Digitalized Traditional-Japanese Wood Joints within a Voxel-based System of Discrete Timber Elements

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Abstract

The global climate crisis, the rising inequality, and the question of AI are the main challenges of this century. In essence, these are ecological, social, and economic tasks, affecting each other. One of the big culprits is the current state of the built environment. It is the least digitalized, the most polluting, and one of the least innovative sectors. Therefore, change is desperately needed.

I propose a project that addresses these issues. Fundamentally, it is about constructing with timber, which has many benefits besides the ecological implications. It is an organic material with specific properties that adapt to its circumstances. Additionally, there is promising research done with wood. I introduce the different methods of joining pieces of timber. Then, I focus on wood joints, more specifically, traditional Japanese and European ones, and compare the different types of connections. After a selection, I compose a complex synergetic connection of five pieces of timber. These discrete elements are part of one voxel. For that, I develop an algorithm that digitalizes the joints and prepares them for fabrication. Then, I design a system of discrete voxels that can abstract any geometric form depending on its resolution. These voxels are placeholders for the timber elements they contain. For that, I develop another algorithm that places the correct timber elements and their correct joints in each voxel. It requires the design of the assembly process, which I also incorporate in the script. Finally, I demonstrate that my system facilitates exploration of the design space with an example.

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Contents

Index of Abbreviations

AEC	Architecture, Engineering, and Construction Industry
CAM	Computer-aided manufacturing
CNC	Computer numerical control
DCL	Design Computation Lab
EU	European Union
ICD	Institute for Computational Design and Construction
KKAA	Kengo Kuma and Associates
LCA	Life-Cycle Assessement

Chapter 1

Introduction

Mankind is confronted with many problems today. These range from rising inequality to the question of AI and the global climate crisis. The built environment is fundamental in this context. In the European Union (EU) today, the architecture, engineering, and construction (AEC) industry is responsible for 36% of total CO2 emissions, 40% of total energy consumed, and 38% of total waste generated.[1] At first glance, this appears to be an environmental problem. However, it is at the same time a profound socio-political and economic one.[2] Therefore, the question is: How can we change the way we build to create a more sustainable—i.e. ecological, social, economic, and equitable—world?

1.1 The Ecological Task

In our current economic system, the construction costs must be as low as possible to get the maximum return by selling or renting the buildings.[3] At first, this is an issue from an ecological point of view. Low priced materials, such as concrete and steel, are mostly preferred to more sustainable alternatives with a higher price, e.g., wood or clay.[4] However, sustainable edifices are prestigious today. Increasingly, investors recognize the market value of *green* buildings.[5] This shift is also demanded and promoted by the AEC.[6] Many concepts for change already exist within the ecological implications. The first is the Circular Economy or the Cradle to Cradle model.[7] In it, there is no waste, and everything is reused or recycled. The goal is "to eliminate the concept of waste [and] to design things–products, packaging, and systems–from the very beginning on [with] the understanding that waste does not exist."[8] This design approach is broken down into the biological and the technical cycles (Fig. 1).

A prerequisite for that is the notion of Design for Disassembly, meaning the deconstruction of products or buildings without damaging their parts.[9] Another tool within this framework is the Material Passport.[10] In it, every element is documented with its properties. The passports also include data about the performance and state of the elements. That is useful so that they can be exchanged simply if they are damaged,

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1 European Construction Sector Observatory, "Analytical Report: Improving energy and resource efficiency" (European Commission, 2018), 5.; European Construction Sector Observatory, "Analytical Report," 14.

2 Günther Bachmann, "Urban Resource Exploration: Produzieren in Geschlossenen Stoffkreisläufen," in Hillebrandt et al., *Atlas Recycling*, 7.

3 Mollie Claypool et al., "Architecture in the Age of Automation," in Claypool et al., *Robotic Building*, 15.

4 Case for Green Building: A Review of the Costs and Benefits for Developers, Investors and Occupants" (2013), 22.

5 World Green Building Council, "The Business Case for Green Building," 36.

6 Construction Declares, "Construction Declares Climate and Biodiversity Emergency," accessed February 1, 2021, https://constructiondeclares.com/.

7 Bachmann, "Urban Resource Exploration," 6–7.

8 William McDonough and Michael Braungart, *Cradle to Cradle: Remaking the Way We Make Things*, 1st ed. (New York, NY: North Point Press, 2002), 104.

9 Kasper Guldager Jensen et al., Building a Circular Future, 3rd ed. (Copenhagen: GXN, 2019), 34.

10 Guldager Jensen et al., Building a Circular Future, 121–22.

for instance.[11] These passports are structured in a Material Bank, where resources are stored through assembly and reused through disassembly.

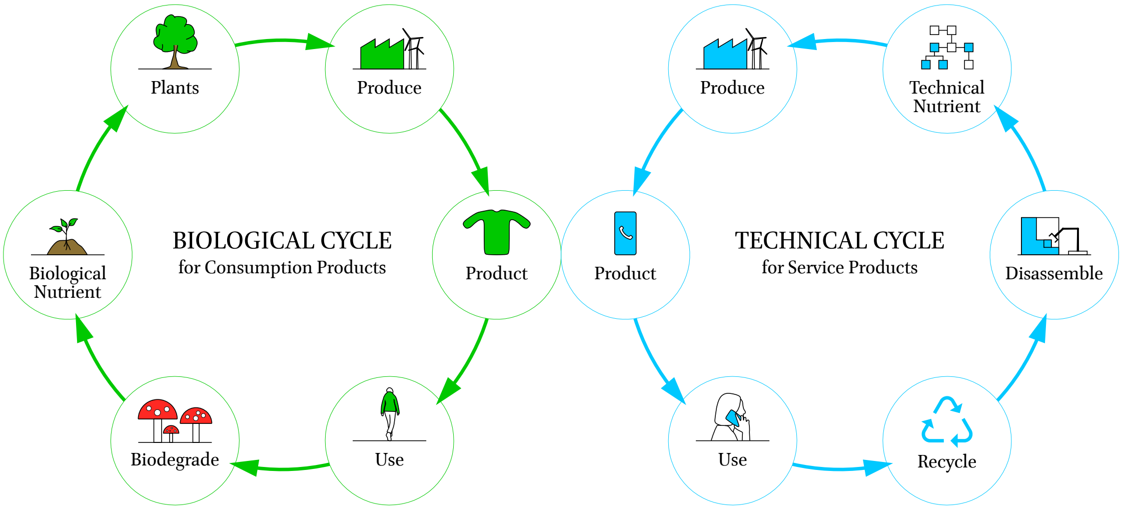

Figure 1: Biological Cycle and Technical Cycle of the Cradle to Cradle concept.

Regarding the construction concepts, it is also relevant to use materials with a low or negative CO2 footprint. Many of these materials—like wood and clay—have additional benefits. They are hazard-free, provide a healthier indoor climate, and can be recycled again.[12] The ecological task is an important pillar of sustainability, though it is not the only one. There are also social and economic challenges.

1.2 The Social Task

The advances within the framework of sustainability mainly address its ecological implications. However, its other pillars—the social and the economic—are equally important. In the social, the debate is mostly about accessible, affordable, and inclusive housing.[13] This is a topic of critical importance, but it is not the only one. The question of *who* is constructing the edifices under *what* conditions is mainly out of focus. From a worker's point of view, the AEC is the most dangerous industry to work in, even in the EU.[14] Meanwhile, a large part of its labor force comes from so-called developing countries, where wages and standards of living are lower.[15] This issue is exemplified if these workers are undocumented. Numerous journalistic investigations reported violations of human rights.[16] There are major concerns even in Europe.[17] However, the change didn't happen because the AEC needs as much cheap labor as it can get in the current

11 Guldager Jensen et al., Building a Circular Future, 35.

12 Annette Hillebrandt and Johanna-Katharina Seggewies, "Recyclingpotenziale Von Baustoffen," in Hillebrandt et al., *Atlas Recycling*, 80–81.

13 Manuel B. Aalbers, "The Great Moderation, the Great Excess and the Global Housing Crisis," *International Journal of Housing Policy* 15, no. 1 (2015), https://doi.org/10.1080/14616718.2014.997431.

14 Mara Lombardi, Mario Fargnoli, and Giuseppe Parise, "Risk Profiling from the European Statistics on Accidents at Work (ESAW) Accidents' Databases: A Case Study in Construction Sites," *International journal of environmental research and public health* 16, no. 23 (2019): 1, https://doi.org/10.3390/ijerph16234748.

15 European Construction Sector Observatory, "Analytical Report: Improving the human capital basis" (European Commission, 2020), 22.

16 Amnesty International, "Reality Check 2020: Countdown to the 2022 World Cup" (Migrant Workers' Rights in Qatar, London, 2020), 4.; Mariam Bhacker, "The Construction Industry Must Step up on Human Rights," *The Guardian*, April 19, 2016, accessed January 31, 2021, https://www.theguardian.com/global-development/2016/apr/19/construction-industry-must-step-up-on-human-rights-migrant-workers-qatar.

17 Shirley Osborn and John Lynham, "Construction Sites Are Aiding Spread of Covid: Letters," *The Guardian*, November 1, 2021, accessed January 31, 2021, https://www.theguardian.com/global/2021/jan/11/construction-sites-are-aiding-spread-of-covid.

construction boom.[18] As will be addressed in Chapter 2.2, the robotic automation of construction could potentially solve this issue. No dangerous activities must be done by human labor, then. It would also be a necessary step since the AEC is the least digitalized industry.[19] Instead, it is still driven by increasingly complex, manual, and unique construction processes that have not changed much since the industrial revolution. This "results in high costs, inconsistent work quality and significant waste of human and material resources."[20] It means that these issues are also economic.

1.3 The Economic Task

Currently, big tech companies like Sidewalk Labs or Airbnb heavily invest in the AEC, pushing their agenda on the future of construction.[21] However, this change should come from within the profession itself. To this end, it is necessary to address the digitalization in the AEC. The theoretical and practical frameworks of how we want to build in a digital society in the future should be developed. However, there are challenges, like "[...] increasing professionalization, legal responsibilities, and litigation [that have] created a risk-averse climate of architectural production that subsumes innovation across the built environment [...]."[22] The necessary concepts are (as mentioned above) already available, e.g., the Circular Economy, the Material Bank, the Design for Disassembly, and the robotic fabrication and construction. These lead to a substantial reduction in the cost of construction.[23] They also save resources in the form of time, materials, and human labor. This could potentially lead to a democratization of building since it gets more affordable for everyone.[24] The global FabLab movement already pioneered that stance and established a community of *makers*.[25] An extension of this idea to the construction of buildings could potentially have similar effects.[26] In this framework, the architect takes the role of "a designer of a system, where [he] manages a conceptual and methodological framework for architectural production."[27] It also enables users to participate in the process of construction, leading to its full democratization.[28]

18 European Construction Sector Observatory, "Analytical Report," 7.

19 Mollie Claypool, "Discrete Automation," accessed November 16, 2020, https://www.e-flux.com/architecture/becoming-digital/248060/discrete-automation/.

20 Jan Willmann, Fabio Gramazio, and Matthias Kohler, "New Paradigms of the Automatic: Robotic Timber Construction in Architecture," in Menges; Schwinn; Krieg, *Advancing Wood Architecture*, 17–18.

21 Claypool, "Discrete Automation"

22 Ibid.

23 Annette Hillebrandt, "Architekturkreisläufe: Urban-Mining-Design," in Hillebrandt et al., *Atlas Recycling*, 13–15.

24 Mollie Claypool et al., "Diffuse," in Claypool et al., *Robotic Building*, 97.

25 The Fab Foundation, accessed January 31, 2021, https://fabfoundation.org/.

26 Claypool et al., "Architecture in the Age of Automation," 15–16.

27 Mollie Claypool, "Our Automated Future: A Discrete Framework for the Production of Housing," in Retsin, *Discrete*, 50.

28 Claypool, "Our Automated Future," 50.

Chapter 2

State of Scientific Research

2.1 Related Work

Currently, there are research projects that deal with wood joints, discretization, and robotic assembly of aggregation structures.

