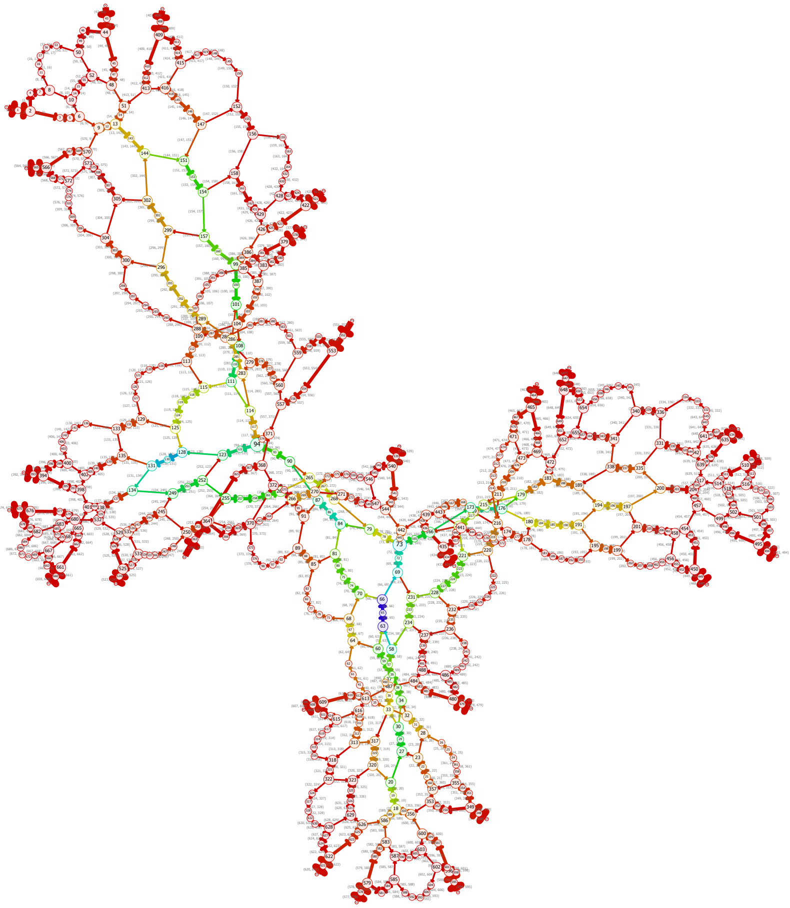
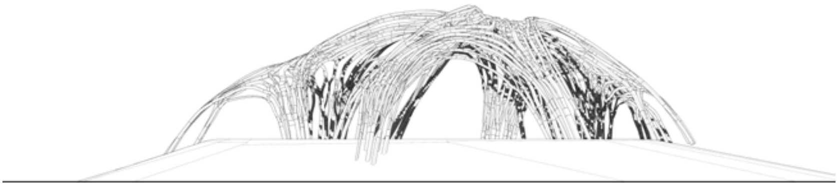
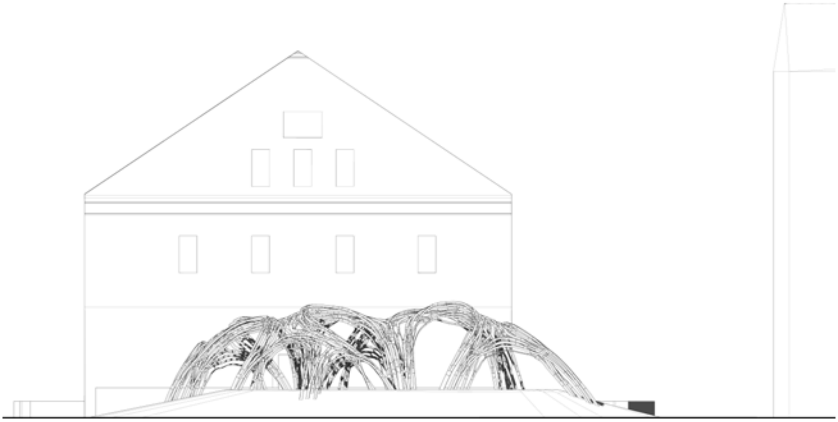


Fig. 6.14: The graph of the whole Grove proposal. Image: Paul Poinet



(a) Long elevation.



(b) Short elevation.

Fig. 6.15: Elevations of the Grove proposal.

Fig. 6.16: The entry proposal for the Tallinn Architecture Biennale 2017 folly competition. Image: Tom Svilans, Leonardo Castaman

Fig. 6.17: The entry proposal for the Tallinn Architecture Biennale 2017 folly competition. Image: Tom Svilans, Leonardo Castaman

(a) The bare glulam structure.

(b) A coarse textile substrate stretched in between the bifurcating arms.

(c) The growth of foliage slowly overtakes the structure.

Fig. 6.18: The infill between the bifurcating glulam modules was imagined to be either a textile or planting surface for foliage. Image: Leonardo Castaman

6.4 Material feedback in architectural design practice

The developments of Probe 5: Branching Probe and Prototype 2: Grove illustrate how the glulam blank model facilitates the design modelling of complex free-form structures and how the prototyping of non-standard glulam elements can drive new timber morphologies. These are performed within a tight collaboration between like-minded researchers in response to very open and provocative design briefs. The collaboration with *White Arkitekter* is an opportunity to move from this design of experimental pavilions and prototypes into a larger and more multi-disciplinary setting. While the previous two projects are tightly controlled from conception to physical outcome, large-scale architectural projects exist on different time scales and involve a multitude of stakeholders, sometimes with competing or indifferent interests.

A three-month secondment at *White Arkitekter* places the research in this context to explore how these developments can facilitate the early-stage design of timber proposals, and how they can be accommodated within an architectural design practice setting. The secondment involves the research in two architectural design projects: Prototype 4: Slussen benches and Prototype 5: Magelungen Park Bridge. The secondment is conducted in close collaboration with the *Dsearch* team. The engagement with both projects therefore depends on the role that *Dsearch* is playing for the particular project: a supporting and developmental role for the Prototype 4: Slussen benches and a design lead role for Prototype 5: Magelungen Park Bridge. Both *Blumer Lehmann AG* and *Design-to-Production GmbH* are consulted throughout both projects - both as partners in the InnoChain research network and as professional consultants to *White Arkitekter*.

A key aspect of these projects is the role of the research as a broker of knowledge between *White Arkitekter* and the domain of materializing glue-laminated timber components. In both, physical prototypes crafted as part of this research form the basis for early design development and the strengthening of the case for using timber. The brokering also consists of taking into consideration the principles of glulam production and communicating these to the design teams. The glulam blank modelling tools help to further transfer production principles to the design context. This *brokering feedback* - consisting of physical models, communication of fabrication knowledge, and the use of constrained glulam modelling tools - allows the proposed material practice from this research to act as a boundary object as described by Runberger and Magnusson (2015). This transfer of material knowledge and how it impacts Prototype 5: Magelungen

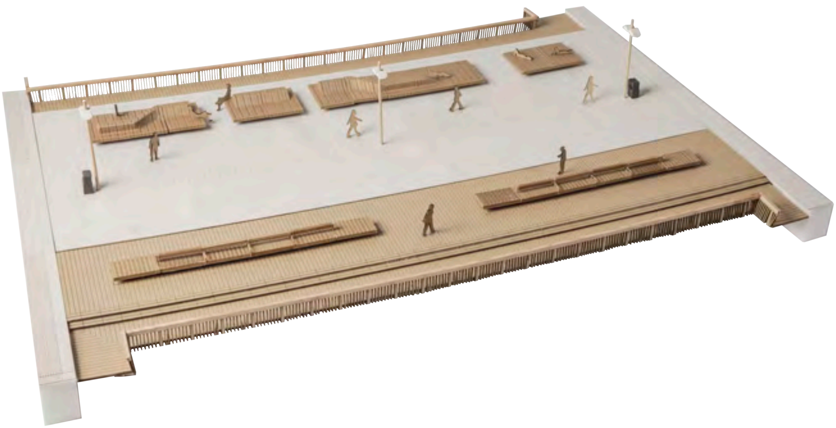


Fig. 6.19: A physical model produced by *White Arkitekter* of the whole bench area.

Park Bridge and its divergence into Demonstrator: MBridge is also described in Svilans, Runberger, and Strehlke (2020).

6.4.1 Slussen public benches

Context

Prototype 4: Slussen benches is part of the New Slussen Masterplan, a redevelopment of the Slussen area in the centre of Stockholm by Foster and Partners in collaboration with *White Arkitekter*. Slussen (”the Sluice”) is named after the sluice between the Baltic Sea and Lake Mälaren, forming an interface between the brackish salt water on one side and freshwater on the other. Part of this redevelopment includes the landscaping of a public plaza by *White Arkitekter* ((Fig. 6.19) and (Fig. 6.20)). The wish is for the decking and the public furniture of this plaza to be made out of wood. The Swedish climate and the proximity of this exterior plaza to the brackish water and sea air mean that durability and maintenance are fundamental considerations for the design of the public furniture. The public furniture consists of a series of free-form benches with a rectangular footprint, spaced in rows throughout the plaza. The tops of the benches are formally a single, inflected surface, providing both the seating surface and backrest. At the beginning of the secondment, the general form and arrangement of the benches are already designed and are being coordinated by a landscaping team at *White Arkitekter*. The role of *Dsearch* is to come up with modelling and fabrication strategies for the benches, prioritizing durability and material performance.

The initial strategy for the benches is to create a steel frame that would be

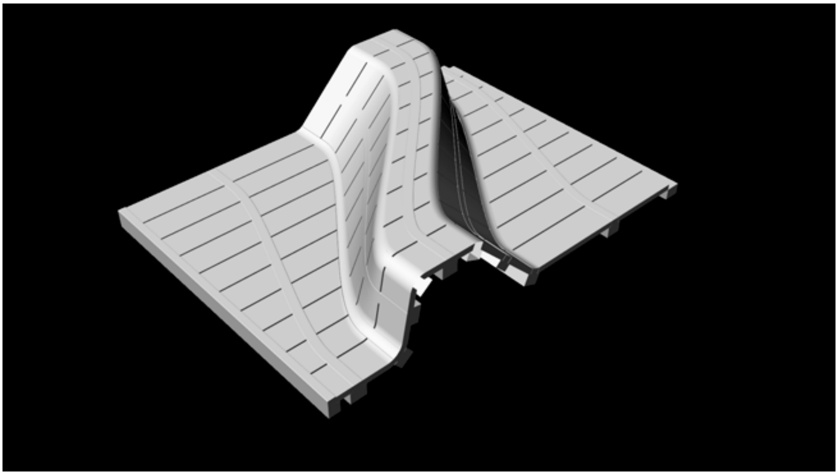
Fig. 6.20: A close-up of the physical model produced by *White Arkitekter*.

clad with a wood skin. The steel forms the structural skeleton of the benches, and sits on a concrete footing. In this iteration, the timber cladding is only used as a surface and covering. While this simplifies the maintenance of the benches - boards could be easily replaced - and structure, it is a heavy solution, requiring a large mass of steel, and it does not exploit the capacity of timber as a structural material.

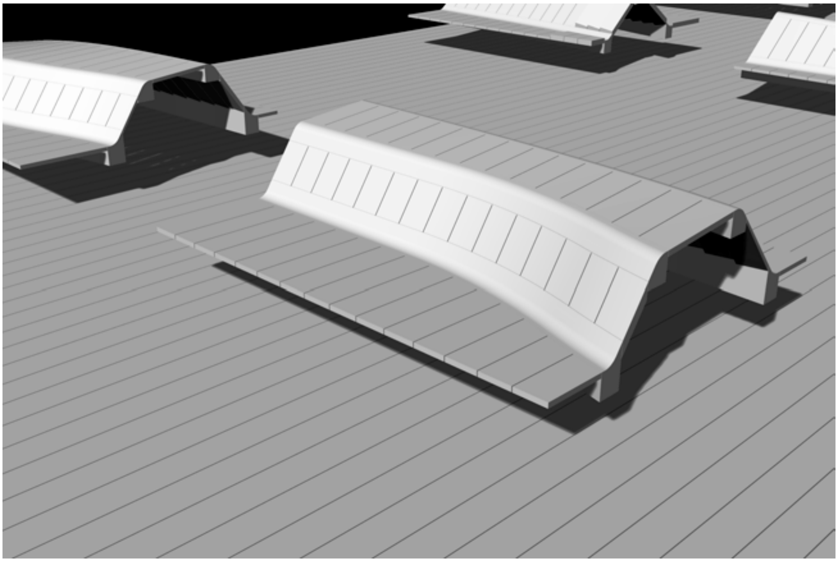
Deploying timber alternatives

The role of the secondment for this project is to look at ways in which the bench design can incorporate more timber and exploit its properties and behaviour. The bench is therefore reconsidered as an engineered timber bench, without any steel frame, interfacing directly with a baseplate or podium on the ground. The bench form presents a challenge in the fairly sharp inflections of the seating surface. The small radii - only about 100mm - mean that, if curved glulams are to be used, their lamellae would have to be less than a millimetre thick. If the timber skin of the surface is also meant to be structural and thick enough for public use as seating and - probably - climbing and playing, then the number of lamellae in such a glulam would make their cutting and production very laborious and expensive. Further, since the inflections only form a small part of otherwise linear segments, using so much thin wood for straight sections would be very wasteful.

Drawing from Probe 4: CITAstudio glulam workshop and the Kinky Blank



(a) A variation with free-form ridge beams that would handle the tight curvatures around the inflection points.



(b) A somewhat rationalized version with limited bending on the ridge beams.

Fig. 6.21: Digital study models of the Slussen benches.

prototype, a solution is proposed where the bench is divided into linear sections across the inflected surface. The division of the benches into linear sections allows each section to be fixed individually - meaning individual sections can be easily replaced if necessary. Each section is then be composed of several linear boards that are oriented on-edge and cross-laminated at the inflection points, much like a large finger joint. The boards are deep enough to perform adequately as a structural skin. The inflections are then machined back from the inflection points. The shortcoming of this method are that the finger joining or cross-laminating of the rounded corners creates areas of end-grain exposure - detrimental for the durability of the timber benches. A solution is therefore proposed - much like the secondary lamination of the Voxel Blank in Probe 4: CITAstudio glulam workshop - to skin the outside of the timber surface in continuous, laminated veneer. This avoids exposed end-grain by covering it with the laminated veneer, and minimizes the amount of thin lamellae required, as the outer skin does not have to perform structurally and can therefore remain quite thin.

However, the thinness of the skin remains a concern: due to the seasonal variations in moisture and temperature, a thin veneered skin might be stressed too much by the expanding and contracting timber substructure. This may lead to an eventual degradation of the veneer surface and potential cracks which would allow the ingress of moisture and water into the end-grain underneath. The thin veneer is also particularly susceptible to damage from other sources such as aggressive use or impacts from other objects. Such damage would affect the fine layers of the skin by penetrating through one or more layers of veneer and glue whereas this damage would be less visible on a solid timber surface.

A second strategy deploys free-form glulams along the curvy folds or ridges and valleys, with simple, straight elements spanning in-between. This prevents end-grain exposure since the ridge and valley glulams are rounded around their grain direction, not across it as in the previous iteration. Since the curving of the fold along the length of bench is much more severe than the curvature across the folds, cross-wise, the ridge and valley glulams can be made with larger lamellae. This lowers the fabrication complexity and avoids having thinly veneered components or large amounts of exposed end-grain. The issue with this iteration is that the interface between the straight infill pieces and the ridge and valley glulams need a solution that prevents water ingress in the contact surfaces and allows movement due to hygroscopic expansion and contraction. This strategy also ties the bench together into one piece, making replacing individual sections more difficult.

These strategies are explored through physically prototyping a small portion of the bench. The cross-laminated ridge connection is fabricated and becomes a key point of discussion between the project team and *Dsearch*. It allows a closer look at the details and material behaviour - the expansion and contraction of the laminated pieces can be seen and measured over time - and make the modelled proposal more believable by demonstrating its fabrication feasibility. Once again, the modelling tools from Prototype 1: Glulam blank model are used to estimate material quantities and determine the required thicknesses of lamellae.

Results

The benefit of moving between 3D modelling of the overall bench form and the material prototyping of its composition is demonstrated through this design development process. The all-timber design proposals convinces the design team to eschew the first steel substructure strategy. The issues with timber expansion and end-grain exposure are proposed to be mitigated by using treated wood products such as Accoya or Kebony, which have a much greater form stability and resistance to deterioration in the face of weathering.

The development of the Prototype 4: Slussen benches has subsequently been put on hold pending decisions and design development of the whole Slussen master plan.

(a) The cross-laminated material prototype without the laminated skin.

(b) An edited version of the prototype to show the ridge beam variation.

Fig. 6.22: The infill between the bifurcating glulam modules was imagined to be either a textile or planting surface for foliage.

Fig. 6.23: The Magelungen Park Bridge.

Fig. 6.24: A visualization of the second iteration of the Magelungen Park Bridge scheme.

Fig. 6.25: Additional views of the second iteration of the Magelungen Park Bridge scheme. The 3D scans of the site provided detailed feedback about site conditions and constraints.

