



THE DIGITAL CARPENTER

An Exploration In Manufacturing Complex Timber
Structures Through Digital Design Techniques

By
David Hensel

THE DIGITAL CARPENTER:
AN EXPLORATION IN MANUFACTURING COMPLEX
TIMBER STRUCTURES THROUGH DIGITAL DESIGN
TECHNIQUES

BY

DAVID HENSEL

*A thesis
submitted to the Victoria University of Wellington
in fulfilment of the requirements for the degree of
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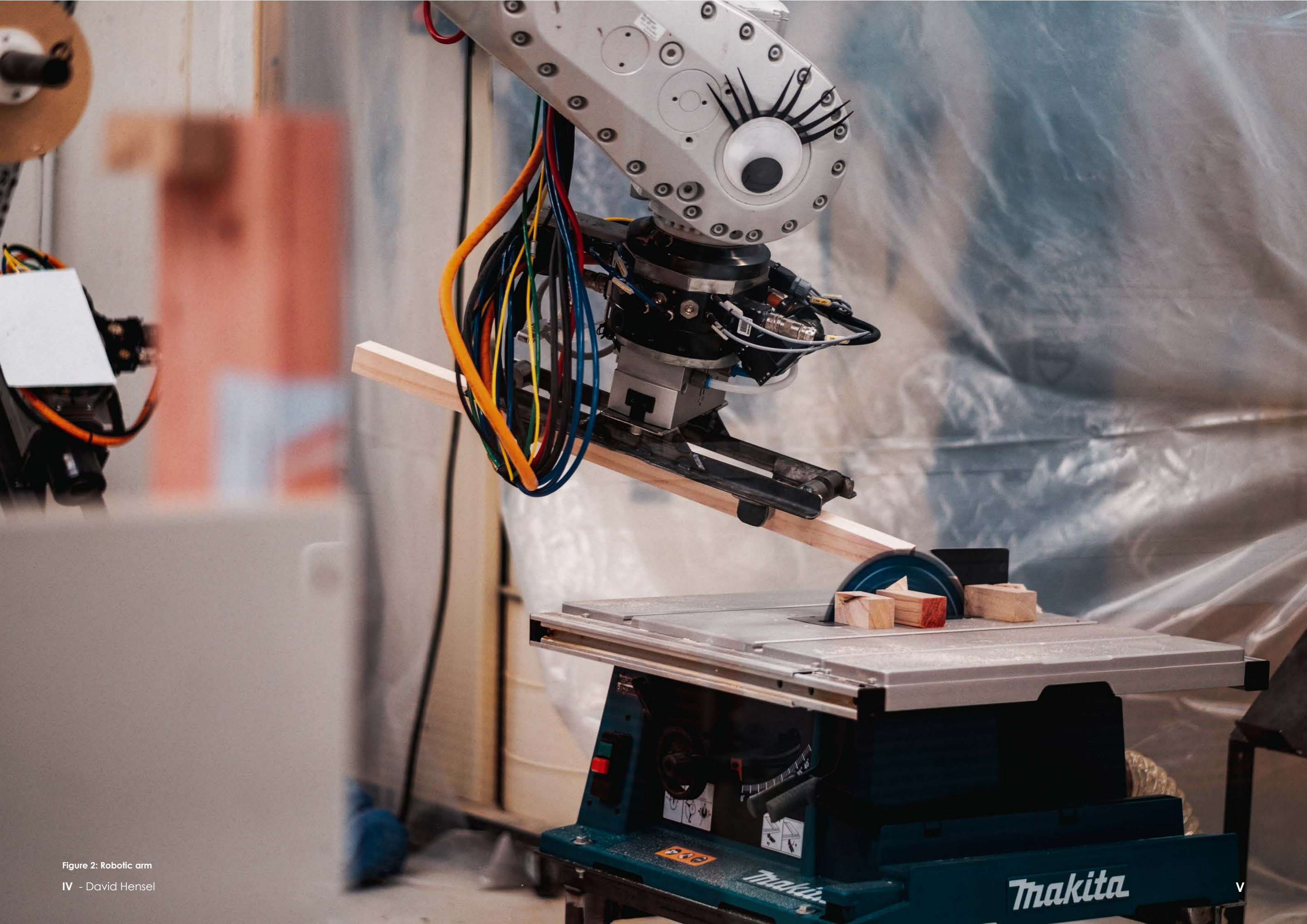


Figure 2: Robotic arm

IV - David Hensel

ACKNOWLEDGMENTS:

My supervisors, Guy Marriage and Jae Warrander, for pushing me, providing constructive ideas and feedback, and helping me get through this last chapter in my degree.

Kevin Sweet and Hamish Morgan, who introduced me to the robotic arm and provided inspiration and technical help.

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Lola, the robot. Looking forward to seeing what you do next.

The friends I've made along the way, for the many laughs, stupid conversations, dumb ideas, late nights doing everything from working to obscure food fiestas. It's been a blast.

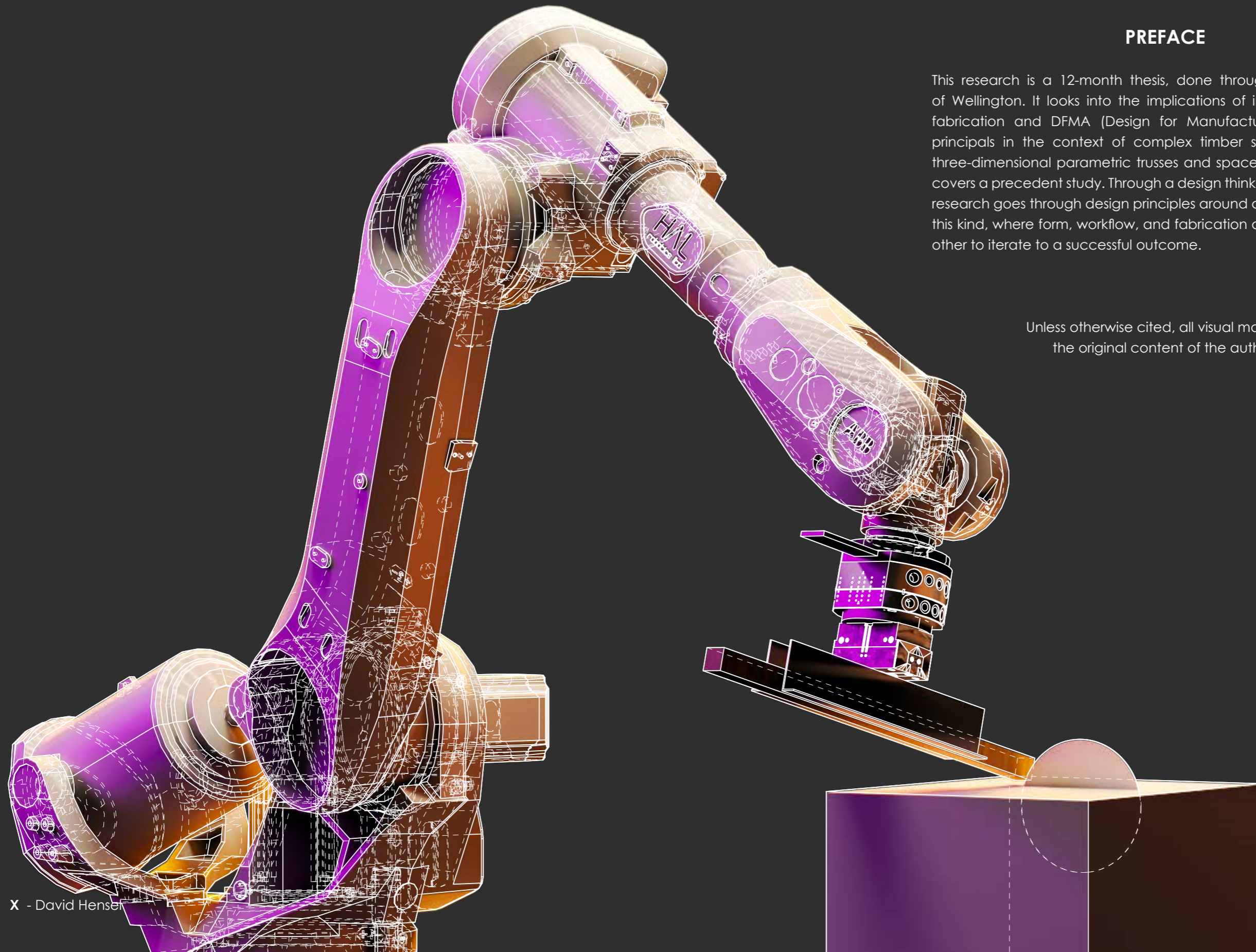
My parents and brothers, for all the love, support and food, I couldn't have done it without you.



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Figure 3: Final assembly



PREFACE

This research is a 12-month thesis, done through Victoria University of Wellington. It looks into the implications of implementing robotic fabrication and DFMA (Design for Manufacturing and Assembly) principals in the context of complex timber structures, specifically three-dimensional parametric trusses and spaceframes. The research covers a precedent study. Through a design thinking methodology, the research goes through design principles around creating a structure of this kind, where form, workflow, and fabrication are all talking to each other to iterate to a successful outcome.

Unless otherwise cited, all visual material is the original content of the author.

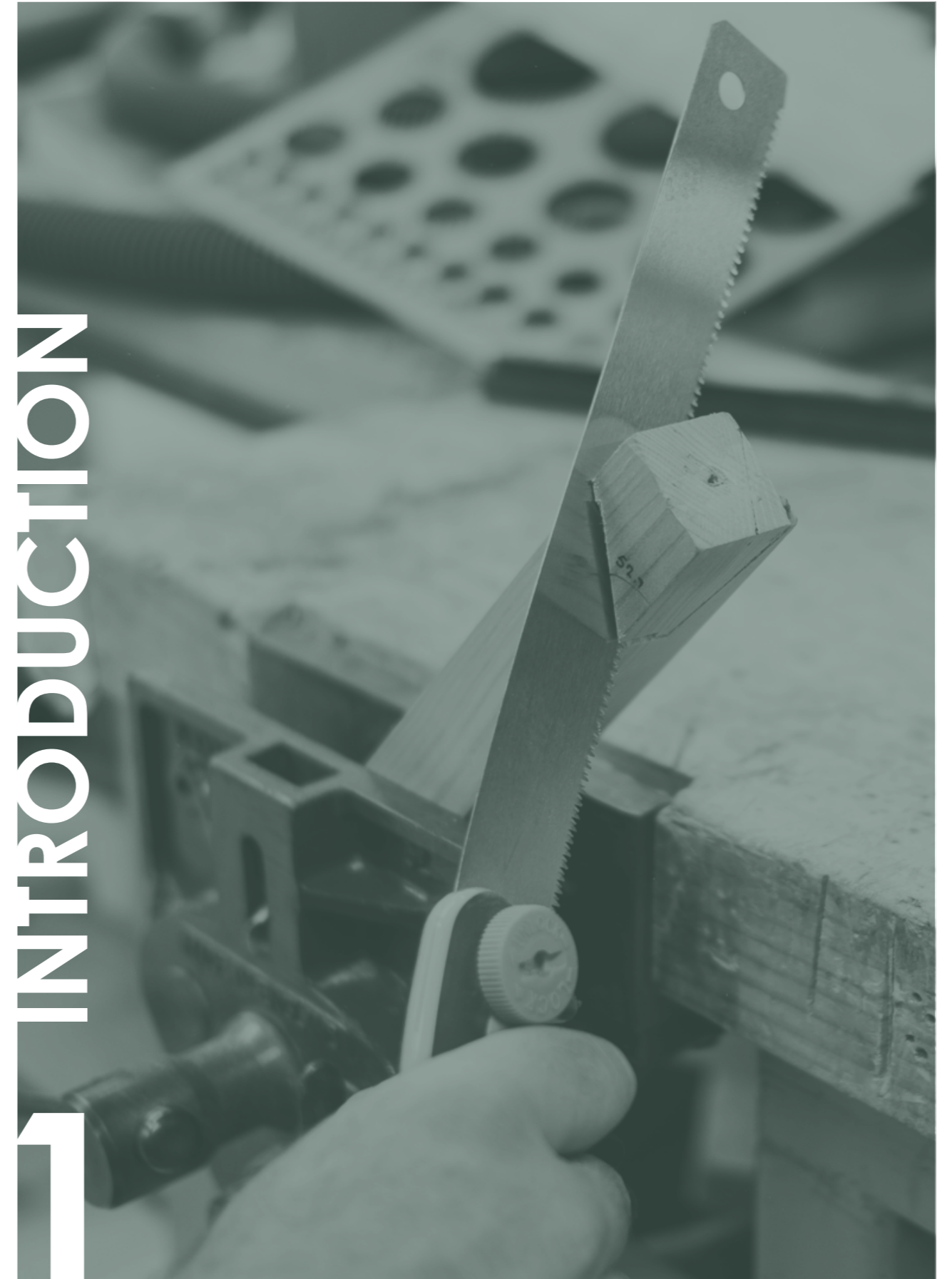


Mission statement:

The following thesis is part of the Advanced Manufacturing and Prototyping for Design Research Lab. AMPD aims to investigate and define innovative techniques and methods of modern construction applicable to the architecture and construction sector through the use of advanced tools of design, fabrication, and manufacturing. The fourth industrial revolution is core to our research exploring methods of improving information flow from design to fabrication—across the digital continuum—to design architecture that builds wellbeing for people and the planet. We can't keep doing what we have always done—our research questions the status quo by designing and constructing prototypes. You should consider the thesis within the larger body of research that AMPD Research Lab undertakes. Each thesis has focused on an aspect of AMPD's aim.

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INTRODUCTION

**USING DIGITAL
DESIGN AND
FABRICATION
METHODS, CAN
A BESPOKE
VISUAL TIMBER
SPACEFRAME
BE FEASIBLY
CONSTRUCTED
TO ALLOW
GREATER
CHOICE IN
ARCHITECTURAL
FREEDOM?**



1.1

ABSTRACT

Using digital design and fabrication methods, can a bespoke visual timber spaceframe be feasibly constructed to allow greater choice in architectural freedom?

At present, three-dimensional timber spaceframes are often not feasible as an architectural solution, as the end conditions are quite complex. The result of these complex situations is that they are not time or cost-effective when constructed by hand.

Subsequently, architects and designers tend not to frequently use these trusses as an expressive structural member over steel and concrete alternatives.

The fourth industrial revolution is making massive technological advancements in bringing together the digital realm and the physical. Architecture and the building industry as a whole are making steps towards harnessing some of these new technologies. However, there is far more that can be explored with what is already available.

Robotic fabrication brings with it the ability to automate specific tasks with an incredibly high tolerance of precision, allowing for the potential methods of construction, craft, and customisation that have previously been difficult, slow, and ultimately not cost-effective enough to pursue.

This thesis sets out on the premise that designing through DFMA (Design For Manufacturing and Assembly), the precision of robotic fabrication could be used to make these complex end conditions and assembly of these timber structures much faster, and therefore more feasible as an architectural solution.

Figure 6: Aspen Art Museum / Shigeru Ban Architects, 2014
©Michael Moran/OTTO - Image reproduced with permission.

**“THE ARCHITECT REMAINS CONTENT,
APPARENTLY, TO FOCUS ON THE
APPEARANCE OF THINGS, WHILE THE
PROCESS ENGINEER GOES BEYOND
INTO THE DEEPEST SUBSTANCE OF
MAKING”**

(Kieran & Timberlake, 2004)

1.2

AIMS

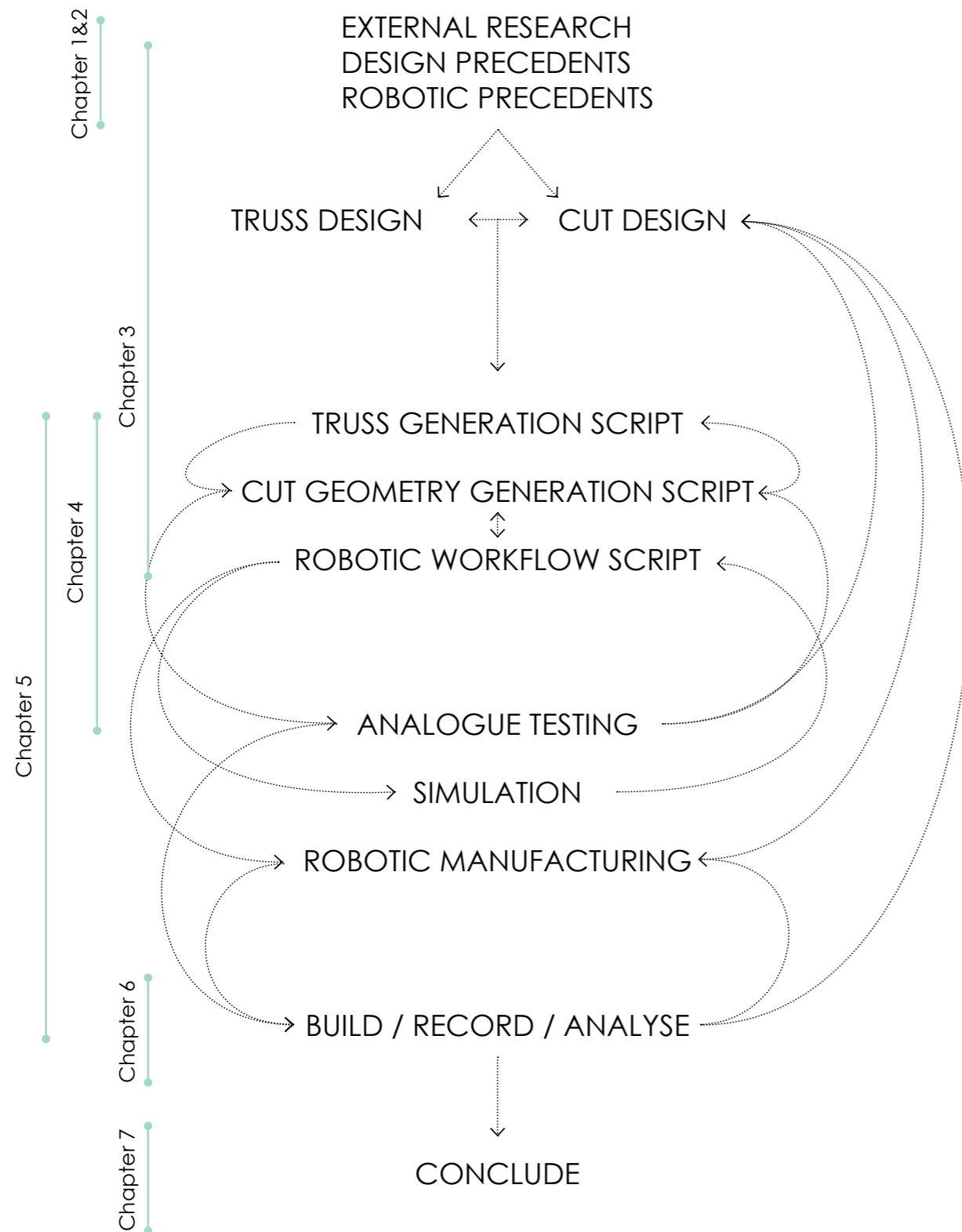
This research aims to look into existing complex timber assemblies and space frame systems and derive from them design principles. Simultaneously, the differences between traditional methods of making and computational manufacturing processes are explored. The outcome of this is to design and produce timber structures that use the control and efficiency that robotic fabrication allows. Using parametric design with a feedback loop of rapid prototyping and evaluation, the research objectives are:

To create a workflow that allows for a direct link between parametric adjustments and the final physical product.

To prototype several different complex timber joints and structures and critically evaluate them from the perspective of form and fabrication.

To produce a full-scale prototype to evaluate how the research could be implemented in the construction industry and interrogate its feasibility and opportunities.

To present the issues and opportunities of these findings as a case study for robotic fabrication.



1.3

METHODOLOGY

This research project follows a model of design thinking. After an initial phase to develop a workflow, designing leads into making and evaluating, which can then feedback into design and develop through this. By using this feedback loop, the exploration continues to build on itself, and allows the development of the design, process and outcome to be informed by the outcome of previous iterations.

While the actual process of carrying out the research is a fluid, non-linear process, it can be divided into a number of critical stages, which has informed the layout of this final research document and corresponds to the different chapters.

First, the problem needed to be identified, which was done through a stage of literature and precedent research. Coming into this research, there was a rough idea of the direction it was going to take. However, it was not until this literature study was carried out that the specifics of the project's scope was to be, and the specific direction that it took could be identified.

Once a clear scope of the project was defined, a design stage came into play. Throughout the circular design thinking process, the findings and constraints of digital design, analogue material testing, and fabrication tests start to make more significant contributions to the design phase. These factors inform what is possible and what is not in design.

Design within this research is constant and remains open-ended. It can however, be split into two fundamental paradigms, one with a clear focus on studies to do with form, structure and jointing. The second stage has a greater concentration on designing workflows and engineering a fabrication process.

Following this, the next phases to investigate were analogue material testing and fabrication testing. These processes revealed opportunities and constraints to do with the physical possibilities of the materials and making processes, which either were not evident in the digital design stages or did not appear to have as much of an implication as they actually did. These findings continued to inform the design process, from the architectural language of the joints all the way back to the processes of making.

Finally, a selection of different architectural forms are designed through the processes found through the design thinking stage, and one is selected to create a full-scale prototype to produce. This combines the form design, joint design, and all the constraints of fabrication in one exercise. Alongside these considerations, it begins to talk about the implications of assembly and producing structures at a real-world scale.

1.4

DEFINITIONS

AMPD	Advanced Manufacturing and Prototyping for Design
ABB	Manufacturer of industrial robots.
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CLUSTER	A group of Grasshopper script condensed into a box.
CNC	Computer numerically controlled, typically in reference to a milling machine
COMPOUND	A cut with two or more angular conditions
DFMA	Design For Manufacturing and Assembly
END-EFFECTOR	Tool attached to the end of the robotic arm.
GRASSHOPPER	Parametric plugin for Rhino, allows for visual scripting
HAL	Plugin for Grasshopper to create Rapid code
RAPID	Code language for controlling an ABB robot
TCP	Tool centre point. This is a point to be calibrated to match the reference point of the end effector/tool being used on the robotic arm.
TOOLPATH	Series of planes in Rapid code that create a path. TCP will follow the instructed path.
VISUAL TIMBER SPACE FRAME	Timber structure with care taken to keep the joints and structure beautiful.
RB6700 260	ABB robot used in this design research.
RHINO	3d modelling software

2 LITERATURE REVIEW

Image redacted

Figure 7: Alberni / Kengo Kuma - 2020 Visualisation, building under construction - © Hayes Davidson

**“THE EMPLOYMENT OF ROBOTICS IN
ARCHITECTURE IS OPENING UP THE
PROSPECT OF ENTIRELY NEW AESTHETIC
AND FUNCTIONAL POTENTIALS THAT
COULD FUNDAMENTALLY ALTER
ARCHITECTURAL DESIGN AND THE
BUILDING CULTURE ALIKE”**

(Gramazio & Kohler, 2014, p. 14)

2.1

CONTEXT - INDUSTRY 4.0

The building industry is not changing at a rate that reflects the way that technology is evolving. Simultaneously, there is a growing demand for new buildings that perform better, are more environmentally conscious and sustainably built, and are faster and cheaper to construct. *“The global construction industry is one of the last craft industries yet to fully embrace the technology age.”*

(Kattera, 2020)

Prefabrication is becoming more common, but is still largely built in the same way as traditional construction, just in a more controlled environment with a few processes to make the production more efficient. Embracing new technology could have incredible implications for the scope that prefabricated architecture could take. Robert Corser writes:

“The promise of mass customization and architecture’s adoption of computerized manufacturing techniques is a higher quality building at lower cost” - architectural production will become a realm “where quality and scope can increase out of all proportion to cost and time, where art transcends resources.”