2.1.1 Wood Joints

Kanasaki and Tanaka digitalized traditional Japanese joints and prepared them for fabrication. The location of the joints within a Lego-like block determines their selection. It covers all relevant connection possibilities.[29] Both additive and subtractive manufacturing processes are possible.[30]

Larsson et al. developed on Kanasaki and Tanaka and elaborated TSUGITE, "an interactive system for designing and fabricating wood joints for frame structures."[31] The program enables the creation of custom joints and provides feedback on its performance.[32] Up until now, the tool is limited to one joint in one sliding axis. However, future improvements may include multiple sliding axes and may provide the possibility to create custom joints that might outperform traditional Japanese ones (Fig. 2).[33]

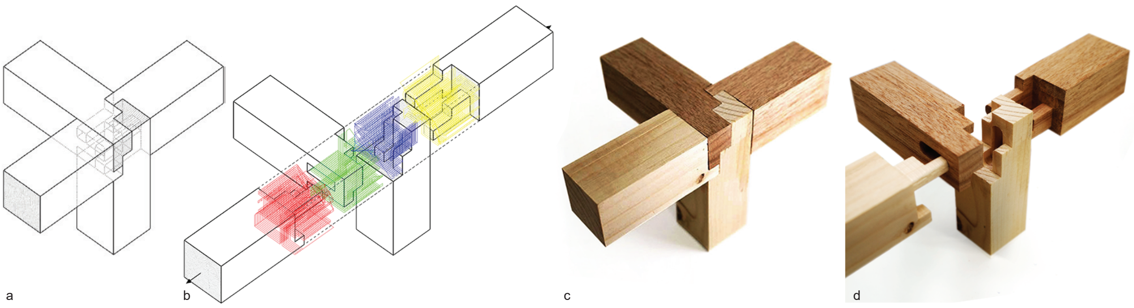

Figure 2: Maria Larsson et al., *Connecting four timbers designed and CNC-fabricated using the Tsugite system. a) Interface screenshot of closed joint. b) Interface screenshot of open joint with a preview of milling paths. c) Fabricated joint closed. d) Fabricated joint open.*, 2020, accessed February 4, 2021, http://ma-la.com/tsugite.html.

2.1.2 Discrete Aggregation

Japanese architecture firm Kengo Kuma and Associates (KKAA) is an important protagonist in the merger of traditional Japanese craftsmanship and digital technology. KKAA incorporated them into their projects and "went on to develop the non-figural,

29 Kenji Kanasaki and Hiroya Tanaka, "Traditional Wood Joint System in Digital Fabrication," in *Computation and Performance: Proceedings of the 31st International Conference on Education and Research in Computer Aided Architectural Design in Europe*, ed. Rudi Stouffs and Sevil Sariyildiz, 1st ed. (Brussels, Delft: eCAADe and Faculty of Architecture, Delft University of Technology, 2013), http://resolver.tudelft.nl/uuid:d36152ad-7cfc-44b6-bdfe-654f159a3e65, 711.

30 Kanasaki and Tanaka, "Traditional Wood Joint System in Digital Fabrication," 715.

31 Maria Larsson et al., "Tsugite: Interactive Design and Fabrication of Wood Joints," in *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, ed. Shamsi Iqbal, ACM Digital Library (New York: Association for Computing Machinery, 2020), accessed January 23, 2021, 317.

32 Larsson et al., "Tsugite," 317.

33 Ibid, 326.

aggregational, atomised or 'particlised' style for which he is now famous, and which has become his trademark and rallying call."[34]

Researchers at the Design Computation Lab (DCL) at the Bartlett School of Architecture, University College London, are conducting research in the field of *Discrete Architecture*.[35] That framework "seeks to redefine the entire production chain of architecture by accelerating the notion of discreteness in both computation and the physical assembly of buildings [and] asserts that a digital form of assembly, based on parts that are as accessible and versatile as digital data, offers the greatest promise for a complex yet scalable open-ended and distributed architecture."[36] It is physically expressed through the aggregation of modular building elements, so-called discrete parts.[37] Several projects and prototypes have been realized on a 1:1 scale—e.g., the Tallinn Architecture Biennale Installation by Gilles Retsin (Fig. 3).[38]

Figure 3: Studio Naaro, *Tallinn Architecture Biennale Pavilion by Gilles Retsin*, 2017, accessed February 4, 2021, https://www.retsin.org/Tallinn-Architecture-Biennale-Pavilion.

Furthermore, this approach includes the concept of *Discrete Automation*. Claypool argues that automated technologies—e.g., industrial and modular robots—provide an alternative framework for assembly and disassembly within construction.[39]

> In this, it is cultural, it is economic and it is social. Automation does not distinguish between design and fabrication or even economy. Automation instead directs us to a point on the horizon: the obsolescence of labour. [...] It immediately forces positions, questions about what a fully automated society would mean [...].[40]

34 Mario Carpo, "Particlised: Computational Discretism, or the Rise of the Digital Discrete," in Retsin, *Discrete*, 91.

35 Gilles Retsin, "Discrete Timber Assembly," in Burry et al., *Fabricate 2020*, 264.

36 Gilles Retsin, "Introduction: Discrete Architecture in the Age of Automation," in Retsin, *Discrete*, 8.

37 Retsin, "Discrete Timber Assembly," 267.

38 Ibid.

39 Mollie Claypool, "Towards Discrete Automation," in Burry et al., *Fabricate 2020*, 272.

40 Claypool et al., "Architecture in the Age of Automation," 12–13.

2.1.3 Robotic Assembly

Similar research is being conducted at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart. Overall, the focus is on computational design and manufacturing in architecture. Specifically, the research project of Leder et al. deals with the fabrication and assembly processes with distributed robots and robot-material collaborations. The wood elements and the robots can be considered as discrete parts that assemble and disassemble highly differentiated timber structures (Fig. 4).[41] Additionally, Yablonina et al. propose a system of autonomous, mobile robotics for the fabrication of filament and composite fiber structures. Here, the robot itself becomes a discrete part, that fabricates a preconceived structure in situ according to the specific properties of the fiber composites.[42]

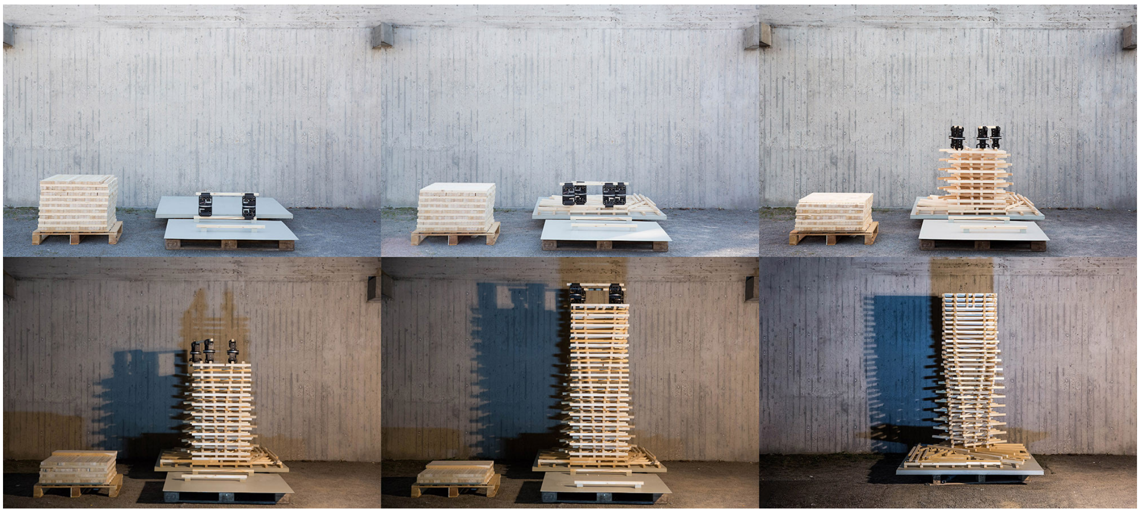

Figure 4: ICD/ITKE University of Stuttgart, Leder, Weber, *Construction Sequence*, 2018, accessed February 4, 2021, http://www.rewdesign.ch/robotic-timber-2019/.

Gramazio Kohler Research at ETH Zurich researches in the field of robotic fabrication. In this context, the Sequential Roof research project is particularly relevant.[43] It is a robotically fabricated wooden truss consisting of a huge number of small, low-engineered timber elements. The robots layered these elements in an additive effort according to a specific assembly logic. It connected the timber pieces with mechanical joints in the form of metal nails.[44] This project illustrates a major shift within the research in construction: from layering standardized elements, e.g. bricks, to assembling complex wooden structures, both performed by robots. The introduction of these non-standard, minimally customized timber components required the incorporation of the entire process: from fabrication to assembly, relevant data is an integral part of each element. These discrete elements can then be robotically machined and assembled. As a result, this process combines the advantages of mass customization and mass production. Its goal is to explore "novel timber constructions, and their relation to the design freedom, the structural performance and the robotic assembly itself."[45]

42 Maria Yablonina et al., "Mobile Robotic Fabrication System for Filament Structures," in *Fabricate 2017: Rethinking Design and Construction*, ed. Achim Menges et al. (London: UCL Press, 2017), 202.

43 Aleksandra A. Apolinarska et al., "The Sequential Roof," in Menges; Schwinn; Krieg, *Advancing Wood Architecture*, 45.

44 Apolinarska et al., "The Sequential Roof," 46–49.

45 Willmann, Gramazio and Kohler, "New paradigms of the automatic," 16.

2.2 Materiality

2.2.1 The Circularity of Wood

Today, wood is the third most used resource globally.[46] Half of the annual grown timber is used for energy, the other half for products of all kinds.[47] Decisive for its ecological use is sustainable forestry. It provides the basis for stable ecosystems and CO_2 storage.[48] The newly grown wood is harvested, used—e.g., in construction—and becomes a part of the Material Bank, saving resources and storing CO_2. Additionally, in a meta-analysis, Petersen and Solberg compared the Life-Cycle Assessment (LCA) of common construction materials in similar buildings. The data shows that wood performed significantly better than concrete or steel within all Environmental Impact Categories considered by the EU.[49] Therefore, it is one of the most ecological materials in the EU.

If the wood is properly assembled, it will perform its service for a long time. Reusing the material in another configuration would not diminish its lifetime either. Many old timber structures account for that. They are comprised of first use and reused elements, still standing today.[50] The size of the timber elements determines their lifespan, i.e., the bigger it is, the longer it lasts.[51] Wood's low weight also makes transporting it easy. However, this does not diminish its structural capabilities.[52] Besides, today's machines can fabricate wood with high precision, making it a primary material for the development of modular systems.[53] Within these, parts are easily exchangeable, further prolonging the lifespan of the overall structure. If the wood gets damaged, though, it can still be recycled into a new product. The range is endless: from burning it for energy to upcycling it into hard plastic made from Wood Polymer Composites, or "liquid wood."[54] These properties make timber a relevant resource for the Circular Economy.

In the past, wood was the primary building material in Europe north of the Alps, in Eastern Europe, and the Far East. Even though it was widely available, it had been considered a precious resource.[55] Today, building with wood is competitively viable from an economic point of view. Depending on the location, timber structures are "within a range of ± 20% the price of similar solutions in steel."[56] However, currently, the costs of wood plunged in the EU because of bug-infested timber flooding the market. It is a result of low precipitation and devastating storms due to climate change. This threat will only exemplify the more the temperatures rise.[57] Foresters have a big challenge in planning the future of these ecosystems. The species of trees currently growing

46 Gerd Wegener, "Ressource Holz," in Kaufmann; Krötsch; Winter, *Atlas Mehrgeschossiger Holzbau*, 15.

47 Wegener, "Ressource Holz," 15.

48 Ibid, 17.

49 Ann K. Petersen and Birger Solberg, "Environmental and Economic Impacts of Substitution Between Wood Products and Alternative Materials: A Review of Micro-Level Analyses from Norway and Sweden," *Forest Policy and Economics* 7, no. 3 (2005): 254, https://doi.org/10.1016/S1389-9341(03)00063-7.; European Committee for Standardization, *Sustainability of Construction Works: Assessment of Environmental Performance of Buildings – Calculation Method* (Brussels, 2012), EN 15978:2011, 43.