6.4.2 Magelungen Park Bridge

Context

The Prototype 5: Magelungen Park Bridge project is part of another larger redevelopment of the surrounding area in a suburb south of Stockholm. This larger development includes new residential development and parkland adjacent to the Magelungen Lake. The program calls for a pedestrian bridge to connect the parkland by the lake with the new housing development across the main road - Magelungsvägen - and the train tracks running parallel to it that lead to the nearby station of Farsta Strand. Because of the elevated position of the parkland and clearance required for the roadway and train tracks, the bridge has to be made longer than the span in order to maintain a maximum slope of 5%. Further, a stand of protected

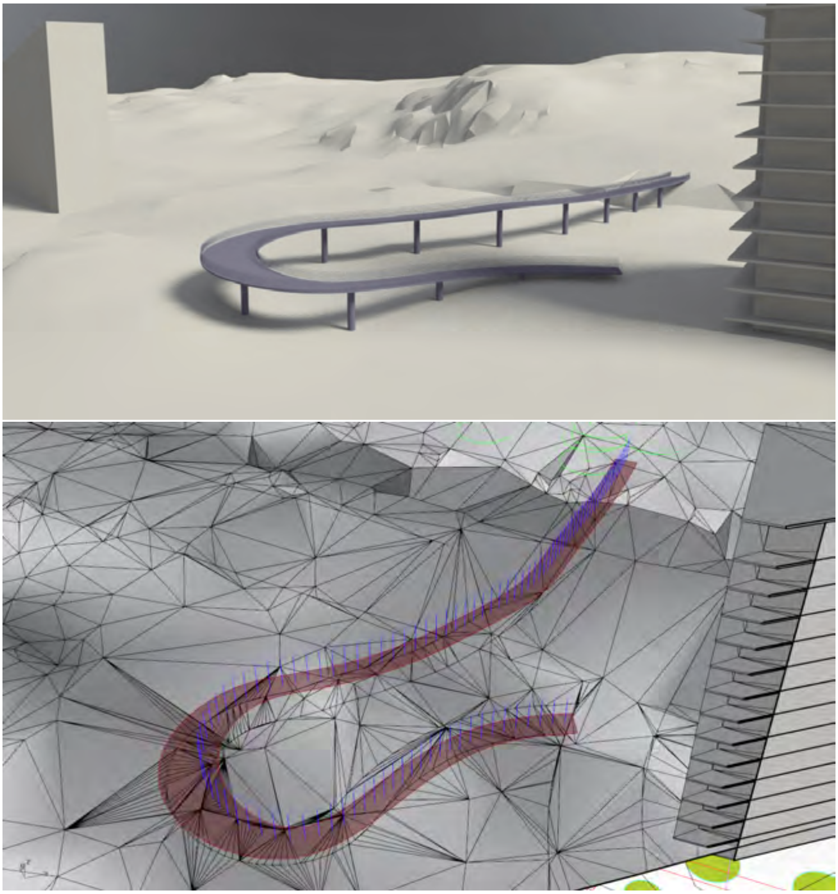


Fig. 6.26: The initial pedestrian bridge scheme - a simple concrete path. Image: *Dsearch*, *White Arkitekter*

old-growth oak trees in the forest on the lake side has to be accommodated and preserved. These length, height, and slope requirements, along with the positions of the protected oak trees, set the overall parameters for the bridge.

In the development master plan, the initial bridge design is assumed to be a simple concrete or steel bridge that satisfies these requirements. The secondment with *Dsearch* at *White Arkitekter* creates the opportunity to challenge this assumption and propose an alternative scheme based on engineered timber. Because the bridge is to be shared by pedestrians and cyclists, and its length has to be increased to account for the slope and clearance limitations, the overall bridge form is curved into a bulging loop.

The path of this loop has to be balanced between the protected oak trees and the height requirements of the roadway, train track, and endpoint. This curved form, along with the timber material choice, make the Prototype 5: Magelungen Park Bridge especially relevant as a case study for the glulam blank modelling tools as well as the free-form glulam prototyping strategies described in the previous chapter. The goal is to build a case for using as much engineered timber as possible, both to showcase its use in an outdoor, load-bearing structure as well as to promote the use and development of timber structures and joinery at *White Arkitekter*.

From the point of view of the project design team, there are three main concerns: durability, site impact, and construction feasibility. Mitigating these concerns with a timber-based outcome becomes the design target for the bridge proposal.

Stockholm has a variable climate, oscillating between cold winters with much snow, and hot summers. Exposure to melting snow, rain, and temperature fluctuations are the main climatic issues to address. The design of the timber bridge needs to therefore minimize end-grain exposure, facilitate the fast shedding and drainage of water, and otherwise protect the timber from the elements.

The impact on the surrounding site must be minimized, and the roadway and tracks cannot be disrupted during the construction and assembly of the bridge. This means that a light and modular structural solution must be prioritized - something that can be ideally lifted into place and assembled in large sections.

The design of the bridge must also take into account the capabilities of local Swedish producers and contractors, meaning that the high production complexity and expertise in complex timber forms demonstrated by *Blumer Lehmann AG* cannot be assumed to be available. This implies a degree of rationalization and mitigation of complexity in the proposal.

Design iterations

Given the established bridge path - the ”loop” - the critical clearances, and the fixed end-points, the proposal goes through several iterations of a structural scheme and cladding strategy. The first design iteration proposes a timber-clad ”hull” which wraps the bridge path and contains a series of structural frames - rib-like timber columns that distribute the bridge load across the site underneath the path. Each frame is a pair of inclined timber columns, connected to two curved glulam rim beams that define the edges of the bridge deck. A timber beam running between the two inclined columns tie them together and reinforce the deck members. The deck itself

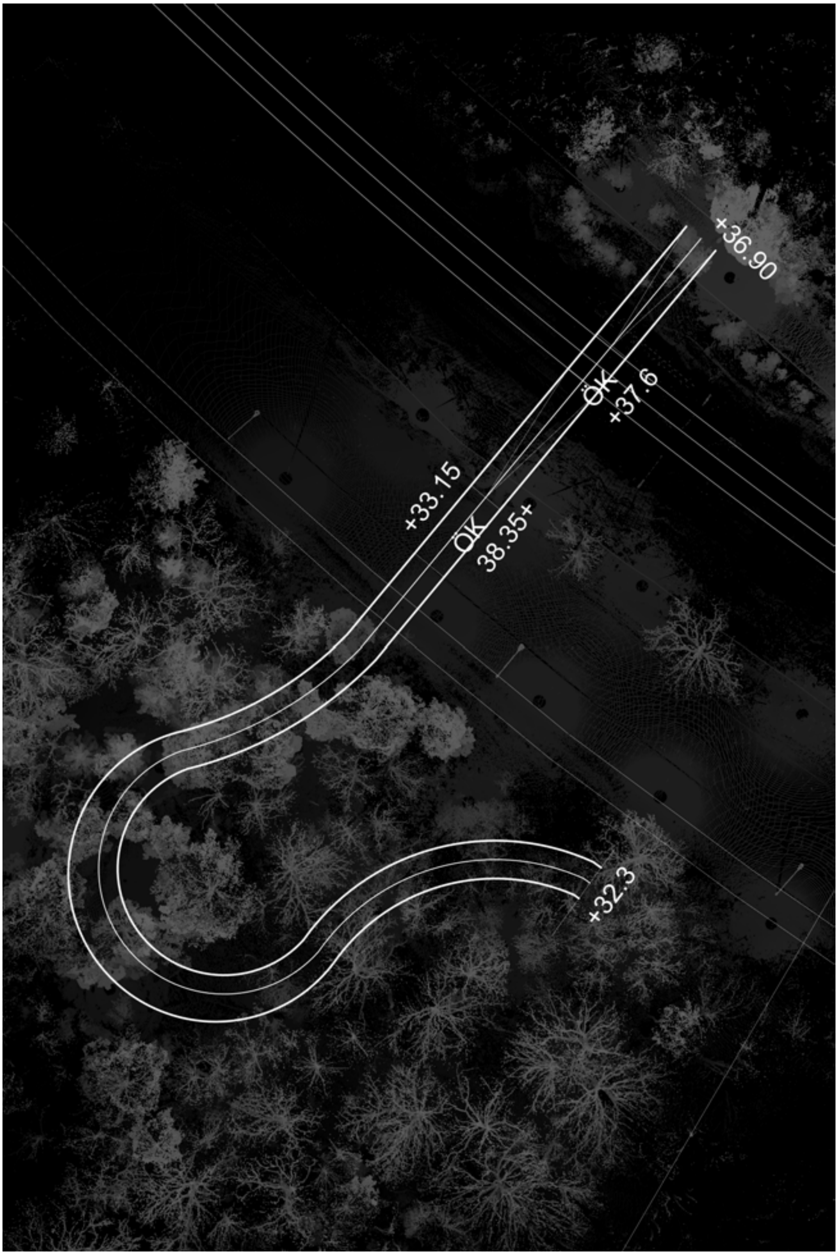


Fig. 6.27: The ”loop” in plan. The end-point height difference (+36.90m and +32.3m) as well as the requirements above the road (+38.35m) and tracks (+37.6m) required the bridge path to extend substantially beyond the direct span length.

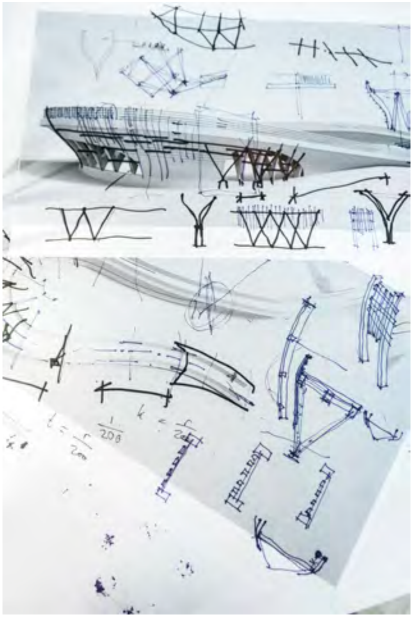


Fig. 6.28: Initial sketches of the bridge explored different ideas of structure and cladding.

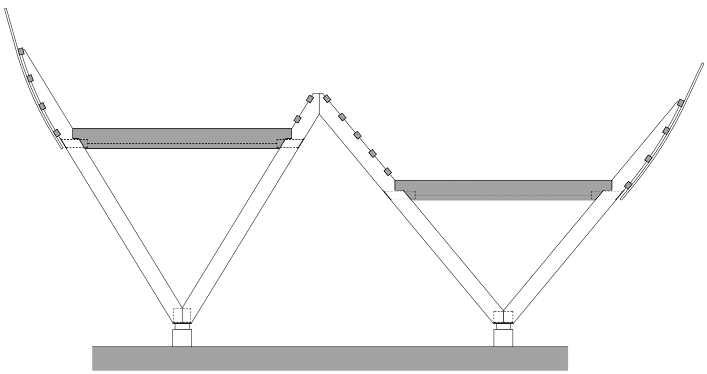


Fig. 6.29: A cross-section study of the Prototype 5: Magelungen Park Bridge.

Fig. 6.30: The Magelungen Park Bridge design approach was based on a parametric model which integrated the Prototype 1: Glulam blank model tools.

is conceived as either a CLT panel covered in an asphalt-type membrane, or as timber planks spanning between the rim beams. The timber cladding is fixed horizontally onto the frames, extending past the deck level to form the railing.

The horizontal arrangement of the cladding is rejected due to concerns about climbing and small children. Guidelines for barriers and railings prohibit solutions that would encourage climbing due to the risk of thusly circumventing the barriers and leading to falling and injury. Switching the cladding from a horizontal arrangement - which accentuates the lines of the bridge - to a vertical one solves this issue while also hinting at another design strategy that would utilize the bending capacity of the cladding elements. In this strategy, the bridge structure is ordered in three hierarchical layers: the large, inclined structural trusses that form the primary supporting structure, the secondary horizontal edge and railing beams that both connect the primary structure at the deck level as well as at the tips of the trusses, and the tertiary cladding system which is fixed to the secondary, horizontal beams and actively bent into shape. The deck is still fabricated out of either CLT slabs or timber deck planks. This iteration of the proposal can be summed up as an array of repeating structural trusses - either straight or single-curved glulam members - connected by free-form glulam beams that trace the curvilinear path of the bridge, and clad with vertical, actively-bent timber planks to provide a barrier against wind and falling.

A third iteration of the proposal is developed after more consultation with timber engineers at *Blumer Lehmann AG* and *Design-to-Production GmbH*. This iteration essentially flips the cladding and structure: the vertical timber planks that make up the cladding are put on the inside of the structural trusses and edge beams. This increases the amount of possible drainage from rainfall and snow, reducing the risk of deterioration due to moisture and rotting. Also, by considering the exoskeletal structure as a truss, the sides of the bridge gain a double role as both structure and railing. This

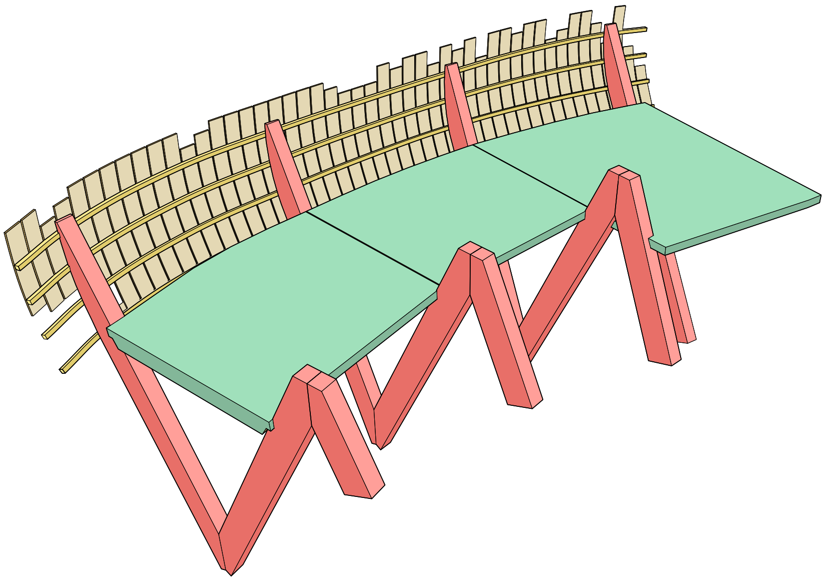


Fig. 6.31: The structural hierarchy of the Prototype 5: Magelungen Park Bridge. The supporting inclined columns (red), support the deck panels (green). Secondary edge elements (yellow) hold the outer actively-bent cladding (tan).

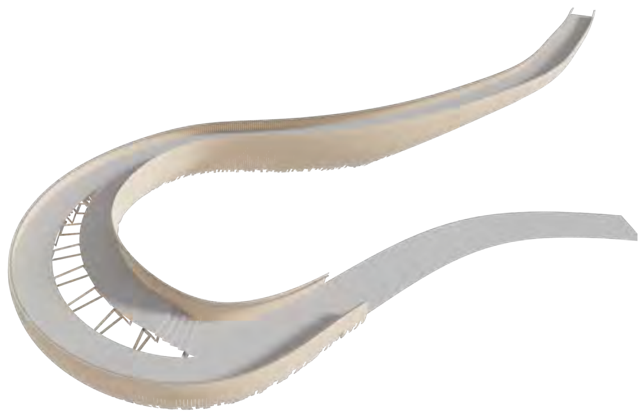
minimizes the depth of structure required underneath the bridge deck, which helps to lower the maximum bridge height where it clears the roadway and tracks, and helps to ”vertically compact” the bridge section. Also, segmenting the bridge sides - or free-form trusses - into larger chunks leads to a simpler assembly strategy: supporting columns or trusses are minimized to the points in between bridge truss segments, and these larger bridge truss segments are transported and lifted into place in fewer steps than assembling the whole bridge on-site.

Deploying the glulam blank model

For the modelling of the bridge, a parametric and computational approach is used to both maintain the programmatic and site constraints as well as permit flexibility in exploring different design options. The bridge path is driven by a drawn curve which denotes the top and centre of the bridge deck. The maximum slope constraint for the bridge deck is enforced by monitoring the slope of this bridge path curve at regular intervals and highlighting any segments that exceed this constraint. A similar constraint keeps the bridge height above the clearance heights required by the roadway and rail tracks. The combination of these two constraints and the two fixed endpoints determine the length of the bridge path. Since the required length of this path is longer than the horizontal span between the endpoints, the path needs to extend past the lower endpoint and fold back on itself, creating a switchback. Adapting this further, this switchback is turned into a more gradual loop with a large enough radius to comfortably accommodate cyclists. The midpoint of this loop is further expanded into a ”bulge” to create more space around the bridge bend.

The extra space afforded by the bulge allows a separation between cycle and pedestrian paths, and an opportunity to create a level rest area on the pedestrian path. The rest area, positioned in the middle of the bulge where the bridge path is still in the parkland, functions also as a nature lookout towards the Magelungen lake. The positioning and ”smoothness” of this bulge is also defined parametrically so that different variations of the bulge can be assessed by the project team. Since the level rest area interrupts the continuous slope of the bridge path, it requires a few stair steps, depending on how long the rest area extends. Placing the pedestrian path on the outside of the bulge therefore puts the pedestrians and rest area closer to the forest and parkland view, but puts the cycling lane on inside of the bulge, where the turn was tighter. On the other hand, putting the rest area on the inside of the bulge means that the cycle lane has a more generous turning radius, but the view from the rest area is interrupted and more removed from the parkland (Fig. 6.32).

The implementation of the design happens within the Rhinoceros 3D



(a) The viewing surface on the inside, giving the sloped cycling route a more gradual turn.

(b) The viewing surface on the outside, giving it a closer engagement with the surrounding forest.

Fig. 6.32: Two options for splitting the bulge of the bridge into a viewing surface and circulation slope.