(Corser, 2010, p.198)

This is supported in the writings of Kieran and Timberlake:

“...advances in the design and fabrication of automobiles, airplanes, and ships. In these constructions, new materials and processes abound. Fabrication times have decreased along with production costs and waste, while quality has increased exponentially.”

(Kieran & Timberlake, 2004, p. xi)

Matthias Kohler and Fabio Gramazio, Professors of Architecture and Digital Fabrication at ETH Zurich are two key players in taking robotics and other digital technologies, and applying them into fabricating architecture in new ways.

“The employment of robotics in architecture is opening up the prospect of entirely new aesthetic and functional potentials that could fundamentally alter architectural design and the building culture alike”

(Gramazio & Kohler, 2014, p. 14)



Figure 8: Nine Bridges Country Club / Shigeru Ban Architects, 2009
Authors sketch.

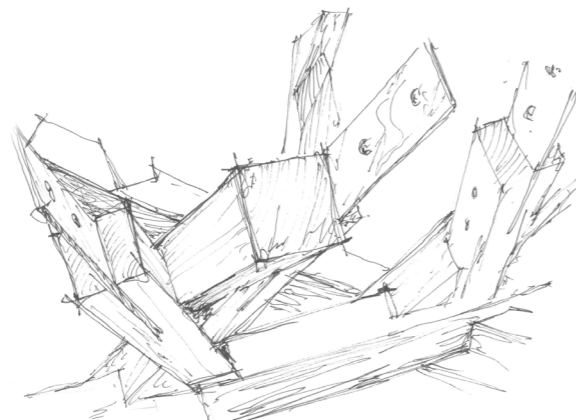


Figure 9: Joinery in Sunny Hills cake shop / Kengo Kuma, Authors sketch.

2.2

CONTEXT - TIMBER ASSEMBLIES

The use of engineered timber is becoming a more popular structural system, with even high-rise architecture adopting cross-laminated timber (CLT) floor slabs and glue-laminated (Glulam) beams. (Abrahamsen & Malo, 2014)(Voll Arkitekter, 2019b). This use of timber allows some of the large spans that architects and engineers use steel and concrete for, achieved with a sustainably grown, renewable material. Timber has a much lower embodied energy and greater ease of recycling than steel and concrete within construction. (Marriage, 2019, p. 76)

Alongside the technological advances in engineered timber, the use of the space frame typology allows for greater spans made up of smaller members. The structural language of a space frame has the advantage of lesser material use, engineered loading optimisation, and more intricate architectural opportunities.

Timber assemblies have a rich history of craft associated with them, which has become more and more scarce as time and budget become more defining factors within architecture. Where complex timber connections do exist, they tend to rely on steel nodal conditions. While this predicament provides structural advantages and offers a reduction in complexity, the resultant joint does not come out nearly as clean or elegant. Digital fabrication and a DFMA approach present an opportunity for the feasible construction of these assemblies, with much greater care for a beautiful, crafted joint.

There is a vast opportunity within architecture to make use of these complex timber assemblies in everything from small bespoke pavilions all the way to civic scale buildings. The illustration in figure 6 portrays an organic tree formation webbing out to support the roof of the Nine Bridges Country Club. Shigeru Ban Architects utilise engineered Glulam beams coupled with CNC milling to create these geometries. Another key case study is Sunny Hills by KKAA. Part of a series of studies in using a timber weave as a dominant tectonic element, Kengo Kuma wraps a commercial building in complex timber joinery inspired by a bamboo basket, paying tribute to the vernacular of traditional Japanese craft. This project, while designed in CAD software, does not make use of digital fabrication, but instead, a great number of cabinet makers and other skilled woodworkers fabricated the intricate façade.

Image redacted

Figure 10: Spatial Timber Assemblies / Gramazio Kohler Research, ETH Zurich and ERNE AG Holzbau, 2018

Yuteki Dozono, one of the project architects working on this work, talks about the complexity of the project being “too great for modern fabrication technology” (Antropova, 2015, p. 58), and that the construction process “is not always about the efficiency - it’s about doing something because you can do it” (Antropova, 2015, p. 88)

2.3

CASE STUDIES

Spatial timber assemblies

DFAB house by Gramazio Kohler Research, ETH Zurich and ERNE AG Holzbau.

This precedent was one of the key inspirations behind this thesis. Using robotic fabrication, a structure is built that is enabled by the opportunities that this digital method of making brings. Geometric forms are made which would have been otherwise incredibly difficult to manufacture, as they require exact compound angled cuts and placement.

This paper makes use of “two six-axis industrial robotic arms, each attached to a base with three axis of movement” (Thoma et al., 2018) giving them an additional level of mobility over the set up currently available for this research testing. Despite there being two arms working in unison, the structure still requires human involvement to apply fixings.

ETH Zurich’s fabrication process features a table saw fixed in space; a robotic arm collects timber and brings it through the saw at the required angle. From there, it moves on to placing it within the structure at the required place for it to be fixed.



Figure 11: Robotic Pavillion / Gramazio Kohler Research, ETH Zurich , 2017. Photograph by Kasia Jackowska.

Robotic Pavilion

Gramazio Kohler Research, ETH Zurich

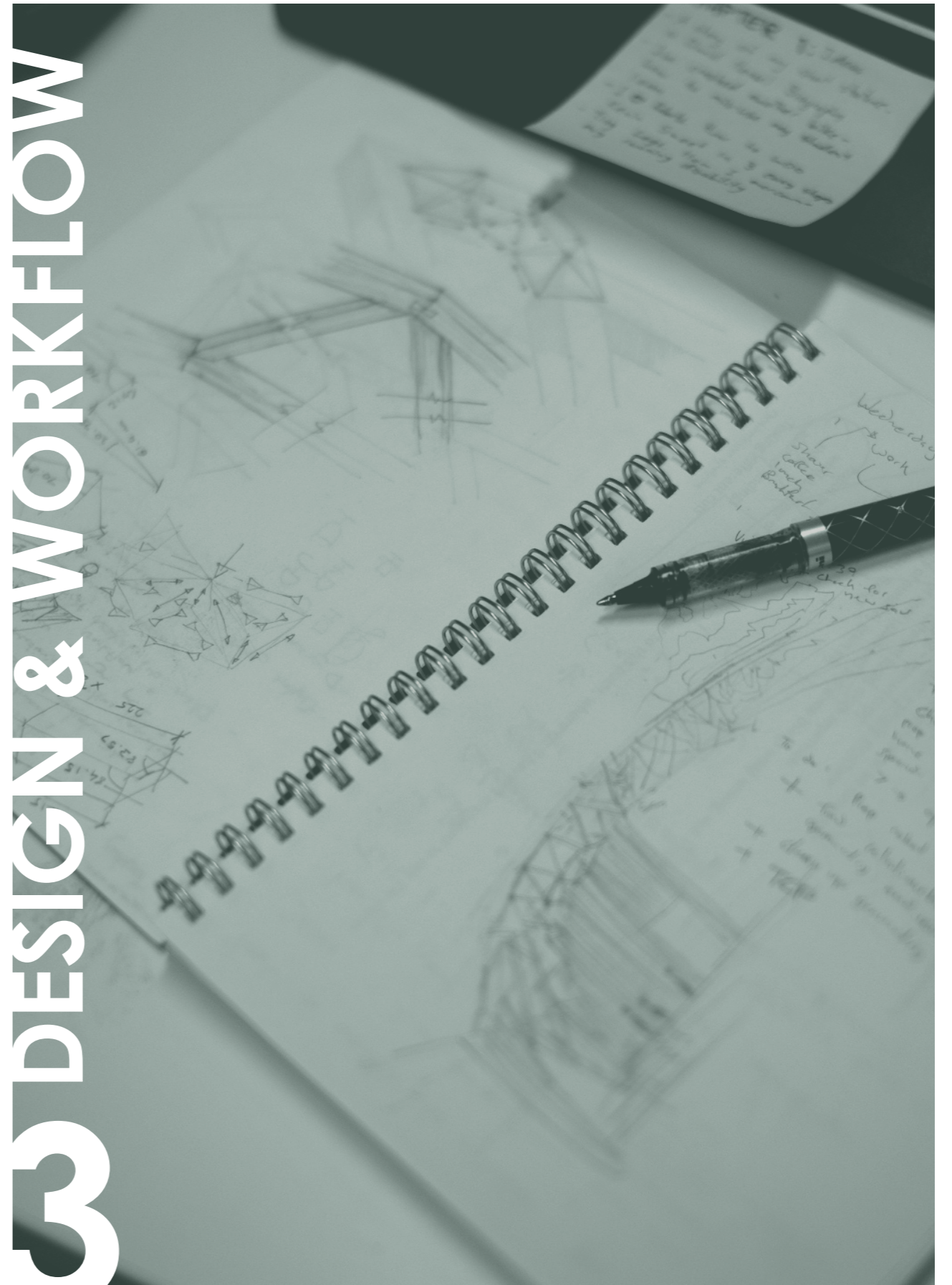
Another key precedent by Gramazio Kohler Research, ETH Zurich, the robotic pavilion goes a step further, breaking away from the post and beam wall construction and moves into a system of creating rhizomatic space frame modules which can then be transported and assembled off-site.

Both of these case studies were crucial in the inspiration to this research – where they differ is that these projects pull away timber members from the node. Eversmann writes about the Robotic Pavilion and an “arrangement routine which computationally aligned the joints between members so that only joints between two members occur.” (Eversmann, 2019, p. 173)

By pulling members out of the node, the condition of only two members intersecting removes a large portion of each connection's complexity. Furthermore, it appears that only a single compound cut (a cut with two different angular conditions) exists in each end. This does have several advantages, namely, to do with simplicity.

These structures are in their own right impressive feats of combining the capabilities of digital design and fabrication techniques to create a vernacular of architecture that tends to be too complex to be considered feasible. This being said, a further opportunity arises to focus in on the joint and bring back every relevant member to its node. Not for the sake of complexity itself, but creating a joint which would express and celebrate craft and digital methodologies. The focus on beauty and aesthetic does add another layer of complexity.

3 DESIGN & WORKFLOW



Chapter three

Figure 12: Notebook

3.1

OVERVIEW

Chapter three begins to look into the design of spaceframes from the lens of the overall form and how they could be generated through digital workflows. It then zooms into the more intimate scale of how the end geometries might be processed and assembled in a feasible, functional way and carries high regard for aesthetic and beauty.

The design element of this thesis exists throughout the entire project; however, this chapter contains much of the design considerations, development of code and workflow, and setting of constraints for the project prior to the iterative design thinking process which is to follow. Many considerations from the following two chapters aided in the decisions made within this design stage.

The thesis initially set out to build off work in 'The Robotic Craftsman' (Heesterman, 2019). However, it was decided that in order to build from Mikayla's work in any meaningful way, the production of large scale prototypes for structural testing was required. This fell outside the scope of this thesis and the expertise and capability with the tools available.

Still longing to explore the possibilities of computational fabrication methods with timber, the work that Gramazio Kohler Research from ETH Zurich had been doing with complex timber assemblies was referred to (Thoma et al., 2018). The paradigm of a rhizomatic space frame was chosen as the formal condition to work towards, allowing the formal studies to have a clearly defined scope and for that to then be put aside to allow a focus on the joint and fabrication, where the scope of the research lies.

This is the point at which the thesis question finally began to settle. It was concluded that there was little point in spending more time designing 'new' types of structures with unnecessary complexity in pursuance of exploring the opportunities of robotic fabrication. Instead, a decision was made to focus on the prismatic space frame, which works out to be a robust and beautiful structural system with great design opportunity. Additionally, as elaborated in chapter one, a prismatic truss is seldom used as an expressed timber design element due to the high cost of fabrication.

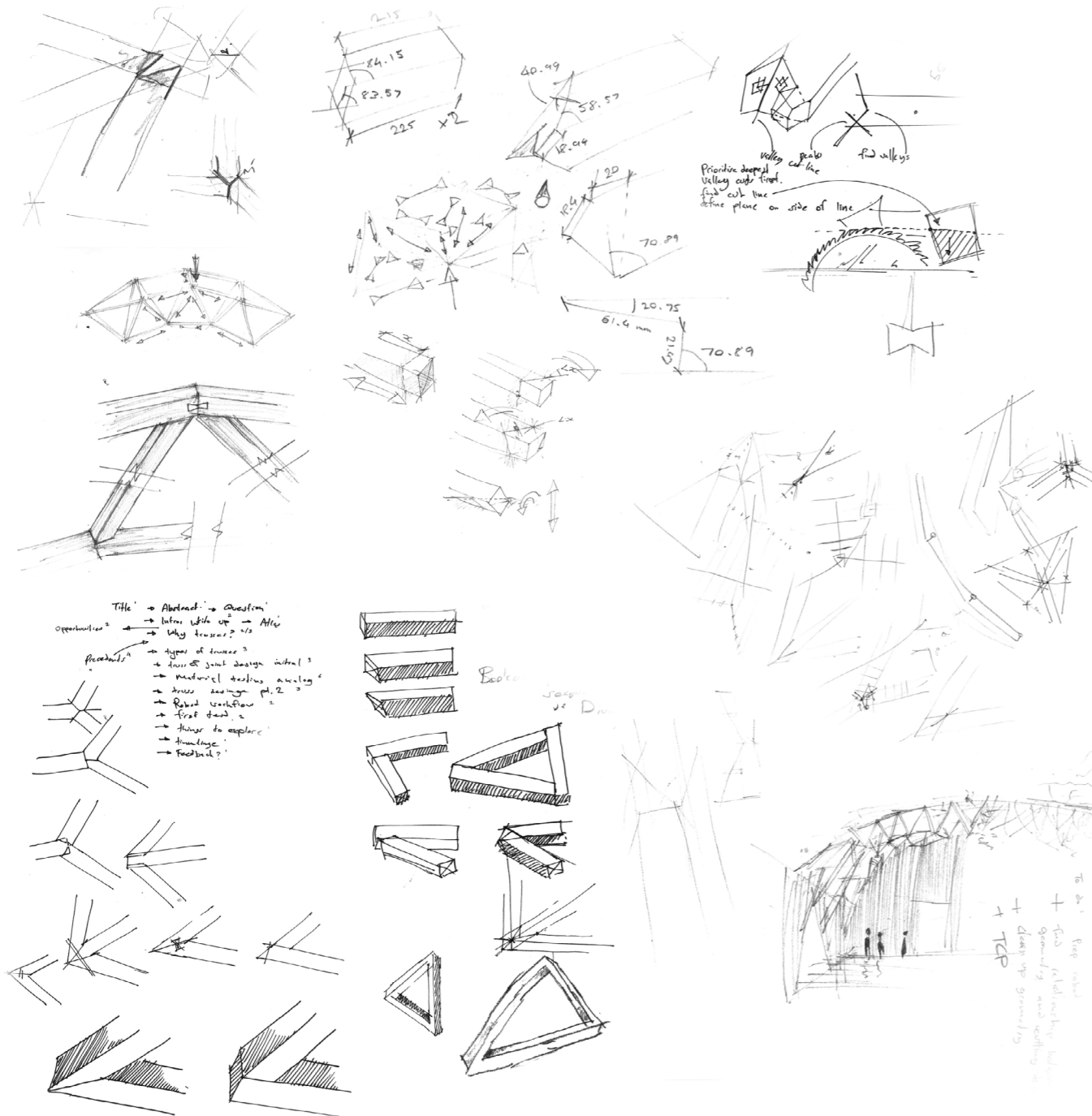


Figure 13: Sketches

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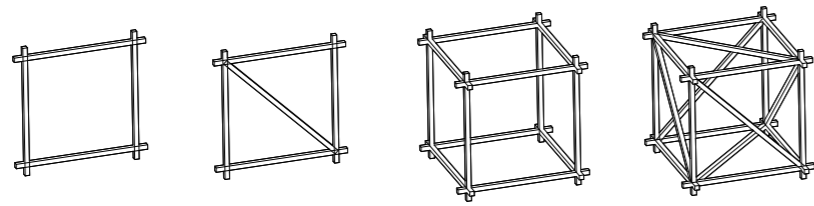
Figure 14: Structural roadmap left side, Atlas of Novel Tectonics / Jesse Reiser Nanako Umemoto , 2006

3.2

FRAME DESIGN

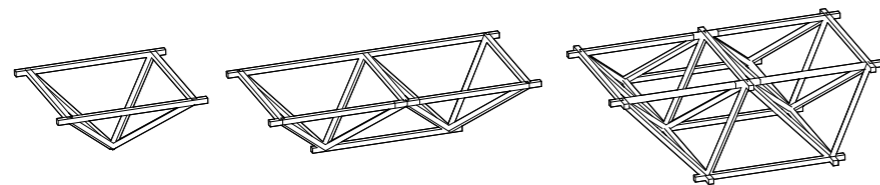
The design of frames that are explored begins with the structural roadmap found in 'Atlas of novel tectonics' (Reiser & Umemoto, 2006, p. 130,131). This elegantly links the progression of different structural systems to take gravity and sheer loadings, in a simple diagrammatic way.

Starting from the simplest of structural systems, the post and beam, a quick analysis was made of some of the flow-on structures towards the complex modulated three-dimensional truss systems that were being pursued. This analysis was factoring the structural merits, complexity, and aesthetic as one part of the analysis. Then, the implications for making said structure out of timber using the jointing methods explored in this thesis. The following sections discuss the various frames and trusses and their jointing complexity before creating workflows to generate them.



Vierindeel Truss/Frames

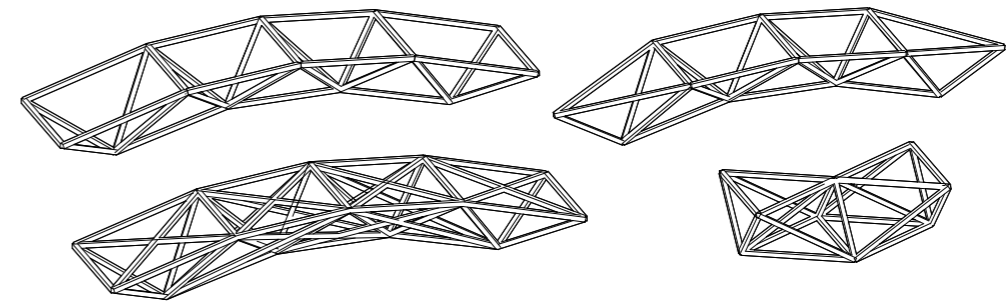
These structures are the simplest to create from the selection the research looks at. While three-dimensional versions are shown as well as two dimensional, they are simple layouts of structural members with simple end geometry. Many elements will be repeatable, and most joints are at right angles to each other. The few joint conditions that are not at 90 degrees are only cut in a single axis, which is relatively easy to achieve quickly and effectively using power tools. Compound mitre cuts are not necessary for this kind of structure.



Regular Space Frames

Space frames, or a regular prismatic truss begin to add a greater amount of complexity into the manufacturing process, as well as requiring a high level of accuracy in the workmanship. There are still many of the same repeated elements, and a two dimensional base to work from (inverted), but the introduction of compound cuts in the end geometry creates a more challenging condition to manufacture, and more skill and care is required to create these cuts for them to work perfectly. Once angles become ever so slightly out, the resulting structure will magnify the mistake once at scale.

Figure 15: Different structural typologies,



Modulated/Rhizomatic Space Frames

Bringing in modulation to these frames is where a large amount of complexity is introduced, and consequently greater difficulty to manufacture. These structures will be the end goal of this thesis, as they provide the most challenges. The hypothesis is that this will be where the greatest difference between traditional construction methods and DFMA lies, both in time and cost.

The diagrams above illustrate what are still quite regular forms for a rhizomatic truss, but these forms encompass warped parametric forms. They become greatly complicated when the joints have anything above three members joining at a single node, all of them at unique compound angles and different lengths. In this situation, there are very few, if any, members that repeat, and the joint geometry gets into multiple compound angle cuts. Furthermore, the precision required is again higher, as every mistake will be magnified as the structure grows in scale. These structures have no two dimensional base to act as a safety reset.

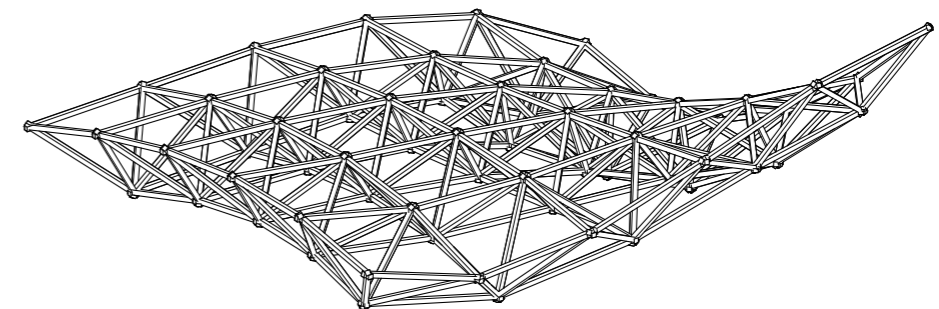


Figure 16: Different structural typologies,

3.3

FRAME GENERATOR V1

The first version of a digital workflow that creates a truss structure started as a manual nodal input. A script was created that would take a series of points from Rhino, or defined points in Grasshopper, and a truss structure was built from that.

In the first draft, a series of clusters that joined point A to B, B to C and so on was built to connect each point, but this manual method proved to be computationally intensive and very time consuming, and it was essentially still a manual process of selecting where structural members would be created.

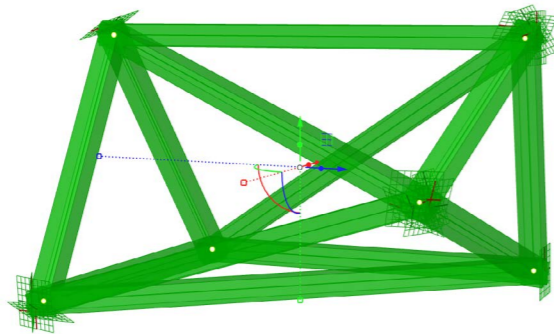


Figure 17: Interconnected points, Rhino/Grasshopper capture

This was then substituted for a Delaunay triangulation input. Delaunay is an algorithm that works out a triangulation pattern to connect all points in a three-dimensional cloud of points. A specific rule set optimises the arrangement to make the largest possible number of triangles within a Delaunay arrangement as close to equilateral as possible.

This method made it possible to parametrically generate a series of structural lines that intersect at varied angles from a collection of points. Later parts of the process were then tested against. However, as a structural solution, there was much to be desired. The algorithm would connect every node to at least two others but would miss what should have been critical connections.

The next method was to take the series of nodes and use the grasshopper function “interconnect” – this solution connects every node to every other node. Initially, this generates a web of intersecting structural lines. However, these can then be culled according to some parametric rules that are added to the script.

All duplicate sets of data are removed so that no unnecessary data is being processed further down the track – this involves flipping half the dataset, as the line from A to B, while the same line as B to A, does not register as the same.

Next, the script checks for intersections (away from nodal intersections) to ensure that every four-sided section did not result in an X brace through the middle. This became one of a few input parameter controls, where one can select to leave all intersecting members, remove all, or keep one and remove the member it intersects with.