50 Klaus Zwerger, *Wood and Wood Joints: Building Traditions of Europe, Japan and China*, 3rd ed. (Basel: Birkhäuser, 2015), 11.

51 Zwerger, *Wood and Wood Joints*, 10.

52 Ibid, 11.

53 Wolfgang Huß, "Vorfertigung," in Kaufmann; Krötsch; Winter, *Atlas Mehrgeschossiger Holzbau*, 142.

54 Sascha Peters, *Material Revolution: Sustainable and Multi-Purpose Materials for Design and Architecture*, Material Revolution 1 (Basel: Birkhäuser, 2011), 44.

55 Zwerger, *Wood and Wood Joints*, 239.

56 Petersen and Solberg, "Environmental and economic impacts of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden," 257.

57 Bundesministerium für Ernährung und Landwirtschaft, "Deutschlands Wald im Klimawandel: Eckpunkte und Maßnahmen" (Diskussionspapier zum Nationalen Waldgipfel, Berlin, 2019), 5.

might not survive in 50 years. Those—native to hotter climates—might not survive today.[58] Despite these substantial challenges, the forests within the European Union are expanding each year.[59] When these are sustainably managed, their wood becomes a highly ecological material. However, building with wood requires an understanding of its properties.

2.2.2 The Properties of Wood

Wood is an anisotropic, organic material.[60] Its fibers grow in parallel with a slight tilt, giving it a pyramid-like shape.[61] Additionally, the orientation of the wood grain is also significant. At the crown and the root of a tree, it exhibits different strengths.[62] Therefore, the direction of its use is relevant. It has its biggest load capacity in the direction of its fibers.[63] Furthermore, different kinds of wood have different properties. There are hardwoods, softwoods, and tropical woods—all with specific species and individual properties. Each type had its specific use and needed different handling as well.[64] Because of these properties, most construction needs can be met with wood.

Today, the requirements are so high that building with natural wood requires in-depth knowledge. By comparing it to reinforced concrete and steel, its unique properties seem more like a liability.[65] Because of this, most of the wood used in construction today is highly processed engineered timber.[66] These products use a technique to improve the structural capabilities of wood, which the Romans were already familiar with, i.e., layering the pieces of wood on top of each other.[67] The glue connects all layers perfectly and enables a consistent distribution of forces. These so-called mass timber products allow building structures not possible before with natural wood, like ever taller high-rises.[68] However, through this process, wood loses a lot of its properties, becoming a more homogenous material.[69] Additionally, the layering also works with other types of connections, like metal fasteners or wooden dowels.[70] There, the forces are not as evenly distributed as with the glue, though.

Glued timber poses considerable challenges. The production and usage of industrial adhesives consume valuable resources and has a substantial negative impact on the environment.[71] More specifically, the type determines the overall sustainability of the product itself. For instance, many types of glue are on a formaldehyde basis, a harmful

58 Bundesministerium für Ernährung und Landwirtschaft, "Deutschlands Wald im Klimawandel," 7.

59 Edward Cook, *Agriculture, Forestry and Fishery Statistics: 2018 Edition* (Luxembourg: Publications Office of the European Union, 2018), 92.

60 Pekka Heikkinen and Philip Tidwell, "Designing Through Experimentation: Timber Joints at the Aalto University Wood Program," in Hudert; Pfeiffer, *Rethinking Wood*, 62.

61 Klaus Zwerger, "Die »Trennende Holzverbindung« in Japan," *DBZ Deutsche Bauzeitschrift* 44, no. 7 (1996): 143.

62 Zwerger, *Wood and Wood Joints*, 19.

63 Ibid, 10.

64 Ibid, 33.

65 Simone Jeska, "New Technologies and Methods," in Hascher; Jeska; Pascha, *Emergent Timber Technologies*, 15.

66 Jeska, "New technologies and methods," 17.

67 Zwerger, *Wood and Wood Joints*, 42.

68 Michael Green and Jim Taggart, *Tall Wood Buildings: Design, Construction and Performance* (Basel: Birkhäuser, 2017), 158.; Oliver D. Krieg, "Engineering Perspectives: Oliver David Krieg in Conversation with Manfred Grohmann and Jan Knippers," in Menges; Schwinn; Krieg, *Advancing Wood Architecture*, 202.

69 Zwerger, "Die »trennende Holzverbindung« in Japan," 141.

70 Annette Hillebrandt et al., eds., *Atlas Recycling: Gebäude Als Materialressource*, 1st ed., DETAIL Atlas (Munich: DETAIL, 2018), 206.

71 David E. Packham, "A crisis in the environment? The impact of polymers and adhesives" (Paper presented at POLYCHAR 20, World Forum on Advanced Materials, Dubrovnik, Croatia, 2012), 3.

substance for the environment and humans alike.[72] Furthermore, attention must be paid to a building's end-of-life scenario. At best, the timber elements can be reused, as mentioned in Chapter 3.1. Otherwise, wood follows a cascading mode of down-cycling. There—at least in Germany—the level of processing determines the recycling potential of the wood. In the future, stricter rules might make it more difficult to recycle engineered timber products. Therefore, it is best to use natural wood.[73]

Understanding these principles is fundamental when working with unprocessed wood. Especially the connections between the timber elements depend on the consideration of this knowledge. Section 2.3 addresses the different joining techniques and their properties in detail.

2.3 Joinery

This section addresses the different possibilities of joining pieces of timber. Historically, the connections were part of the wood itself and handcrafted in a subtractive effort. Different methods of joining wood together came with the industrial revolution. Most prominently, these were metal joints, but also glue. Furthermore, mixed types exist, e.g., wood or metal joints supported by glue, and wood joints supported by metal.[74] All methods have benefits and drawbacks themselves.

2.3.1 Timber Connections

Metal joints are a widely used type of connection with many benefits.[75] The static connections can be calculated and built very accurately.[76] However, when joining timber structures with metal fasteners, there are many disadvantages. These are physical, economic, and ecological issues, as well as problems in the construction process, which is why this type of connection has not been considered.[77]

Glued joints are still relatively rare, apart from the finger joint (Fig. 5).[78] Their great advantage is the uniform transmission of force and the low weakening of the wood.[79]

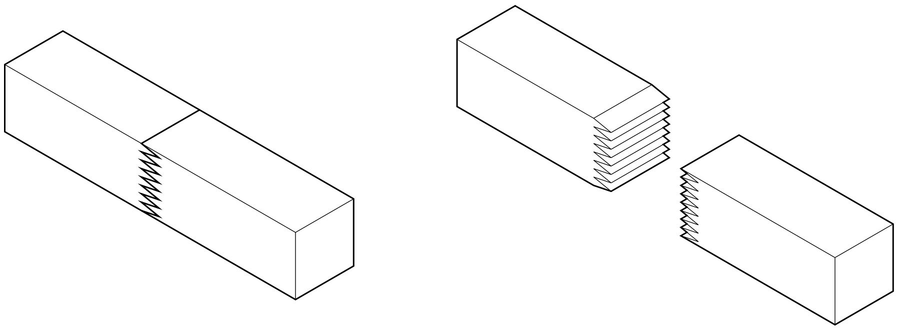

Figure 5: Finger joint.

72 Michael Wengert and Tobias Edelmann, "Herausforderungen Bei Der Bauphysikalischen Konzeption Rückbau- Und Recyclinggerechter Konstruktionen," in Hillebrandt et al., *Atlas Recycling*, 118.

73 Hillebrandt and Seggewies, "Recyclingpotenziale von Baustoffen," 65.

74 Philipp Eversmann, "Concepts for Timber Joints in Robotic Building Processes," in Hudert; Pfeiffer, *Rethinking Wood*, 166–68.

75 Jeska, "New technologies and methods," 15.

76 Apolinarska et al., "The Sequential Roof," 49.

77 Gerhard Fink and Robert Jockwer, "Glued Connections in Timber Structures," in Hudert; Pfeiffer, *Rethinking Wood*, 122.; Wolfram Graubner, *Holzverbindungen: Gegenüberstellungen japanischer und europäischer Lösungen*, 3rd ed. (Stuttgart: Deutsche Verlags-Anstalt, 1990), 20–22.; Hans Drexler, "Press-Fit Timber Building Systems: Developing a Construction System for Flexible Housing Solutions," in Hudert; Pfeiffer, *Rethinking Wood*, 113.

78 Jeska, "New technologies and methods," 20.; Zwerger, *Wood and Wood Joints*, 90.

79 Jeska, "New technologies and methods," 23–24.

However, the static calculability, the disassembly of the joint, as well as the ecological aspects of the adhesive are very problematic.[80] Therefore, this type of connection has not been considered.

A wood joint is a connection of two or more pieces of timber, where the fasteners are part of the elements themselves. In the past, carpenters handcrafted these joints by carving them out of the wood in a subtractive effort. This laborious process brought a multitude of regionally distinct variations of joints. Their form depended on the type of wood, the type of connection, and the tools used.[81] Many classification systems exist, e.g., an organization into (1) joints that can be disassembled and (2) joints that cannot.[82]

In Japan, artisans utilized more sophisticated joints than their European counterparts.[83] That was possible because their woodworking tools were more precise.[84] The earlier advancements in technology, e.g., steel, but also the logic of operation enabled this. Japanese tools are operated by a pulling rather than a pushing motion.[85] Additionally, there were different expectations:

> [...] in most Japanese architecture, a wood member serves a dual purpose as both structural member and as finishing material. As a structural member, it must be durable and the joint tightly fitted, and as a finishing material, it must be aesthetically pleasing.[86]

Because of the geometric complexity, the process of designing, analyzing, and hand-crafting joints is a time-consuming task.[87] It is also comparably expensive to pay highly trained artisans to do this job.[88] Therefore today, most wood joints are fabricated with CNC (computer numerical control) technology.[89] In this process, a reduction in their variety took place. Only the most reliable and common joints exist within the framework of industrial fabrication.[90] Furthermore, through the processes of planning and milling with computer-controlled machines, the elements and connections have very high precision. Further achievements include the automatic production of complex geometries and structures.[91] These advancements make the wood industry the most digitalized within the AEC.[92]

The disadvantage of the advanced fabrication techniques (compared to using chisels, planes, or axes) is that it damages the wood's fibers in the process. That makes it susceptible to damage through the water. The exposed surfaces absorb it like a sponge, which leads to a faster decay of the wood.[93] However, there are several measures for prevention. If the wood gets wet, it needs ventilation to dry again. It should

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80 Fink and Jockwer, "Glued Connections in Timber Structures," 122.; Apolinarska et al., "The Sequential Roof," 49.

81 Zwerger, *Wood and Wood Joints*, 32–33.

82 Ibid, 87.

83 Graubner, Holzverbindungen, 17.

84 Zwerger, *Wood and Wood Joints*, 57.

85 Ibid, 67–68.

86 Hideo Sato and Yasua Nakahara, *The Complete Japanese Joinery: Japanese Woodworking* (Vancouver: Hartley & Marks Publishers, 1995), 173.

87 Larsson et al., "Tsugite," 317.

88 Zwerger, *Wood and Wood Joints*, XV.

89 Simone Jeska, "CNC Production for Timber Structures," in Hascher; Jeska; Pascha, *Emergent Timber Technologies*, 66.

90 Zwerger, *Wood and Wood Joints*, 100.

91 Rainer Hascher, "Introduction," in Hascher; Jeska; Pascha, *Emergent Timber Technologies*, 7.

92 Willmann, Gramazio and Kohler, "New paradigms of the automatic," 18.

93 Zwerger, *Wood and Wood Joints*, 26.

also be possible for the water to drain away.[94] Furthermore, constructional measures can protect a piece of timber's end grain.[95] With these preventive measures, there are no drawbacks to the advanced fabrication techniques. Therefore, they are unrivaled.

94 Hao-Yang Wei, *Die Fügesysteme der traditionellen chinesischen Holzverbindung: Erstellung und Anwendung der Konstruktionskataloge der zimmermannsmäßigen Holzverbindungen* (Düsseldorf: VDI-Verlag, 1999), 104.