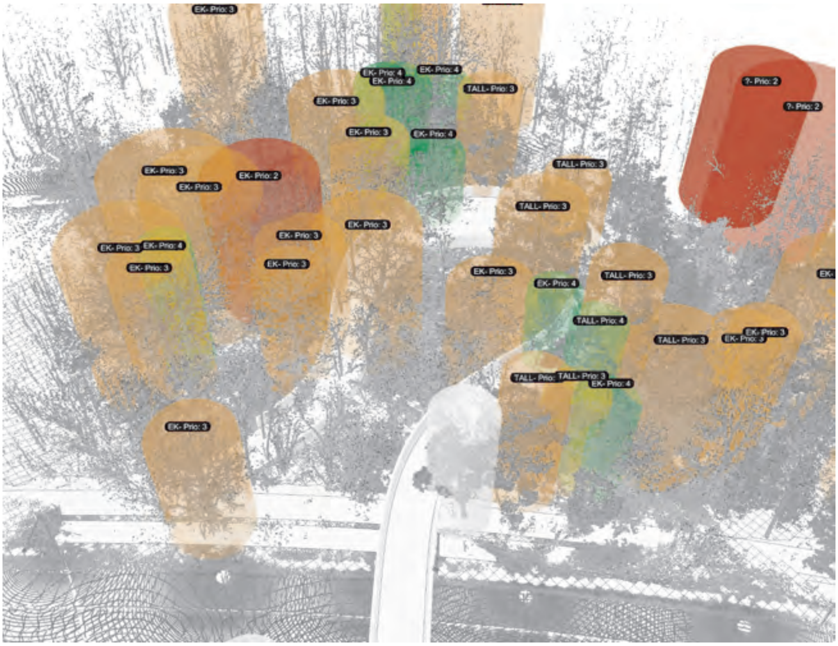


Fig. 6.33: The 3D scans of the site precisely identified the extents of the protected oak trees. Image: *Dsearch*, *White Arkitekter*

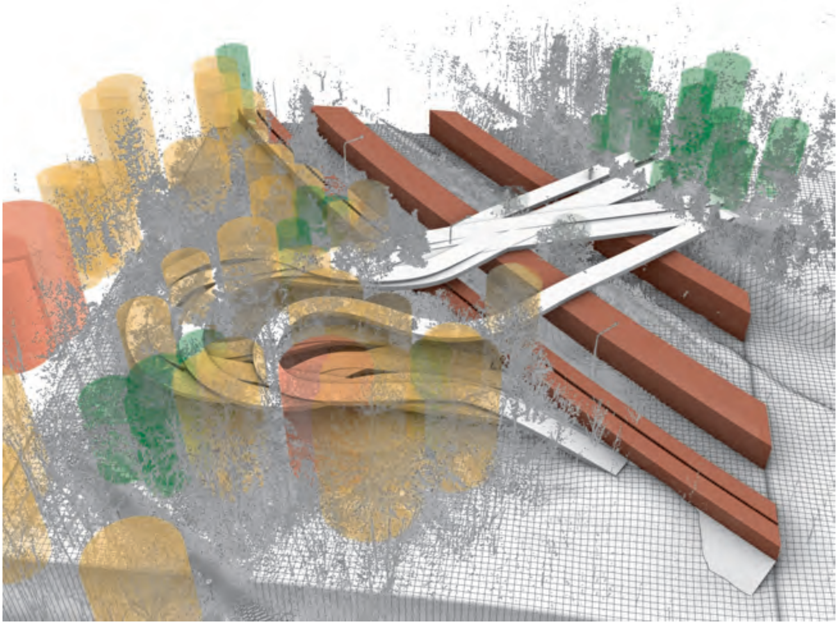


Fig. 6.34: The 3D scans of the site informed different options of the bridge path. Image: *Dsearch*, *White Arkitekter*

modelling environment - a tool also familiar to *White Arkitekter*. Using this environment permits defining the necessary parametric relationships between the drawn bridge path curve and the programmatic constraints such as endpoints, height clearances, and maximum slope. The glulam blank modelling tools are deployed to initiate a proposal based on free-form glulams. The critical extents of the bridge are defined by the bridge path and varying width of the bridge deck - including the bulge - therefore the modelling focuses on possible structural schemes for supporting this. Much like the modelling of free-form glulams, the orientation of the bridge structure is defined as a series of perpendicular curve planes, thus linking the orientation of structural frames and beam elements to the bridge path curve. This assists in calculating correct offsets and connection points over the whole free-form structure.

The Prototype 5: Magelungen Park Bridge proposal is led by *Dsearch*, however it is overseen by the Magelungen development design team. This entails regular meetings with the project manager to discuss the design and identify any issues. Data drawn from the glulam blank modelling tools about end-grain, types of glulams, volume of wood, and so on, is therefore relayed to the project team from the very beginning. This informs conversations about the evolving design strategy as well as discussions with engineers. The

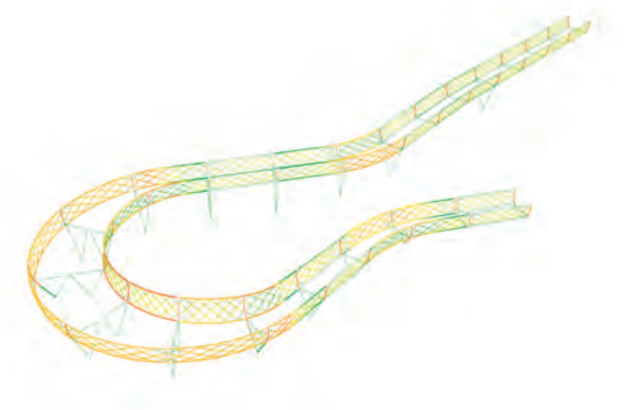


Fig. 6.35: The relative curvature of the glulam elements of the bridge, showing the degree of lamellae bending (red is high, green is low).

structural strategy is discussed with engineers from Sweco, further adding detail and inputs to the proposal. An observation from this point in the design process is that, despite the parametric model and developed design modelling tools, most of these meetings and conversations happen through still images, drawings, and hand-drawn sketches. The immediacy of paper, conversation, and sketching in multi-disciplinary and inter-team discussions remains a preferred way of communicating, something that is less apparent or not at all apparent in previous, more integrative design projects such as Prototype 2: Grove. This confirms the more interpersonal aspect of the brokering feedback proposed by this research: principles and strategies are exchanged and discussed by a meeting of involved stakeholders and a collaborative exchange of ideas throughout the design process.

Rationalization for construction

Where the glulam blank modelling tools really begin to have an impact is during an effort to optimize the fabrication complexity of the third bridge proposal iteration. Due to the curvilinear bridge path and resultant bridge deck surface, the bridge side trusses end up being comprised of mostly double-curved glulam elements. A quick analysis of the glulam types show that almost 90% of all structural members in the bridge design are double-curved. Because of the differences in production complexity between the different types of glulam blanks, the possibility of minimizing this is explored.

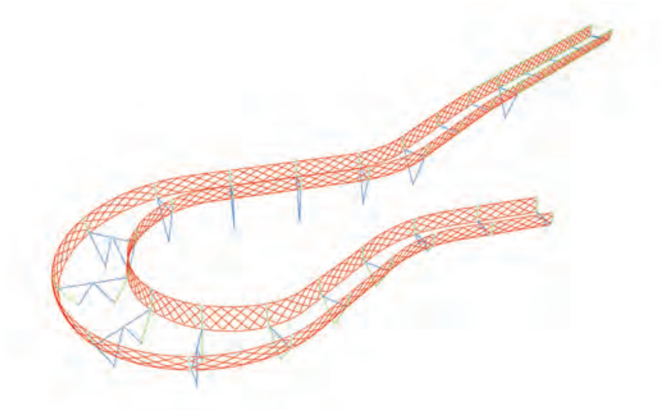
Using the glulam blank modelling tools allows a quick rationalization of the these elements to happen. Most of the double-curved elements are only very slightly double-curved, meaning that, if they are machined out of a single-curved blank, the amount of extra material waste and the amount of fibre-cutting is minimal. Categorizing the double-curved elements that are only slightly double-curved as single-curved glulams that are machined into form greatly minimizes the amount of required double-curved glulam blanks, therefore also minimizing the overall construction complexity of the bridge. The reduction of construction complexity makes the proposal approachable by a wider variety of fabricators and contractors, satisfying one of the project team's concerns.

The way this rationalization is performed is in two ways. Glulam centrelines that are double-curved are projected onto their plane of best fit. If the maximum distance of the original curve to this plane is less than a user-defined ”simplification distance”, then the planar projected curve is used as the centreline for the glulam blank instead - a single-curved glulam.

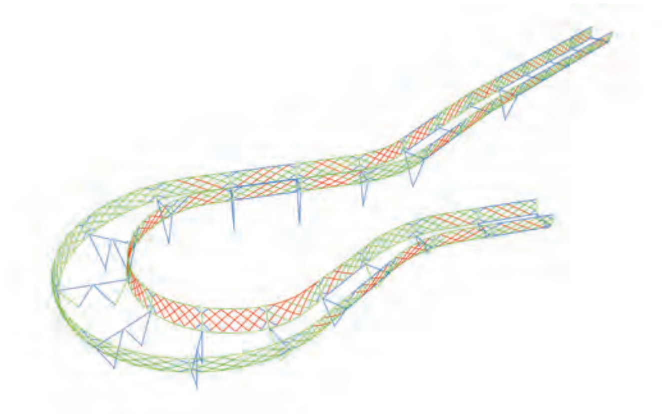
Glulam centrelines that are single-curved are compared with a line that spans between the endpoints of the centreline curve. If the maximum distance from the original curve to the line is less than the same simplification distance, then the line is used as the glulam blank centreline - a straight glulam.

Variations of this rationalization are tested on the bridge model with different simplification distances (Fig. 6.36). The original version of the third iteration is composed of 61 straight glulams, 73 single-curved glulams, and 654 double-curved glulams. A rationalization with a simplification distance of 10mm decreases this to 268 straight glulams, 500 single-curved glulams, and 20 double-curved glulams. Using a simplification distance of 20mm, this is further brought down to 273 straight glulams, 515 single-curved glulams, and 0 double-curved glulams. Considering the cost difference between straight, single-curved, and double-curved glulam blanks - a nominal ratio of roughly 1:2:5, depending on curvatures - the rationalization translates into a glulam blank cost saving of just over 60% for the 10mm variant and 63% for the 20mm variant, if only the glulam blank type is considered.

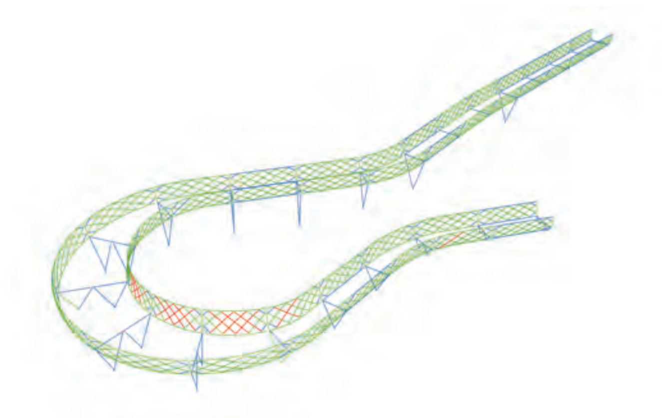
The cost saving of this rationalization has to be weighed against the implications of cutting a double-curved element out of a single-curved blank, or a single-curved element out of a straight blank. Material waste and increased time due to the extra machining, as well as the adverse effects on fibre continuity and end-grain exposure need to be evaluated by the engineering team, though these factors are highly specific to the exact geometry of each individual member. Because the specific cross-section sizes are not engineered yet, it is difficult to get a more accurate approximation of the total volume of each type of glulam blank - a much better indicator of cost.



(a) Unrationalized glulam elements in the bridge.



(b) Rationalization using a 5 mm simplification distance.



(c) Rationalization using a 10 mm simplification distance.

Fig. 6.36: The proportion of double-curved (red), single-curved (green) and straight (blue) glulams is optimized by slight adjustments to the glulam blank geometry.

Fig. 6.37: The Magelungen Park Bridge proposal as further developed by *Dsearch*. Image: *Dsearch*, *White Arkitekter*

Building a material case

What the integration of the glulam blank modelling tools and discussions with *Blumer Lehmann AG* and *Design-to-Production GmbH* demonstrate is the ability to build a case for a primarily timber exterior structure based on material performance and durability considerations, from a very early design stage. This is accomplished by a combination of *simulated feedback* given by the modelling tools, *process feedback* given by the exploration of timber processes and how they can apply to the bridge proposal, and *brokering feedback* which bridges the knowledge domains that participate in the project. Production complexities such as the different types of glulam blanks can be identified from a schematic stage, without delving too deep into the design development of the project. End-grain and durability considerations are identified from the beginning and drive the development of the structural scheme. The ability to communicate these aspects to the project team leader at such early stages, and effect substantial changes based on new information in a fluid and flexible manner help to garner support for the continued development of the bridge in timber. Further progress is awaiting actions on the part of the greater Magelungen development.

Fig. 6.38: The Magelungen Park Bridge proposal as further developed by *Dsearch*. Image: *Dsearch*, *White Arkitekter*

Divergence

In the meantime, the final iteration of the Prototype 5: Magelungen Park Bridge at *White Arkitekter* during the secondment requires some rationalization and re-conceptualization of the assembly sequence to make it easier for the building contractors to approach the project. The division of the bridge into components is also done to make the assembly and erection less invasive and time-consuming. At a material level, this means that the potential of the timber is not exploited to its maximum capacity: rationalizing the glulam elements into single-curved and straight blanks mean that the fibre direction is not always completely aligned with the element geometries. On top of this, the dependence on the rest of the project team and the separation from the contractor prevent the kind of holistic and integrative workflow that is demonstrated in earlier projects such as Prototype 2: Grove and desired by the proposed material practice. For these reasons, Prototype 5: Magelungen Park Bridge project is bifurcated into two ”tracks”: the *practice track* at *White Arkitekter* continues to develop the scheme according to the constraints and requirements of the client, project team, contractor, and other involved stakeholders, while the *research track* at *CITA* explores a derivative design proposal that seeks to exploit more of the material capacity of timber and demonstrate the integrative design-to-fabrication workflow presented in this research.

Fig. 6.39: The assembly strategy of the third iteration. The side trusses are lifted onto the timber columns and the deck is placed in between. Image: *Dsearch*, *White Arkitekter*

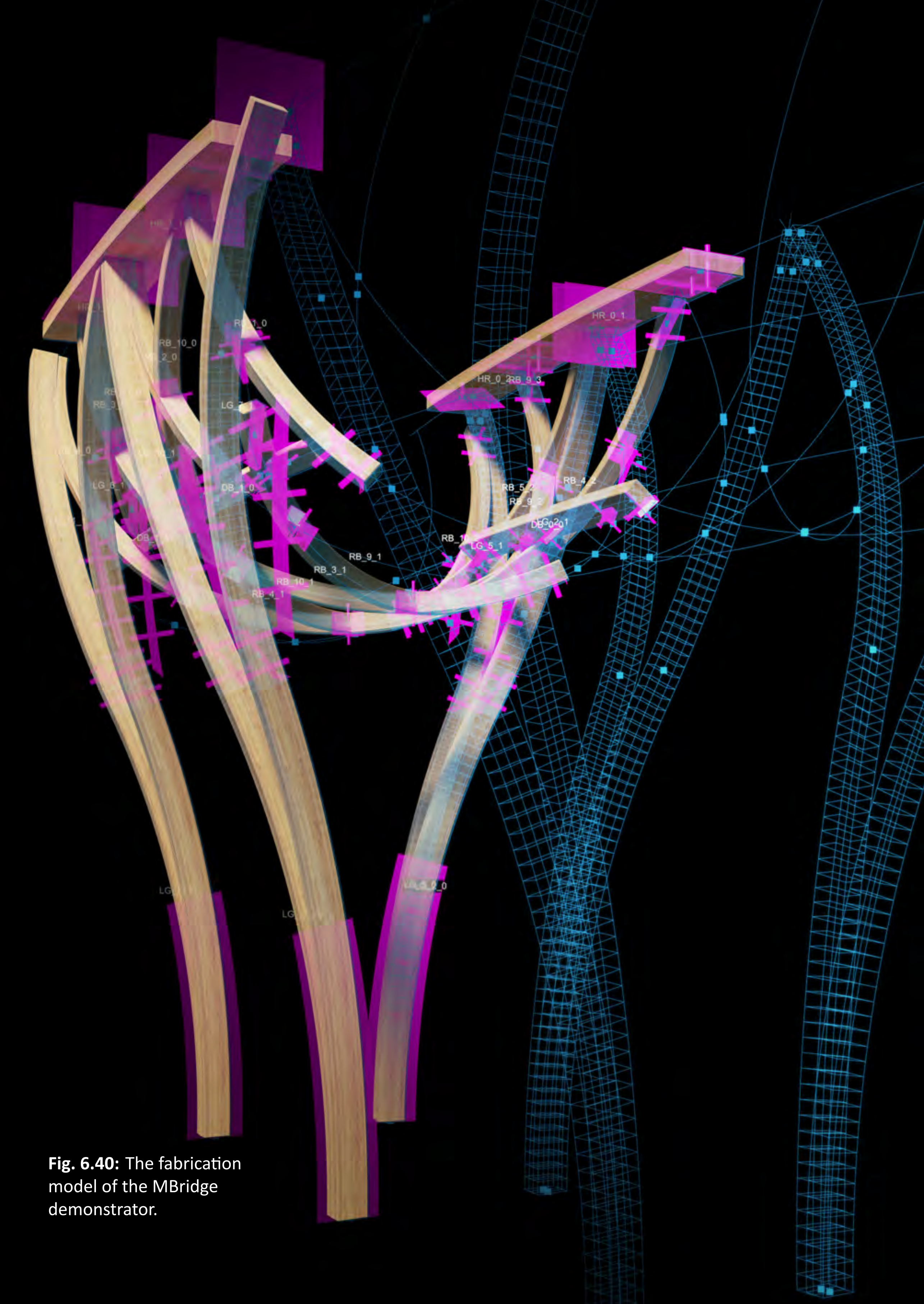


Fig. 6.40: The fabrication model of the MBridge demonstrator.

6.5 Demonstrating an integrated material practice in free-form timber structures

The research offshoot from the Prototype 5: Magelungen Park Bridge project is an effort to further develop the *simulated feedback* given by the glulam blank modelling tools from Prototype 1: Glulam blank model, the speculative glulam blank prototypes and *process feedback* from Probe 4: CITAstudio glulam workshop, and the digital sensing experiments comprising *direct feedback* in Prototype 3: Four methods of digital feedback into a holistic design-to-fabrication workflow, using the Prototype 5: Magelungen Park Bridge as a design basis and case study. As the culmination of the experiments and projects in this thesis, it serves as a demonstrator of the material practice that is based on glue-laminated timber and augmented by computational tools and digital feedback. To test this material practice, the demonstrator is a way to release the design from the limitations in commercial practice - such as the larger team with various decision-making levels, limited contractor capabilities, budget limits, and so on - and to evolve the design with the integrated design-to-fabrication workflow solely in mind. This cohesive workflow therefore includes the iterative lamination and machining prototyping processes driven by a computational model that provides material specification and feedback about material performance, as well as the tight integration of point cloud scanning within the fabrication of the individual elements.