Finally, all members above a certain length are culled. This is done for two reasons; one being to rationalise a mess of lines into something that resembles a truss or space frame and, more importantly, to allow a maximum span based on the timber members’ structural cross-sections implemented further down the track.

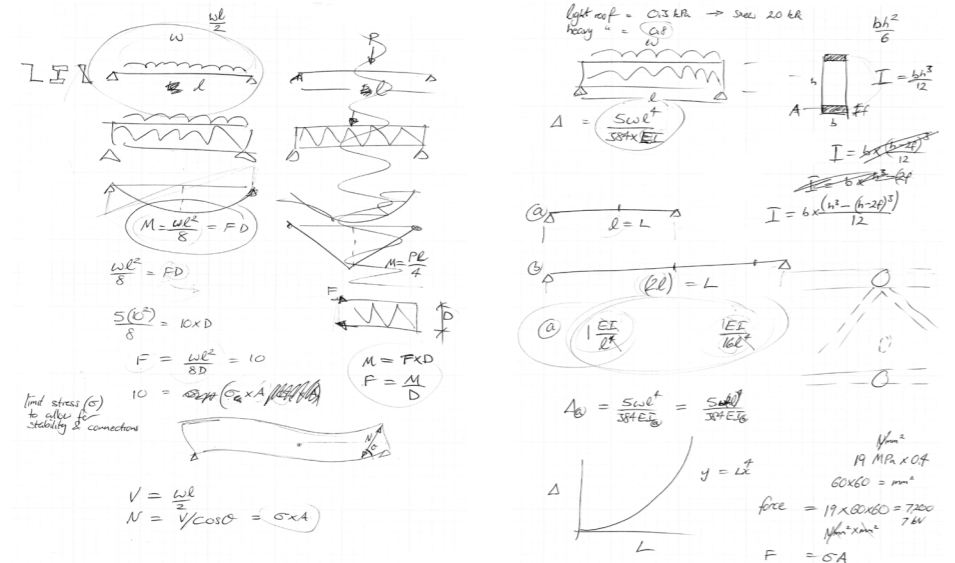
At this point a functional method of generating trusses from nodal inputs was used. The lines between nodes are able to be taken into the following sections of the script to become timber members, then have the intersecting geometry worked out. This is then converted to Rapid code for the robotic arm to manufacture, or to create shop drawings to create the geometry through analogue methods.

Upon review, it was decided that the nodal input was possibly a valid method and, without a doubt, the option with the highest level of control. However, the truss generation needed to become simplified down to something that the average designer might not be overwhelmed with.

The next iteration of this truss generation script took a slightly different approach, which aimed to minimise the interface with the script down to something almost plug and play.

Unlike the previous iteration, where all the nodes are defined by the person using the tool, the new script takes the approach to generate nodes from existing roof geometry.

In this instance, the architect or designer can take a roof plane from Rhino – this can be flat, all the way to a non-orthogonal form with a modulated edge condition – and plug that into the script. The designer is then faced with a few simple parameters that determine a grid set-out, member sizes, maximum spans, overall depth of the truss, whether the bottom layer roughly offsets the top, or if it is a flat plane. The same interconnect/cull methods from above are then employed before being passed onto the joint geometry aspects of the design workflow. The next phase was to start considering structural factors in order to add further validity to the design.



Deflection vs load	1.74	1.865	2.525	2.521	2.5
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5	5	5	5	5	5	5	7.5	10
1	1	1	0.7	0.7	0.5	0.5	1.05	1.4
1.12	1.12	1.12	0.84	0.84	0.71	0.71	1.29	1.7
1	1	1	1	1	1	1	1.5	2
2	1	0.3	2	2	2	2	2	2
63.4349488	63.43495	63.43495	54.46232	54.46232	45	45	54.46232	54.46232
60	60	60	45	60	45	60	60	60
6.2	3.1	0.9	8.8		12.3		13.2	17.7
6.2	3.1	0.9	8.8		12.3		13.2	17.7
2.361	1.18	0.35	7.07	3.5	11.14	5.78	9.6	21.6
1.56	0.78	0.235	4.63	1.9	6	2.665	6.8	18.9
1.1805	1.18	1.166667	3.535	1.75	5.57	2.89	4.8	10.8

Figure 18: Structural analysis

3.4

STRUCTURAL DESIGN

Using the two-dimensional structural analysis software 'Ftool', a series of tests were carried out on simple truss structures, changing a variable each time to find relationships between those variables and the resulting structural requirements. Using Ftool, information could be found from each test, such as the axial forces, sheer, bending moments and deflection values at each member.

When first looking into scripting trusses, the vision was to code an algorithm into the frame design scripts that could take rules of thumb calculations and apply them to size members according to inputs, like gravity loading and windspeeds. There are precedents for structural optimisation with novel timber assemblies, using algorithms to reduce material usage “by more than 30%” - (Hudert, 2019, p. 173), or the implementation of topological optimisation used to design “*high-performance structural designs in automotive, naval and aeronautic industries.*” (Søndergaard, 2015)

However, though this is possible, especially with specialist software like Karamba3D, the number of variables found that had to be considered when designing for a parametric form upon doing structural testing are too vast.

In the Sunny Hills project explored in chapter 2, Kengo Kuma limits the angular relationship of every member to 30 and 60 degrees, and even with this repetitive structural condition, the engineering of Sunny Hills was complicated enough that engineers had to resort to converting each member's forces into 2D. In an interview with Yuteki Dozono on the engineering, Antropova writes:

"...Parametric programs like Grasshopper failed to work because the parameters were simply too vast for the plugin." - "The initial inspiration was developed in close collaboration between an architect, an engineer and a craftsman. The architects would work in Rhino for the rough design, then pass the drawings to the engineer who would make them 2D for ease of calculating forces." (Antropova, 2015, p. 58)

To write out this algorithm would increase the scope of this thesis massively and push it into the realms of a structural engineering thesis rather than architectural. For this reason, further structural analysis was not carried out. However, the fundamental principles of load paths and deflection were considered while developing the parameters for the following generative design scripts.

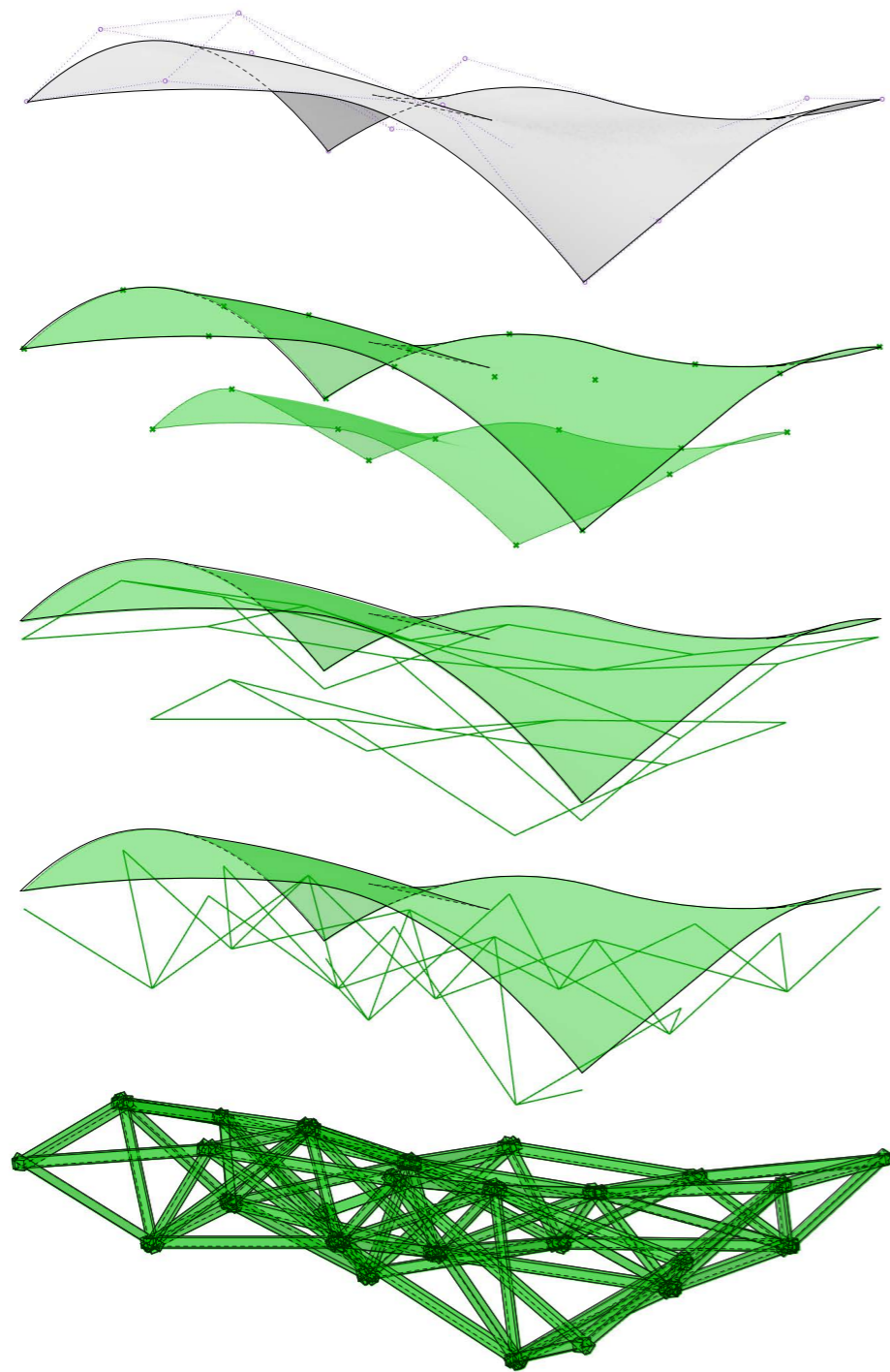


Figure 19: Script generation diagram

3.5

FRAME GENERATOR V2

Up until this point, the frame generation script was working to create a form that resembles a truss, but there were some serious issues with it. The critical issue with the previous script is that it does not provide any hierarchy between members, which causes issues structurally, aesthetically, and from the aspect of lack of prioritisation between cutting types.

The analogue material testing revealed the difficulty with a strictly boolean sequential method of creating geometry and likewise with a purely divisional splicing method (see section 3.6 and chapter four). Combining the two methods allows for the cleanest, most elegant cuts, and combining them with a structural hierarchy allows for a logic that defines how splicing and sequencing can be prioritised.

Building from the structure of the previous generative code, the architect or designer would still have the same interaction with the script – a mesh or other geometry is brought in from Rhino, and a few adjustable parameters at the beginning of the script allow for the grid spacings, member sizes, maximum spans and some other factors to be determined. However, where this new one branches off is that instead of a mass interconnect and cull method (which was quite straining computationally once a large roof geometry made it into the script), the members are separated so that bottom nodes form a grid at the bottom, the same for the top. Every node at the bottom level is connected only to the four closest nodes at the top level. This removes all the unnecessary members that would otherwise need to be culled and delivers three different datasets: top plates, bottom plates, and diagonal in-between (web) members.

The advantage of splitting these datasets is that each member group can now have its own set of rules and structural requirements, which was previously lacking.

The rule found to be most effective in analogue testing is that all three member types have a divisional splice cut with themselves. Boolean sequencing is then used at the intersections between member types, with the top and bottom chords always acting as the parent member.

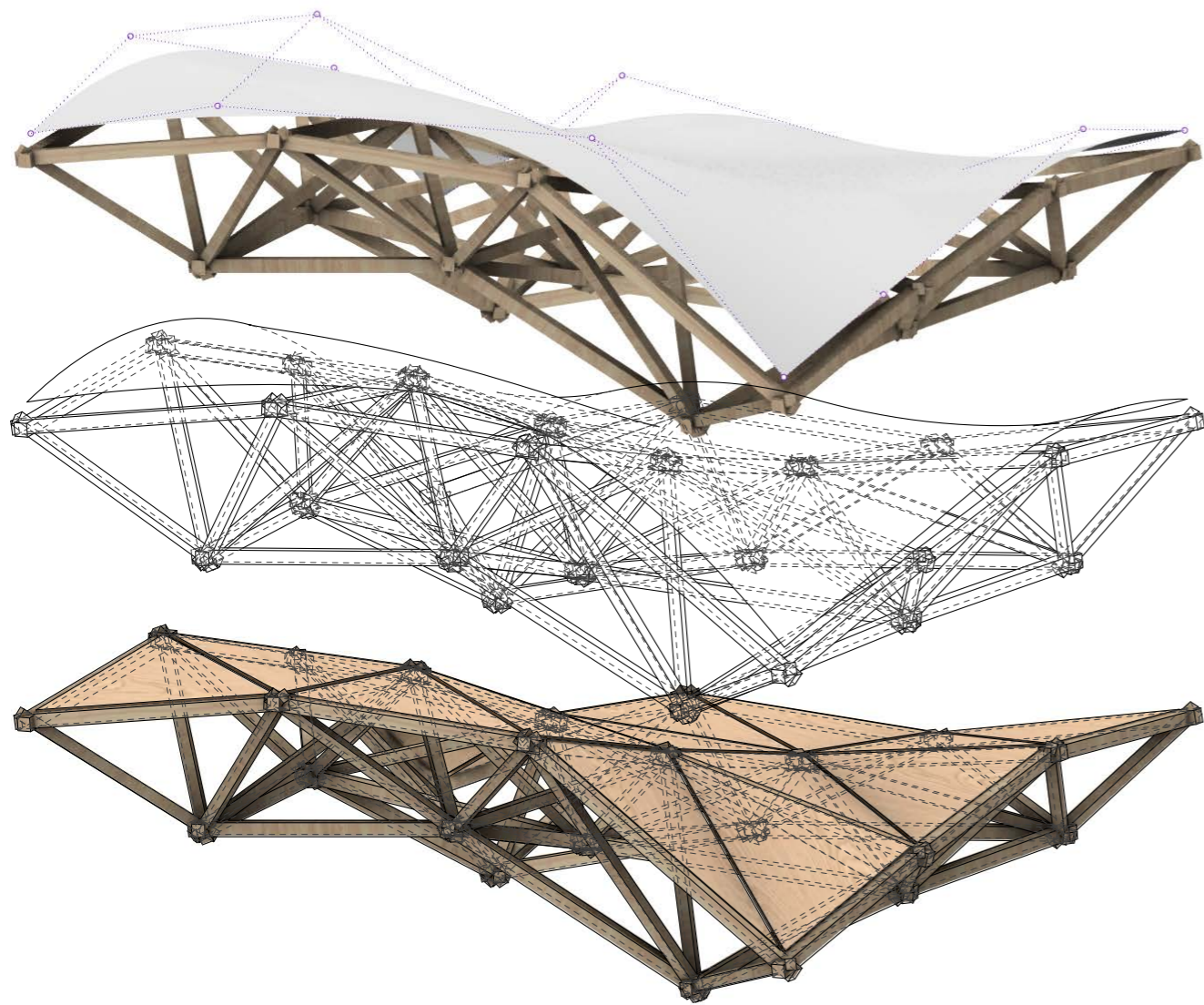


Figure 20: Script generation diagram, rendered output.

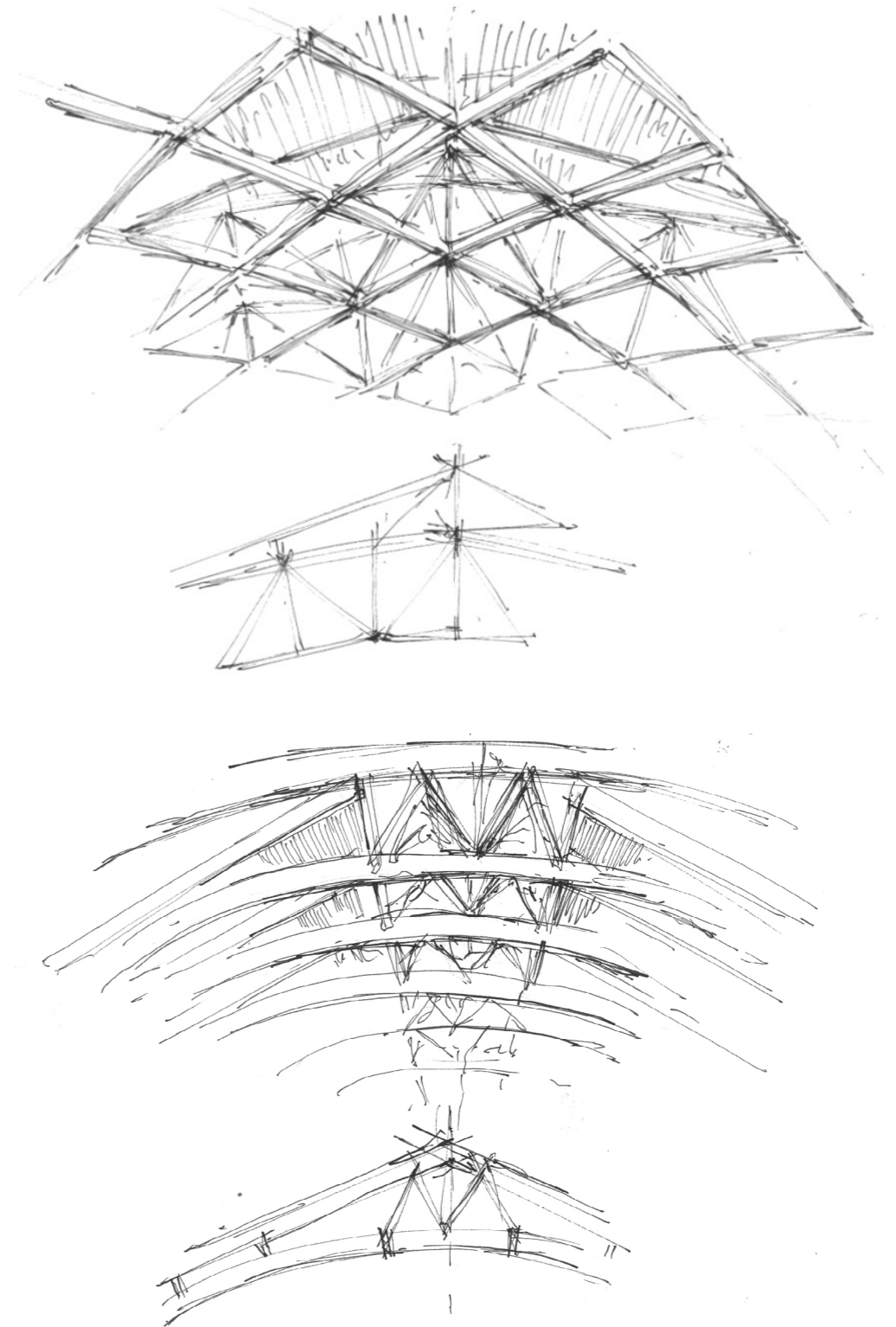


Figure 21: Shelter for Remain of Kutani Kiln/
Naito Architect & Associates 2009
Authors sketch.
Figure 22: Sea Folk Museum / Naito Architect
& Associates 1992
Authors sketch.

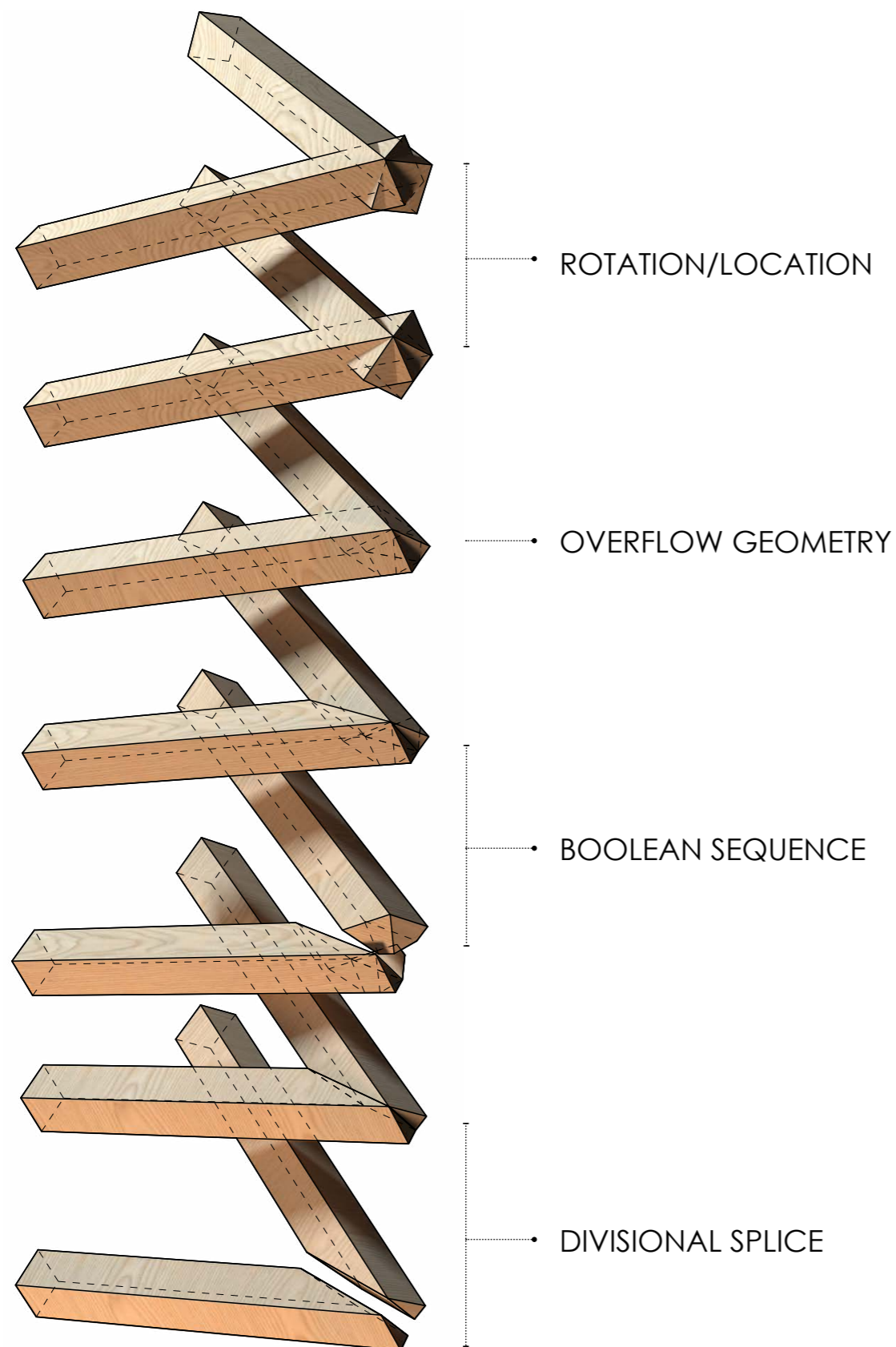


Figure 23: Geometry handling diagram

3.6

JOINT DESIGN

The next stage in design was to develop how geometry was to be handled. This encompasses both how members would interact with each other and how cutting geometry was to be determined.

The first consideration in this process is the way each element meets its counterparts. A decision was made that the centreline of every member was to meet at the centrum of each node. This decision exists both for aesthetic reasons but also for load transfer to and from nodes. The more challenging consideration is the orientation of each member in relation to those it is interacting with. This is something fairly straight forward to do in the event of two members interacting, yet incredibly complex when a multitude of members meet at a single node. Every orientation shift to suit one node will have a follow-on effect at the other end of each member. Throughout the design testing, this consideration became less of a focus, and other methods were used to keep a clean aesthetic joint. Taking inspiration from design precedents such as Shelter for Remain of Kutani Kiln by Naito Architect & Associates and Sea Folk Museum by Hiroshi Naito, (see Figure 19 and 20), different cross-sections of timber are utilised. While this decision reflects structural requirements, it also serves an aesthetic function to hide overflow, where an undesirable nodal interaction cannot be avoided.