95 Zwerger, *Wood and Wood Joints*, 23.

Chapter 3

Wood Joints and Discrete Timber Elements

3.1 The Relevance of Wood Joints

After evaluating the possible joining methods based on the prerequisites made in Chapter 1, I decided to use wood joints in this project. More specifically, I implemented and adjusted traditional Japanese joints. Designing new joints requires a lot of testing and evaluation. That is not the aim of the project, though. Furthermore, it is relevant to have a realistic view of the types of joints and their benefits and drawbacks. Each additional connector weakens the cross-section of the timber.[96] However, certain wood joints are easy to assemble and disassemble without damaging the timber, compared to metal and glue.[97] Additionally, by only using wood joints, the elements become mono-materials. These are easy to reuse and, therefore, preferred in the Circular Economy.[98] Furthermore, the manufacturing of these joints is also as simple as possible since only the raw material, and the machines are necessary. The progress the timber industry made regarding the digital fabrication and structural calculation of geometrically complex wood joints; both exemplify this. It is now possible to manufacture elements with high precision, leading to a significant reduction in cost. In this context, metal or glue fasteners become unnecessary.[99] If, in this case, the fabrication code is available globally through the internet. That facilitates the democratization of fabrication.[100] Thereby, the production of the components is decentralized, which is also beneficial from an ecological and economic stance.[101]

As proposed in Chapter 3.2.1, for the system's elements to become discrete parts, there should be as few types of joints as possible. Therefore, it is necessary to give a short overview of the joints considered, each with its specific properties. A selection and adjustments are made based on a comparison. Thereby, the focus is on the connections existing within the system: (1) end-to-end joints within one axis (*x*, *y*, or *z*) and (2) an intersection between timber elements in three axes (*x*, *y*, and *z*). Both can resist all relevant forces, i.e., bending, moment, compression, tension, and shear forces.[102] Additionally, the assembly and disassembly processes were major factors. They must be as simple and similar as possible so that a swarm of discrete robots could construct them.[103]

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96 Jeska, "New technologies and methods," 23.

97 Petra Riegler-Floors and Annette Hillebrandt, "Lösbare Verbindungen und Konstruktionen," in Hillebrandt et al., *Atlas Recycling*, 49.

98 Hillebrandt, "Architekturkreisläufe," 13.

99 Tobias Schwinn, "Manufacturing Perspectives: Tobias Schwinn in Conversation with Holzbau Amann and Müller-blaustein," in Menges; Schwinn; Krieg, *Advancing Wood Architecture*, 187.

100 Claypool, "Discrete Automation"

101 Schwinn, "Manufacturing perspectives," 189.

102 Sato and Nakahara, *The Complete Japanese Joinery*, 173.

103 Mollie Claypool et al., "Many," in Claypool et al., *Robotic Building*, 77.

3.1.1 End Joints

The first option is to use wooden dowels (Fig. 6).[104] These can mainly react to pressure and shear forces.[105] Torsion, bending, and tensile forces pose major challenges to this joint, making it either break or disconnect completely.[106] Its great benefit is the simplicity of its assembly: two timber pieces are connected by pushing a dowel into their ends. Even though this makes it a promising option, it doesn't meet all the requirements necessary for a completely independent form, i.e., resistance to tensile stress.

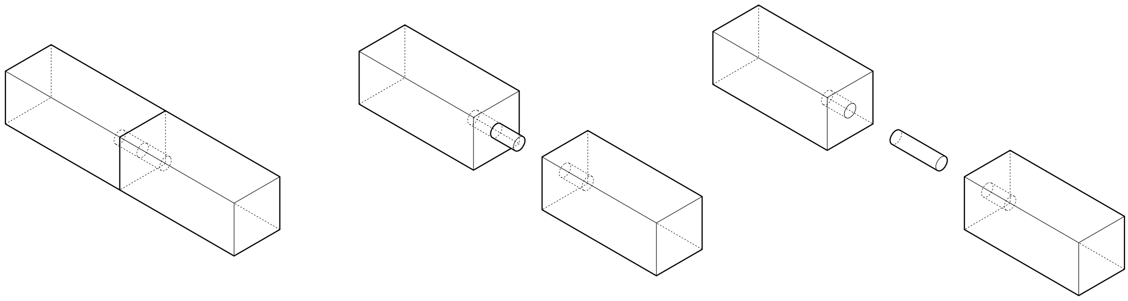

Figure 6: Dowel joint.

Following this logic, another option is using inserted tenon joints, also called *spline joints*, made of dry hardwood (Fig. 7).[107] Both ends of the timber elements have female connections, that then receive the male joints.[108] For its assembly, this requires that both parts stay in place while the tenon is inserted. The joints also need supports and are unusable in the vertical direction. However, this type of connection is useful if the length of the timber elements should be preserved.[109]

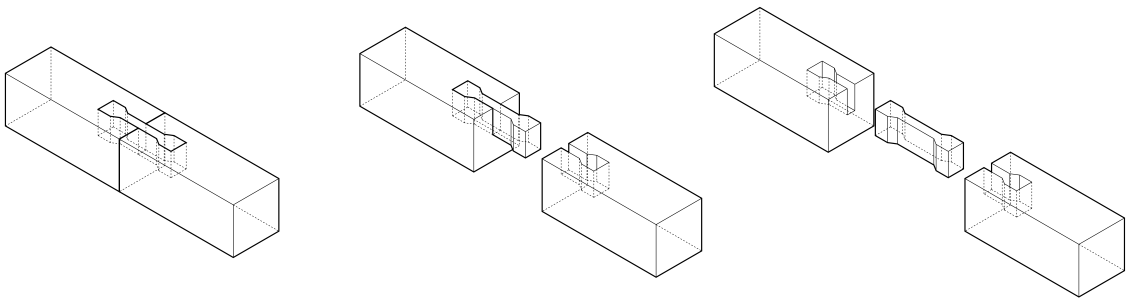

Figure 7: Inserted tenon joint.

Another possibility is using key haunch mortise and tenon joints (Fig. 8).[110] It has excellent properties in terms of tensile, torsional, and bending forces.[111] This joint is also very relevant in the stiffening of structures. The stability of a structure is achieved by connecting all elements in a tension-proof manner.[112] The issue with this joint is its complexity, again. Even though sliding the *male* and *female* pieces into each other is a simple move, inserting the keys for fixation is comparably complicated.

Dovetail joints (Fig. 9) are common in Europe and the Far East alike.[113] Again, it is another joint that has good properties regarding tensile, torsion, and bending forces.

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104 Graubner, *Holzverbindungen*, 166–67.

105 Ibid, 96.

106 Ibid, 62.

107 Kiyosi Seike, *The Art of Japanese Joinery* (New York: Weatherhill, 1979), 48.

108 Sato and Nakahara, *The Complete Japanese Joinery*, 193.

109 Graubner, *Holzverbindungen*, 68.

110 Sato and Nakahara, *The Complete Japanese Joinery*, 181.

111 Graubner, *Holzverbindungen*, 58.

112 Ibid, 70.

113 Sato and Nakahara, *The Complete Japanese Joinery*, 175.

However, this depends on the variation of the type.[114] The most sophisticated one is the *double-sided dovetail joint*, with resistance to shear forces and perpendicular movement.[115] The assembly is simple and only requires a movement perpendicular to the timber elements.

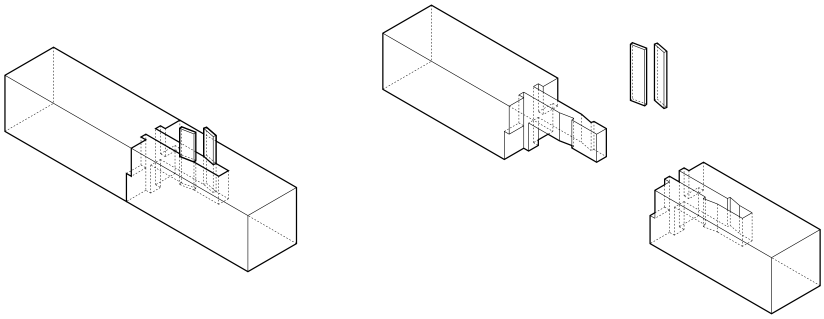

Figure 8: Key haunch mortise and tenon joint.

Another joint with similar structural logic, but better performance is the gooseneck joint (Fig. 10). This connection is more complicated to build in all its variations.[116] Its length minimizes the risk of the end of the timber piece breaking away. The drawback is that it can therefore break more easily due to bending. However, there are sufficient design measures to minimize this problem.[117]

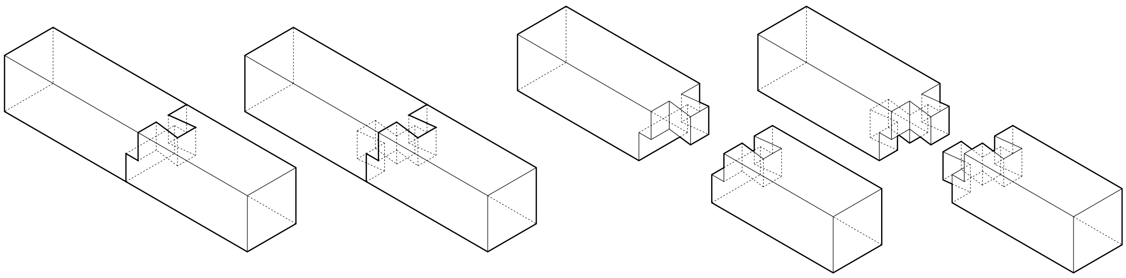

Figure 9: Dovetail joint and double-sided dovetail joint.

Inspired by the double-sided dovetail joint, a double-sided gooseneck joint is developed for this project. It follows the structural logic of a half-blind mortised and tenoned gooseneck joint, though being double-sided and combining the properties of both (Fig. 11).[118] The assembly logic is the same as with the double-sided gooseneck joint, and therefore simple. This new connection can be used both in the horizontal axes (*x* and *y*) and in the vertical axis (*z*). In the latter, it follows the structural logic of a four-faced gooseneck joint (Fig. 12).[119]

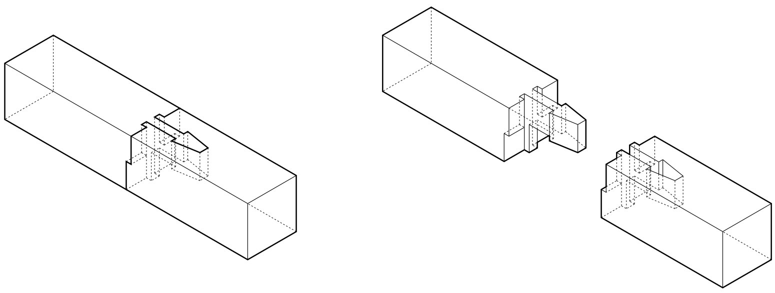

Figure 10: Gooseneck joint.

114 Graubner, *Holzverbindungen*, 64.

115 Ibid, 65.

116 Wei, *Die Fügesysteme der traditionellen chinesischen Holzverbindung*, 66.

117 Graubner, *Holzverbindungen*, 64.

118 Sato and Nakahara, The Complete Japanese Joinery, 177.

119 Ibid, 190.

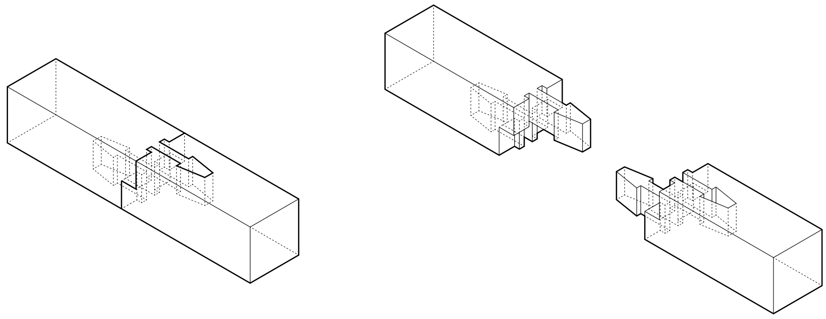

Figure 11: Double-sided gooseneck joint.