6.5.1 Design strategy

As a result, Demonstrator: MBridge adapts the design of Prototype 5: Magelungen Park Bridge but prioritizes the exploitation of the structural performance of timber. The design uses a similar approach as before of considering the bridge as a structural ”hull” with legs but lessens the differentiation between deck and sides by proposing a continuous lattice-like surface that wraps around the sides and deck (Fig. 6.42). The deck ties the sides of this rounded hull together to stiffen the cross-section. Seating the deck within this hull also lowers the cross-sectional profile of the bridge since, as in the last iteration in Prototype 5: Magelungen Park Bridge, the sides of the hull serve both as structural trusses as well as handrails. Using the logic of the Branching Blank, the legs are ”grafted” onto the hull, creating a more three-dimensional and spatial articulation of the free-form glulam elements. Each leg consists of a pair of glulam elements that peel off the bridge hull and merge together at the ground point - another instance of the Branching Blank (Fig. 6.44).

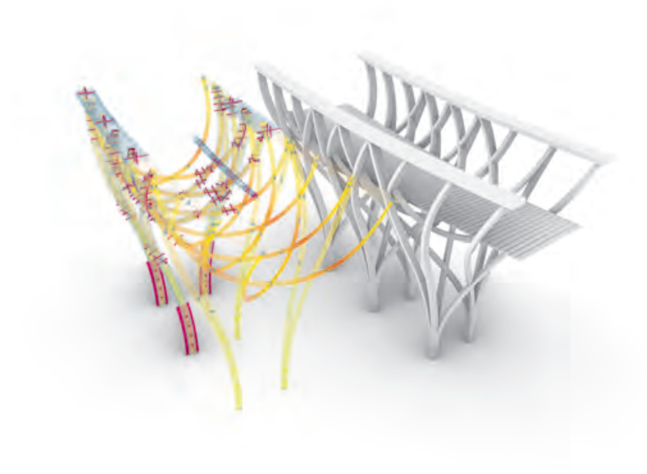


Fig. 6.41: The Prototype 1: Glulam blank model tools are used to interrogate the material specifications and performance of the Demonstrator: MBridge.

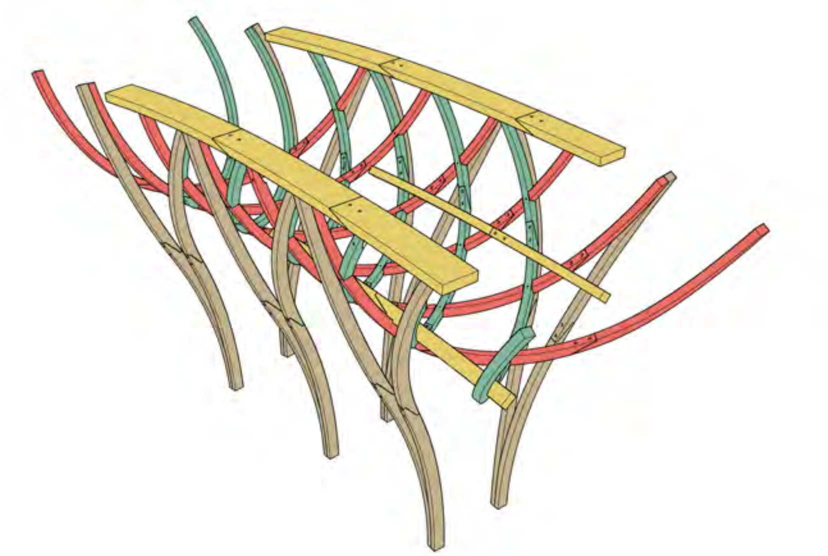


Fig. 6.42: The Demonstrator: MBridge design features a hull-like truss, supported by legs that peel off the main structure.

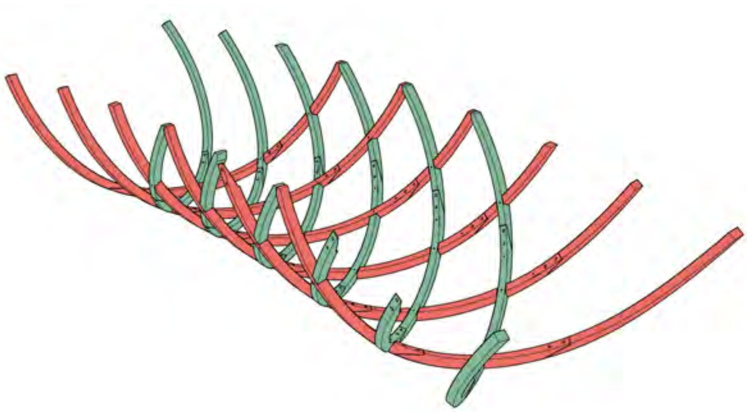


Fig. 6.43: The Demonstrator: MBridge hull is composed of two directions of intersecting members or *grid lines* (red and blue).

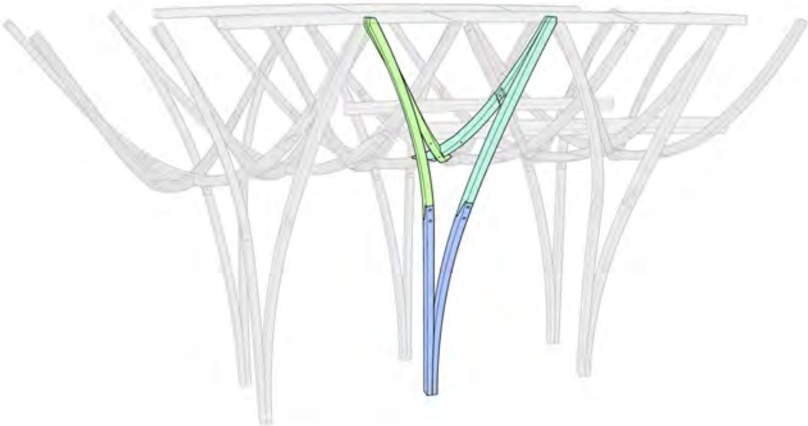


Fig. 6.44: The Demonstrator: MBridge uses the Branching Blank as an interface between the leg and the hull grid.

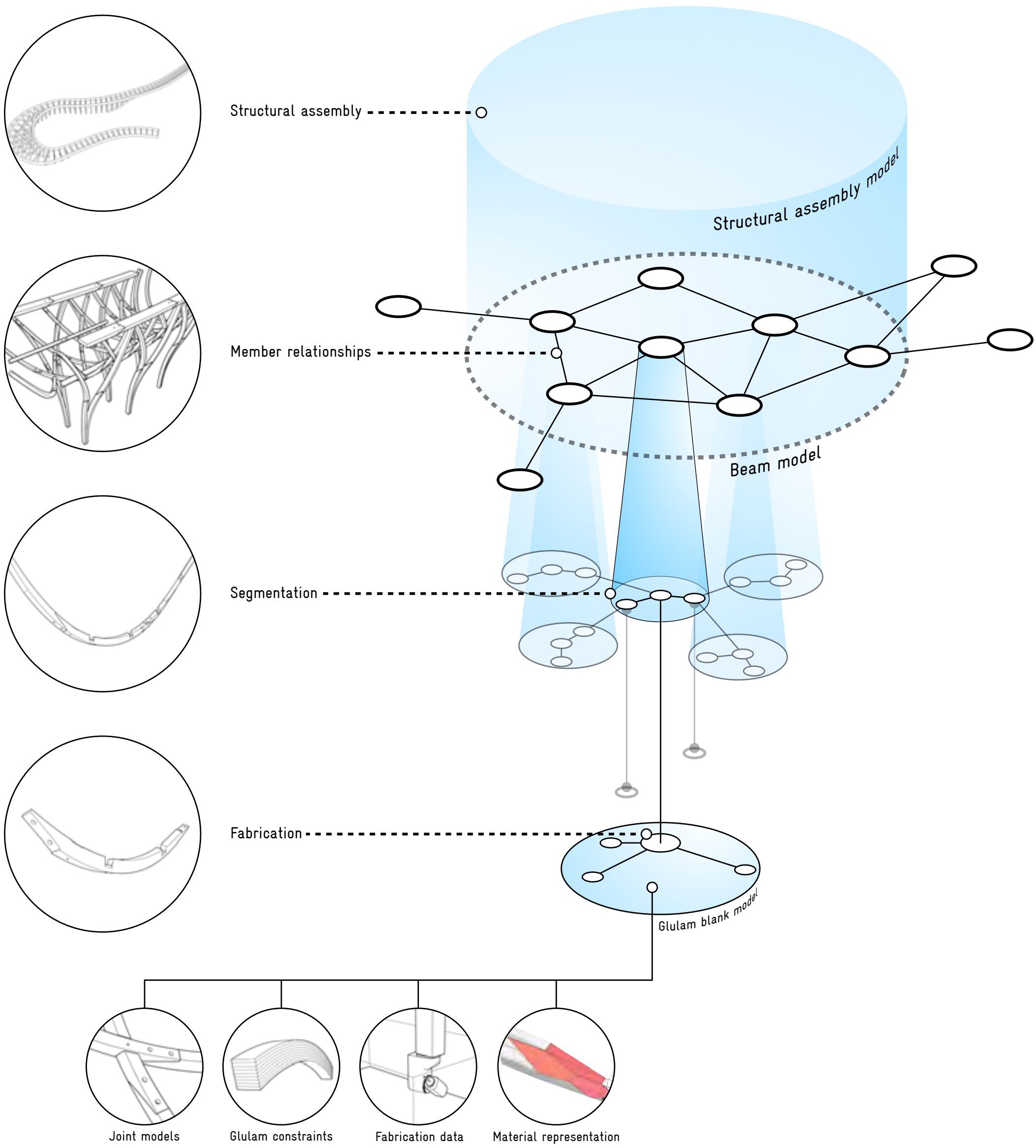


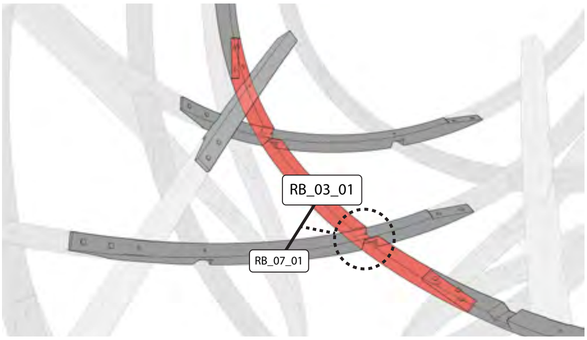
Fig. 6.45: The multiple levels in the Demonstrator: MBridge model. A graph-based model tracks relationships between the structural elements and is further refined into a graph that shows the grouping of every glulam segment and its relevant fabrication data.

6.5.2 Graph modelling

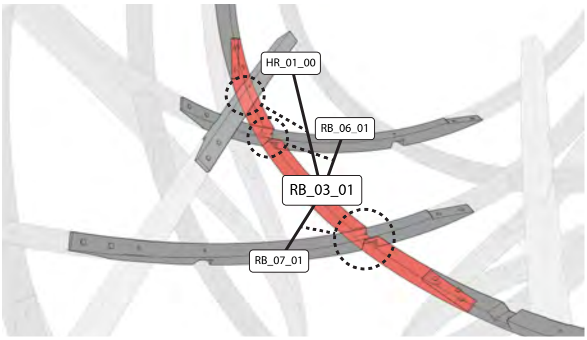
Like Probe 5: Branching Probe and Prototype 2: Grove before, the design of Demonstrator: MBridge is organized using an undirected graph. In this case, however, the graph-based approach is slightly modified to take into account the segmentation of the continuous spans of the hull grid lines (Fig. 6.43). The two-directional bridge hull grid consists of two rows of continuous bands that spiral around the hull surface and intersect each other at roughly perpendicular angles - varying depending on the bend of the bridge and tightness of the ”coil”. Due to material and production limitations, each grid line is segmented into shorter elements. The splitting point has to be carefully placed to avoid interference with a crossing connection with a perpendicular grid line, to ensure a minimum distance between other joints, and to create as long of a segment as possible. The initial graph therefore represents each grid line as a node, with edges between nodes representing the crossing connections with perpendicular grid lines. The segmentation results in several sub-nodes for each node, and the crossing connections between grid lines have to be re-allocated to the various sub-nodes as appropriate (Fig. 6.47). The grouping of the sub-nodes - or the relationship with their ”parent” node - must be kept. At this point, the original - or parent - node functions only as a way to keep track of the sub-nodes - or child nodes - since these segments now represent the individual glulam elements that are to be manufactured. Each group of sub-nodes form a chain of nodes, with the edges between them representing the segmentation points and accompanying splice joint. Edges between sub-nodes of one group and sub-nodes of another group denote crossing joints between segments of another grid line or an interface with a column element. An overview at the highest level show all parent nodes that describe the architectural division of elements across the whole bridge. The children of each parent node go a step further in describing the individual manufactured pieces that constitute each long architectural element. Data associated with the edges between these child nodes describe joints. This gives the graph a particular tree-like hierarchy while still allowing arbitrary references to other elements or nodes in the graph. As a model for communication and planning, the graph makes it very simple to assess the complexity of prototype, independently of its specific geometry or spatial position: counting the number of edges from a node yields the amount of joint details that need to be cut into that particular element. This also facilitates the traversal of the graph to find specific information regarding materials, production data, or joint conditions (Fig. 6.45).

The priority of the Demonstrator: MBridge design is to maximize the use of free-form glulams, thereby aligning the fibres more closely to the curvilinear axes of the structural elements for maximum strength and minimal end-grain exposure. The rationalization and production of these elements is based on

(a) A single rib element, annotated as *RB_03_01*: where *RB* signifies *rib*, *03* denotes the third grid line, and *01* denotes the second segment of the grid line.



(b) The rib *RB_03_01* is connected to rib *RB_07_01* (second segment of the seventh grid line) through a crossing joint (dashed circle). This is represented as an edge int he graph.



(c) The rib *RB_03_01* therefore is a node connected to three other nodes: *RB_07_01* (rib, seventh group or grid line, second segement), *RB_06_01* (rib, sixth group or grid line, second segment), and *HR_01_00* (handrail, first group, first segment).

Fig. 6.46: Representing each structural element as a node and the connections between elements as graph edges.

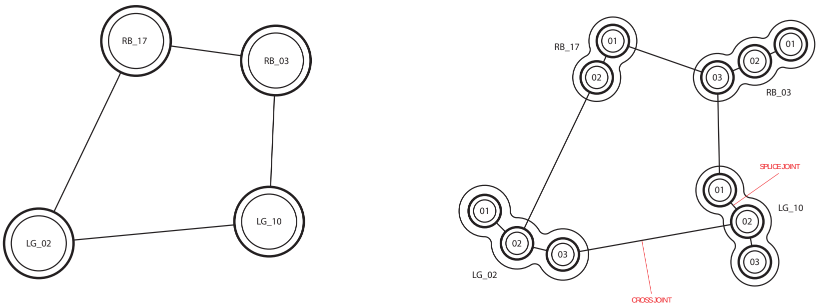


Fig. 6.47: Segmentation of the grid lines means that the original nodes (left) are split into groups of sub-nodes (right) with connections between them. Connections between grid lines (parent nodes) are re-allocated to the appropriate sub-node.

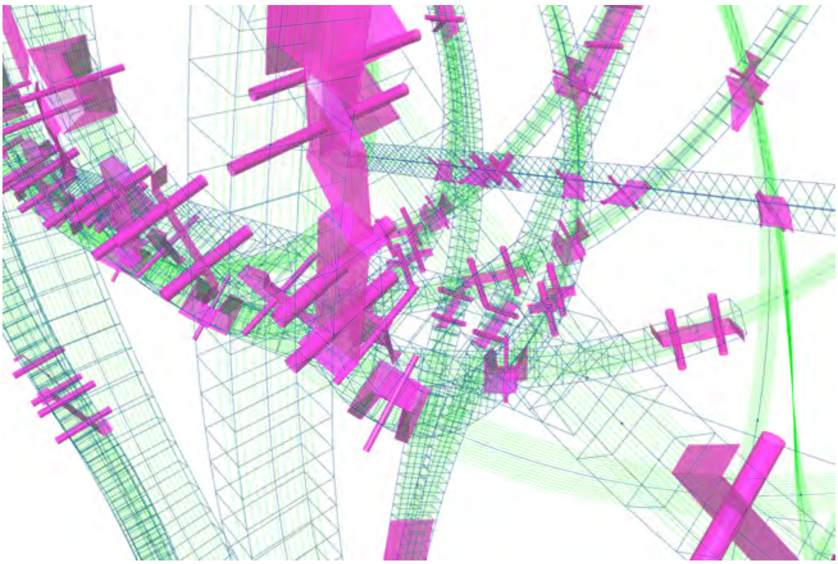


Fig. 6.48: The Prototype 1: Glulam blank model tools allow the required lamella dimensions to be visualized. Geometry used to drive machining strategies is generated by the `GlulamWorkpiece` models.

Fig. 6.49: The sawn spruce lamellae and a finished glulam blank.

the earlier glulam experiments and prototyping for Probe 5: Branching Probe and Prototype 2: Grove. The end goal is to produce a scaled mock-up of several elements that showcases the important junctions and connections between them. A small portion of the bridge that encompasses two leg conditions and a span in-between is therefore extracted for prototyping. The prototype is developed and fabricated over the course of the three weeks in advance of the *Practice Futures – Building Design for a new Material Age* exhibition - the culminating exhibition of results from the InnoChain research network. The prototype is produced at the Aarhus Architecture School, using the wood workshop and a 5-axis wood processing centre.

6.5.3 Prototyping and production

The production framework of Demonstrator: MBridge represents an evolution from the earlier prototyping in Prototype 2: Grove and Probe 5: Branching Probe, both in terms of lamination and machining.