Another reason the orientation consideration became less critical throughout the design research is that the orientation of a structural member is often determined by the directions of forces that it is withstanding. Should this research be taken further and implement proper structural optimisation, that would determine the orientation of members.

Handling overflow geometry was the next item to consider. An overflowing condition where all members stick proud from the node would create needlessly complex geometric situations. To deal with these geometries, a solid union from each intersection was analysed and separated into internal and external faces. Internal faces are redacted, while external faces are then used as cutting planes to trim down the geometries.

Two different methods of dividing geometry were explored, referred to in this research as a divisional splice and a boolean sequence. A boolean split basically takes the interaction of two intersecting members and subtracts the volume of one from the other. This creates geometries that would allow members to meet in any way desired; however, it is laced with issues.

First and foremost, there must always be a 'parent' member and a 'child' member, from which the parents' volume is subtracted. Through analogue design methods, this has the potential to be a simple task; through digital processing, several considerations need to be scripted in order for this to work.

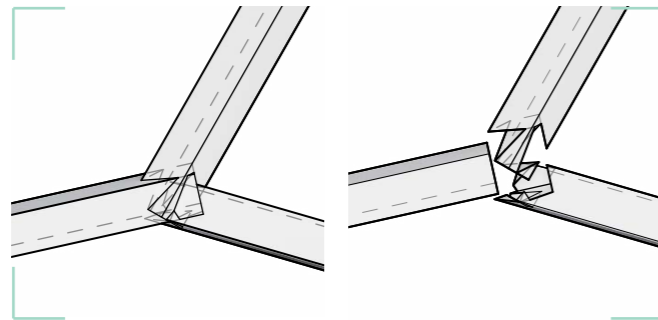


Figure 24: Boolean sequence diagram

In order to solve the digital workflow, looping functions were needed. These enabled the script to sequentially work through each part interaction one by one, analysing if there is an interaction, and making the Boolean split before analysing the next piece (analysing all at once does not function, hence the 'sequence' part of the title).

Even with looping functions, the script was creating some geometry that was too fragile and intricate to work. Without a sense of hierarchical prioritisation when choosing the order to analyse members and create geometries, some of the end conditions were entirely impractical to make or fix. This method can work on its own with a method of hierarchy implemented (something that might come intuitively to an engineer or craftsman, but a digital workflow would need a great deal of coding procedures or artificial intelligence to make the appropriate decisions on sequencing).

The other method explored when handling geometry was to create a divisional splice. This method takes the intersecting geometries and divides them into a single cutting face (in an instance of two members). This method appears straightforward yet contains within it many challenges. The simplest method of scripting this condition is to take the intersecting centerlines of the member intersections, and from there, create the cutting line to the inner intersecting vertice. In two dimensions, this works flawlessly.

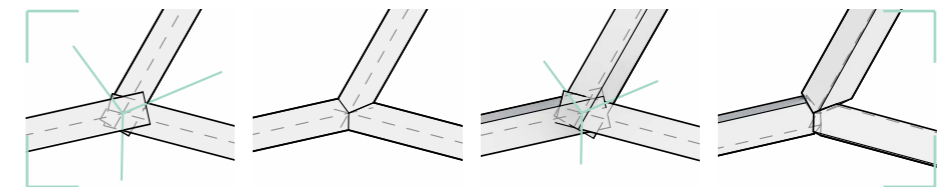


Figure 25: Divisional splice diagram

However, when the three-dimensionality of these complex assemblies comes into play, the cut line becomes a cutting plane. It needs to start considering several intersection vertices at once in order to make a clean cut. Case studies such as 'Robotic-built Pavilion' (Robotic-Built Pavilion - WEI YU HSIAO, n.d.-a) and Topology Optimization and Robotic Fabrication of Advanced Timber Space-Frame Structures (Søndergaard, 2015) both make use of this type of geometry creation, with the latter using it exclusively.

Søndergaard talks about the benefits of this method, maximising surface area for glued connections. However, from the perspective of a beautiful architectural joint, this method is not refined enough in the configurations used in these case studies. Without optimisation accounting for every single interception vertice, some undesirable conditions exist that sacrifice the aesthetic to maintain simple cuts and algorithms.

Through this exploration, in conjunction with analysis from analogue testing, robotic fabrication constraints, and the frame generation scripting, a combination of Boolean sequence and divisional splice was used, with a hierarchy based on angular relationships, structural hierarchy and assembly sequence.

Image redacted

Figure 26: Additive Robotic Fabrication of Complex Timber Structures / Gramazio Kohler Research, 2017

3.7

FIXING DESIGN

The research had a few key requirements from the start, one of them being that the joint needed to be aesthetically pleasing. Aesthetics are of course subjective, and one could argue that an exposed steel plate is beautiful, because it perfectly fulfils its functional purpose. Because of the ambiguity around the subject, the criteria that the joint needs to be clean and elegant were set. This applies not only to the proportion and meeting of members as discussed in the previous clause, but also to the finishing.

Taking this into account, a number of fixing methods are immediately ruled out. This section briefly explores different methods of fixings that could still be applicable to this type of structure.

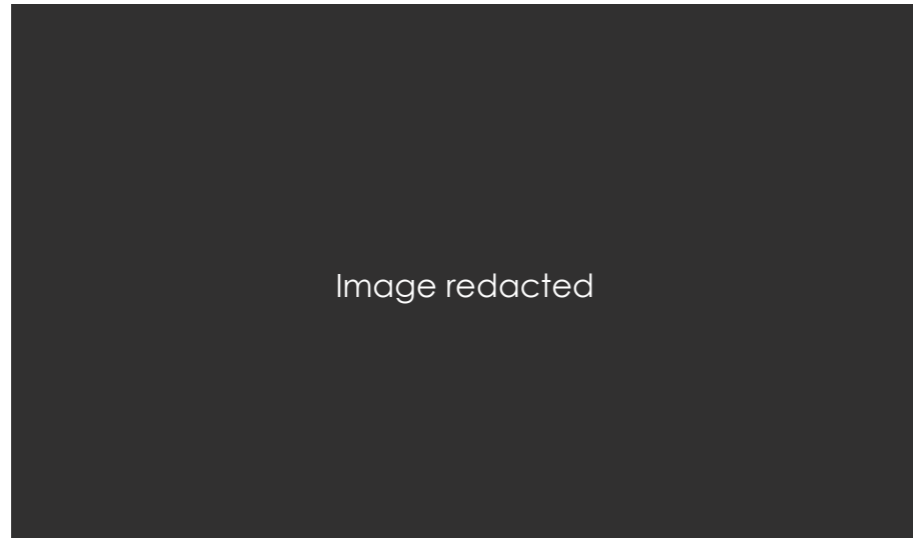


Figure 27: Robotic built pavillion / Wei Yu Hsiao, Cheung Shiu Lun, 2015.

Screw fixed:

While one of the least elegant methods from those explored, screw fixing could provide the required lateral forces to hold a structure together under both tension or compression, with different grades of screw obviously having varying levels of strength. A similar research paper, "Robotic built pavilion" (Hsiao, 2015), as well as many others referenced in this thesis, employ screw fixings to secure timber together.

Pros:

- Inexpensive solution.
- Achievable by both robotic arm or a general labourer, absolute precision isn't a requirement.
- Structurally effective.
- Easy to fill in or plug.

Cons:

- External fixing is far less elegant than other solutions.
- Even with a covering, a small indication of the fixing is visible.

Dowels:

Doweling is a great method of fixing in certain areas, but not in all. This is one of the few methods that was physically tested, with a few furniture dowels on compound cuts. What was found is that these joints worked incredibly well when a joint is in compression, but without a bonding agent, two members in tension would pull apart through this method of fixing.

Another issue that comes with this method is drilling the holes in the perfect spot at the perfect angle – something that the robotic arm could in theory do without issue, but by hand is incredibly difficult – refer to the following chapter for more detail. A situation with multiple members meeting at a single node makes this method more difficult still, as the dowels should act in the direction of the load path, which could mean there are impossible junctions, or dowels going into the splice between two members and retaining no strength.

Pros:

- Inexpensive solution.
- Simple to script.
- Great in compression.
- Simple procedure for robotic fabrication.
- Clean, hidden fixing.

Cons:

- Weak in tension.
- Difficult to do by hand.
- Certain joints impossible.

Slotted joinery:

Drawing inspiration from 'The Robotic Craftsman' (Heesterman, 2019), this method of jointing looks at traditional Japanese and Chinese carpentry where members slot together through intricate end conditions. It has already been proved to work from a manufacturing point of view through a milling end effector on the robotic arm, and can be done by hand by a very skilled carpenter. There are some disadvantages to this method in this context though, since carving away timber will inherently weaken the end conditions which are required to act as structural fixings. On top of this, when joining anything from 4 to conceivably 12 pieces in a single nodal condition, the amount carved away and the intricacy of these geometries will amplify this problem.

Finally, every nodal connection is unique, and will need customised jointing systems per piece and a carefully arranged assembly sequence. While not impossible, this method would be the most time consuming done by hand, with the most potential for human error, and would require a much greater depth of parametric scripting and robotic testing than any other method.

Pros:

- Most technically beautiful structure.
- No additional materials required.
- Incredibly elegant.

Cons:

- Highest probability of human error.
- Largest demand for design, planning, workflow and manufacture time for both analogue and digital methods of making.
- The required geometry could compromise structural integrity of materials at critical points.

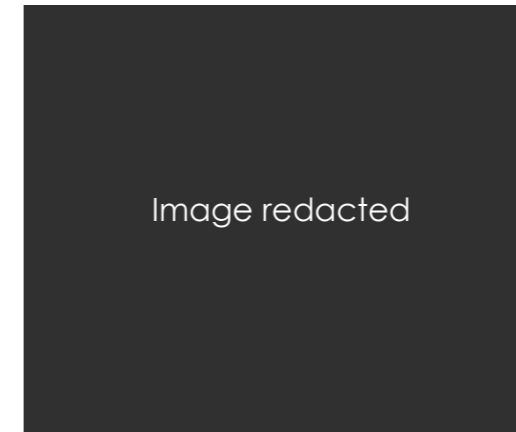


Figure 28: Glued node connection from Topology Optimization of Spatial Timber Structures / ETH Zurich, 2015.

© Gramazio Kohler Research, ETH Zurich, and Asbjørn Søndergaard, Aarhus School of Architecture

Glue fixing:

Glue fixing is the simplest of the methods explored in this research, and in the physical testing, it performed incredibly well. The spaceframe built in the research paper 'Topology Optimization of Spatial Timber Structures' (Søndergaard, 2015) makes use of glued joints with structural performance being the main design driver.

Several wood-glues bind with the fibres in the timber and bond stronger than the timber itself. On a 1m equilateral triangle made of 40x40mm pine, with angled splice joints (with the most significant potential for the joint to slip out), a force of 800N was applied at the centerpoint of a member. The joints resisted without any signs of giving. Significant bending could be seen within the timber, indicating that the actual member may have failed prior to the glue fixing with the cross-section used. The downsides over other methods are that there is obviously a period of time required for drying, where the timber needs to be held in place somehow – an issue on a three-dimensional structure. Each member must also be placed perfectly before the drying time begins, which could be problematic as there may not be any indicative geometrical aids on the joints to line up members. Of course, this predicament only exists when assembling by hand, a robotic arm can place the item perfectly in space and, if need be, hold it as the bonding agent sets, though multiple robots would be required for this.

Pros:

- Subject to loading requirements, structurally viable solution in both tension and compression.
- Simplest geometry of any solution.
- Clean fixing solution.

Cons:

- Room for members to be incorrectly placed or held incorrectly as glue cures.

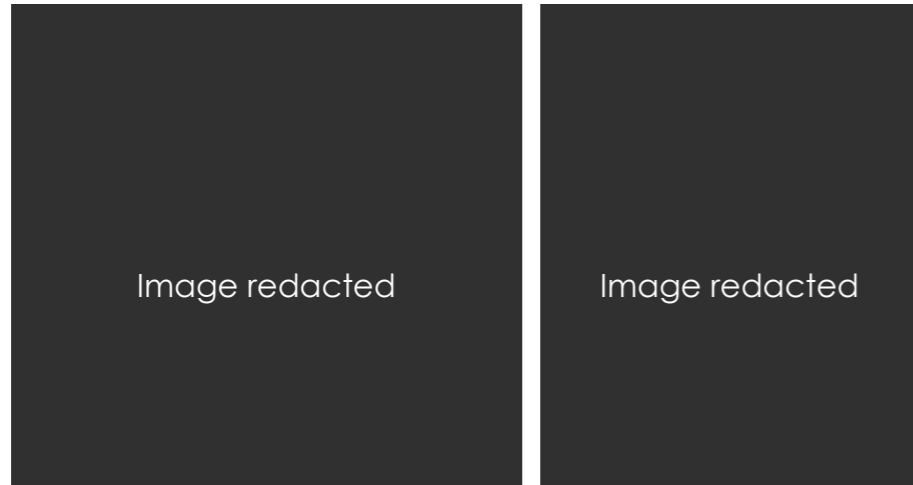


Figure 29: Takenaka connector / MX3D, 2019

Figure 30: Custom steel plate from Upsilon Pavillion / CIROS 2018

Free-form printed steel:

An internal steel connection is another fixing option, though one of the least achievable through traditional means of construction. Upsilon Pavillion (Hua et al., 2018) uses unique steel plates cut out for each joint, with slots in the timber members routed out with a spindle end-effector. In this configuration, there is a maximum angular condition allowable. However, with the development of WAAM technology (Wire-Arc Additive Manufacturing), bespoke three-dimensional brackets could theoretically be manufactured for each nodal condition that accommodates any angle. MX3D have been working on manufacturing steel connections for complex multi-member nodal intersections (MX3D, 2019); this however was under the paradigm of expressing the process and potential of WAAM through exposed steel joints.

This method of fixing needs to be done with a high level of precision, not only in the timber processing but in the steel nodes themselves. In Upsilon Pavillion, the resulting structure has gaps in the joints that do not quite read as solution driven by aesthetic.

Pros:

- Excellent structural performance in tension and compression.
- Customisable to suit any angles, with structural optimisation.

Cons:

- Only feasible through digital fabrication.
- Expensive and time consuming.
- Separate geometry algorithms required.
- Additional manufacturing workflows and tools required.

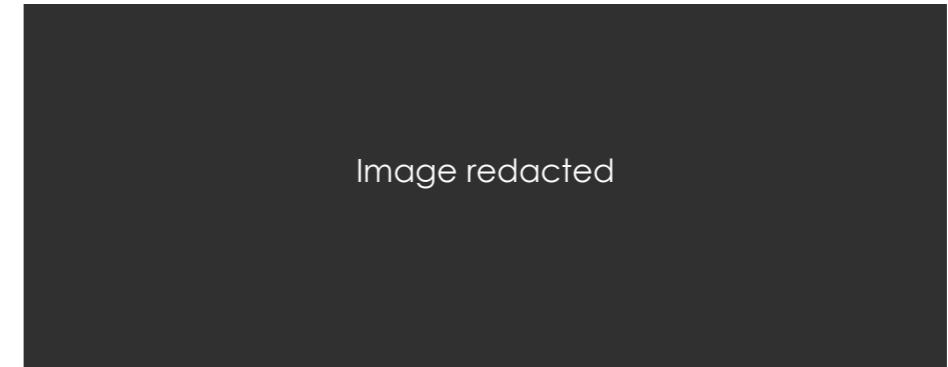


Figure 31: Injection joinery visualisation / Omar Geneidy ,2018.

Injection moulded dovetail:

This last option takes a concept explored by the Institute for Advanced Architecture of Catalonia (Geneidy et al., 2018). Each member has a cavity routed out from it to then have an internal 3D dovetail-type joint injection moulded into it. This process is only feasibly possible through industry 4.0, and needs to be coupled with a digital assembly process. It does provide an opportunity for completely internal joints with high structural performance, that mould to any angular condition, and could meet any number of nodes.

This would need further testing, as the case study only goes as far as joining two members at any point, without the challenge of three dimensions. Multiple robotic arms would be required.

Pros:

- Hidden joint set into the timber.
- Potential for excellent structural performance based on the angle of dovetails and injection material.
- Low material cost.

Cons:

- Multiple robotic arms needed to hold the timber in place while joints are moulded.
- Several different processes required for fabrication and assembly.
- Touching up injection holes would be required.
- Any imperfections in the jointing geometry would result in moulding spilling out.

4 ANALOGUE TESTING



Chapter four

Figure 32: Timber cuts

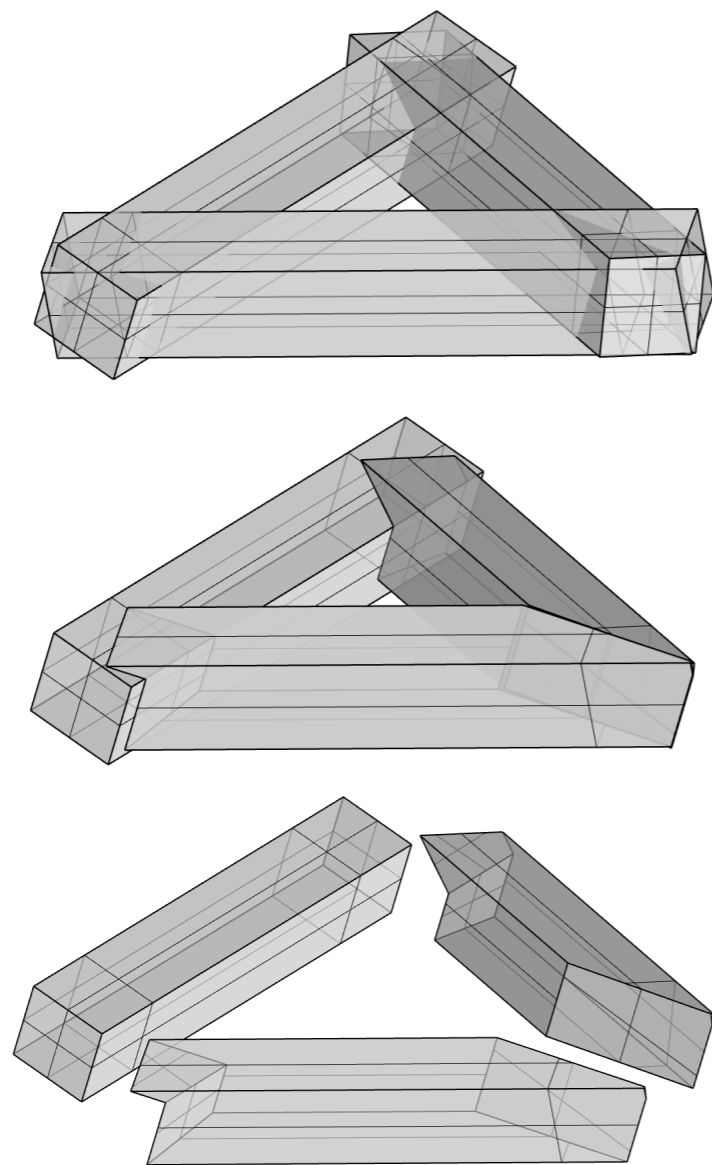


Figure 33: First test digital model

4.1

TEST I

The first of the material tests that were carried out with analog methods was quite possibly too complex to start on already, regardless of the fact that it was really quite simplistic in the grand scheme of things. The test looked at cutting a triangle, three pieces of timber that connected at angles. A light rotation was applied to each member along the central axis. Two of the members rotated slightly in one direction, while the third was rotated in the opposite direction to create some interesting end geometry. A boolean intersection was used for two intersections, while the third used a splice joint.

A Rhino model was made to create the geometry. At this point, the grasshopper script was still in its primitive state, so the end geometries were modelled manually by creating cutting planes and then using them to trim the BREPs. This ultimately achieved the same result as the Grasshopper script would later achieve in terms of a visual output, and was enough to take measurements of the dimensional and angular values needed to create said geometry by hand.

This first phase of modelling the geometry took around 20 minutes to complete. Not a great deal of time, but there is a fairly limited amount of complexity to this triangular geometry. Retrieving the geometry as information that was appropriate for cutting with was another matter though.

For this first test, the cutting drawings were done by hand. This served as an opportunity to test how the information could be communicated effectively. Much like the cutting to follow, the single compound angle cut was fairly simple, as it merely requires a reference point and then the two angles that it needs to be cut. When it came to the second cut, sequencing became required as the reference measurements are then from the previous cut(s), and multiple intersecting cuts become even more complicated to convey effectively in a drawing.

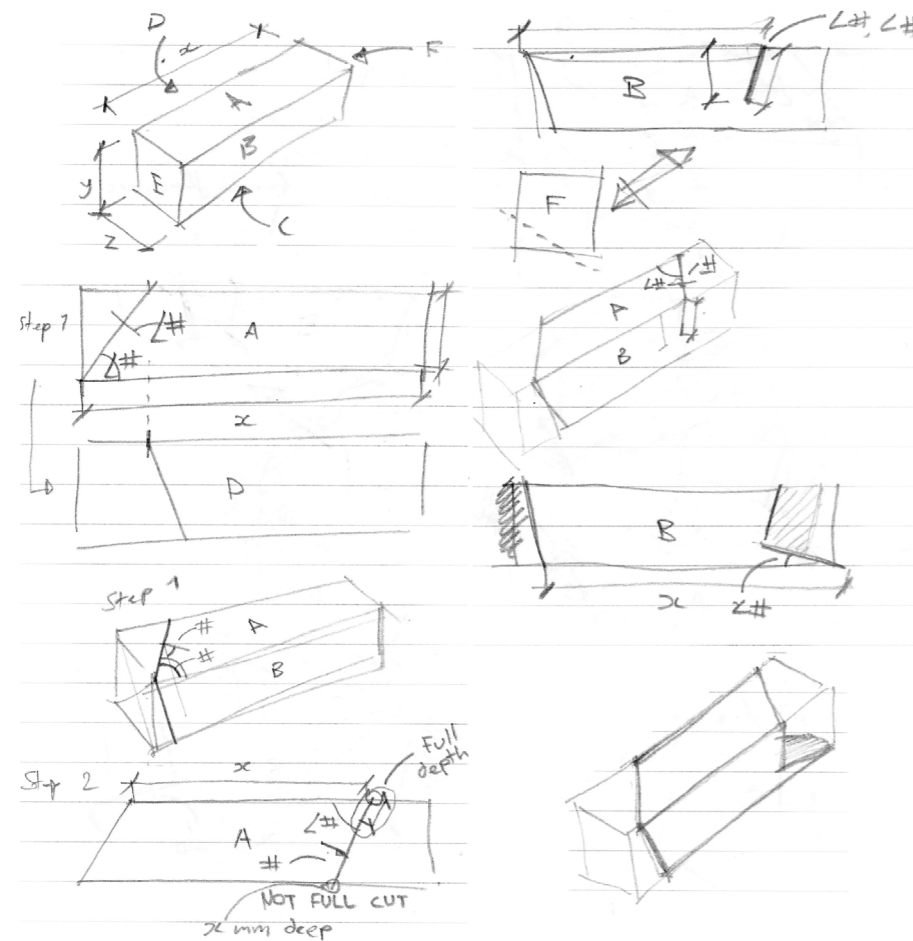


Figure 34: Data communication

Using a single axonometric drawing could show the necessary information for some configurations of geometry, but not all. Furthermore, it would become too busy to read in a logical way, creating the opportunity for human error.