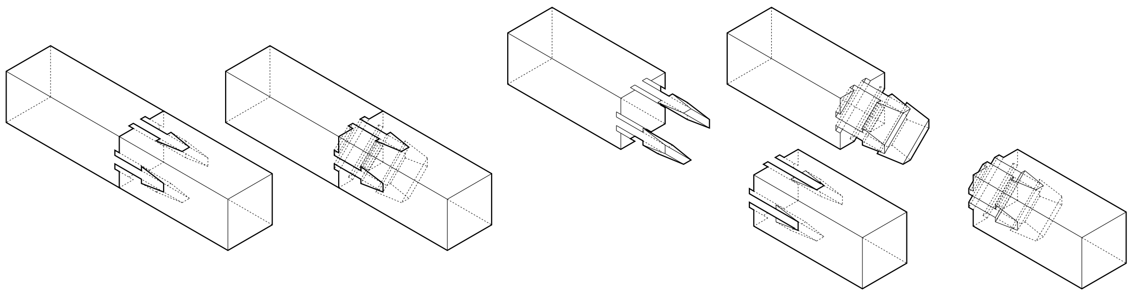

Figure 12: Four-faced gooseneck joint.

3.1.2 Center Joints

The point, where the timber elements on all three axes meet, is the most difficult part of the connection—both structurally and in terms of assembly. Several possibilities are considerable. Important in this regard is the location of the connections at the timber elements. Considering the three axes (*x*, *y*, and *z*) there are four possibilities to connect the horizontal and vertical elements: end-to-end, mid-to-mid, mid-to-end, and end-to-mid (Fig. 13).

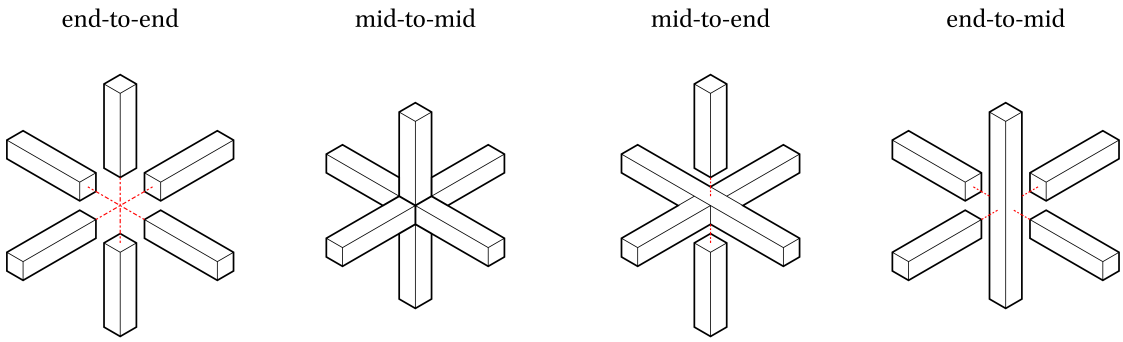

Figure 13: Center joint possibilities.

(1) A specific piece of wood is preconceived, into which the timber pieces are inserted (Fig. 14). That may be an appropriate solution if the pieces consist of a different material than wood or engineered timber. The subtractive fabrication process leads to a loss of resources because of its specific shape necessary for structural integrity. However, such a connector could be 3d-printed, e.g., in liquid wood. That would then lead to a further discretization of the elements since only one joint is necessary.

(2) Mid-to-mid connections are geometrically challenging. A sophisticated possibility to solving this type is *Cidori* (Fig. 15). The invisibility of the connection explains its aesthetic appeal. Though it is a promising center joint, there is an issue with the end joints. Because of the assembly logic, which includes movement in multiple axes and rotation, there are limitations with the end joints and complicated assembly and dis-assembly processes. Nevertheless, KKAA applied this joint at the GC Prostho Museum and Research Center in Aichi, Japan. There, four Cidori joints comprise one element. Various elements are then connected with wooden dowels.[120]

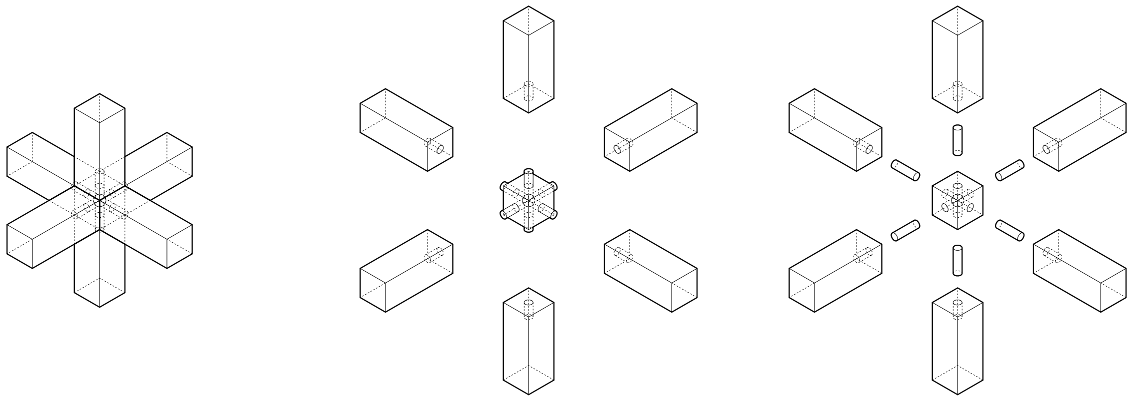

Figure 14: End-to-end connection with dowels.

(3) A mid-to-end connection is constructed only using the timber elements. For this to work, there are two joints necessary. One possibility is using (1) cross lap joints in the horizontal direction and (2) cross-shaped mortise and tenon joints in the vertical direction (Fig. 16).[121] This constellation is simple to assemble. The horizontal elements overlap each other at their center, with the vertical one fitting around it. However, the cross lap joint reduces the cross-section of the timber elements substantially, making it a kind of predetermined breaking point. Additionally, the joints cannot respond to tensile stress in the vertical direction.

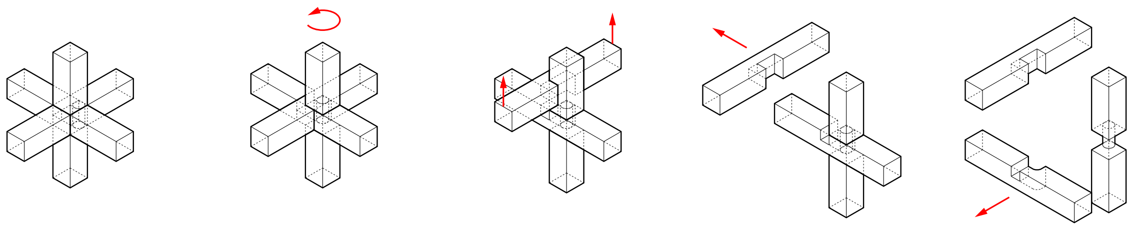

Figure 15: Cidori joint.

(4) End-to-mid connections are constructed only using the wood elements. That is the most common method used to join timber, meaning there is a variety of possible solutions. In general, the intersecting geometry from the horizontal elements is subtracted from the vertical timber piece. The most promising connections are the key haunch mortise and tenon joint and the gooseneck joint (Fig. 17 and Fig. 18). The benefit of applying this constellation is its ability to respond to tensile stress in all directions, and most relevantly, the vertical one. Additionally, this is the best way to stiffening a structure without diagonal bracings.[122]

120 Barbara Glasner and Stephan Ott, *Wonder Wood: A Favorite Material for Design, Architecture and Art* (Basel: Birkhäuser, 2013). https://doi.org/10.1515/9783034610896, 152–53.

121 Sato and Nakahara, *The Complete Japanese Joinery*, 201.; Ibid, 182.

122 Wei, *Die Fügesysteme der traditionellen chinesischen Holzverbindung*, 94.

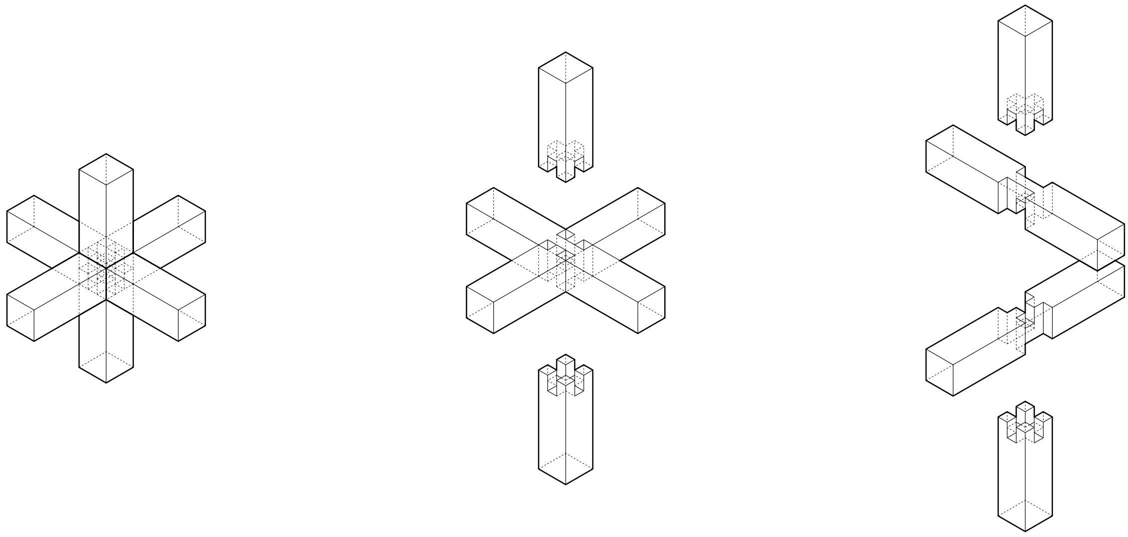

Figure 16: Mid-to-end connection.

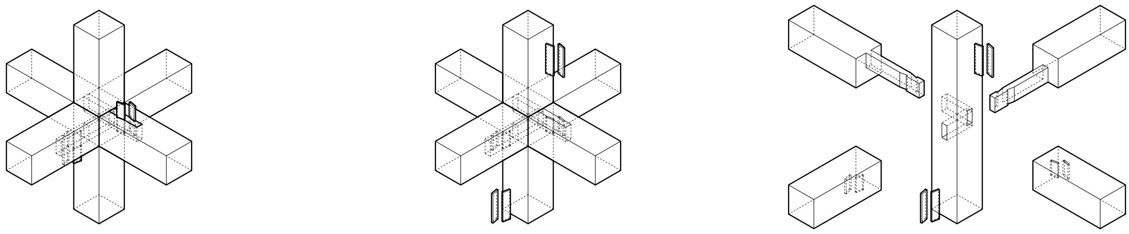

Figure 17: End-to-mid connection with key haunch mortise and tennon joints.

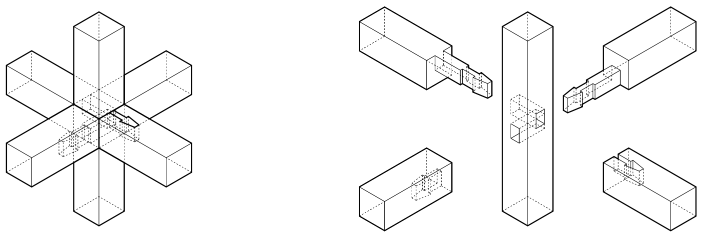

Figure 18: End-to-mid connection with gooseneck joints.

3.1.3 Symbiosis

Based on the comparisons made in sections 3.1.1 and 3.1.2, I selected the joints that are applied in this project. The double-sided gooseneck joint is used for the end joints, whereas a key haunch mortise and tenon joint is used for the center joints (end-to-mid). Figure 19 shows how they look in combination. It is important to note that within this framework, all other joints presented could be implemented as well.

The joints are digitalized within Rhino3d's Grasshopper, a plugin for visual scripting. There, the joints are adjustable parametrically, depending on the dimensions of the timber elements. The size of the defined voxel determines its length. One voxel—as a discrete element itself within the system—consists of three discrete timber beams. All similar joints share the same properties. Furthermore, adjustments were made for fabrication. For instance, all sharp edges are filleted for optimal results with the CNC-mill. If this is not considered, problems may arise during assembly, as the drill cannot produce perfectly sharp inner edges.[123]

123 Shin-Ichiro Matsudome, "Japanese Prefabricated Timber House Construction," *Habitat International* 14, 2-3 (1990): 264, https://doi.org/10.1016/0197-3975(90)90057-8.