The lamination framework is shifted from the use of MDF moulds and hand clamps to the use of a vacuum press and adjustable steel jig for the forming of the glulam blanks (Fig. 6.50). The advantages of this shift are described in the previous chapter in more detail, however it is useful to summarize them again: the vacuum press creates an even pressure across the whole exposed surface of the glulam blank, which removes the risk of applying too much or too little pressure at different points of the glulam. This reduces the risk

Fig. 6.50: The pressing framework uses a vacuum press and minimal hand clamps.

of delamination and generally makes the whole lamination process much faster. Since the vacuum press takes care of squeezing the lamellae together, the adjustable steel jig can be used only to impart the overall bending form onto the glulam blank. The jig is composed of orientable struts that can be changed to accommodate the different curvatures and geometries of the glulam blanks. This is different from the MDF moulds, which have to be fabricated individually for each bespoke glulam member and which are used to press and form the glulam at the same time.

Off-the-shelf D2 PVA glue is used and applied with a glue roller, greatly speeding up the gluing up process (Fig. 6.51). Due to the difficulty in handling and assembling the laminations, the glulam blanks are fabricated in steps: for a blank that requires 16 lamellae, the gluing is done up to 8 lamellae at a time to ensure that the gluing process can be accomplished within the open time of the glue. This creates a small complication in handling and pressing for the subsequent gluing steps. The first gluing step involves spreading glue on flat lamellae, stacking them, and putting the stacked assembly into the vacuum bag as a straight piece, and then bending the assembly into shape while slowly applying the negative pressure with the vacuum. Removing the now-curved assembly from the bag is trickier due to the curved form. Laminating the second group of lamellae is a challenge: instead of stacking them into a relaxed, straight assembly, they have to be assembled onto the previous lamination - now curved. This requires the new lamellae to be fixed to the previous lamination and bent onto it before placing it into the bag. In the end, the new lamellae are fixed to one end up the previous lamination using a wood screw, then incrementally bent and

Fig. 6.51: The necessary hand tools for the pressing framework: a cordless screwdriver, glue roller, clamps, and glue.

screwed along the previous curved lamination. Placing the lamination back into the bag is also tricky, since the form is already curved and is therefore awkward to handle and insert into the bag. After the second lamination, the screws holding the new lamellae in place are removed, and the process repeated if required for a third lamination. Although this makes it possible to build up the glulam blanks to the required thickness using the simple tools available, it also points to the benefit of having a glue with a longer open time - such as a polyurethane glue which is incompatible with the polyurethane vacuum bags without some sort of barrier - and/or a dedicated single-curved glulam press that can incrementally bend a lamination into shape.

The machining framework also moves from the use of a generic robotic arm to a dedicated five-axis machining centre that much more closely resembles the industrial machining framework at *Blumer Lehmann AG* (Fig. 6.52). This also imparts new parameters and size constraints that impact the overall design of the demonstrator. The size of the machining volume dictates the maximum dimensions of individual elements. While the full machining volume is 2600 x 1500 x 1200 mm large, these dimensions have to also accommodate the movement and positioning of the five-axis spindle - meaning any tool or angular offsets that are caused by the size or orientation of the tool. These constraints are highly influenced by the component geometry: for example, machining into the ends of the glulam beam

Fig. 6.52: The five-axis machining framework is more similar to the production mill at *Blumer Lehmann AG* than the robotic arm.

members from the side limits the length of the pieces, as the machining volume has to accommodate the spindle aggregate as well as enough room for movement and rapid clearance. Similarly, oblique cuts have to be handled strategically, since the spindle is mounted asymmetrically on the aggregate, meaning that a wrong spindle configuration or short tool could lead to a collision with the workpiece.

The machining of the blanks requires them to be positioned and robustly fixed onto the machining bed. A jig similar to the form work is used: adjustable struts with orientable steel heads. The heads of the jig are round, waterjet-cut steel plates with holes for driving screws through and into the glulam blank. The blanks are fixed into place with four of these attachment points, which are in turn calculated from the design model to avoid joint locations and machining surfaces, and to provide an even distribution of support across the workpiece. The base of the jig is fixed to the machining bed using the vacuum bed of the machine.

The glulam blanks are composed out of spruce lamellae (Fig. 6.49). The wood for the lamellae is sourced from a local timber supplier outside of Aarhus. Because the lamella thicknesses vary from blank to blank, sections of construction-grade lumber are ordered, planed, manually band sawn into lamellae, and planed again. This process takes up a major portion of the total production schedule and generates a large amount of wood waste. The use

Fig. 6.53: The finished glulam blanks awaiting machining.

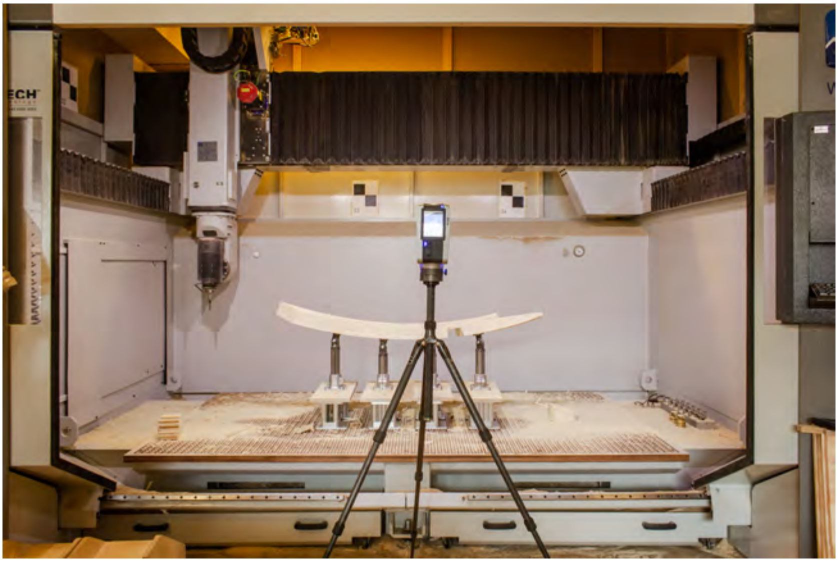


Fig. 6.54: The integration of 3D scanning in the production process builds upon the experiments at *Blumer Lehmann AG*.

of cheaper, lower-grade lumber lowers the material cost, though results in a variable lamella quality.

This is mitigated by effectively creating a composite glulam: placing as much of the lower-quality lamellae on the interior of the glulam blank section and keeping the higher-quality lamellae for the outside layers. This quality appraisal and distribution is done by a simple visual evaluation of the lamellae surfaces: lamellae with larger knots which could crack easier while bending are placed on the interior of the section; clearer lamellae are placed on the outside. The ability to sort the lamellae in this way demonstrates one of the fundamental positive attributes of glue-lamination - the distribution of defects and variable material properties; or the strategic arrangement of wood quality throughout an element. Even large knots are used in this way because, when placed on the interior of the glulam section, the breaking of the lamellae due to the brittle knot is blocked by the lamellae above and below it.

The difficulty in forming double-curved glulams without a dedicated pressing framework motivates the rationalization of slightly double-curved components into single-curved blanks. This is negotiated between the fabrication model of each component and the overall Demonstrator: MBridge geometry. Using single-curved blanks greatly reduces the number of lamellae, which are 8mm-thin planks. The ribs of the bridge need to be

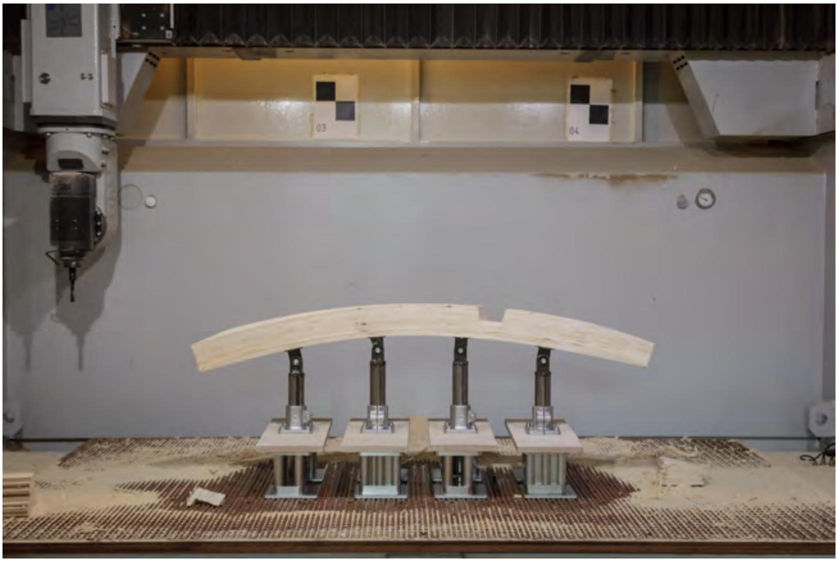


Fig. 6.55: The multi-axis machining of each glulam element.

double-curved so that they can wrap around the free-form hull geometry, however the segmentation strategy the ribs optimizes the splitting of the ribs into individual segments that are each as little double-curved as possible. As in Prototype 5: Magelungen Park Bridge, the rationalization of double-curved elements into single-curved blanks is performed with a small simplification distance. This increases the amount of wood required due to the extra necessary width of the glulam blanks because of the double-curvature, however it makes the handling and pressing possible using the available infrastructure.

This rationalization is made possible by the glulam blank modelling tools, which yield data about the required composition of each glulam blank as well as key characteristics of their curvature, all of which translate into fabrication implications. The negotiation between these concerns and the overall demonstrator design show the utility of both the glulam blank modelling tools - the proposed *simulated feedback* - as well as the prototyping strategies developed in this research.

6.5.4 Integrated digital feedback in production

The digital sensing feedback in Demonstrator: MBridge is a continuation of the last of the four methods in Prototype 3: Four methods of digital feedback: 3D LiDAR scanning with a Faro Focus 3D scanner. To create a calibrated machining environment that could be referenced with 3D scanning, a series of checkerboard markers are printed and mounted on the inside of the machining volume. These are evenly but asymmetrically distributed around the volume boundaries, with particular care to be visible from the 3D scanner and out of the way of the spindle. The asymmetry of the checkerboard targets creates a clear and unambiguous orientation of their constellation. The empty machining volume of the wood processing centre is scanned with all the targets visible. This becomes the *master scan*, to which all the subsequent scans are aligned. A series of test cuts and measurements are performed to align the machine coordinate system with the master scan - a calibration of the machining space with the 3D scanner as discussed in Prototype 3: Four methods of digital feedback. Aligning subsequent scans to the master scan therefore allows a quicker feedback loop between scanning and machining.

Each blank is scanned when placed onto the machine to locate it within the machining framework and align the model data to the physical workpiece. The positioning of the mounting jig is derived from the fabrication model, however this only gives a rough - within 10mm - indication of where the glulam blank is. This helps to ensure that the blank is within the machining volume and can be processed without hitting the machine limits or without any collisions with the machine elements. The alignment using the 3D scan helps to position the data more accurately - to within 1mm.

Because the underside of the blanks cannot be machined - due to the limits of the machine geometry and the mounting jig - the machining has to be done in two passes. After the top surface, joint details, and ends are machined, the workpiece is flipped, and the finished side is mounted onto the mounting jig. Again, the positioning of the mounting jig is informed by the model, but with a large tolerance. Another 3D scan allows the model to be positioned much more precisely onto the flipped workpiece, thus ensuring geometric continuity between both machining passes.

The proposed *direct feedback* is therefore successfully deployed to merge the physical free-form glulam blank with the digital fabrication model and verify its geometric boundary.

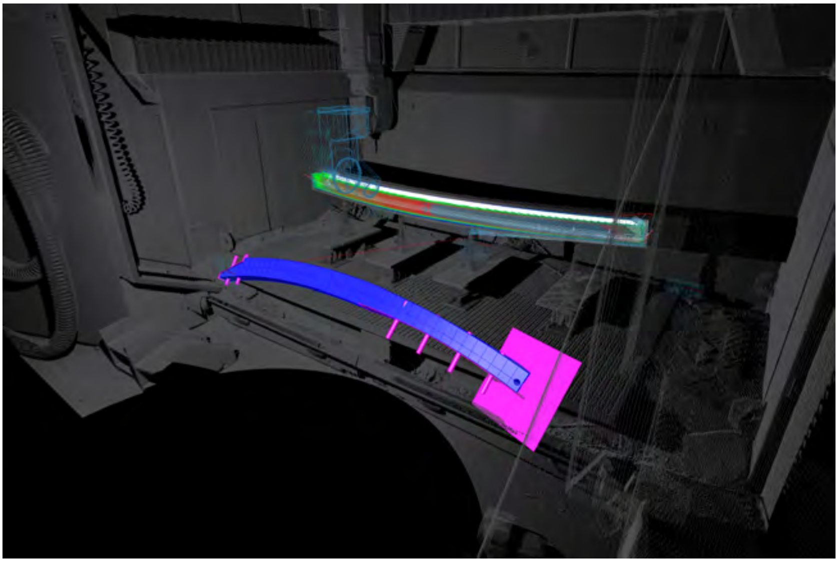


Fig. 6.56: The `GlulamWorkpiece` model (blue) aligned with the 3D point-cloud of the machining environment (red, green, teal). The machining framework (blue wireframe) is aligned with the point-cloud.

6.5.5 Revisiting the Branching Blank

The prototyping of the legs of the Demonstrator: MBridge presents an opportunity to reconsider the Branching Blank from Probe 4: CITAstudio glulam workshop, Probe 5: Branching Probe, and Prototype 2: Grove. Previous attempts highlight the challenge of forming the double-curved arms and the perpendicular reinforcing layer all at once. This is both impractical with clamps and pressing tools, and unfeasible due to the long assembly time required - the amount of elements and the specificity of their placement make executing the work within the open time of the glue very difficult. Therefore, the formulation of the Branching Blank is performed more sequentially and iteratively. Each arm is formed and machined separately and then glued together in an additional lamination process. Each half includes the machining of circular holes for the perpendicular bracing layer. Instead of a continuous layer of spruce lamellae as before, this layer is made up of beech dowels both for added strength as well as to avoid the need to cut rectangular slots to fit the lamellae. The dowels are glued into the halves as they are joined together in the final lamination step. This is a more iterative approach in line with the cyclical thinking in glulam production that is explored in Probe 4: CITAstudio glulam workshop: the glue-laminated and machined elements become a component of a new glue-laminated element.

Fig. 6.57: Testing the assembly of individual components.

The engagement of the designer with glue-laminated timber processes and the introduction of iteration into the production framework of laminating and machining is emblematic of the *process feedback* proposed by this research.

In the end, the Demonstrator: MBridge consists of 6 components: 4 branching elements and 2 double-curved elements. Each branching element is composed of 2 double-curved elements, for a total of 10 individually-machined elements. Each element is machined twice - once for the top and joint details, and a second time for the bottom and leftover side surfacings. This means that 10 glulam blanks are formed and 20 machining jobs are processed in the production of the demonstrator.

The final steps are the packing of the machined components into a crate the size of two shipping pallets and the transportation by truck from the workshop in Aarhus to the exhibition space in Copenhagen for assembly. The final demonstrator is assembled in one hour using standard M10 bolts in a simple sequence: the Branching Blank components for the legs are assembled, each leg is raised and stabilized by cables, and the rib elements are lifted and connected to both leg assemblies. Since only two legs are fabricated, the final piece is stabilized by cables from the ceiling.

Fig. 6.58: The machined components, awaiting assembly.


02
INTEGRATED MATERIAL PRACTICE

6.6 Summary

This chapter charts the development of a material practice that engages with the complexity and multi-scalar nature of contemporary glue-laminated timber construction through the lens of digital technology. This material practice begins with the intersection of computation and wood - how to digitally model the material and manage its transformation into structure and space; and how to physically manipulate the material and respond to its behaviours and particularities - and activates this to create novel design possibilities.

The progression begins with open-ended and playful explorations of speculative spaces that are framed by large free-form glulam components in Probe 3: Future Wood workshop. This helps to reconsider early prototyping experiments as spatial elements and drivers of design. These are therefore subsequently deployed in Probe 5: Branching Probe and Prototype 2: Grove, which also address architectural issues of programme, site, structure, and collaboration. The research is then recontextualized within a multi-disciplinary architectural design practice setting during an industry secondment with *White Arkitekter*. This reveals the role of the material practice as a broker of knowledge between domains of materialization and modelling, and demonstrates the utility of the glulam blank modelling tools in imparting fabrication knowledge within the early-design stages of Prototype 4: Slussen benches and Prototype 5: Magelungen Park Bridge. The integration of timber and its behaviour in these projects significantly shifts their narrative and outcome of their design process.

The development of Prototype 5: Magelungen Park Bridge leads to a case study that is taken up by Demonstrator: MBridge which synthesizes the domains of materialization, modelling, and design implementation by articulating and employing the four proposed notions of feedback - simulated, process, direct, and brokering. The ability of these feedback linkages to modify and facilitate the successful outcome of Demonstrator: MBridge - whether or not it can be successfully executed - is demonstrated. The evolution of the glulam blank modelling tools and Branching Blank between the initial prototypes and Demonstrator: MBridge further demonstrates the material practice in action: a reflective and iterative engagement with the material properties and behaviours of glue-laminated timber, augmented by computational means.

7

CONCLUSION

7.1 Overview

This chapter concludes the thesis in seven main sections, including this overview. The second section restates the aims of the research. The third section summarizes the findings of the research in relation to the experimental work. Based on these findings, the fourth section answers the research questions. The fifth section restates the contributions of the research. The sixth section discusses the limitations in the research. The final section opens up future directions through a discussion of perspectives for further work.

7.2 Restatement of aims

The aim of this research is to develop a link between early-stage architectural design processes and the fabrication of free-form glue-laminated timber buildings by integrating materialization concerns into computational modelling workflows and by expanding the architectural design space into the realm of the glulam blank.