The result was that for even these simple members with no more than 3 cuts in them, a series of elevations and axonometric drawings with a sequential order was the most intuitive way to communicate the required information to the craftsman, which becomes a very time consuming exercise.



Figure 35: Cutting with a hacksaw



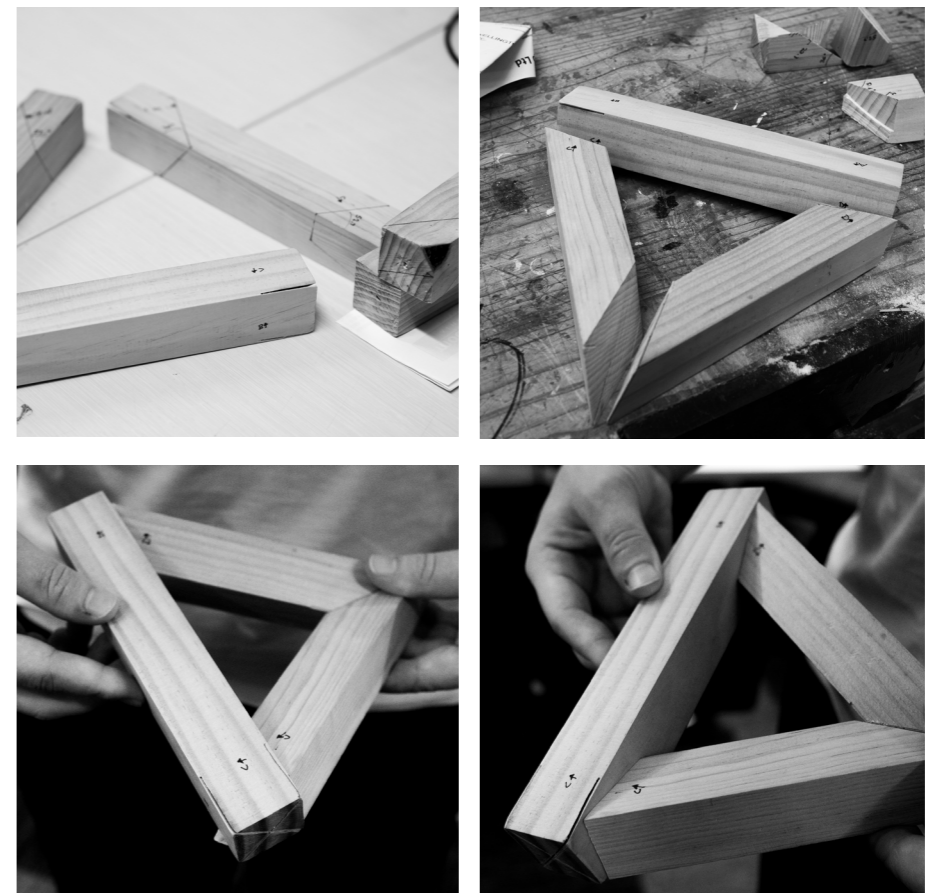
Figure 36:
Figure 37:
Figure 38:
Figure 39: Testing analog methods



The construction of this first test brought to light many things and reinforced the hypothesis that robotic fabrication really would make the making process far more efficient. A single compound cut is fairly simple with a good drop saw. The one available had two axis of rotation, with angle markers up to the accuracy of one degree. Unfortunately this does mean there is always the possibility of error, which even in the margin of half a degree off, could create substantial flaws over the entirety of a complex structure. Margin of error aside, the drop saw does deliver a fairly clean cut in a very short period of time



Figure 40:
Figure 41:
Figure 42:
Figure 43:
Figure 44: First physical test



The results of this first test showed just how difficult complex structures are to manufacture. This test took roughly 8 hours to draw up and cut out, and the results were far off what they should have been. Placed together, angled cuts that should have met each other perfectly had a two-millimetre gap between them. Throughout an entire structure, that is an entirely unacceptable level of tolerance, as angular errors compound throughout a structure.

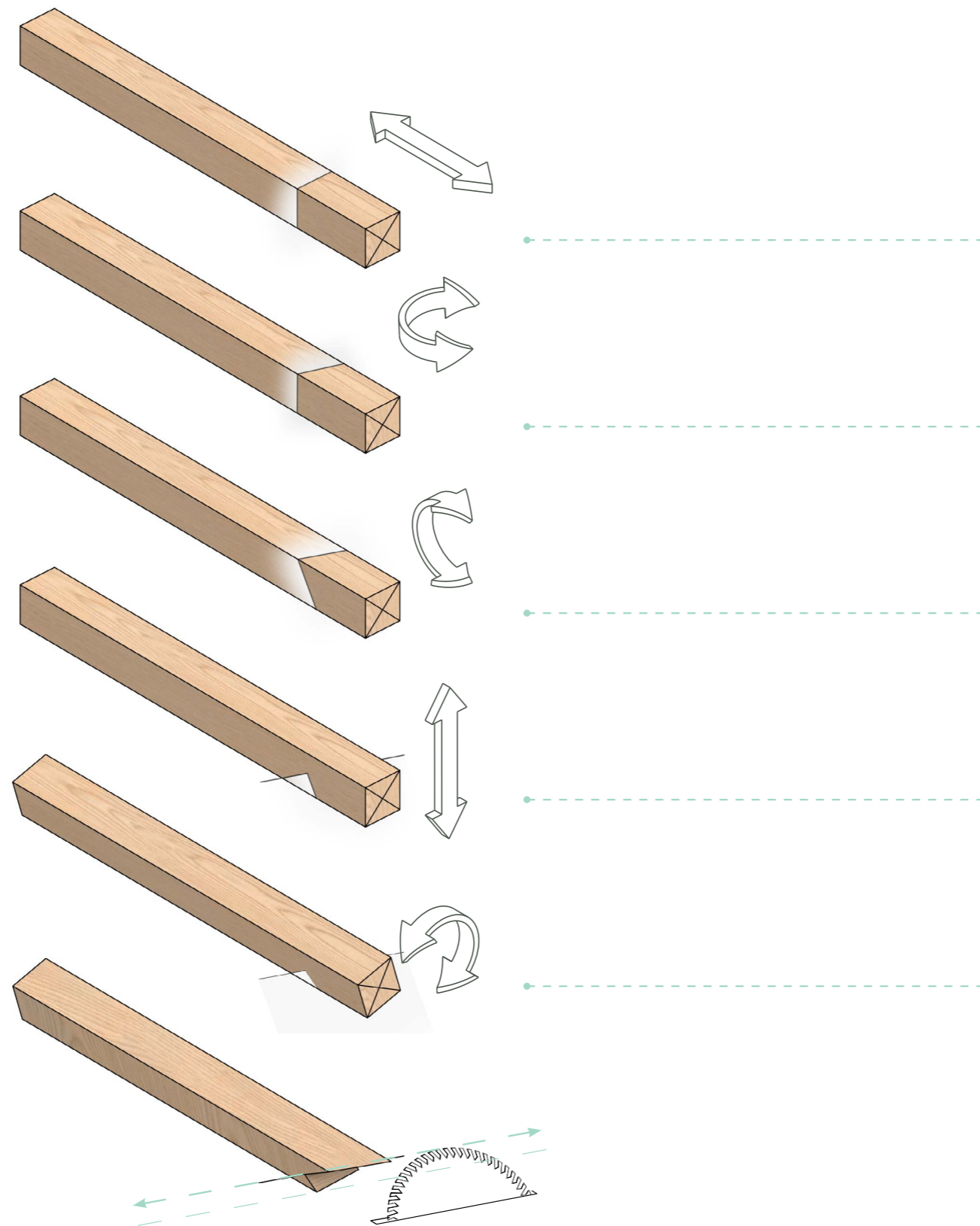


Figure 45: Cutting stages diagram

Glossary of cut types:

Cutting to length:

The most straightforward of any of these cuts, this cut only requires the location on the timber that the cut is to be made and then cut at a right angle. Any saw can do this with ease.

Single angle cut:

This cut brings with it an angular condition on a single axis. While still possible with most commercial and personal use saws, small inaccuracies and errors begin to come through with these, whether that be the angle itself or the positioning along the timber.

Compound angle cut:

This cut adds a secondary angular condition on another axis, typically measured in relation to the first angle. Certain drop-saws or table saws can still achieve these cuts; however, the opportunity for misplacing or mistaking the angle increases as the complexity does.

Partial depth compound cut:

Essentially the same as the above cut; however, the setup and therefore time dedicated is more involving as the cut can only go so deep. For instance, a table saw can do this cut, but every different cut requires the setup of two different angles and depth and location on the member.

Variable depth compound cut:

A compound angle cut, which is partial depth at a third angular condition. These are accomplishable using hand tools, but not with the likes of a table or drop saw.

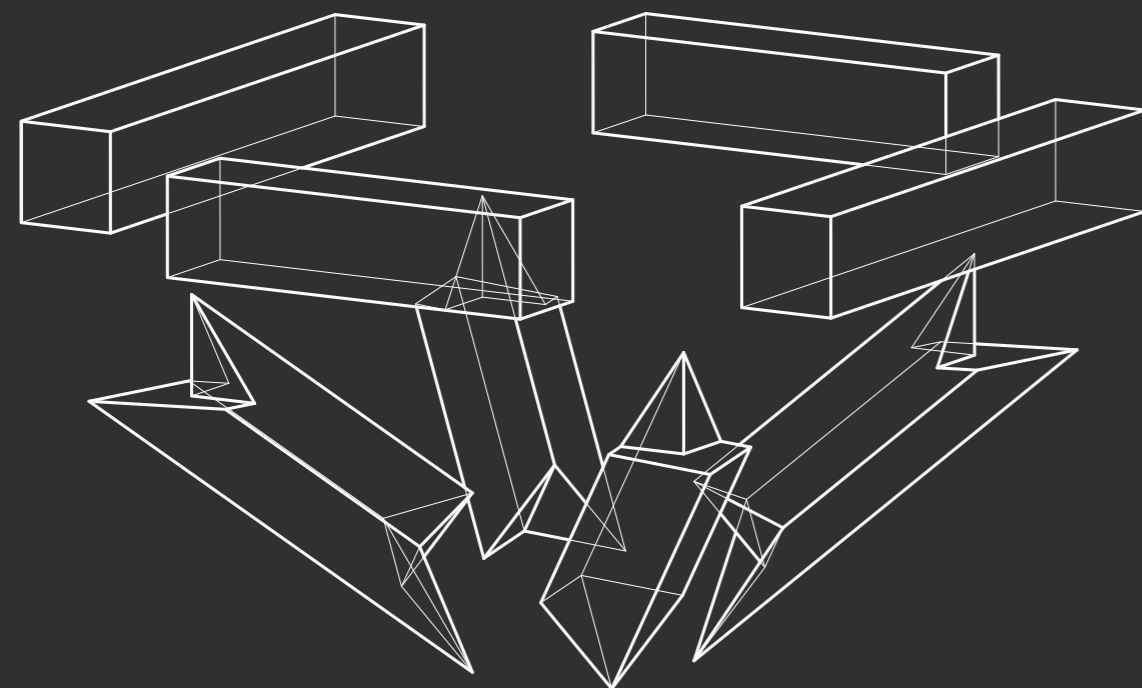


Figure 46: Second physical test exploded digital diagram

4.2

TEST II

The second test done gravitated more towards the typology of a section of a space frame, with a 4-sided inverted pyramid. This has a square top section, and the members branching out from that to the node are at 45 degree angles and have repeating elements. This gave the opportunity to test more than two elements coming in together at a single node (3 and 4), and test some different sorts of cutting and pieces interacting from the previous test.

This time it became really clear just how difficult the shop drawings are to communicate the end geometry for crafting these joints. Some of the cutting patterns are really complex to convey the information across, since not only are there multiple compound angle cuts, but the compound cuts also have varying depths to them.

A cut may start at a depth of 12mm and finish at 22mm for example, which means that instead of two values of rotation per cut, there are three angular conditions to convey.

"Typical architectural drawings, such as sections, elevations and floor plans are losing their importance, because they are unable to entirely describe complex geometrical structures."
(Agkathidis & Brown, 2013, p. 103)

This is something that in theory, robotic fabrication will make light work of as it can simply analyse the cutting line and drag a timber member across the saw at the correct angle.

The method of construction used this time round did not involve power tools at all. After the previous test and finding the limitations of the drop saw with multiple compound angle cuts, a hack saw and chisels were used to cut out these geometries.

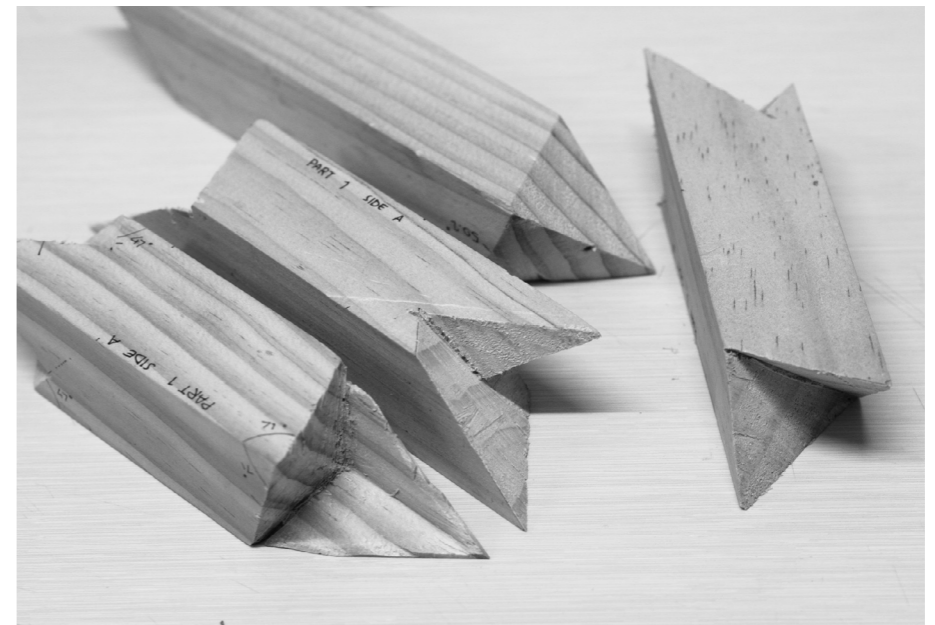


Figure 47: (R) Timber pieces post-cut.
Figure 48: (R) Retrieving dimensions from Rhino model
Figure 49: (L) Pre-cut timber with guides marked out.
Figure 50: (L) Final assembly.



Figure 51: Impossible geometry
 Figure 52: "
 Figure 53: "
 Figure 54: Difference in grain
 Figure 55: Cutting process
 Figure 56: "

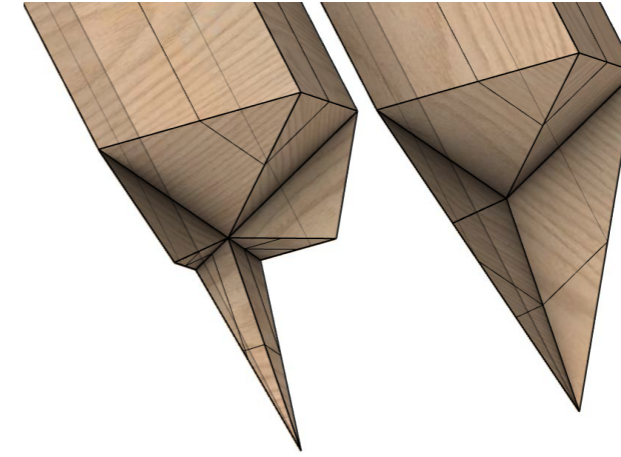


Figure 57: Impossible geometry

Key learnings from this test was how much of a difference repetition makes in the ease of construction joints, the flaws in a boolean sequence when it comes to complex geometries, and the inconsistency in the material.

The four web members all featured one end that consisted of four of the exact same valley cuts. This is not to say that they became fast and easy to create, but the repetition of the process did result in the final three taking less time to create, and being marginally tidier than the first attempt. In something like SunnyHills, where all the angles repeat, this would help create the joinery, but is a benefit lost in a bespoke modulated structure.

As seen in figures 49-52 and 55, two of the end conditions feature a ridge meeting a valley. This geometry was possible to create by hand, but not through the use of saws alone. First, the ridge had to be cut out by saws. Then, after a saw cut was made over the edges of the valley, the valley needed to be chiselled out. Geometry like this would not be possible with robotic fabrication in the configuration that this research approaches it.

Lastly, the two pieces with this geometry reacted differently to the same tools due to the grain structure and direction of the timber. This contributed to inaccuracies in the final result. Much like the first test, the final fitment is not at all acceptable and needs far greater care in order to fit flush together.

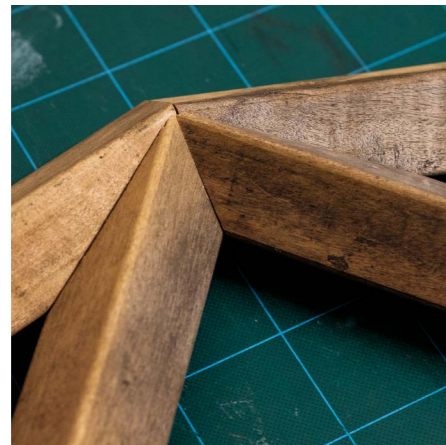


Figure 58: Cut members.
Figure 59: Clean cuts, sequential heirarchy.
Figure 60: "
Figure 61: Human error

4.3

TEST III

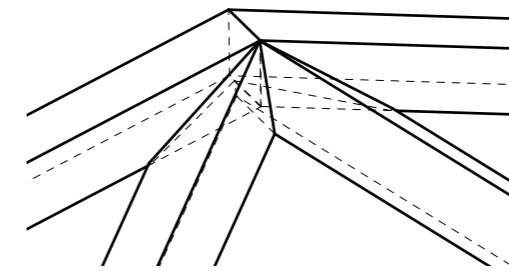


Figure 62: Test three

In this test, a number of things were done differently. This was the first attempt at the divisional - boolean sequence of cutting, which did prove to make much simpler geometry that does in fact fit together quite nicely.

This test also uses Vitex, a hardwood from the Solomon Islands. Changing timber in theory should not really have any effect on the outcome of the geometry, but the tight grain structure of the wood actually made a substantial difference in the cuts. When compared to the pine that was used for the previous tests, not only are there no 'frayed edges' within the timber, but the cuts are a lot cleaner and straighter. Cutting the vitex required a lot more effort than the pine, however once a cut was started, the saw would keep a very true line of travel.

This test exemplifies the importance of having the right material and tools. By using a hardwood that was not full of knots, clean cuts that were almost dimensionally accurate could be created.

'Almost', as this test also brought up human error as one of the major disadvantages of using analogue methods of making.

When setting up these cuts, the self-made instructional diagrams were misread, resulting in the correct angle cut on the wrong side of the timber. As seen in figure 59; this resulted in one side of the joint fitting together perfectly as planned, while the other side completely misses the mark.



Figure 63: Dowel tests

Figure 64: “

Figure 65: “

Figure 66: “

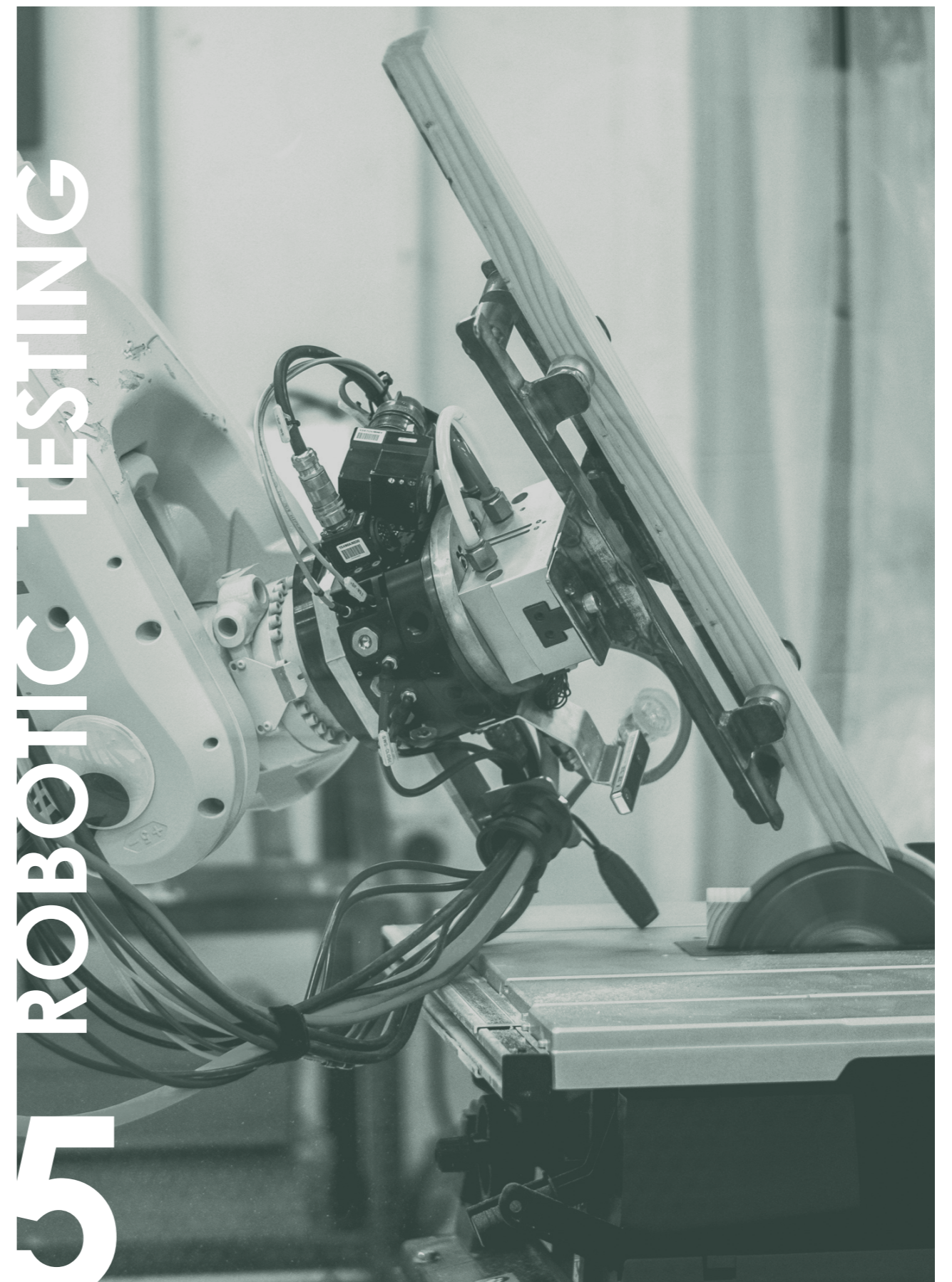
The final analogue testing was to trial doweling as a jointing option. Both of the two joints attempted came across the same issue when using manually operated tools; locating and maintaining the correct angle in a dowel hole on a compound angle surface is incredibly difficult to achieve. A drill press is not an option, as the members need to be propped at a compound angle relative to the drill, meaning clamping is not possible without a custom built jig. Making the dowel holes with a hand drill gives an immense opportunity for human error, with some holes ending up ever so slightly off on the angle or the drill shifting away from the desired location.