The script outputs the discrete timber elements as closed meshes. Mesh geometries—in comparison to NURBS geometries—reduce calculation times for all subsequent processes. They can be exported in files that fabrication machines can read. For 3d-printing, the stereolithography STL-file format is sufficient. Once imported into the specific software of a 3d-printer, the elements are ready for fabrication. For CNC-milling, the process is a bit more complicated because the manufacturing machines need explicit instructions. Depending on the machines and tools used, CAM (computer-aided manufacturing) software generates the necessary code. A toolpath simulation forms its basis and translates the fabrication instructions into a G-CODE, i.e., a programming language that machines can read.[124] This software is usually able to read mesh geometries.

Each discrete voxel stores data besides the fabrication process of all elements within it, e.g., the assembly and disassembly processes, the volumes of the voxels and the timber, the number of elements and their dimensions, and the number of each connection used. Therefore, it is a Digital Material, ready for automated assembly.[125] Further improvements include the implementation of wood specific knowledge as data in a digital framework, i.e., the synthesis of data and material.[126] Within the system presented in section 3.2.1, all the data produced by each voxel is gathered. There, the algorithm can generate a huge number of elements, making it almost impossible to otherwise collect the data. They are necessary for the Material Bank, the assembly, and reassembly of the structure—processes of such scale that they justify the deployment of robots.[127]

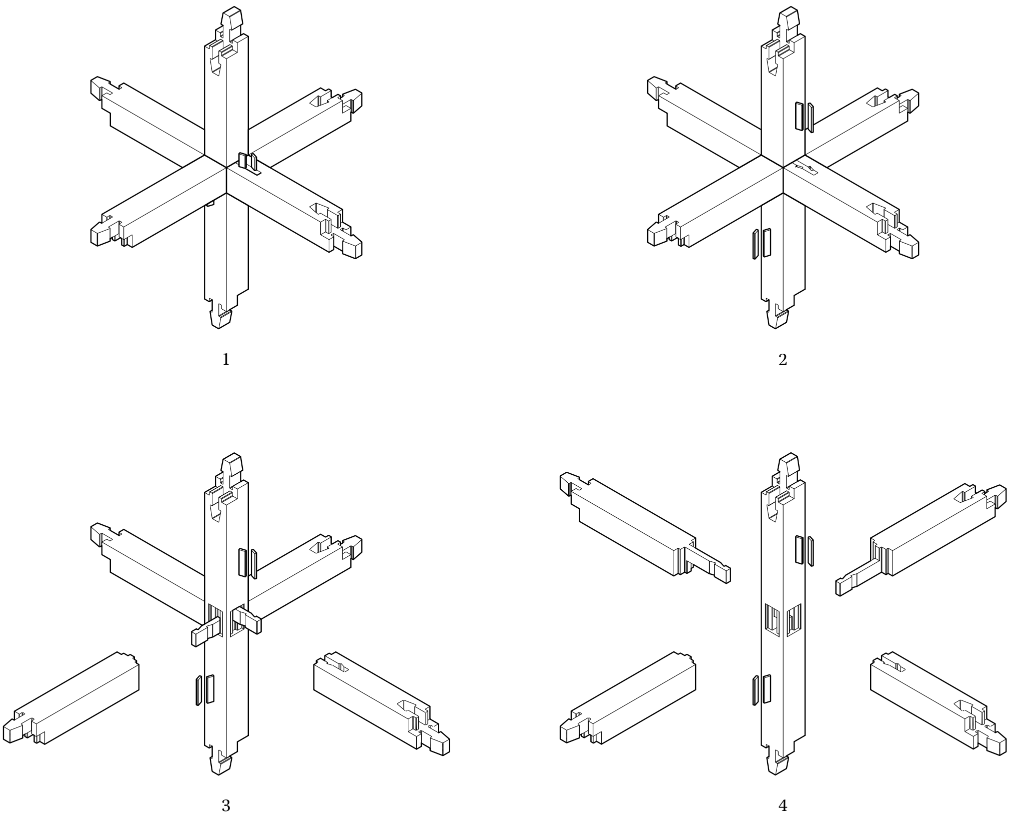

Figure 19: Final joint composition with assembly logic (1–4).

124 K. Lysek, A. Gwiazda, and K. Herbus, "Application of CAM Systems to Simulate of a Milling Machine Work," *IOP Conference Series: Materials Science and Engineering* 400, no. 042037 (2018), https://doi.org/10.1088/1757-899X/400/4/042037.

125 Mollie Claypool et al., "Assemble," in Claypool et al., Robotic Building, 56–57.

126 Matthias Kohler, Fabio Gramazio, and Jan Willmann, "Operationality of Data and Material in the Digital Age," in *The Future of Building: Perspectives: Methods, Objectives, Prospects*, ed. Cornelia Hellstern, Sandra Leitte and Sandra Hofmeister, 1st ed. (Munich: Detail Institut für internationale Architektur-Dokumentation, 2012), 9.

127 Kohler, Gramazio and Willmann, "Operationality of Data and Material in the Digital Age," 18.

3.2 Implementation

3.2.1 Discretization

How can these digitalized and parametrized joints now be used in architecture? One possible answer—and the approach this project takes—is Discretization. As showed in Chapter 2.1.2, aggregation structures with discrete parts were first used on an architectural scale by KKAA. The theoretical background and the implementation of the Discrete were further developed at the DCL. The necessity of this approach is addressed in Chapters 1.2 and 1.3.

The *Discrete* appears to address these issues and, therefore, is the foundation for the system. It is less complex than an aggregation structure with multiple rules. Instead, it consists of a 3d-grid of voxels. The assembly logic stays the same, though. Within this framework, every form can be abstracted (Fig. 20). The resolution of the grid determines the precision of the abstraction. This system expresses itself in a skeletal structure. These are favorable since they use less material and separate "the functions of space creation and load-bearing."[128] Again, I created the script of the implemented system within Grasshopper.

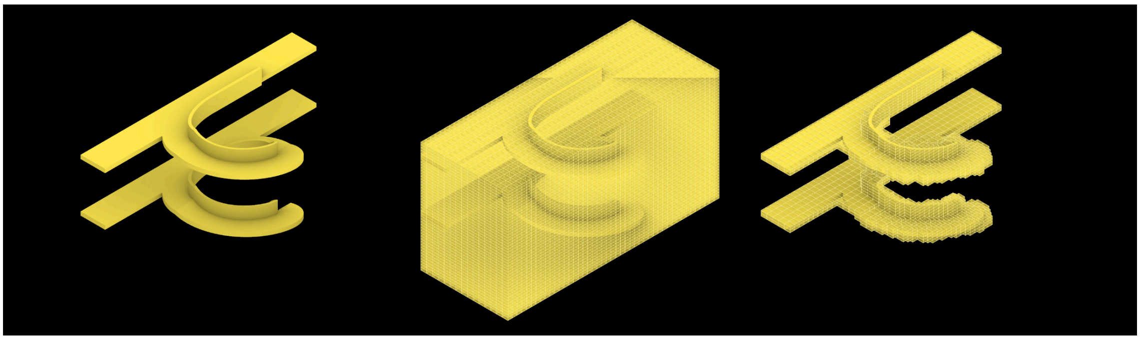

Figure 20: Geometric abstraction of the spiral staircase through voxelization.

3.2.2 The Aggregation Algorithm

The script has six parts. In the first part, it creates the grid according to the boundary of a given geometry and the number of voxels in *x*, *y*, and *z* directions. Rotating the boundary to adjust the direction of the elements is also possible. Then, all voxels that don't intersect with the predefined geometry are culled. In the second part, the script performs a structural analysis using Kiwi!3d, a plugin for Grasshopper performing an Isogeometric B-Rep Analysis on NURBS geometries.[129] For that, it is necessary to use the centerlines of the timber beams of all voxels. These are connected at their ends and get a customizable cross-section for the analysis. Then, it is necessary to define supports and load cases. The results are the stress values for each beam and each voxel. In the third part, the script performs an optimization of the grid based on the analysis. It does so by selecting a voxel according to the stress it receives. Subsequently, it subdivides the voxel by three in the *x*, *y*, and *z* directions. That is the smallest division possible for the joints to connect at the center of the voxel's faces. As a result, the process creates 27 sub-voxels. The iterations of the structural analysis and the optimization can be defined as well. After finishing this step, the script fills the voxels with the timber elements in the fourth part of the script.

128 Drexler, "Press-Fit Timber Building Systems," 103.

129 Ann-Kathrin Goldbach et al., "CAD-Integrated Parametric Lightweight Design with Isogeometric B-Rep Analysis," *Frontiers in Built Environment* 6 (2020): 3, https://doi.org/10.3389/fbuil.2020.00044.

Each voxel is a placeholder for the geometry, which it shall contain (Fig. 21). In this case, it is a specific version of the wood joints of the timber elements (see section 3.1.3). There are up to 64 possible variations of the voxel. They depend on its location, the overall form, and the resolution of the grid.

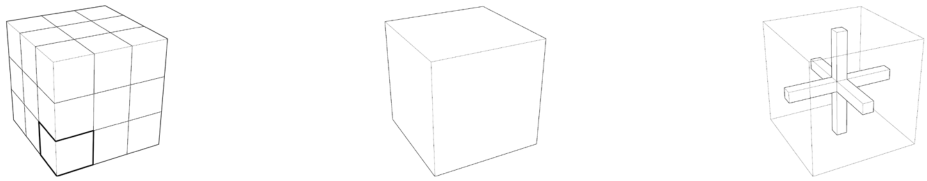

Figure 21: (1) 3d-grid of voxels, (2) a single voxel in this grid, (3) voxel as a placeholder for geometries.

In the fourth part of the script, the program evaluates the location of each voxel according to its faces. For that, it applies the principles of the *marching cubes algorithm*.[130] The script then decides which kind of joint it uses: (1) a connector or (2) an end-type, i.e., no connection (Fig. 22). If the joints have a specific direction, the identical orientation of all voxels is critical. The script checks all voxels one by one in a simple loop and places the correct combination of timber elements. In this process, precisely in the fifth part, the program gathers all the data that are for manufacturing (see section 3.1.3). Subsequently, all elements are sorted and portrayed in a grid in the final part of the script. Thereby, it provides a visual overview of the material and elements necessary. The starting point of the assembly determines its logical order. The algorithm places the content of the first voxel, and then, the subsequent ones aggregate around that. This logic gives each voxel, and subsequently, each element within the voxel, a number. In essence, it is "the design of a manufacturing process, which significantly informs the constructive organization of a component and [...] its execution".[131]

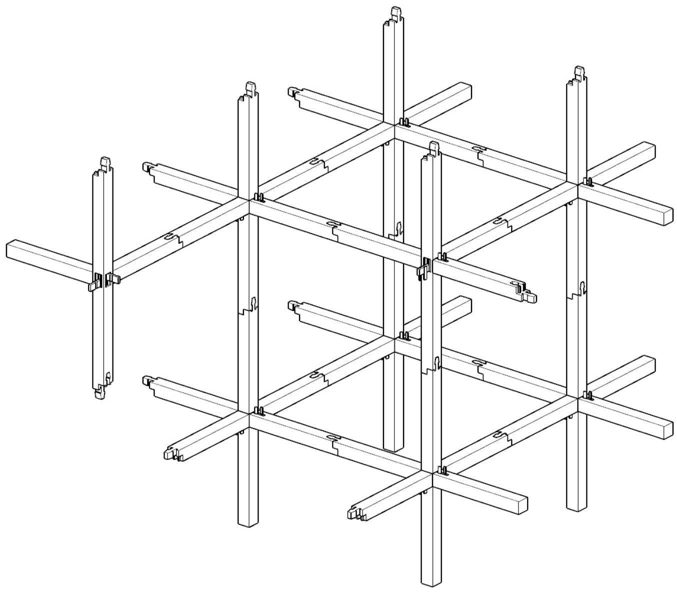

Figure 22: Placement logic. The algorithm decides if a piece of timber has an end connector or not.