This is contextualized against the digitization of the timber industry and its shift towards information processes, the maturing of digital tools and subsequent simulation-based developments of material practices in architecture, and the changing role of digital models from tools of representation to functional participants in the design-build process. This requires established design and timber practices to be re-examined.

Disrupting the linearity of the design chain introduces opportunities for feedback and a closer integration of design intent and material knowledge. The need for an earlier gathering of stakeholders in free-form timber projects is apparent, as is the need for interfaces or boundary objects between the knowledge domains of early-stage architectural design and industrial timber fabrication.

This research addresses these needs through a collaboration with two industrial partners - *Blumer Lehmann AG* and *White Arkitekter* - that each represents one end of the design chain. The partnership between *CITA* - the academic partner - and the industrial partners conveniently creates three distinct environments of computational modelling, architectural design, and industrial fabrication which the research aims to synthesize.

By making relationships between design and material performance explicit and embedded in deployable modelling tools and workflows, the research brings forward the domain of materialization into the domain of modelling. By expanding the design space of timber structures to encompass the design of the glulam blank and a reconsideration of the linearity of timber processes, the research retargets the interface between design and timber processing to an environment that is more aligned with material and production constraints. The formulation of a digitally-enabled material practice leads to new architectural timber morphologies and conversations between design and making by acting as an interface - or broker - between these two realms.

7.3 Summary of findings

In support of the aims summarized above, the research presents a number of findings borne out of the experimental work presented in the previous three chapters.

7.3.1 Integrated material modelling

The research finds that the integration of timber properties and production constraints into lightweight modelling tools can speed up the modelling of free-form timber structures and provide valuable insights into the consequences of design decisions for downstream fabrication during iterative early-stage design processes. The ability to foresee production challenges and impacts on aspects such as durability and cost at the very beginning of the design process have a positive effect on lowering risk and creating a convincing case for the design project. The multi-scalar implementation creates interfaces for material simulation - such as finite element modelling - and the analysis of localized material distribution and orientation, as well as larger-scaled, analyses on entire structures. The influencing of design decisions by simulated material and process constraints constitutes *simulated feedback*.

The work performed in the domain of modelling develops digital tools and workflows that embed materialization concerns - material behaviour, material properties, production constraints, geometric limits - into lightweight computational modelling tools. This software is developed as a plug-in to familiar architectural CAD environments, lowering the barriers for its use and extending rather than replacing existing architectural design tools. The development of these tools begins in Probe 1: Modelling wood properties and proceeds through Prototype 1: Glulam blank model.

The design of Probe 5: Branching Probe and Prototype 2: Grove show how these modelling tools can greatly speed up the modelling of free-form glulam structures. These design projects contain several hundred unique free-form glulam components. The integrated modelling tools allow the project model to be regenerated quickly and iteratively adjusted to minimize production difficulties. The multi-scalar approach used here is described in Svilans, Poinet, et al. (2017) and shows how a hierarchy of lightweight models - between a global skeleton model and a component-wise fabrication model - work together to allow a confident overview of the many components.

The use of the integrated material modelling tools in the context of architectural practice at *White Arkitekter* is explored in Prototype 4: Slussen benches and Prototype 5: Magelungen Park Bridge. While Prototype 4: Slussen benches relies more on physical prototypes of details to inform the project team, the modelling tools and rationalization of free-form glulam elements that is made possible by them increases the acceptance of the bridge proposal in Prototype 5: Magelungen Park Bridge. Svilans, Runberger, and Strehlke (2020) describe how lightweight materially-informed modelling tools in an architectural design setting have a direct impact on cost and production feasibility.

This finding is further supported by the intensive application of the material modelling tools in Demonstrator: MBridge. The success of the project - whether or not it could be executed - relies on reconciling production and material limitations with a free-form bridge design. The ability to rationalize the design geometry to use single-curved glulam blanks and extract their precise material specification allows the project to be successfully executed by an individual - from design to manufacture.

7.3.2 New glulam morphologies

The research finds that the challenging of the sequencing and linear nature of glulam processing can yield novel types of glue-laminated timber elements that respond to specific performance and functional requirements. The glulam experiments in Probe 4: CITAstudio glulam workshop ask how specific joints or timber processes could be reimagined through glue-lamination techniques and re-sequencing of timber processes. Several of the glulam components are functionally targeted: the *Cross-laminated Joint Blank* and the *Branching Blank* are designed for a particular, non-generic architectural situation due to their integration of multi-element connections and multiple endpoints. This is contrasted by the genericness of off-the-shelf glulams or even free-form glulam blanks, whose form is already largely determined by the glulam press. This means that the design of the glulam blank becomes more bespoke and tailored for the design project that it is fabricated for.

The involvement of the architectural designer within the space of the glulam blank and the introduction of iterative lamination and process steps forms *process feedback*.

7.3.3 The necessity of digital sensors

The research finds that, due to the new complexity created by double-curved glulams and the novel types of glulam blanks described above, the synchronizing of the physical workpiece with its information model through digital sensors and 3D scanning is a necessity. Aligning these non-orientable forms with the coordinate space of the production machine is extremely labour- and material-intensive with conventional datums and methods. Further, the material behaviour of timber components and relevant processing steps result in dimensional discrepancies due to anisotropic swelling, shrinkage, springback, and variable lamination tolerances. The trialling of different scanning methods in Prototype 3: Four methods of digital feedback indicate that these sensor systems are feasible to implement and useful for the production of complex 3D elements. The production of Demonstrator: MBridge makes extensive use of LiDAR scanning for the registering and relocating of the glulam elements on the 5-axis machining centre, without templates or jigs. Once again, the successful double-sided machining of each element is only made possible by this application of 3D scanning.

This *direct feedback* permits a reflexive relationship between the process of making and the process of modelling.

7.3.4 Brokering actions

The research finds that computational modelling methods are not enough to fully integrate material performance in early-stage architectural design. The design modelling tools offer simulated feedback regarding material specification, performance, and production constraints, but the knowledge of what to input and what to do with the outputs of these tools is still required. For the modelling tools to be usable, they must serve an actionable purpose that cannot be computationally defined, such as design objectives and overall design intent.

During the development of Prototype 4: Slussen benches and Prototype 5: Magelungen Park Bridge, conversations between *White Arkitekter*, *Blumer Lehmann AG*, and *Design-to-Production GmbH* centre around the development of a *material concept* that is an overarching set of values and decisions that is to drive the design and modelling of both projects. This sharing and discussion of principles defies computational encoding and relies instead on the meeting of different domains: the gathering of stakeholders.

This *brokering feedback* is provided by this research as an actor between both industrial partners. The transfer of knowledge from the domain of production to the domain of architectural design through an independent researcher is described in Svilans, Runberger, and Strehlke (2020) and details its application to Prototype 5: Magelungen Park Bridge and Demonstrator: MBridge.

7.4 Answering the research questions

In light of the findings above, the research questions posed in the beginning of this thesis are now answered.

How can tacit knowledge of glue-laminated timber behaviour and performance be encoded through computational tools of modelling and simulation?

The material practice formulated in this thesis identifies four different notions of feedback that allow a deeper interfacing with material behaviour and performance. Two of these are computational in nature - *simulated feedback* and *direct feedback* - however the research also demonstrates that these are not sufficient in themselves to fully link early-stage architectural design of free-form timber structures with their material realization.

The four main notions of feedback are:

- *Simulated feedback* is brought about by the computational modelling tools described in *Chapter 4: COMPUTING TIMBER*. Parametric and analytical models inform the designer of the consequences of their design decisions for the materialization of their design. Constraints that affect late-stage fabrication are embedded in computational models which are used in early design stages. Simulated feedback is the translation of principles and nominal constraints into design modelling tools.

- *Direct feedback* is digital data that is derived from sensors such as scanners and encoders. This type of feedback translates sensor data into indications of the present state of a material process. Direct feedback links the physical object to its virtual counterpart. This creates the opportunity for materialization to inform the propositional processes and models.

- *Process feedback* introduces recursion into previously linear production processes. When broken down into individual unit processes, the production sequence of pressing and machining glulam components is rearranged and fed into itself. This type of feedback unpacks the glulam production process into a collection of processes that can be rearranged, multiplied, and mixed. This leads to a reconception of standard glulam blanks and the potential for novel morphologies of glulam components.

- *Brokering feedback* transfers knowledge between the domain of industrial timber fabrication and the domain of architectural design through an actor that is involved in both domains. This actor assumes the role of a facilitator and broker in order to bring late-stage materialization knowledge forward into early-stage design processes. The collaboration between this research, *White Arkitekter*, and *Blumer Lehmann AG* demonstrates this type of feedback and is described in Svilans, Runberger, and Strehlke (2020). This research acted as a go-between in a network of project teams, architects, engineers, and consultants for several early-stage architectural design projects.

The secondary questions are focused on each of the three experimental domains - modelling, materializing, and design integrating - reflective of the three previous project chapters.

7.4.1 Computing timber

How can the heterogeneity of timber be stored and represented across digital architectural models at micro, meso, and macro scales?

The multi-scalar computational developments in Probe 1: Modelling wood properties and Prototype 1: Glulam blank model put forward ways of layering heterogeneous material data on top of geometric models of architectural components and representing it through a discretization into elements and the mapping of colour.

- The discretization and colour mapping experiments in Probe 1: Modelling wood properties tessellate geometric models of timber components into simple elements, thus allowing varying micro-scale properties such as grain direction to be encoded and represented throughout volumes on a per-element basis.

- The meso-scale modelling in Prototype 1: Glulam blank model attaches fabrication and material specification data to a constrained glulam blank model. As in Probe 1: Modelling wood properties, material orientation is represented through colour mapping. Material bending constraints are linked to lamella specifications, directly relating geometry to material performance. The link between micro-scale element models and component scale geometric models is demonstrated as a mapping of one to the other, and a cross-referencing between the two types of models.

- The graph-based models deployed in Probe 5: Branching Probe, Prototype 2: Grove, and Demonstrator: MBridge are shown to be especially effective in moving between coarse macro-scale representations of an entire structure and machining details on individual glulam components at the meso-scale using referencing and the on-demand generation of data. This is made especially apparent in the design of Prototype 2: Grove, as described in Svilans, Poinet, et al. (2017).

The added complexity of representing orientation - consisting not only of a single direction but an orthotropic frame of reference - is discussed and the need for further work is highlighted. Possible interfaces with detailed material simulation such as FEA are shown, though these remain to be explored in further detail.

What computational modelling methods are able to communicate the performance and production implications of free-form timber structures to the architectural designer?

Graph-based and relational models are explored through projects such as Probe 5: Branching Probe, Prototype 2: Grove, Prototype 5: Magelungen Park Bridge, and Demonstrator: MBridge. These modelling methods prove to be effective in managing large counts of different sub-models for individual glulam elements, connections, and other objects. The decoupled glulam blank model developed in Prototype 1: Glulam blank model allows on-demand creation of geometry from lightweight data and the inclusion of joint details and fabrication information. This allows a large network (or graph) of elements to be traversed and decomposed into individual sub-models that can be further analysed for fabrication implications, grain direction, end-grain exposure, and so on. This directly communicates production and material implications to the architectural designer in a familiar 3D modelling environment. This agility allows these implications to be embedded into iterative early-stage design phases.

7.4.2 Glulam provocations

How can a reflexive interrogation of the wood value chain and glulam production line lead to alternative morphologies of free-form glue-laminated elements?

Projects Probe 2: IBT glulam workshop and Probe 4: CITAstudio glulam workshop show that a basic understanding of sawmilling, glue-lamination processes, and assembly principles can lead to new morphologies of free-form glue-laminated timber elements. Although the resulting prototypes are not rigorously tested from an engineering point of view, the resulting elements are clearly different from existing glue-laminated timber market products. This suggests that a deeper involvement of an architectural designer in the wood value chain can have benefits for the novelty and diversity of timber design, as well as potential alternate solutions to structural or design problems.

How can digital sensing methods during production be used to more closely relate virtual production model and material workpiece?

The 3D scanning and sensing experiments initiated in Probe 4: CITAstudio glulam workshop and further expanded and developed in Prototype 3: Four methods of digital feedback demonstrate different methods of spatially synchronizing the virtual model and the glulam blank. These experiments also show that the tools themselves did not have to be complicated or new by themselves, but rather that the development of a legible and clear user interface helps to integrated digital sensing technologies into established industrial production processes.

7.4.3 Design implementation

How does the digitally-augmented material practice developed in this research transfer to the context of architectural design practice?

Prototype 4: Slussen benches applies the thinking from the glulam prototypes in Probe 2: IBT glulam workshop and Probe 4: CITAstudio glulam workshop to a public furniture project developed at *White Arkitekter*. Material prototypes of potential glue-laminated solutions for the benches are fabricated and presented to the project team, making discussions with the wider project team and consultants possible. A similar approach is used in the Prototype 5: Magelungen Park Bridge project, where the early-stage design development culminates in the Demonstrator: MBridge project. The computational modelling tools from Prototype 1: Glulam blank model are deployed in the Stockholm studio during the industry secondment and are used to create and evaluate early models of the bridge. The modelling tools help to identify types of blanks and to prepare a structural concept that is brought before the project engineering consultants at Sweco Engineering for feedback. The consensus among the industry partners - both at *White Arkitekter* and *Blumer Lehmann AG* - is that early prototyping and mock-ups are indispensable tools for driving design development in timber projects. Another effect of bringing in the prototypes early into the process is inspiring more trust in the material system for the project leaders and wider project teams.

How can the brokering of knowledge between stakeholders introduce productive feedback loops at the early-stages of a design project within an architectural practice setting?

As discussed above, beyond the integration of simulation and digital modelling tools into design processes, the material practice proposed by this thesis serves as a communicative linkage between the material - glue-laminated timber - and the designer - the architectural practice. The communication of late-stage (fabrication, materializing) concerns to early-stage (concept design, initial development and proposals) processes achieves this circularity. The projects developed with *White Arkitekter* - Prototype 4: Slussen benches, Prototype 5: Magelungen Park Bridge, and Demonstrator: MBridge - show how the knowledge gleaned from the previous secondment with *Blumer Lehmann AG* contributes to real, actionable shifts in the design development. The modelling tools from Prototype 1: Glulam blank model help to illustrate and facilitate this brokering of knowledge, and provide more information for the designer, such as the implication of design choices and the relationship of design geometry to fabrication complexity.

Another aspect, which should be elaborated on in future work, is the role of the thesis itself in acting out the material practice and the brokering of knowledge between *White Arkitekter* and *Blumer Lehmann AG*. During both Prototype 4: Slussen benches and Prototype 5: Magelungen Park Bridge projects, meetings and discussions about the thesis development - involving both industrial partners - also serve as opportunities to exchange knowledge between the partners without the complications of a contractual overhead. This almost clandestine consultation allows fabrication and material expertise to be brought on board both projects through the framework of the InnoChain network and this thesis project, without incurring the legal and contractual demands such an exchange would otherwise entail.

7.5 Restatement of contributions

This section reiterates the contributions of the research. These are divided into the main contribution of the thesis, the secondary contributions of the thesis which are mapped onto the experimental domains, and tertiary or collateral contributions.

7.5.1 Main contribution

The central contribution of this thesis is a framework for a digitally-augmented material practice that is centred around glue-laminated timber, and positioned between the realms of architectural design and large-scale timber fabrication.

This practice is driven by an intertwining of modelling and materializing, and supported by four different notions of feedback which allow it to be reflexive. Digital modelling integrates material affordances within design processes, and digital interfaces such as sensors and 3D scanning are used to create a reflexive relationship between digital model and physical material. This practice is multi-scalar in that it considers material properties, distribution, and orientation at a highly localized level; material specification, production processes, and fabrication constraints at a component level; and relational modelling of interconnected glulam structures at an assembly level.

This practice identifies the ”in-between” product in large-scale engineered timber building - the glulam blank, an assemblage of active, biological material into forms that are dictated by geometric operations and industrial processing machinery - as a fertile ground for fusing architectural design with industrial production, aided by digital tools that expose and make explicit certain parameters that drive the conception and specification of the glulam blank. Through its ability to be aggregated, composed, and assembled in any number of ways, the glulam blank allows a wide range of adjustable, designed performances.

Although it is digitally-augmented, the practice recognizes that computational and digital modelling processes alone are not enough to traverse the gap between an innate knowledge of materialization and its deployment within broader practices of design with a multiplicity and diversity of stakeholders. In this sense, it recognizes that the gap must be ”transgressed” (Sheil 2005) by opening up the glulam blank as a space of design, and that knowledge must be brokered through principles and shared vision between stakeholders. Nevertheless, the practice contributes a computational means to address several key factors in the design of free-form glue-laminated structures that can substantially expedite their conception.

7.5.2 Secondary contributions

The secondary contributions are specific to each of the three experimental domains through which the material practice is interrogated.

- In the modelling domain, the main contribution is a software library and digital modelling workflows for free-form glulam blanks that embed particular material and production constraints. The software library encompasses the results from Probe 1: Modelling wood properties and Prototype 1: Glulam blank model and consolidates them in a library that is made accessible through plug-ins for the Rhinoceros 3D CAD environment. A series of workflows demonstrate its application to architectural design projects, such as those used for Probe 5: Branching Probe, Prototype 2: Grove, Prototype 5: Magelungen Park Bridge, and Demonstrator: MBridge.

- In the materializing domain, the main contribution is the design space of the glulam blank - or *blank space* - as well as the procedures it involves, such as the iterative re-thinking of industrial timber processes and the integration of 3D scanning and digital sensing within industrial timber workflows. In particular, Prototype 3: Four methods of digital feedback contributes an overview of different types of sensing technology for use within industrial free-form timber machining workflows. The exposition of the glulam blank as a productive source of new timber morphologies and the development of the necessary workflows to manage and process bespoke, non-orientable geometries of timber components contributes a new direction for timber design and architecture.

- In the domain of design implementation, the main contribution is a demonstration of how this practice is deployed and developed. This involves an application of the previous two contributions from the two preceding domains to a variety of architectural design projects and case studies: Probe 3: Future Wood workshop, Probe 5: Branching Probe, Prototype 2: Grove, Prototype 4: Slussen benches, Prototype 5: Magelungen Park Bridge, and Demonstrator: MBridge. These provide evidence for how such a practice can be deployed beyond the scope of this research.