4.4

CRITICAL REFLECTION

On reflection, this chapter revealed several things that back up the hypothesis that robotic fabrication can make the fabrication of complex timber assemblies far quicker, therefore making them more feasible as an architectural solution. All the geometries can be made by hand, but the time required is immense, and the opportunity for human error is great. The joinery needs to be exact, or the resulting assembly does not fit together the way it should. An unskilled tradesman is not fit for the task of creating such complexities; a carpenter with great attention to detail and care for their craft is necessary.

These tests also revealed how difficult it is to convey data for complex geometries through traditional 2D drawing conventions. In projects like SunnyHills, or Dunescape by SHoP architects, plans of every timber member are printed 1:1 and overlaid onto the members to create the joinery, even with a singular angular condition acting on Dunescape (Overall et al., 2018). In some instances, more time was spent retrieving and conveying the information than that put into cutting the geometries. Cutting out this process entirely with a CAM workflow would significantly reduce the time investment that the architect or technician put into creating such a structure.



51 ROBOTIC TESTING

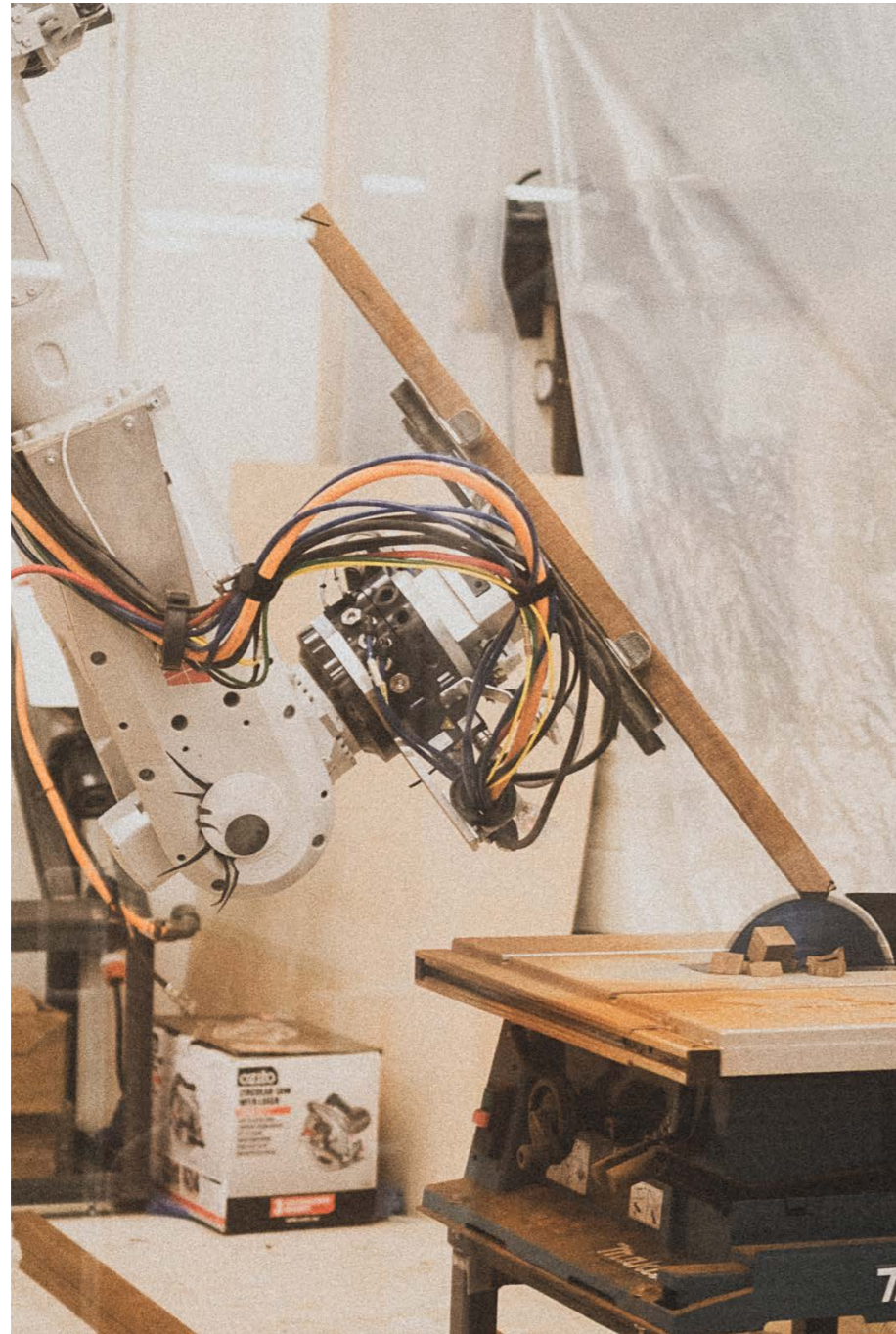


Figure 68: Lola doing tricks.

5.1

OVERVIEW

This chapter of the thesis covers the set up and testing of the robotic fabrication segment of the research, and talks through the findings of this method of fabrication. This includes both the opportunities and the limitations that are found with a computationally controlled method of making, and all the considerations that are all necessary for it.

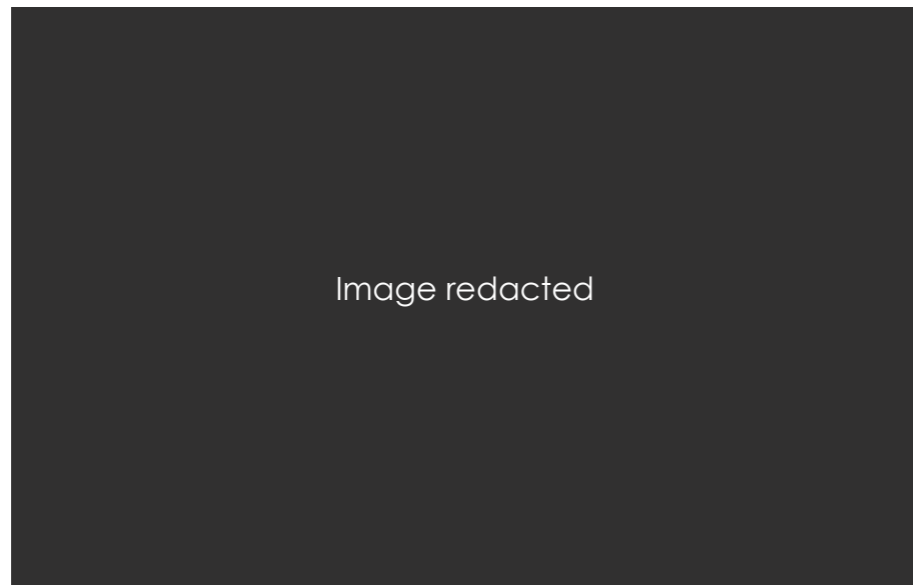


Figure 69: Lola cutting timber in "Robotic Arm Prefab Panels: A Proof of Concept" (Stricot-Tarboton, 2019). Screenshot from process video.

5.2

SETUP:

The first hurdle was to have a saw set up. In the paper "Robotic Arm Prefab Panels: A Proof of Concept" (Stricot-Tarboton, 2019), Glen had used a 180mm skill saw mounted to a 45-degree steel platform. A 180mm cutting blade gave a maximum cutting depth of 55mm - This worked well for what he was doing as he was never cutting deeper than a 45mm deep piece of timber and mostly perpendicular to the saw blade.

The issue this research had with this was the cutting depth. The research testing was set to roughly a 50x50mm cross section of timber, with the knowledge that much larger in scale would bring up the cost of machinery to actually carry out this thesis to a level that wasn't plausible. While the RB6700 260 has a payload capacity of 200 kilograms, the implications that this has on the size of the robot cell, the saw capacity, and the cost of larger timber meant the scale had to be restricted.

The issue with a 50x50 cross section in relation to the saw setup that was available, is that at an angle, for example 45 degrees, it requires a cutting depth of 70.7mm. Because the premise is that the kinds of cuts that this looks at are angular", the decision to move to a new saw with a larger cutting depth was considered necessary. After toying with a larger skill saw retrofitted into the same layout, the solution that got approved was a table saw, as it required no (major*) modifications to make it functional. With BRANZ funding, a Makita 2704N table saw was procured. This was chosen due to its high capacity 1650w motor, and more importantly, 93mm cutting depth, which was greater than all the similarly priced competitors available at the time. This was mounted on a 50x50x3 SHS steel profile base and bolted into the concrete floor to give the saw as much rigidity as possible to remove potential vibration.

**the writhing knife needed to be cut down in order to allow for partial depth cuts to pass through the saw.*

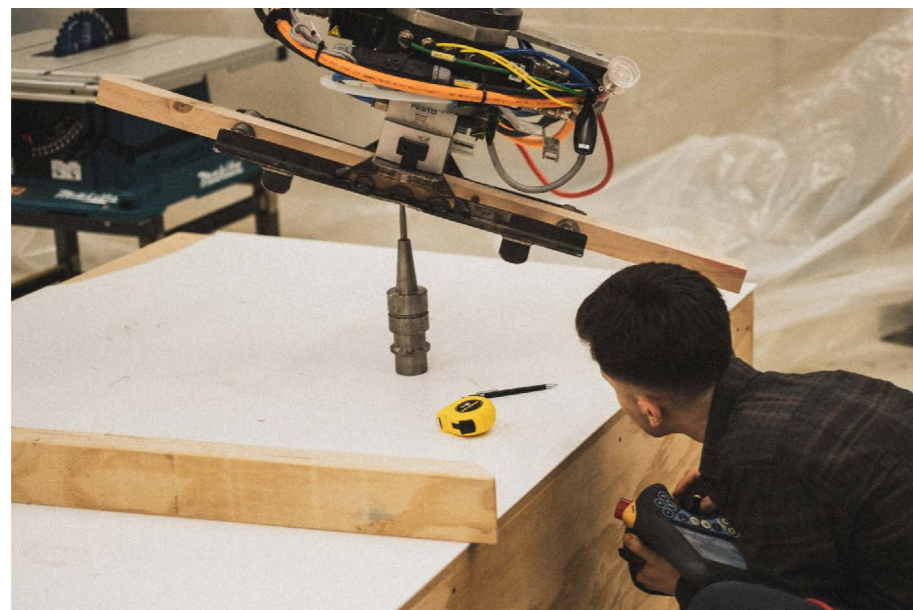
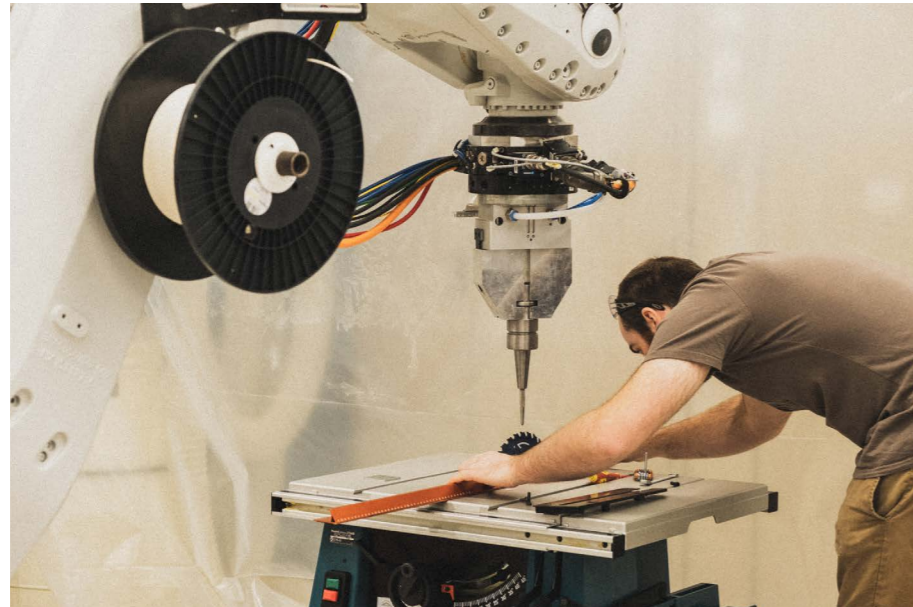
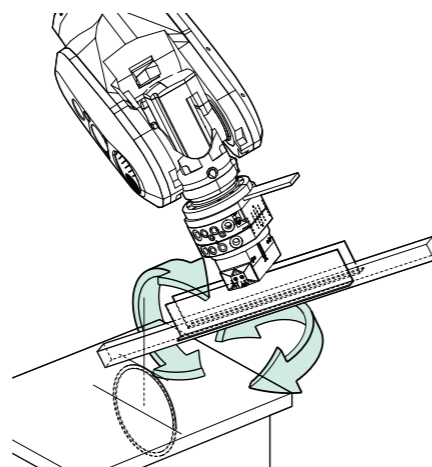
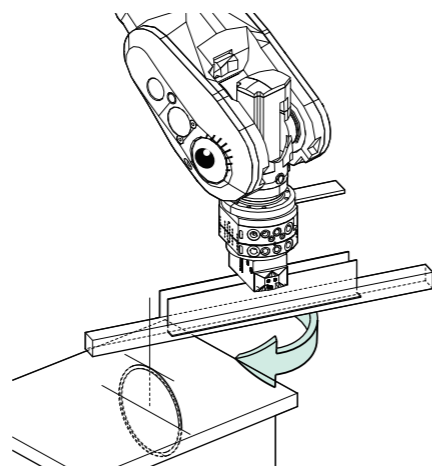


Figure 70: Aligning the saw
Figure 71: Calibrating the TCP

Alignment

On installation the saw blade was aligned as close as possible to the XYZ world plane of the robot. This would allow for the cutting motion of the robot scripting to be simpler, if moving up and down the Z axis correlates directly to the depth, and moving in the Y direction is perfectly aligned with the saw. This alignment was achieved through going back and fourth on a manual toggle, measuring points from a 1m ruler flush against the saw blade, and adjusting the saw base accordingly before the bolts where tightened. Aligning with the Z axis was done in the same way and achieved with several thin metal packers between the saw and concrete floor (which isn't at all level with the robot plane).

It should be noted that the tool used to set this up (a hole punch in the grippers) had a small margin of error when setting the TCP (tool centre point). This may have resulted in inaccuracies in the measuring where the saw was in space by some fractions of a millimetre. The alignment was also near impossible to get absolutely perfect, and the end result was that the front of the saw blade was roughly 0.2mm out of alignment with the back of the saw blade in the robotic XYZ world. Over the length of the sawblade, this is 0.000816 degrees out of alignment, which was deemed to be an acceptable level of tolerance.



Saw sweep:

Before any robotic testing was carried out, the method of lowering the timber onto the saw to the desired depth and then raising it again was to be avoided. The radius and curvature of the sawblade would become apparent, and any offcuts remaining on the table saw could become obstacles and prevent the robotic arm from achieving its task.

A sweep over the saw blade was put in place to avoid these factors. This was quickly increased to sweep from before the table due to the unpredictability of where the offcuts might land.

This sweep was turned into a cluster to minimise clutter in the scripting. Every oriented cutting plane is fed through a move component according to the following vectors.

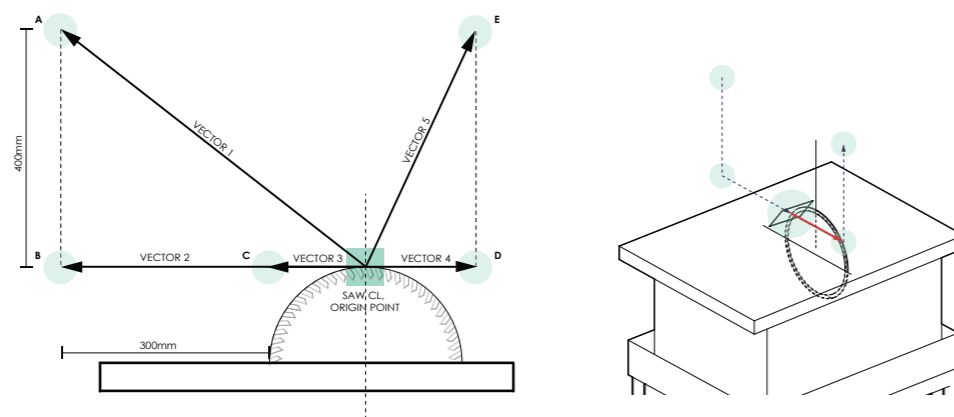


Figure 73: Setup diagrams

Point A and E is a hover over, allowing the robotic arm to make cartesian (see page 85) movements between cuts without running into clearance issues with the sawblade or table, as it alternates between different orientations.

Point B to C is the sweep to remove any offcuts in the way of the robot.

Point C to D is the cutting procedure. In order to make the procedures faster, only the cutting procedure is carried out at 30mm/s, while the remainder is set up to run at 500mm/s*.

This cluster converts each plane into a toolpath with its relevant tool, speed, direction and procedure data.

* 500mm per second is only possible when the robot is running in automatic mode. Due to the health and safety restrictions in place, the robot could only be operated with the saw with a 'dead man switch', which restricts the speed to 200mm per second.

Timber stack:

Under inspection, the cuts that came out of this first batch of testing were not 100% square with the edges. This could be due to the fact that a lot of the timbers were bowing and twisting, even within a day after dressing them through a planer and thicknesser.

The other factor that was most likely contributing to the cuts not being level (as the saw blade was calibrated to the robotic XYZ world) is that the ground itself is not level in the robotic world. This would cause the grippers to be able to pick up a piece of timber that is not perfectly lined up with the saw, despite the grippers being perfectly calibrated in relation to the saw and robot.

In order to deal with the timber pickup not being perfectly level, a simple pickup rack was created, and mounted on the university's printing surface. The robotic arm used a spindle end effector to route out a surface into an MDF board. This surface is perfectly aligned to the robotic XYZ world, meaning that the timber would no longer be picked up in a way that wasn't level in relation to the saw.

While designing this stand, Two small sidewalls were used to roughly centre the timber, which needed to be far enough apart from the grippers that the robot would at no point interact with them. Two larger sidewalls at the back of the structure provide a platform that the robot could then place a piece of timber, and approach it from a different face. This functionality was not yet of any use, but as more complicated cuts were being produced, especially valley cuts, the timber needed to be rotated in order to work around the physical boundaries of the robot and saw set up.

Without rotation of the timber, the robotic arm is forced into physical impossibilities in order to have the correct interaction with the saw. A lot of these errors are easily seen in a digital simulation of the workflow prior to actually running a fabrication run. There are unfortunately a number of scenarios to do with the cables (electrical and pneumatic) that can't be seen on a digital simulation. The wires have a certain amount of slack in them (which was increased to accommodate a wider range of movements), but this slack only allows so much before the robot arm is twisting them in to a dangerously tight situation. Increasing the slack also meant that there was risk that the wires were occasionally at risk of being cut by the saw, so bungee cords were used to restrain them when they weren't in a tense state. The most serious incident that did end up occurring was one cable (fortunately an inactive one) being crushed between the Y flange and the wrist.



Figure 74: Timber stack

Along with the rotation of the timber members to assist in mitigating damage and impossible scenarios, a number of tool paths had 'safe frames' scripted into them. These stopped the robot from taking the most direct path from one state of a toolpath to the next, which could lead to it twisting itself into an undesirable position, to instead returning to a 'home' quaternion state between certain movements.

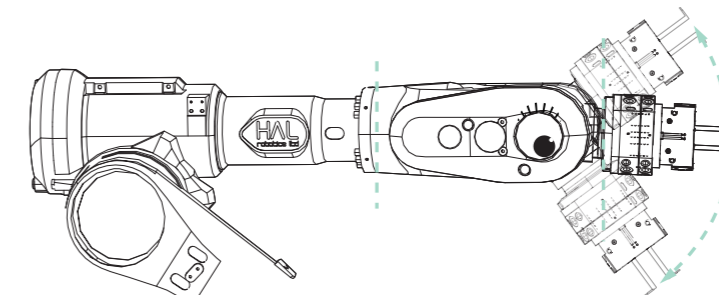


Figure 75: Wrist singularity

Singularities:

In order to complete the rotation of timber manoeuvre in the configuration set up, the wrist of the robotic arm needs to pass through what's referred to as a singularity. In this particular instance, an internal singularity at the wrist refers to the arm attempting to pass through a point in space where joint 4 and joint 6 are perfectly lined up. This causes a mathematical weakness (a Jacobian matrix) (Eng, 2019) which the robot, through cartesian motion, will do everything to avoid.

The six-axis robot can move through space in two different ways; cartesian space and joint space. Cartesian space refers to the method of robotic control that has been used throughout this research up until this point, where the end effector prioritises moving from one quaternion location in a toolpath to the next, taking the most direct path possible, and all the joints react accordingly. In almost all scenarios, this method works perfectly and allows for predictable motions through space, and is required in order to keep the cutting process accurate.

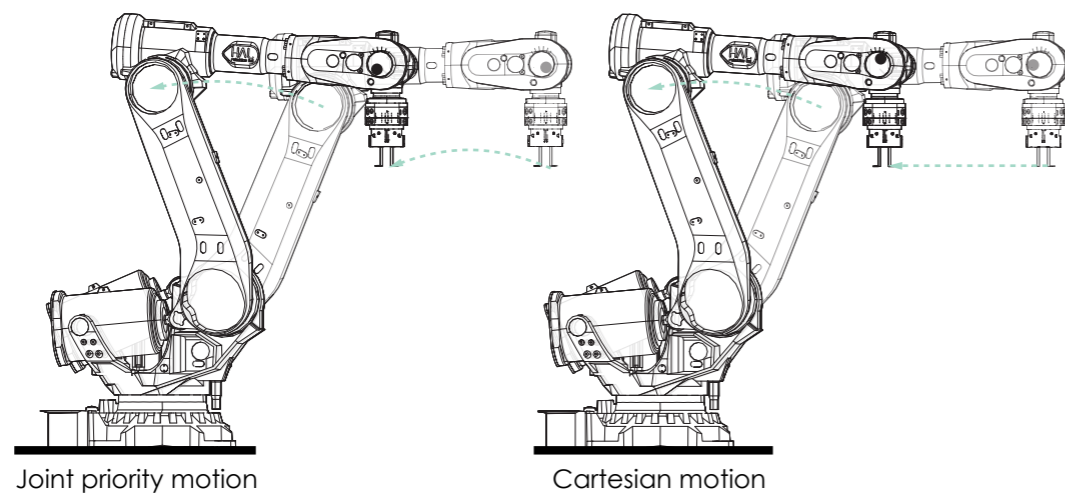


Figure 76: Motion types

There is of course the alternative method, which prioritises the motion around how each joint moves. Prioritising joint motion results in an indirect path of travel from one toolpath point to the next, as the pivot arc from the effected joints is expressed in the toolpath. Because of this factor, this is not the standard method of motion, and it requires a different set of scripting procedures to create code for it.

By switching from cartesian motion to joint motion, the possibility to travel through the singularity does become available, with one additional step. Within HAL, there are expandable components that allow the user to go deeper into the robotic interface. In order for the wrist to move through the singularity, a joint specific condition override is required.