130 William E. Lorensen and Harvey E. Cline, "Marching Cubes: A High Resolution 3D Surface Construction Algorithm," *ACM SIGGRAPH Computer Graphics* 21, no. 4 (1987): 163, https://doi.org/10.1145/37402.37422.

131 Kohler, Gramazio and Willmann, "Operationality of Data and Material in the Digital Age," 9.

3.2.3 Case: X.Stahl

The developed system can be applied in countless cases. However, a specific case was developed for illustration purposes. The Bauhaus University Weimar has a structure, the X.Stahl research building, which is used for this project.[132] An aggregation structure makes the steel framework usable and provides studio spaces for students during the semester. In the non-lecture period, the structure is then dismantled and reassembled in a new configuration for exhibition purposes.

To create the workspaces, the individual areas in between the steel frame are filled with small voxels that create ceiling and wall elements. The newly created levels are then accessed through an arcade. A spiral staircase, modeled after the one in the main building, serves as vertical circulation. The algorithm abstracts this geometric configuration. The different parts have a different resolution for an optimal result. In particular, the resolution is increased for the areas subject to high static loads and complex forms, such as the corners and the staircase. Additional support points are defined on the steel frame for the static calculation. After the algorithm has placed all voxels, it determines an assembly order. This depends on the starting point (see section 3.2.2), which is located at the very bottom in the middle of the structure. The content, i.e. the timber elements, of the first voxel are placed. After that, all other elements accumulate around it until the structure is completely created. This logic is shown in Fig. 23. The algorithm also collects all relevant data in the process, which is shown in Table 1. The final visualizations portray a design proposal that combines the traditional Japanese wooden connections with the aggregation structure and its digital logic (Fig. 24, Fig. 25, Fig. 26, and Fig. 27). Based on the collected data, this structure is ready for digital fabrication and automated assembly.

total connections	88,717.00
end connections	62,809.00
center connections	25,908.00
total voxels	25,908.00
total timber elements	129,540.00
total keys	103,632.00
minimum voxel volume	0.0019 m^3
maximum voxel volume	0.26 m^3
total voxel volume	703.00 m^3
total timber volume	23.49 m^3
reduced mass	679.51 m^3
total timber length	14,682.90 m
longest span	0.85 m
shortest span	0.15 m

Table 1: Data gathered by the algorithm.

132 X.Stahl, accessed January 31, 2021, https://www.uni-weimar.de/projekte/expostahl/index.html.

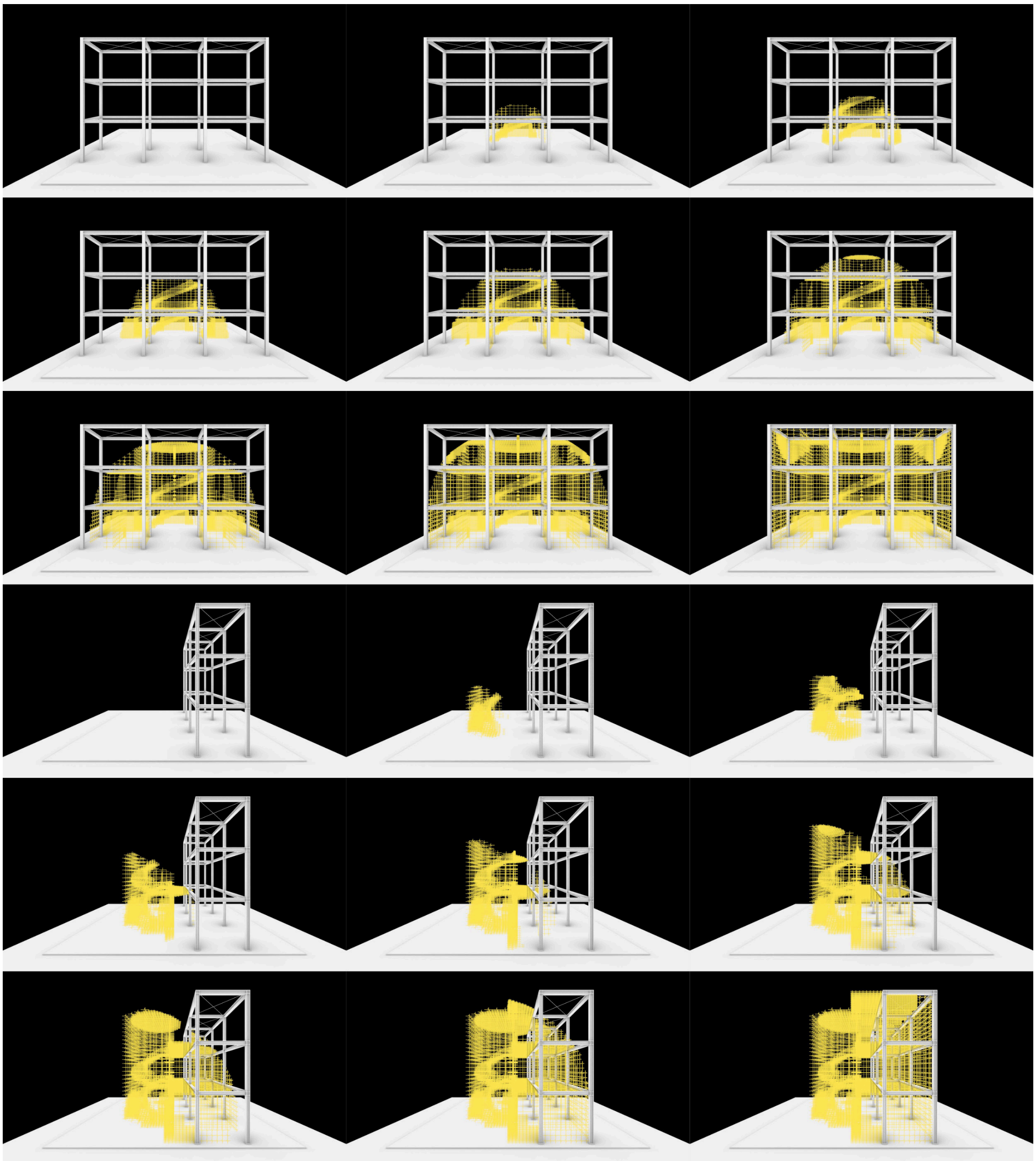

Figure 23: Assembly logic.


Figure 24: Aggregation Structure, view from the front.

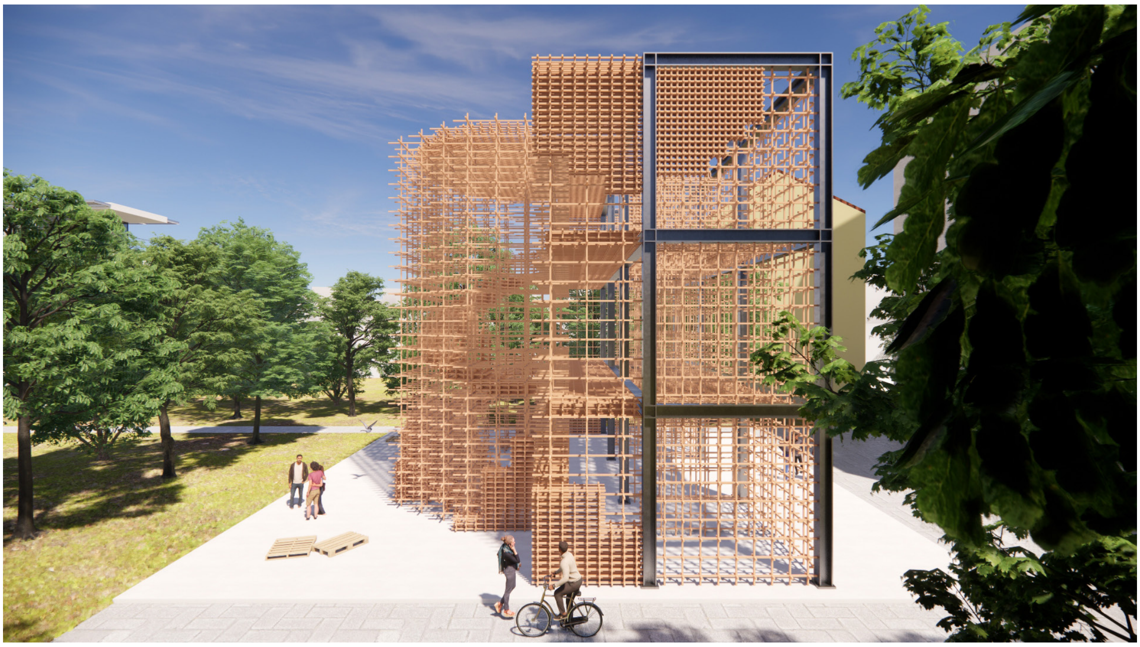
Figure 25: Aggregation Structure, view from the side.


Figure 26: Aggregation Structure interior.


Figure 27: Aggregation Structure, view from behind.

Chapter 4

Future Work

The project documents how digitalized wood joints can be integrated into a system of discrete timber elements. These elements become Digital Materials through the data gathered in the process of their creation. These data are relevant for the fabrication, assembly, and reassembly of the timber elements. Furthermore, it is fundamental for the concept of the Material Bank and the circularity of the wood. The case presented in Chapter 3.2.3 explicitly highlights the necessity of automation and the relevance of this topic. Following the theoretical stance of the *Discrete*, this project also considers the socio-ecological implications. Therefore, it addresses all the challenges proposed in Chapter 1.

However, the framework of the *Discrete* is not without criticism. Leach states that it is "a style in opposition to [...] 'Parametricism'" that is not concisely defined.[133] He further argues that prominent figures like Neri Oxman and Greg Lynn regard the *Discrete* as an obsolete concept.[134] As for Oxman, she argues that Material Computation replaces the notion of discreteness. "This approach to design [...] seeks to advance and embrace strategies of material distribution over strategies of [discrete] material assembly [...]."[135] It supports multifunctional and heterogeneous elements and products inspired by nature.[136] However, the two principles don't exclude each other. Therefore, future research could include both approaches, exemplifying their respective benefits in manufacturing and construction.

The outlook for this project includes testing the structural capabilities of the joints and the system within 1:1-prototypes. Their assembly process could also be a further investigation. For that, its automation with distributed robots is relevant. Furthermore, additional work includes the reassembly of the elements into a new structure. Therefore, the code must be improved and extended to incorporate an algorithm that creates configurations based on evolutionary optimization. In this case, the 3d-scanning of the timber elements would be interesting as well. That is relevant if the structure shall be constructed with reused or unprocessed wood.

133 Neil Leach, "There Is No Such Thing as a Digital Building: A Critique of the Discrete," in Retsin, *Discrete*, 136.

134 Ibid.

135 Neri Oxman, "Material Computation," in *Manufacturing the Bespoke: Making and Prototyping Architecture*, ed. Bob Sheil, AD reader (Hoboken, New Jersey: Wiley, 2012), 259.