7.5.3 Collateral contributions

Collateral contributions are scripts and software programs that are developed in tandem with the research but that do not directly relate to the topics of research. In a sense, they act more like jigs and supporting infrastructure to allow the research work to be conducted.

- **carverino** - A .NET wrapper, Rhino plug-in, and Grasshopper plug-in for the Carve mesh boolean library.
- **tetrino** - A .NET wrapper and Grasshopper plug-in for the Tetgen library.
- **rhino_faro** - A Rhino plug-in for loading and manipulating Faro scan files.
- **bpy_triangle** - A Python wrapper for the Triangle library, exposed as an add-on (plug-in) for Blender.
- **SpeckleBlender** - An add-on (plug-in) for Blender for interfacing with the Speckle framework.
- **rhino_natnet** - A plug-in for Rhino that allows the real-time gathering and visualization of data from NatNet's Optitrack motion tracking system.
- **fls2pcd** - A conversion utility for converting Faro scan files to PCD files, used by the open-source PCL library.
- **PySpeckle** - A Python client for the Speckle framework.
- **CITA Robots** - A fork of the Robots plug-in for off-line industrial robot programming, with specific tools for the CITA robot lab and applications.

7.6 Limitations

This section provides a self-reflective discussion about the limitations of the employed methods in this thesis.

7.6.1 A design perspective

The research is approached from the perspective of architectural design and integration. This specific perspective privileges an overview and a linking of different disparate parts into a new whole - a breadth rather than depth. The experiments in the domain of modelling demonstrate interfaces to other, deeper simulation techniques such as FEA and related fields of mathematics and geometry. It is shown that it is possible to link design models to detailed engineering models, however this research leaves the development and rigorous application of those engineering models to others. Similarly, the entire fields of wood science, production technology, and material testing cannot be apprehended in this thesis. The experiments in the domain of materializing therefore do not claim to demonstrate optimized and marketable products - either through the novel glulam types or the scanning experiments. Instead, they demonstrate how these directions and ways of thinking can be linked to modelling and designing, and subsequently open up new potential trajectories for the digitally-augmented crafting of wood structures.

7.6.2 Scaled experimental work

The material prototyping performed in the research is at a scale that is different from that of the industrial production context. The glulam pressing framework is limited to tools that are operable by hand by an individual or a small team: hand clamps, vacuum presses, jigs made out of standard plywood and MDF sheets. The machining framework is similarly operable by an individual: a robotic arm or a 5-axis wood processing centre. The adhesive used for lamination is that which is commonly available for carpentry and woodwork. While these disparities prevent the prototypes from being immediately put into commercial practice, the principles and strategies developed through the making and reflection on the material prototypes nevertheless are transferable to the larger industrial context.

7.6.3 The context of a partnership

The research is conducted in partnership with two industrial partners - *White Arkitekter* and *Blumer Lehmann AG*. While these are indicative of the state-of-the-art in both architectural practice and industrial timber production, the knowledge gathered from secondments and collaboration with these partners is limited to their specific environments, approaches, and histories. The research acknowledges that there are many architectural practices and many industrial timber fabricators with an equally large diversity of methods and approaches.

7.6.4 Free-form timber

The research focuses specifically on free-form glue-laminated timber structures - ”free-form” because such structures invoke the challenges and constraints of the bending behaviour of wood to its fullest; ”glue-laminated timber” because it is represents timber buildings at the largest scale and offers many possibilities for composition, aggregation, and material distribution. The research acknowledges the many excellent research efforts that both question the need for free-form structures as well as the irony of cutting up at tree only to glue it back together.

7.7 Perspectives and future outlook

The conclusion of this thesis points to several avenues of further exploration and implications for future research into timber design and fabrication.

7.7.1 Extending the chain

This research offers methods with which the domain of architectural design can extend further back into the wood value chain - from the design of glue-laminated timber components to the design of their material composition. A logical extension of this is to speculate about how the domain of design could be extended even further back - into sawmilling and forestry - and how the application of information-communication technologies (ICT) can integrate processes and products of these earlier domains into later domains of fabrication, assembly, maintenance, and disassembly. Further research looks at how information technologies in sawmills - such as the computed tomography (CT) scanning of harvested logs - can bring about a greater specificity and a higher resolution of material performance data. At the other end, embedding sensors into ”smart” glue-laminated building components has the potential to monitor material performance throughout the lifespan and disassembly of a structure, leading to an integration of material performance into late-stage and end-of-life processes. The alternative glulam blanks presented in this research demonstrate a way by which novel glulam types can be designed and put into use. Further ”mutations” of the glulam - in conjunction with other material processes or functions - can therefore benefit from the extension of the wood value chain in both directions.

7.7.2 Interfacing with silos

As discussed in the limitations of this research, the design-centric perspective precludes the research from engaging in detailed engineering analysis of the modelling methods and glulam prototypes. Instead, it offers interfaces that permit the generation and communication of models and data, which are therefore intended to be consumed by experts in other domains. In particular, the computational modelling tools in this research create necessary data for interfacing with structural and material analysis through the discretization of glue-laminated geometry into element models and through the light-weight centreline-based glulam structure models. These provide data such as material orientation and glulam specifications which can be translated into CAE simulations. Further, the glulam prototypes are speculative tools that allow a deeper engagement with fabricators and engineers by demonstrating in physical detail how the prototypes are meant to perform. How the production of these speculative glulam types can be scaled up and made economically feasible is a future research path.

7.7.3 Computational design beyond architectural practice

This research focuses on large-scale multi-disciplinary architectural practice and large-scale industrial timber fabrication in the service of producing large-scale buildings. The research explores complex and demanding structural morphologies along with the complex production infrastructures required to execute them. Considering the ubiquity of computational power and modelling software, the implications of this research must be explored beyond architectural practice and into the realm of non-specialists, trades people, and individuals. Returning for a moment to a more romantic notion of the individual craftsperson in their workshop, the findings of this research are applicable to a small-scale practice as much as they are to a large one. Considering that the final demonstrator could be designed and fabricated by an individual, future paths must explore how computation and modelling can transform the role of the individual carpenter with a smaller production infrastructure. To this end, the miniaturization of CNC systems, the increasing affordability of 3D scanners, and the interconnection of everyday devices with mobile phones offers a glimpse of how the ubiquity of computation could be leveraged.

7.7.4 New workflows in digital timber

Finally, this research explores computational augmentations for industrial timber production through the modelling and generation of material and fabrication data, and the integration of sensors and scanners into the production workspace. This points to ways with which the timber industry can evolve to accommodate cyber-physical systems and take advantage of the offerings of information modelling and the emergent ”material computation”. Challenges such as low profit margins, distributed networks of suppliers, and isolated trades need to be confronted, however the creation of information interfaces can begin to mitigate these. The overlaying of information and virtual models onto the physical production space has the potential to extend the digital continuum into a reflexive, cyber-physical *digital timber continuum*.

A

DISSEMINATION

A.1 Publications

- Tom Svilans, Paul Poinet, et al. (2017). “A Multi-scalar Approach for the Modelling and Fabrication of Free-Form Glue-Laminated Timber Structures”. In: *Humanizing Digital Reality*. Springer, pp. 247–257
- Tom Svilans, Martin Tamke, et al. (2019). “New workflows for digital timber”. In: *Digital Wood Design: Innovative Techniques of Representation in Architectural Design*. Ed. by Fabio Bianconi and Marco Filippucci. Springer, pp. 93–134
- Tom Svilans, Jonas Runberger, and Kai Strehlke (2020). “Agency of Material Production Feedback in Architectural Practice”. In: *Design Transactions: Rethinking Information Modelling for a New Material Age*. Ed. by Bob Sheil et al. UCL Press, pp. 98–105

A.2 Selected presentations

- InnoChain start-up seminar. KADK, Copenhagen, Denmark. March 2016.
- Digital Carpentry. Space 10, Copenhagen, Denmark. December 2016.
- InnoChain colloquium. IOA, Vienna, Austria. March 2017.
- White arkitekter partner meeting. Copenhagen, Denmark. March 2017.
- KADK Research Day. KADK, Copenhagen, Denmark. May 2017.
- Design Modelling Symposium 2017. ENSAV, Versailles, France. September 2017.
- White arkitekter Nobel Vecka. White Arkitekter, Stockholm, Sweden. December 2017.
- InnoChain second year colloquium. COAC, Barcelona, Spain. February 2018.
- Integrated material practice. ENSAV, Versailles, France. February 2018.
- Robotics seminar. BIG, Copenhagen, Denmark. May 2018.
- Integrated material practice. IAAC GSS, Muscat, Oman. July 2018.
- Integrated material practice in free-form timber structures. Woods Bagot, London, UK. September 2018.
- Integrated material practice in free-form timber structure. Heatherwick Studio, London, UK. December 2018.
- Aalborg wood seminar. Utzon Centre, Aalborg, Denmark. February 2019.
- Integrated material practice in free-form timber structures. NEXT / KADK, Copenhagen, Denmark. April 2019.
- Integrated material practice in free-form timber structures. Mae Architects, London, UK. May 2019.
- Strategies for the wood value chain. KADK Klima Youth Summit, Copenhagen, Denmark. October 2019.
- Integrated material practice in free-form timber structures masterclass.

IAAC, Barcelona, Spain. October 2019.

B

SECONDMENTS AND WORKSHOPS

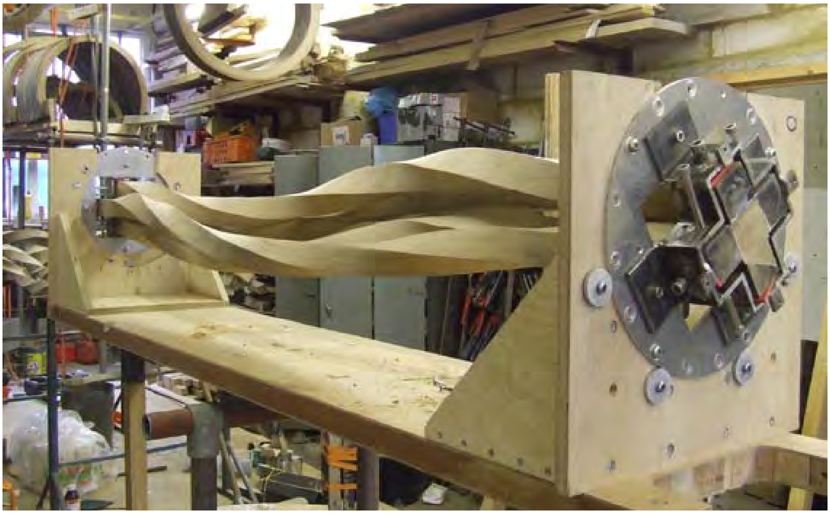
B.1 Industry secondments

This section enumerates the industry secondments undertaken over the course of this research.

- Blumer Lehmann AG
  February 11 - 19, 2017
- Blumer Lehmann AG
  March 15 - May 9, 2017
- White Arkitekter
  October 1 - December 22, 2017

B.2 Workshops

This section consists of the briefs of the two main student workshops Probe 2: IBT glulam workshop and Probe 4: CITAstudio glulam workshop.



Richard Deacon, jig

Richard Deacon, Out of Order, 2003

FREE-FORM GLULAM // CITA

WORKSHOP WITH METTE RAMSGARD THOMSEN /MARTIN TAMKE / TOM SVILANS / CITA

AUD 2 / Monday 18 – 21 APRIL 2016

BRIEF

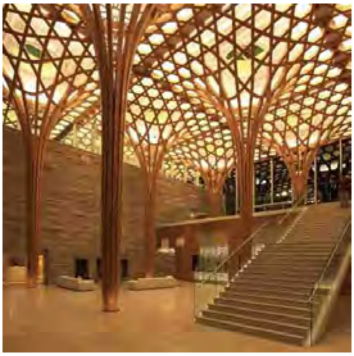
This workshop examines the glulam - glued laminated timber - as an architectonic element, its traditional construction applications, and contemporary architectural and expressive possibilities. Looking towards projects that use complex, free-form, digitally-fabricated glulam elements - such as Centre Pompidou-Metz (Shigeru Ban, 2010), the Nine Bridges Golf Club in South Korea (Shigeru Ban, 2009), and the Vennesla Library and Cultural Centre in Norway (Helen and Hard, 2011) - we want to understand how modern design and fabrication technologies can allow new formal and spatial expressions through the lens of sustainable timber construction.

This workshop will explore how advanced digital design systems that integrate simulation with material and fabrication constraints can be interfaced with state-of-the-art robotically-steered fabrication technologies, allowing for the shaping of highly complex 3-dimensional elements that can be individualized, detailed, and precisely assembled into structural assemblies. The workshop will explore formal, technological, and material challenges that this new practice involves so as to communicate what architectural application of advanced free-form glulams can be.

Students will be introduced to current developments in parametric design and modelling software and will get a hands-on introduction to glulam forming and finishing. Digital models and drawings will drive the development of physical formwork which will be used to produce glulam elements on an architectural scale. State-of-the-art scanning and computer vision technologies will close the digital loop by capturing the physical prototypes for comparison and analysis.

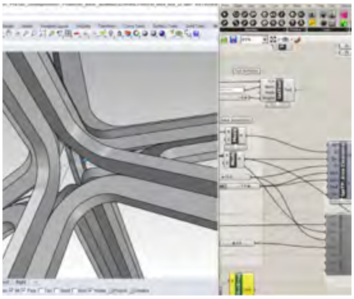
You are not expected to have special digital design skills to join. Everyone can take part.

The workshop will be very short – we therefore expect you to commit your full time to the project and to expect long days.



Shigeru Ban, Nine Bridges Golf Club, 2009

Helen and Hard, Vennesla Library and Cultural Centre, 2011



Rhino + Grasshopper CAD environment.

SCHEDULE

Monday, April 18

9:30	Intro to workshop, setting out schedule / goals for the day.
10:00	Software installation and trouble-shooting.
10:30	Presentation: glulam fabrication, architectural projects that use them, new technologies of architectural production.
11:00	Rhino + Grasshoppe: Introduction.
12:00	Lunch
13:00	Rhino + Grasshopper: Surface and pattern generation.
14:00	Design conception, work period.
17:00	Design review.
18:00	Work session.

Tuesday, April 19

9:30	Design review, choosing design to move forward with.
10:30	Rhino + Grasshopper: parametrising the design, integrating fabrication constraints.
12:00	Lunch
13:00	Presentation: Methods of forming free-form glulams.
14:00	Formwork design, modelling, and fabrication.
17:00	Afternoon review, progress report.
18:00	Work session.

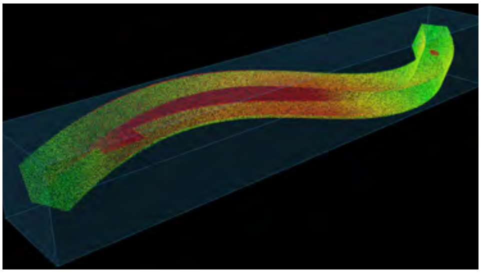
Wednesday, April 20

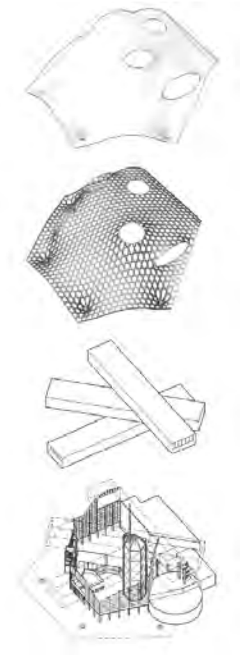
9:30	Morning review, progress report.
10:30	Formwork fabrication and testing.
12:00	Lunch
13:00	Glulam fabrication.
17:00	Afternoon review, progress report.
18:00	Work session.

Thursday, April 21

9:30	Morning review, progress report.
10:30	Glulam fabrication and connection details.
12:00	Lunch
13:00	Finishing, cleaning up.
14:00	Photography, documenting, and 3d scanning.
TBA	Final review and pin-up.

Shigeru Ban, Centre Pompidou-Metz, 2010





Digital Timber Workflows

Integrating material performance in the design and fabrication of laminated timber assemblies.

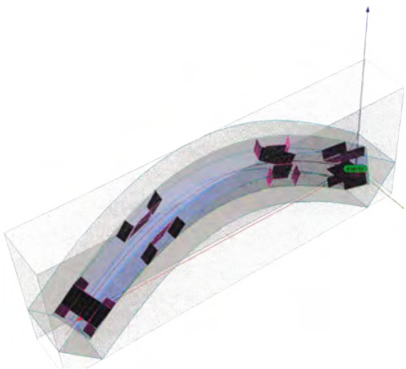
CITAstudio + InnoChain ETN
2016.09.05-16

Centre Pompidou Metz design scheme (Shigeru Ban Architects).

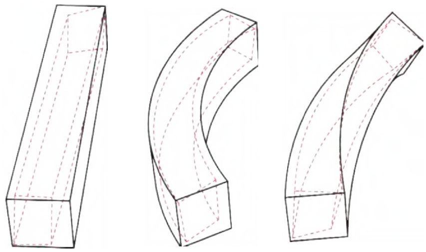
Workshop description

Timber is a not a simple material. It is anisotropic, hydroscopic, live, and heterogeneous. Its complex fibre structure makes it bend, warp, knot, swell, creep, and behave unpredictably. As a result, designing with timber often becomes a sparring match between the designer and these behaviours and characteristics of timber. In spite of this complexity, timber is one of the oldest building materials and is seeing a resurgence in study, use, and innovation in architectural practice and fabrication. Engineered timber and timber laminates have opened up an exciting world of formal, technical, and experiential possibilities, aided and abetted by novel tools of simulation, sensing, and digital fabrication. Empowered by these new tools, architects and designers are able to engage with these complex behaviours and properties, harnessing them and controlling them in much greater detail.