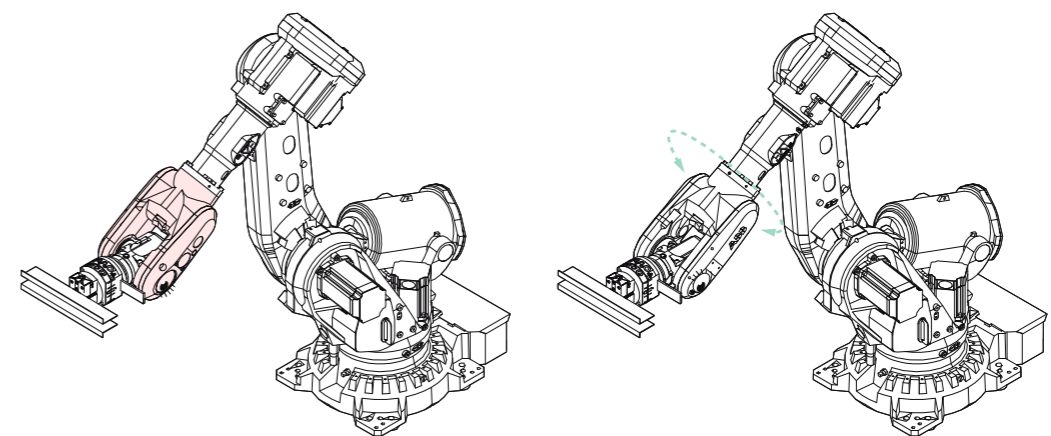
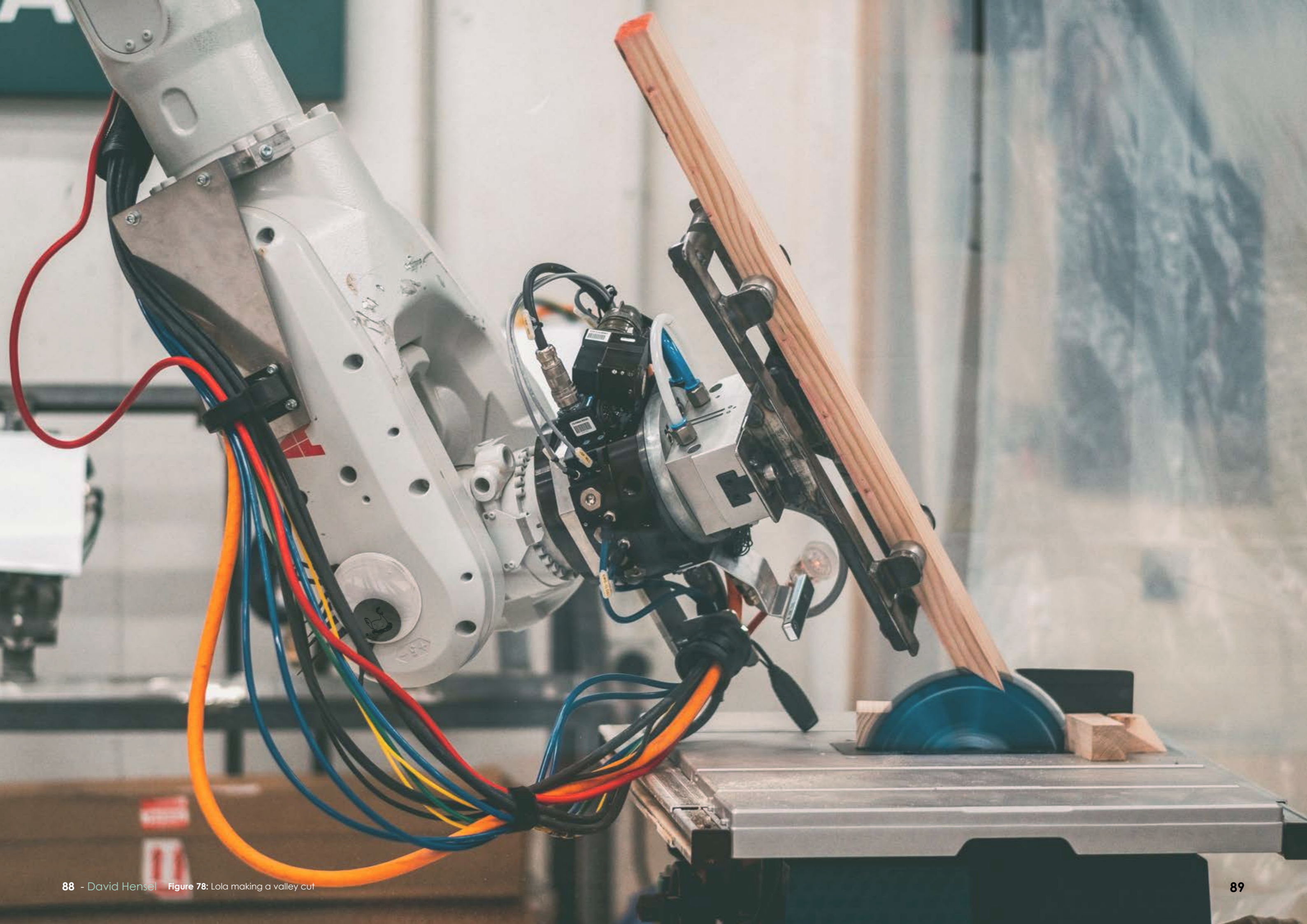


Figure 77: Flip state

By engaging a 'flip state' to a specific joint, the robot will not attempt to twist to what it believes is the correct orientation to achieve the desired quaternion location of the end effector, solving the singularity issue. The only further trouble with the rotation of the timber is that initially the script cluster that rotates the geometry 90 degrees would do it in the opposite direction to the toolpath procedure, which wasn't clear in the simulation but was immediately clear in the physical execution.



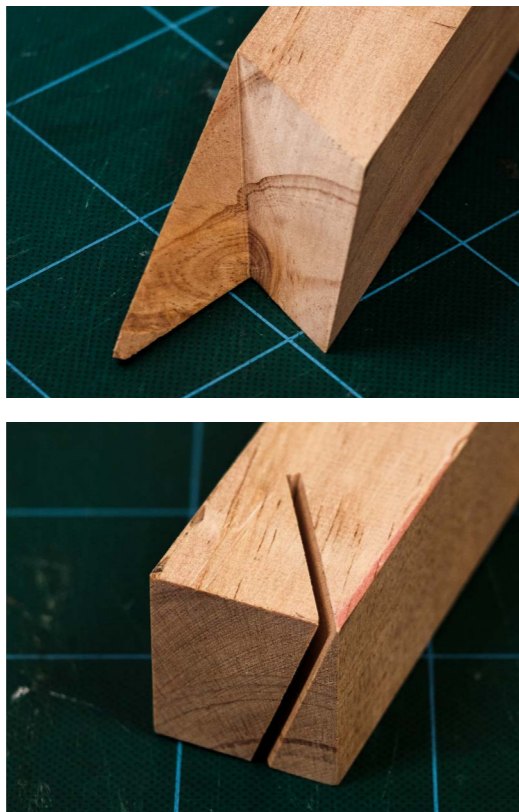


Figure 79: Successful valley cut.
Figure 80: Failed full-depth cut.

Valley cuts:

Setting up a workflow that allowed for the robotic arm to make a compound angle cut initially only required the plane of the cutting face to be oriented to the same plane as the sawblade. However, as established in prior chapters, a single compound cut is achievable with readily available power tools, and in terms of pushing the envelope, has already been done in several of the robotic timber assembly case studies addressed in this thesis.

A compound valley cut requires the location on the timber, the two angles that make up the compound cut, a depth, and an angle of that depth.

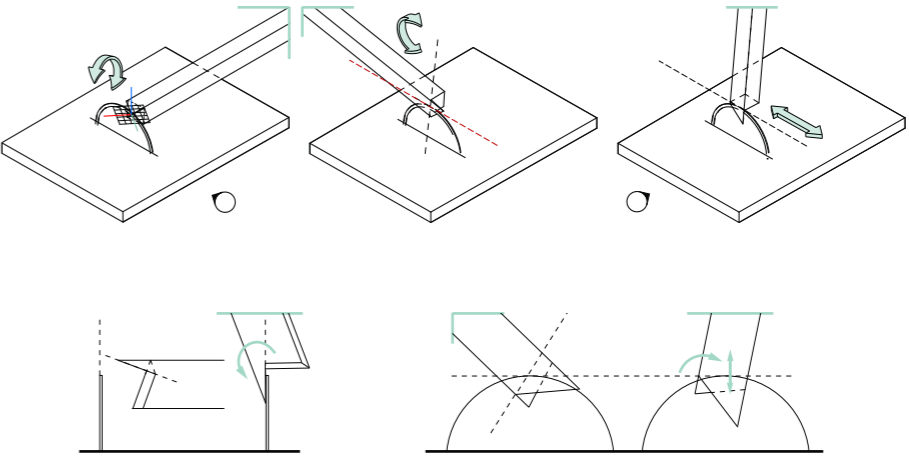
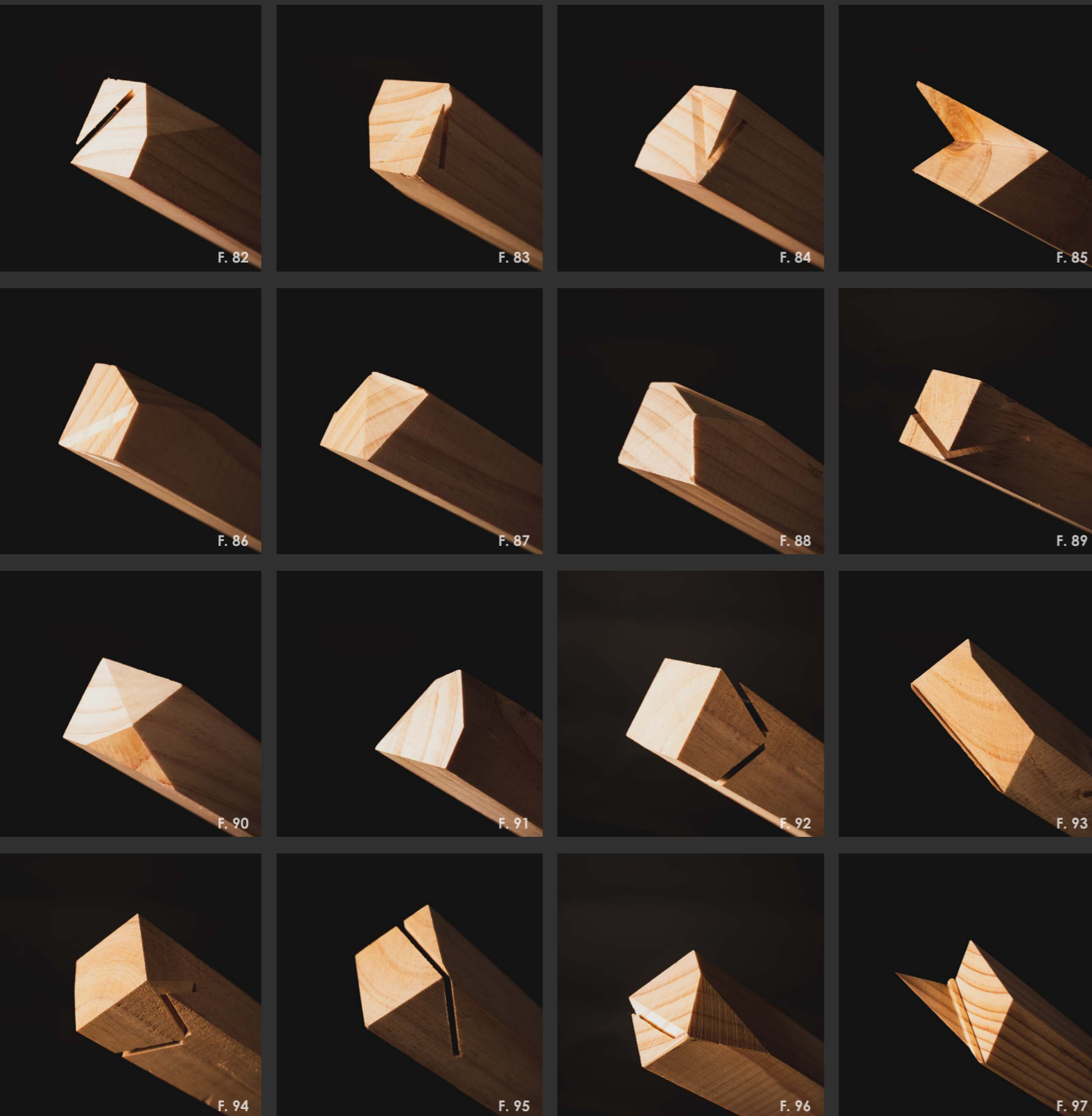


Figure 81: Valley cut logic diagram

The method used to solve this problem is to take all the orientation planes used for cut orientation, and to expand them into surfaces with the same normal as the origin plane. What this allows is for each valley to be tested for an intersection. The line of that intersection is then brought to the saw blade, and the difference in angle on the X axis from the oriented line to the direction the timber passes through the saw is analysed. This data then feeds into the orientation script to rotate the timber on the X axis, and then calculates any variation in the Z axis to align the interception line with the top of the saw blade.



5.4

CALIBRATION

Cutting depth

Throughout the testing, there were several occasions when the script had the incorrect cutting depth set, the pickup calibration was incorrect, or the timber had bowing in it, which resulted in cutting geometry coming out either not deep enough or too deep. This is something that isn't possible to see within digital simulations.

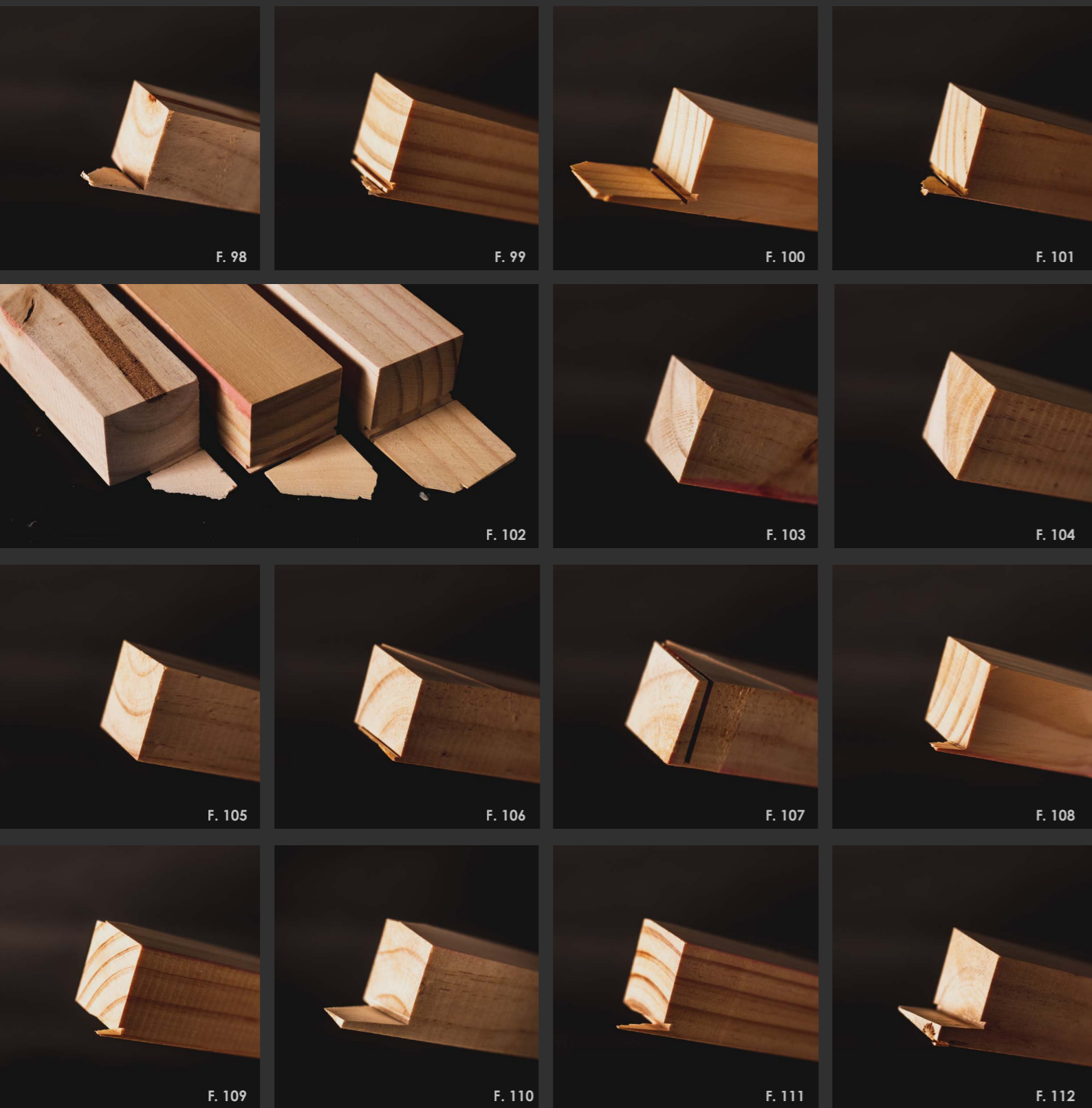
Full depth cut angles

After a number of successful full depth cuts in the early testing, what are meant to be full depth cuts (not part of a valley) started coming through without reaching the full depth of the saw, resulting in unwanted leftovers that would need to be removed later. This was happening due to the depth being set once for a cut 90 degrees to the saw blade, and then never adjusted. The angle of every cut changes how deep into the saw the cut must go. This was the reason a table saw with 93mm of exposed saw blade was purchased over the skill saw set up used by Glen. (Stricot-Tarboton, 2019).

To calibrate this issue within the constraints of the environment, a similar approach to that of the valley cut was employed. Each cutting face is analysed, and through the same rotation and depth procedures, different edges of each cutting face are snapped to the top of the saw blade. A manual slider to toggle through which edge was built into the script to ensure an edge that doesn't require the timber to go through the table can be chosen. A more advanced level of scripting should be able to program this in automatically.

Saw blade thickness

The saw blade thickness caused several issues throughout the testing phase. Initially, the digital space had one edge of the saw blade calibrated, and a cluster that moved any cut on the other side of the blade over 2.77mm, the width of the blade. However, as the scripts became more and more complicated with more cuts being processed, this component became fairly easy misplaced - yet another thing that isn't obvious within a digital simulation. In an attempt to automate it, some aspect of the script malfunctioned, so a cut would either end up



where it was meant to be, 2.77mm off due to the blade thickness, or 5.54mm off as the component would occasionally work in the opposite direction.

The solution that was most successful was to set everything from the centre of the saw, and offset everything by half the blade thickness at the very end of processing, based on what side of the saw the timber is on. This still requires a manual check, as some valley cuts have the centre of the timber on one side of the saw with the cut on the other, but otherwise appears to work.

Timber bowing

This series of robotic testing came about when testing the final robotic interface, which is addressed later in this chapter. With everything calibrated for pickup points, saw offsets and depths, theoretically all of these tests should have yielded perfect results.

In the images to the left on page 94, figures 96-100 are exactly the same cut file being run on a selection of timber pieces that had been cut down to length and dressed, then left to sit for a number of days. The low moisture content of the robot environment, along with any stress in the timber from knots, meant these 1m lengths of 40mm x 40mm timber bowed and twisted. Many other case studies of digital fabrication on natural materials state similar finds, that the “cause of geometrical inconsistencies is the material deviations of the timber beams in comparison with the digital model” (Marielena, 2018, p. 55).

The issue with this is that the robotic arm had a set point to pick up and place, from the centre of each member. The CenterPoint would have still been moving to the correct calibrated locations, however the extremities of the timber would be in an unknown location, depending on the bow and current rotation of the member.

The reaction to these material imperfections is that cuts are happening in the wrong locations. This may be anywhere from a fraction of a millimetre off the required location, to a few millimeters.

There is also the possibility that the cuts, in relation to the surrounding geometries, are cut at the wrong angle due to the bowing. However, if this was the case, the imperfections in angles are so miniscule that through normal observation and typical means of measurement, there was no distinguishable error.

Because of the unpredictability of this error, there can be no tolerance built into the script, as it is unclear which direction an error may occur.



It could be as minor as a cut not being deep enough, which can be fixed manually, or it could be further to one side than it is meant to be. Furthermore, the complexity of these end conditions on any more than two cuts demands that the relationship of one cut to the next needs to be perfect.

Adopting a process utilised in 'The Robotic Pavilion' (Eversmann, 2017) and tweaking it could be a solution to this problem. When applying shingles, every piece of material was 3D scanned, and that data was fed into the algorithm driving the design and robotic arm, allowing for the layout to be computationally optimised in a closed feedback loop. While this process is out of the scope of the ability, time and resources for this research, a similar approach to this case study could be engaged to potentially resolve the issue of imperfect materials. Through scanning each piece of timber into a feedback loop, the processing script could theoretically alter all the toolpaths within the code to account for the defects, or choose to discard the material if it doesn't meet a certain tolerance.

Other issues that occurred consisted of a scripting error, where the tool location was being measured from the wrong place, so cuts were correct, but the entire member might have been 50-100mm longer or shorter than it was meant to be. This was fixed by changing the measurement from the longest edge (which works the majority of the time) to a bounding box edge.

The grippers also leave indentations on the timber. The untreated pine, being relatively soft suffered greatly from this, while later testing on heat treated Abodo timber was less susceptible to this deformation. The first tests on Abodo with a larger size had a calibration period, figure 112 shows where the tool was not fully calibrated and attempted to place the timber on the concrete floor, lower than it could physically go.

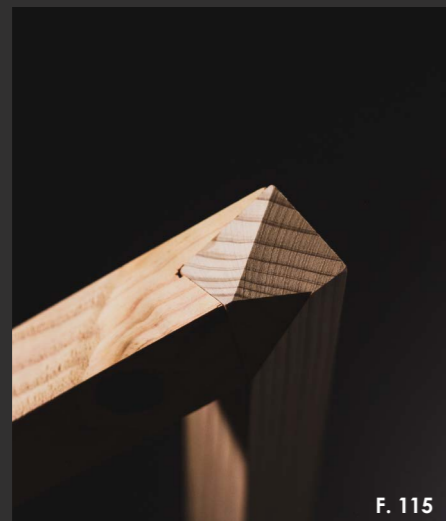
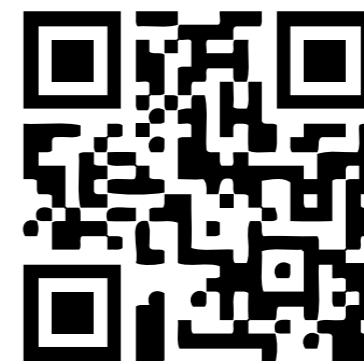


Figure 121: Sad lonely triangle
sulks in the corner



<https://youtu.be/fr-OQe6isLU>
Triangle cuts

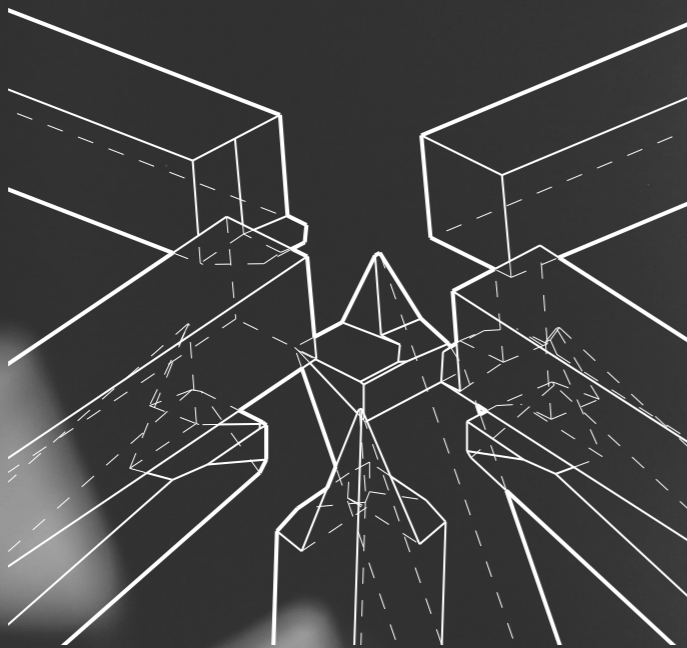


Figure 122: 8 member node

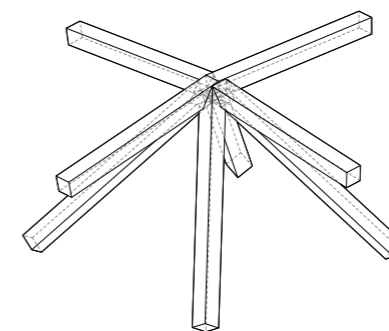


Figure 123: 8 member node

8 node test one:

In this test, having successfully fabricated full depth cuts at the correct depths, and valley cuts meeting perfectly, the next logical stage was to start applying this learning to some of the actual geometry that can be found in one of the truss designs that had been developed. An eight-point node was selected, as it would provide much more complex geometry than a two-point node like the tests previously carried out, but the types of cuts wouldn't differ from previous tests. The sequence of cutting logic had already been figured out in earlier analogue and digital design stages.