136 Oxman, "Material Computation," 259.

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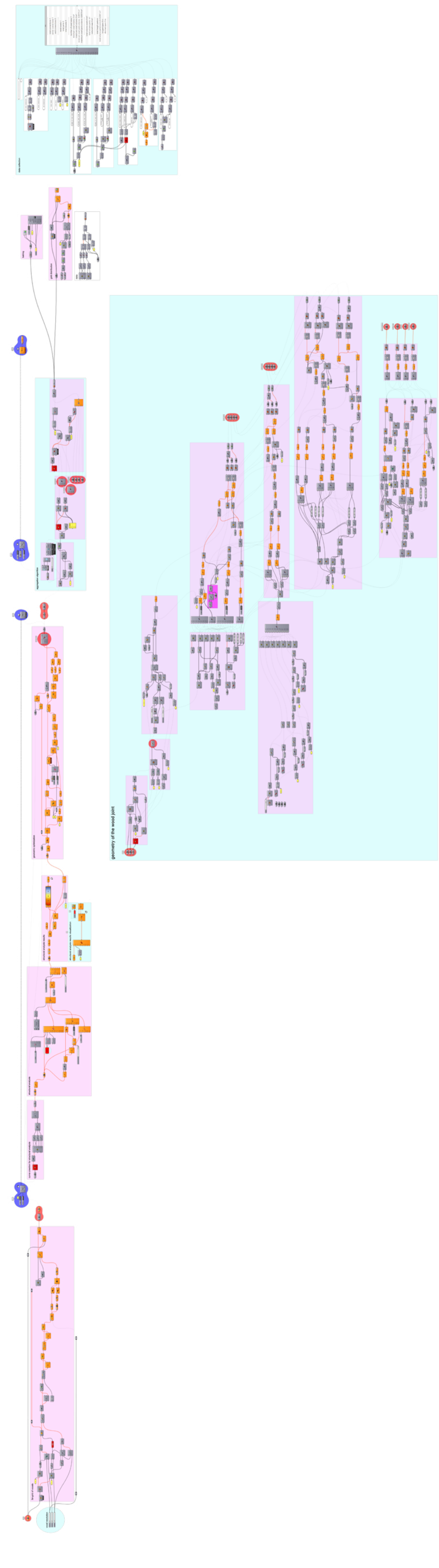
Appendix



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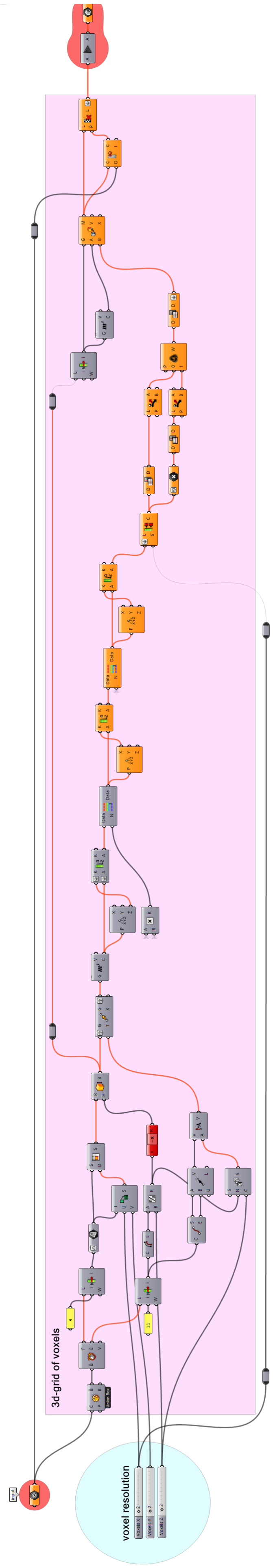
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voxel resolution

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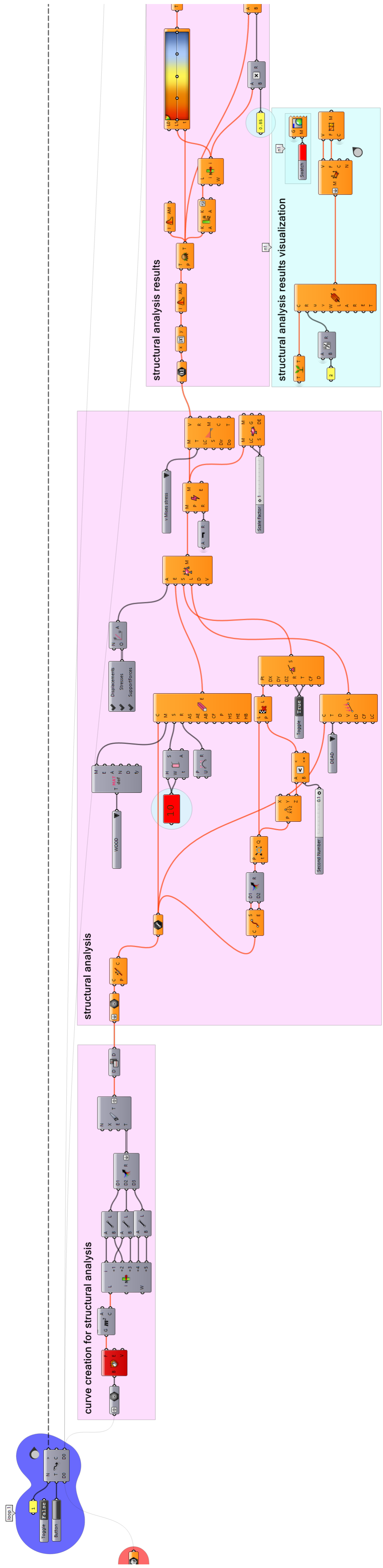
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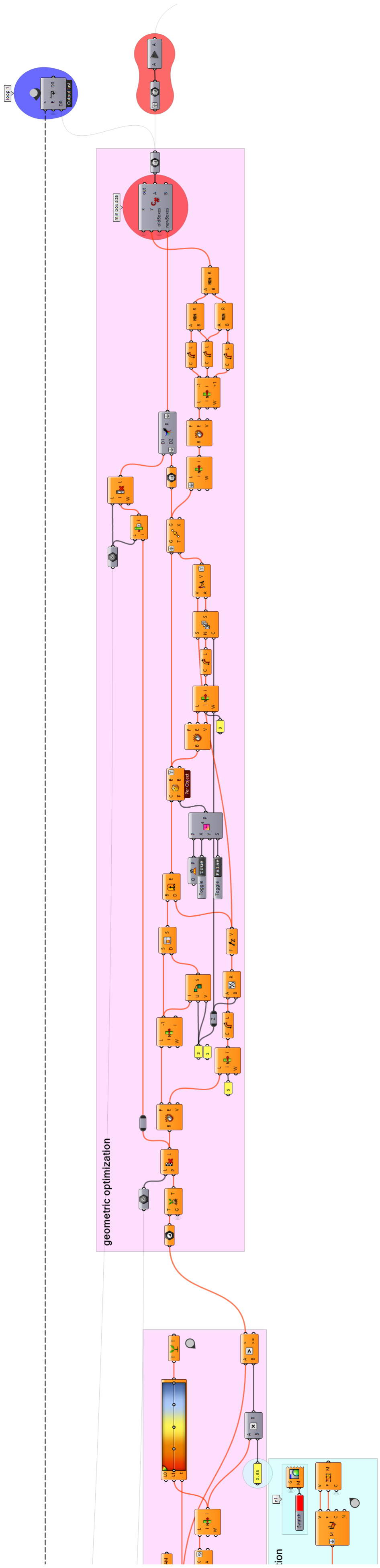

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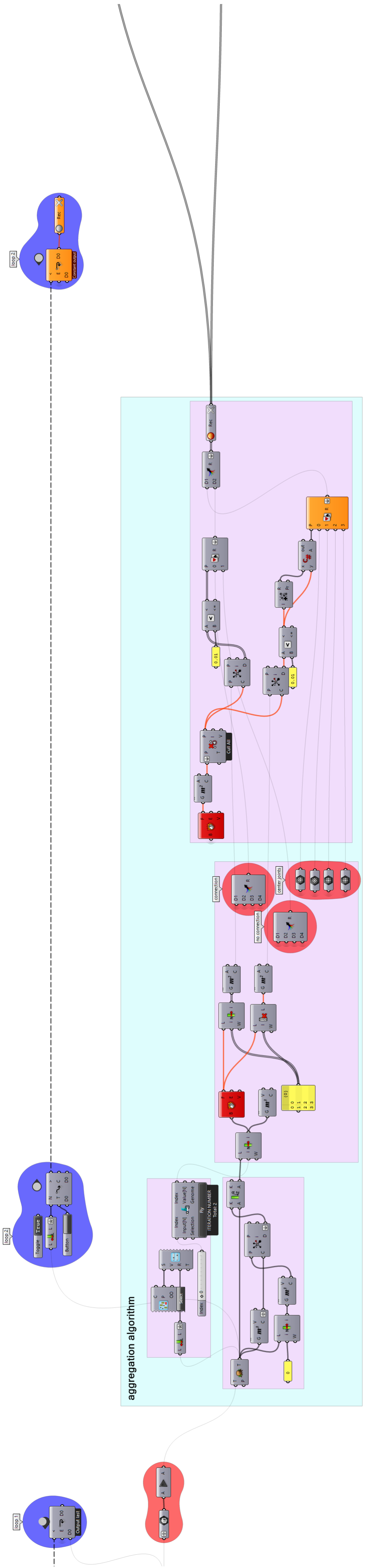

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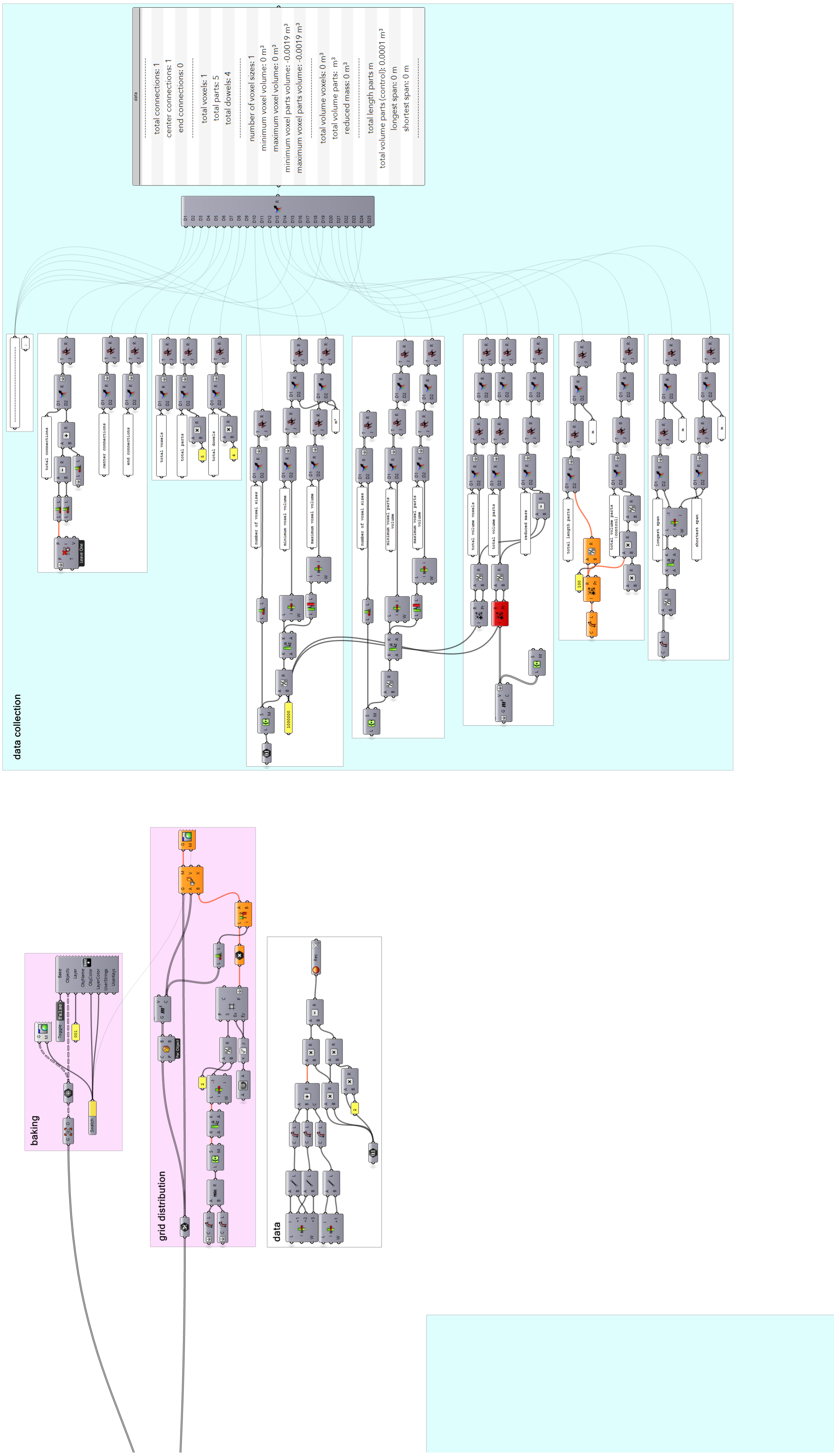
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total length parts m
total volume parts (control): 0.0001 m³
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shortest span: 0 m
baking
grid distribution
data