As digitally-enabled designers - perhaps 'digital craftsmen'[1] - , we will design with laminated timber by integrating a wider range of parameters and material knowledge into our workflow. By embedding the model with multiple layers of information - the structure and layout of the raw material, point-clouds of the blanks and finished piece, structural calculations, detail geometries - we will arrive at a much more complete and nuanced understanding of the finished product. This will be taken through from design to fabrication, and we will learn how this feedback loop can be developed, maintained, and mined throughout the architectural design process.



This workshop is an introduction to engineered timber and fluid digital design workflows between design, rationalization, and fabrication. Digital design workflows in architecture tend to gravitate towards early design exploration and design development. While we as designers mostly concern ourselves with these, they are only the starting point in a much more extensive architectural production network which involves myriad other parties, technologies, and spheres of knowledge. Everything that follows it - rationalization, logistics, planning, fabrication, and assembly - together forms the bulk of the architectural design project, however the deployment of digital design workflows here is often overlooked.



Glulam blanks, design geometry, and connection details (designtoproduction).

Walkthrough

We will begin with an introduction to timber as a material and a hands-on introduction to wood-working. We will look at the current state-of-the-art in timber construction and engineering, and discover the range of possibilites made available through the seemingly simple act of gluing wood together. We will then look at the technologies that are making all of this possible: robotic actuation, multi-axis machining, and 3d scanning.

We will look at the difference between the geometry we design and the geometry we physically

1 F. Scheurer. Digital Craftsmaship : From Thinking to Modeling to Building. *Digital Workflows in Architecture*, 2012.

Multi-axis robotic machining (Heatherwick Studio, Bmade UCL).

make, and the role of the laminated 'blank' or 'billet' as a rough canvas for other, more precise, operations. A laminated workpiece is constrained by the material limits of the individual timber pieces, and these must be sussed out, designed for, and optimized. We will look at the bending limits of various timber thicknesses, cross-lamination, and simulation tools that will help us predict the feasibility and success of our prototypes.

Nine Bridges Golf Club (Shigeru Ban Architects).

We will deploy what we have learned about 3d scanning and robotics to digitize our blanks and design precise connection details and plan machining operations to reveal our design geometry within them. Digital simulation and verification tools will be used to track the changes between our designed blanks, the made blanks, and our design geometry. This will create an opportunity to adjust, adapt, and feed what we have learned back into the early design phase.

We will tackle the often-overlooked problem of positioning, locating, and fixing complex 3d objects within a frame of reference. While digital models comfortably float in space, the harsh realities of gravity and machining forces require us to consider how our prototypes are clamped, how far our robots can reach, and the choreography of toolpaths, collision avoidance, and machine limits.

Finally, using multi-axis robotic machining, we will carve our prototypes out of their blanks, precisely revealing connection details and surfaces. Once again we will deploy 3d scanning to verify and, if need be, correct our digital models, ensuring that our prototypes can be assembled before they even leave the fabrication space.

Workshop learning objectives

- understanding of the complexities of design-to-fabrication workflows
- usage of scripting and parametric tools beyond form generation, into planning and design rationalization
- material understanding of timber and timber laminates
- understanding of precision and tolerance in a production workflow
- a solid grasp of data management and the logistics of project organization

Groupwork

You will be divided into groups of between 4-5. Each group will have a mix of 4th and 5th year students, and a variety of skills within each group is encouraged. Each group must have at least one working laptop / workstation with Windows installed.

Deliverables

Each workshop group will produce a laminated timber assembly with machined connection details and locator points. Each group member will play a part in detailing connections, setting up and managing production of these connections, documenting them through photographs and 3d scanning, and producing a dataset which collects all the design, production, and analysis information of each assembly from the whole process. The geometry for each assembly will be based on a predefined global model to allow the workshop to focus on the design-to-fabrication process.

Prerequisites
Working knowledge of Rhino is required. Basic knowledge of Grasshopper is required, but this will also be explored in the workshop. A familiarity and comfort with hand tools, woodworking, and general messiness would be great. Plug-in for Rhino / Grasshopper, utilities, and template files will be distributed in the workshop and support for their usage will be provided. This workshop will involve physical prototyping and workshop usage; appropriate dress is a must.

Materials
Timber and glue for laminating and constructing blanks will be supplied. Some MDF and dimension steel will also be available, however extra material for jigs and formwork - MDF, dimension steel, hardware - will be up to each group to supply.

Workshop schedule

Monday, 09.05
Morning
Introduction to timber construction.
Introduction to robotics and scanning.

Afternoon
Material exploration, test laminations.

Tuesday, 09.06
Morning
Blank modelling and rationalization.

Afternoon
Group review
Blank preparation and laminating.

Wednesday, 09.07
Morning
Blank fabrication and scanning.
Joint detail modelling.

Afternoon
Group review
Joint detail modelling.

Connection details from the Tamedia Office Building (Shigeru Ban Architects).

Thursday, 09.08
Morning
Blank positioning and locating.
Collision avoidance and path planning.

Afternoon
Positioning jig fabrication.
Project review.

Friday, 09.09
Morning
Detail machining and prototype production.

Afternoon
Group review.

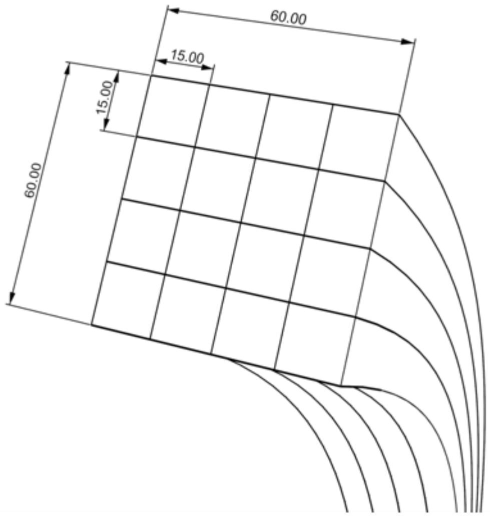
Saturday-Sunday, 09.10-09.11
Prototype production.

Friday, 09.16
Exhibition and final review.
Beer!

Centre Pompidou Metz (Shigeru Ban Architects).

Appendix

General dimensions
Most blanks will be roughly 60x60mm, made up of 15x15mm lamellas. Some will be composed of 33x33mm lamellas, which will not be bent. Each beam will be roughly 1800mm long.



Cutter dimensions
The router cutters with which we will be working with are as follows:

12mm straight endmill
Stepover: 8mm
Stepdown: 6mm
Cutting speed: 12mm / s

15mm v-cutter
V angle: 30d
Stepdown: 3mm
Cutting speed: 12mm / s

C

SOFTWARE

This appendix describes the collateral contributions - software plug-ins, standalone software, and utilities - from the research. Links are provided to the online repositories, including source code.

C.1 tas

URL: `https://github.com/tsvilans/tas`

A personal toolkit for research and exploration. Uses RhinoCommon for geometric types and provides an interface through Grasshopper components. It is licensed under the open-source Apache License, Version 2.0.

This project uses the following libraries:

- `Clipper`
- `Carve` (via the Carverino wrapper)
- `Triangle .NET`

It is divided into four modules:

- tasCore

- tasLam
- tasMachine
- tasFun

tasCore

The Core module contains Types, Extension Methods, and Utility classes. Types include a Polyline that uses planes instead of points as vertices (oriented polyline), a Pose which is a position and orientation with a fitness value, and a couple of Network implementations for facilitating graph-based workflows. Extension Methods provide extra methods for RhinoCommon types (Polyline, Vector3d, Point3d, Plane, Mesh, Brep, Curve, etc.). Utility classes provide some new functionality that doesn't quite fit into the extension methods.

The GH extended version provides some wrapper classes and components for the Grasshopper plug-in.

tasLam

The Lam module contains classes and types developed for this research into free-form timber structures. The `Glulam` class allows the definition of straight, single-curved, and double-curved glulam beams; generating their geometry; analyzing curvature and bending limits; calculating required lamella composition; and more. The `Workpiece` and `Feature` classes extend the `Glulam` model into the fabrication of joints.

Once again, the GH extension for this provides new Grasshopper components for modelling and analyzing free-form glulam members.

tasMachine

The Machine module contains classes and types for toolpath generation and CNC machining. Many of these are self-rolled imitations of common toolpath strategies (area clearance, pocket, flowline, etc.) and are mostly experimental.

Again, the GH extension provides some new Grasshopper components for generating and modifying toolpaths. There is some initial support for post-processors for some specific machines such as the Haas TM-3 3-axis vertical mills and the CMS Antares 5-axis wood processing centre.

tasFun

The Fun module contains implementations of algorithms and other experimental work that is highly volatile and unstable. This is meant as a place to store developing ideas and experiments that don't yet have a home in the other modules. These include basic implementations of Simulated Annealing, K-Means clustering, and Metropolis-Hastings; as well as a tentative next version of the Glulam model.

C.2 carverino

URL: `https://github.com/tsvilans/carverino`

> Carve is a fast, robust constructive solid geometry library. (fork from https://code.google.com/p/carve/)

(`https://github.com/VTREEM/Carve`)

> CarveSharp is a .NET wrapper for the fast and robust constructive solid geometry (CSG) library Carve. Using CarveSharp, you could easily pass triangular meshes and perform boolean operations on them (such as union, intersect, etc.). CarveSharp is targeted for .NET v4 and above (due to the use of parallel for loops for increased performance). It can be easily integrated into Unity by rewriting all Parallel.For loops as regular C# for loops (note that the performance may significantly decrease).

(`https://github.com/Maghoumi/CarveSharp`)

CarveRhino and CarveGH are an adaptation of the two wonderful pieces of software described above, allowing the usage of the Carve library in Rhino and Grasshopper, respectively. At the moment, just the basic operation of Carve is exposed, and outputs a triangulated mesh. Although Carve supports N-gons, Rhino doesn't, so these are instead triangulated. Hopefully this will change in the future with N-gon support in Rhino. There seems to be a lot of functionality in Carve that is not being exploited, so hopefully this can provide a good enough starting point to have good, solid mesh booleans in Rhino.

The libs are provided as-is, with no guarantee of support for now, as I use them internally and do not intend to develop this into a shiny, polished plug-in.

This plug-in consists of five files:

- `CarveLibWrapper.dll` - The actual wrapper for the Carve library.
- `CarveSharp.dll` - The dotNET assembly which exposes Carve, using only basic types.
- `CarveRC.dll` - CarveRhinoCommon, which provides basic conversion from Rhino types (Mesh) to Carve types.
- `CarveGH.gha` - Grasshopper assembly which adds the 'Carve' component to Mesh -> Util.
- `CarveRhino.rhp` - Rhino plug-in which adds the 'Carve' command to Rhino.

C.3 tetrino

URL: `https://github.com/tsvilans/tetrino`

> TetGen is a program to generate tetrahedral meshes of any 3D polyhedral domains. TetGen generates exact constrained Delaunay tetrahedralizations, boundary conforming Delaunay meshes, and Voronoi partitions.
>
> The development of TetGen is executed at the Weierstrass Institute for Applied Analysis and Stochastics in the research group of Numerical Mathematics and Scientific Computing.

(`http://wias-berlin.de/software/index.jsp?id=TetGen&lang=1`)

TetRhino (or Tetrino) is a .NET wrapper for the well-known and pretty amazing TetGen mesh tetrahedralization program. It provides one new GH component for discretizing or remeshing objects using TetGen. Basic tetrahedralization functionality is exposed with a few different output types that can be controlled. At the moment, the only control for tetrahedra sizes is the minimum ratio, which is controlled by a slider. This is hardcoded to always be above 1.0-1.1, as it is very easy to generate a LOT of data (and crash)...

The libs are divided again into different modules to allow flexibility and fun with or without Rhino and GH, so have fun. All 4 libs should be placed in a folder (maybe called 'tetgen') in your GH libraries folder. Remember to unblock.

Once again, the libs are provided as-is, with no guarantee of support for now, as I use them internally and do not intend to develop this into a shiny, polished plug-in. If there is enough interest, I can tidy up the code-base and upload it somewhere if someone more savvy than me wants to play.

- `TetgenGH.gha` - Grasshopper assembly which adds the 'Tetrahedralize' component to Mesh -> Triangulation.
- `TetgenRC.dll` - RhinoCommon interface to the Tetgen wrapper.
- `TetgenSharp.dll` - dotNET wrapper for Tetgen.
- `TetgenWrapper.dll` - Actual wrapper for Tetgen.

To wrap up, some notes about the inputs:

These are the possible integer Flags (F) values and resultant outputs for the GH component:

- 0 - Output M yields a closed boundary mesh. Useful for simply remeshing your input mesh.
- 1 - Output M yields a list of tetra meshes.
- 2 - Output I yields a DataTree of tetra indices, grouped in lists of 4. Output P yields a list of points to which the tetra indices correspond.
- 3 - Output I yields a DataTree of edge indices, grouped in lists of 2. Output P yields a list of points to which the edge indices correspond.

As this component can potentially create a LOT of data, especially with dense meshes, care should be taken with the MinRatio (R) input. This will try to constrain the tetra to be more or less elongated, which also means that the lower this value gets, the more tetra need to be added to satisfy this constraint. Start with very high values and lower them until satisfactory.

Happy tetrahedralizing...

C.4 rhino_faro

URL: `https://github.com/tsvilans/rhino_faro`

A Rhino plug-in for importing Faro scan files.

Exactly what it says on the tin. Uses the Faro .NET SDK to allow importing Faro scan files into Rhino for viewing or processing.

Adds some commands:

- `RFLoadCloud`: Loads a Faro scan file. This is not added to the Rhino document, but is instead kept in its own buffer until it is 'baked'. For some reason baked pointclouds sometimes lose their color data. Keeping it in a separate buffer prevents this from happening.
- `RFClearCloud`: Clear the loaded scan from the buffer.
- `RFLoadSettings`: Load import settings from a file. Not optimal by any means, and subject to change.
- `RFScanSettings`: Set scanner settings. This will eventually allow you to run the scanner from here as well, but not yet.
- `RFTransformCloud`: Move the scan around.
- `RFBakeCloud`: Move the scan from the buffer to the Rhino doc, effectively baking it.

C.5 bpy_triangle

URL: `https://github.com/tsvilans/bpy_triangle`

A Blender add-on for Triangle.

> Triangle: A Two-Dimensional Quality Mesh Generator and
> Delaunay Triangulator
> Copyright 1993, 1995, 1997, 1998, 2002, 2005
> Jonathan Richard Shewchuk
> 2360 Woolsey #H
> Berkeley, California 94705-1927
> jrs@cs.berkeley.edu

(`http://www.cs.cmu.edu/~quake/triangle.html`)

This is a Python wrapper for the Triangle library referenced above. It uses ctypes. The add-on adds a 'Triangulate' operator to Blender, which can take any planar meshable object (curves and meshes) and create a triangulated mesh based on specified input parameters.

Input parameters are provided via a text field and are described in the Triangle documentation.

Further work could be done to expand functionality and add support for meshing Ngon faces or some other way of operating out of the XY plane, but for now it is limited to this.

This is especially useful for creating meshes for sculpting or meshes with good face densities from 2d CAD data, for arch. viz or other uses. Interior edges are respected, meaning creating dense meshes with interior regions is possible. Note the interior circle in the image above.

C.6 SpeckleBlender

URL: `https://github.com/speckleworks/SpeckleBlender`

Speckle add-on for Blender 2.8

Important update: SpeckleBlender now checks for the speckle dependency and installs it if necessary, using pip. If pip is not found, it tries installing that too.

Note: when activating the add-on, the Blender UI will freeze for a bit while it installs all the necessary dependencies. This is to be expected.

The Speckle UI can be found in the 3d viewport toolbar (N), under the Speckle tab.

C.7 rhino_natnet

URL: `https://github.com/tsvilans/rhino_natnet`

A Rhino plug-in for NaturalPoint's NatNet API.

This plug-in provides real-time access to NaturalPoint's Optitrack data directly in the Rhino interface. It provides several new commands:

- `RNNConnect`: Attempts to connect to the NatNet server. At the moment, it is hardcoded for 'localhost'.
- `RNNGetPoints`: Bakes the live points to the Rhino document.
- `RNNSetPlane`: Set a transformation plane. This changes the base frame of the incoming NatNet data.
- `RNNResetPlane`: Reset the transformation plane.
- `RNNToggleNumberDisplay`: Toggle number labels on live points.

The transformation plane is also stored in a block of shared memory, allowing access to it from pretty much anywhere. This MMF block is called `RNN_Plane` and can be accessed through the

`System.IO.MemoryMappedFiles` interface in .NET. Adding the real-time points to this is planned as well, so accessing the real-time data from somewhere like Grasshopper or even another process should be trivial.

C.8 fls2pcd

URL: `https://github.com/tsvilans/fls2pcd`

A conversion utility for converting Faro FLS scan files to PCD files, used by the open-source Point Cloud Library (PCL) (`https://pointclouds.org/`).

C.9 PySpeckle

URL: `https://github.com/tsvilans/PySpeckle`

A Python Speckle Client

> Speckle: open digital infrastructure for designing, making and operating the built environment. We reimagine the design process from the Internet up: Speckle is an open source (MIT) initiative for developing an extensible Design & AEC data communication and collaboration platform.

(`https://www.speckle.works/`)

PySpeckle is a light Python wrapper / interface for the Speckle framework. It can be used independently through Python scripts, or as a base for building various plug-ins, such as SpeckleBlender.

C.10 CITA Robots

URL: `https://github.com/tsvilans/Robots`

A fork of the Robots Grasshopper plug-in by Vicente Soler (`https://github.com/visose/Robots`) for off-line industrial robot programming, with specific tools for the CITA robot lab and applications.

> Grasshopper plugin for programming ABB, KUKA and UR robots for custom applications. Special care is taken to have feature parity between all manufacturers and have them behave as similar as possible. The plugin can also be used as a .NET library to create robot programs through scripting inside Rhino (using

Python, C# or VB.NET). Advanced functionality is only exposed through scripting.

(https://github.com/visose/Robots/wiki)

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