The first issue that came up is that the existing processing script became totally overwhelmed by the amount of data. Not only is the script dealing with eight bits of timber instead of three, but the complex end conditions meant that instead of one or two full depth cuts or a valley cut, some end conditions had as many as eight different valley and full depth cuts that needed to be processed. On-top of this, the way the geometry was set up was that two pieces get cut as the same piece and would then be cut in half afterwards to save on timber in the testing phase. This resulted in the data being read differently, and a few manual overrides needed to be written in as certain clusters rely on a certain way of data input.

To deal with this, the script needed to be rewritten in order to run more efficiently so that it could handle the massive increase in data. Two new clusters were formed, simply named "Valley" and "Ridge" (refer section 5.5).



Figure 124:
Figure 125:
Figure 126: Failed web member cuts.



With this new set of clusters, scripting went from anywhere between 15 minutes to an hour setting up a cut, to setting up 36 cuts in the space of two hours. Of course, this is time that ideally shouldn't have to be spent at all. This script is being approached with no background in computer science or coding, just some basic understanding of parametric modelling and the ability to problem solve logic.

This updated version of the script almost worked exactly as it was meant to. It made all the correct cuts and at the correct depths. The one part of it that failed was the saw blade thickness compensation, which at this point is not an automated procedure, and therefore subject to human error. In this test, a rule applied that every cut on one side of the saw would pass through the thickness compensation cluster before it is output, however the results of the test show that because the data is being handled differently, the cluster was occasionally working in the opposite direction. Where a cut would have been 2.77mm off to the side of where it is meant to be (the thickness of the saw blade), instead of moving to the exact marker, it was moving an additional 2.77mm away which rendered all the test pieces unusable.

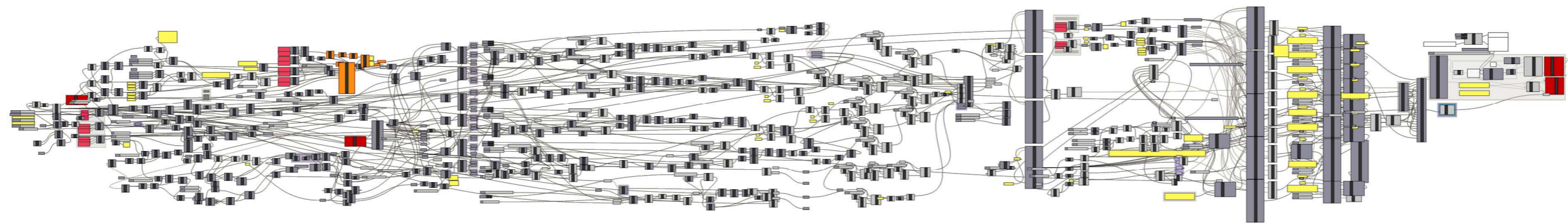


Figure 127: Unpackaged processing for one ridge cut and one valley cut.

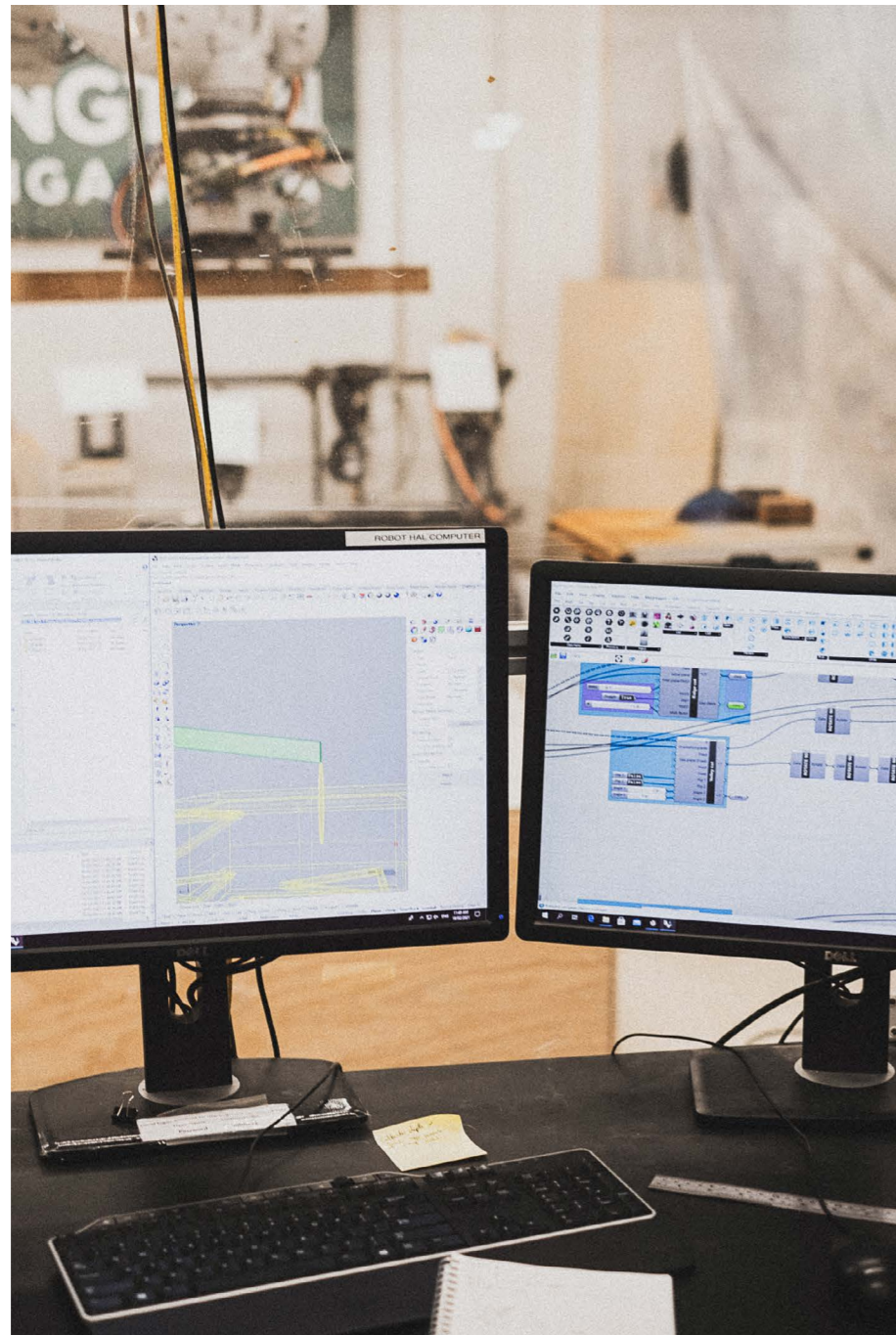


Figure 128: Robot interface

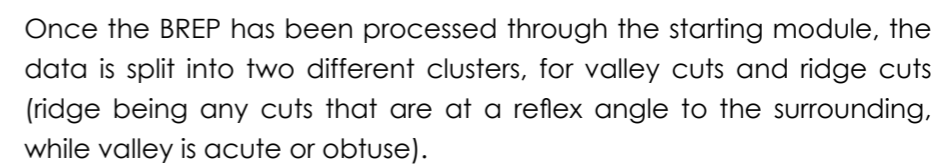
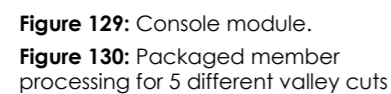
5.5

FINAL SCRIPT INTERFACE

As the project and the understanding of the requirements of the robot, the environment and the process developed, so too did the ability to create a clean cohesive script. This final interface, while really doing exactly the same thing as earlier iterations of the same script, standardises everything that repeats, tidies up several data management issues present in prior versions, and makes for the most intuitive arrangement for setting up cutting files within the scope of my computational ability. As will be touched on in the reflection for this chapter, this is by no means the final step. Were this to go into an actual production scenario, certain elements would be completely bypassed with coding beyond the level of capability here, making the process completely, or as close to fully automated as possible, with fail-safes to prevent human error which is still possible in this current layout.

Breaking down the interface, we have a 'console module' that sets a small number of parameters like timber cross section size and number of timber pieces in the stack, which sets up the tool data and alters how the toolpath is then created. Within this console module is also the code for RAPID code export, and toggling between code generation and running through a digital simulation.

Every piece of timber that is processed has a start module and an end module, with various pieces between depending on what is required for each part. The starting module takes the input BREP, which is processed through a cluster that flat-planes the geometry (takes it from its original position and orientation in space, brings it to the home point $X=0$, $Y=0$, $Z=0$, and changes the orientation to lie flat and parallel with the X axis), then brings 2 instances of the geometry to either side of the sawblade, so that the extreme edges are just touching the saw. This first cluster feeds an index list, which sorts which faces are on the side of the sawblade and which ones aren't, and plugs the ones that are into the second half of the cluster. Through doing this, the indexing log is used to sort out the data being processed, and spits out the cutting faces, orientation planes, and intersection planes for either side of the timber as separate lists for the next stage.



The valley cluster requires the two orientation planes and the intersection planes. This then processes the cutting planes to align with the saw blade, and then the depth and rotation are determined through the intersection planes, giving the toolpath planes for both cuts in the valley.

The ridge cluster requires the orientation planes and the cutting face from the base geometry, which informs the rotation and depth of the cut once the tool has been oriented to the sawblade. There are some manual checks to do with these clusters. Having them set wrong can result in cuts at a right angle to what they should be, or the robotic arm attempting to go through the saw table.

Finally, the toolpath planes are plugged into the output cluster, which creates a series of the hover > table sweep > slow down for saw cut> lift up to move to next cut toolpath for each plane. Along with these, other predefined toolpaths are retrievable, like cutting timber to length, picking up, rotating and placing timber, and a series of different safe frames to prevent the robot putting itself in an impossible or damaging situation. A rotate cluster and flip cluster can be used to allow the robotic arm to approach the same cut in a more accessible way. Once these are plugged into a merge function in the appropriate order, they are fed back into the console module under the 'toolpaths' input, where simulations and RAPID code can be generated.



Figure 131: Timber cuts

5.6

CRITICAL REFLECTION

First and foremost, the robotic arm was not used anywhere near as much as had been hoped. Covid-19 meant that for quite some time there was no access to the facilities, and at several points in the year discussions were had about making the thesis entirely through simulation, which, as is now apparent, wouldn't have worked at all. Set up also took several weeks, and due to unfortunate circumstances, I had a serious head injury and took nearly two months off to recover. Of the remaining time, I was able to access the robotic arm for an average of 8 hours a week due to the demand of the arm and the need for constant supervision while using the saw.

That aside, even the said limited access to the robotic arm offered plenty of learning. The majority of the issues, of which there were many, came about from fixing incredibly minute errors in calibration. In a digital simulation, or at least in the simulations that were possible to run, these subtle errors aren't conveyed.

The digital simulations are still beneficial, and without creating a fully automated CAM solver, were necessary for the procedures executed – these simulations were able to show the different orientations the robotic arm would attempt to put itself into, to indicate where timber rotations, flip states and safe frames were needed to stop it damaging itself. These became easier to read as more experience with the robot was gained, to the point that it became possible to pre-empt every problematic scenario the robot would put itself in and account for it before running a physical simulation.

Looking at what was accomplished, it appears that from the perspective of a proof of concept, this section of the research was successful. As an actual production cycle, too many things remained resolved for it to be a viable alternative.

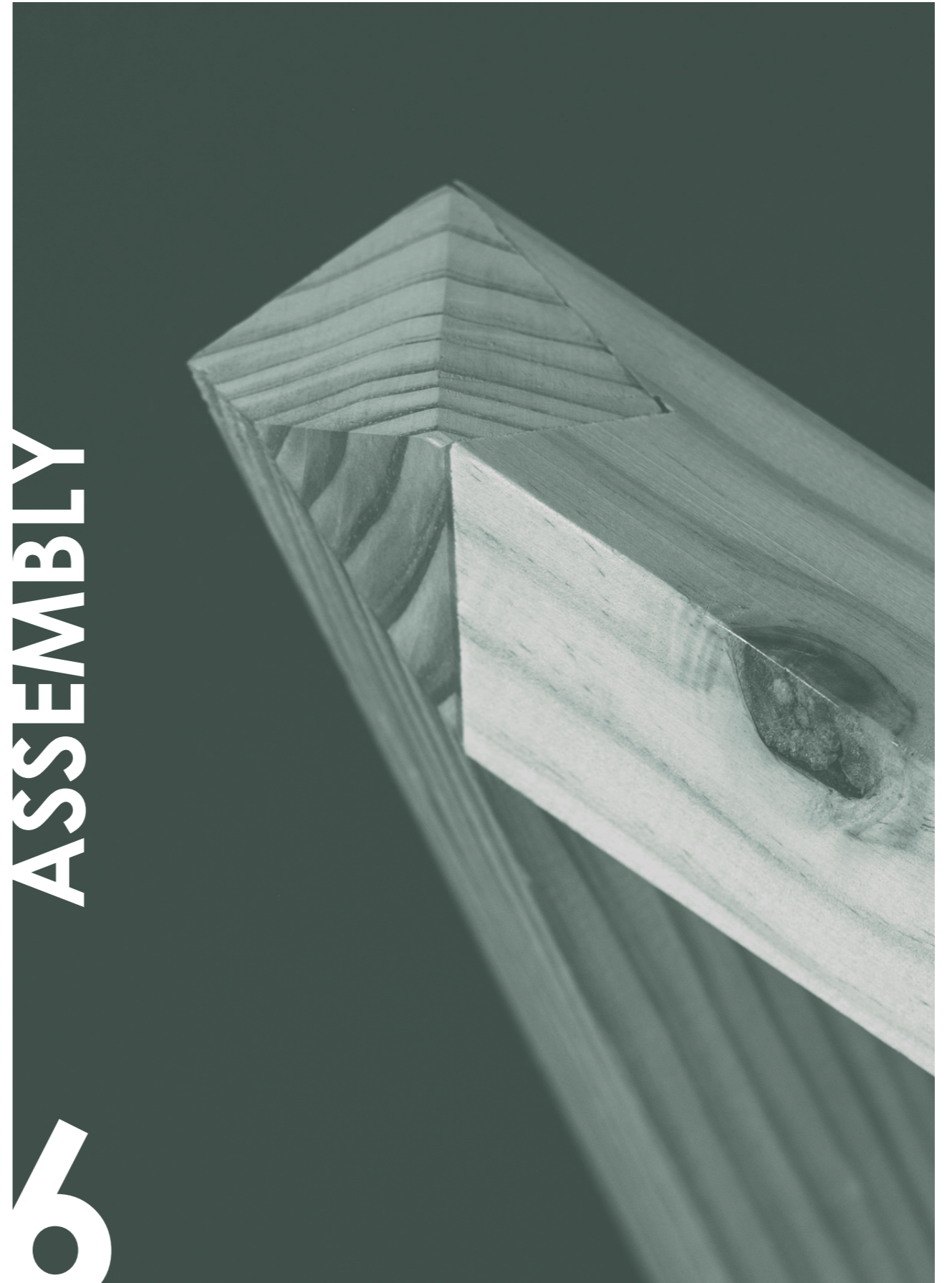
The script and user interface to create rapid code from the input geometry was optimised as much as possible within the timeframe of the research, but a requirement for manual set up means that there is always the possibility for human error. The amount of time to set up these files, combined with running both a digital and physical simulation prior to actually executing a cut file, means that there is still a significant time investment for every cut. Optimisation did prove to cut all admin time down significantly, so a fully automated script

with inverse kinematic analysis would further reduce the time taken to achieve successful results and negate error.

On the subject of error, it goes without saying that this chapter was full of them, a much higher percentage of the time invested in this research was merely fixing malfunctions shown in the results. One of the key learnings taken from this section of the research is an echo from what was one of the significant points of the previous chapter; the materials and their flaws are expressed in the final results. At this stage of testing, this became a crippling drawback which significantly held back progress in the final sessions with the robotic arm during 2020.

Because the members of timber were bowing almost immediately after being dressed, the interaction between the timber and the saw was often misplaced, and in an unpredictable way. Due to the unpredictability and complex relationship each cut has with the next, these errors couldn't be accounted for in scripting in a tolerance, as the error could be in any direction and the geometry requires absolute precision.

6 ASSEMBLY



6.1

OVERVIEW

This section of the research attempts to apply all the findings and workflows into a physical manifestation, to test and assess the design work and methodologies against real world feasibility.

Unlike the preceding work, this section took a linear process, as the jointing design and the majority of the fabrication workflows had been resolved within the scope of works in the research.

Three different design options were developed, with the intent of demonstrating the findings within the research at a real-world scale, to be used as part of the research examination. While there was no architectural context to apply the design to, the following constraints are what informed the arrangements:

- The allocation for presentation space is roughly 3x3 meters.
- A one to one scale, or as close to possible with the fabrication constraints.
- While something abstract and sculptural was possible, the final outcome was to stick to the design principals found in the precedent studies that developed the truss generation scripts.
- Within the construct of a space frame, utilize undulations to exhibit how the processes and workflows can allow for intricate, unique geometries.

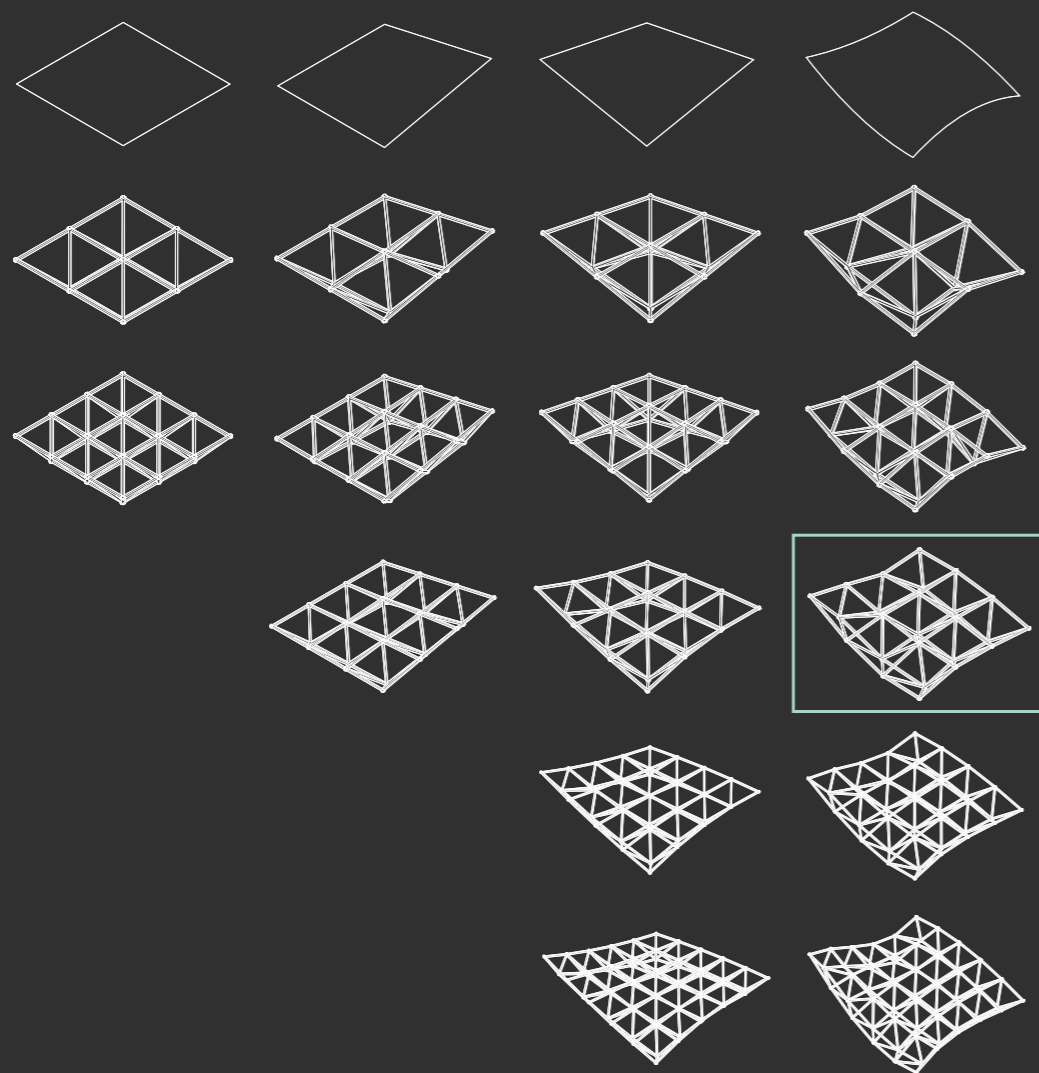


Figure 133: Design series 1

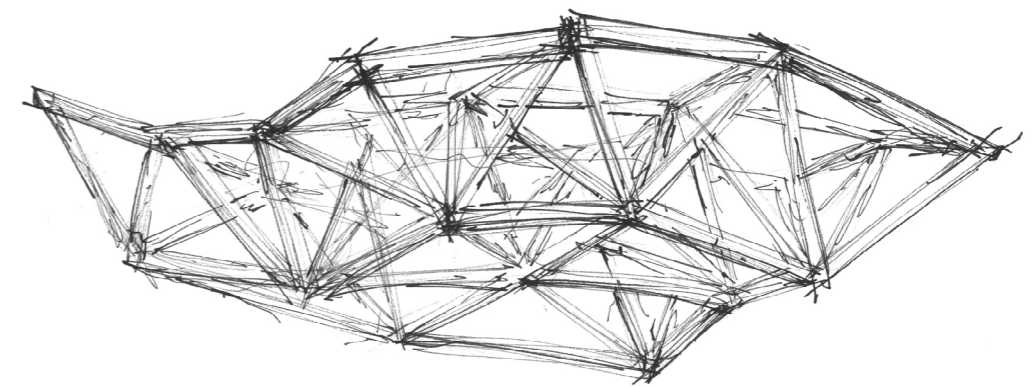


Figure 134: Sketch of design option 1

Design iteration one makes use of the full allocation of presentation space. A simple wave typology in the initial geometry gives the space frame a lightly modulated form. A series of different subdivisions and depths to give the most appropriate display piece was created and critiqued. While the higher concentrations of density carry greater visual interest, a 1x1x0.7 grid was selected to ensure that all the geometry would be possible to manufacture with the robotic arm's constraints.

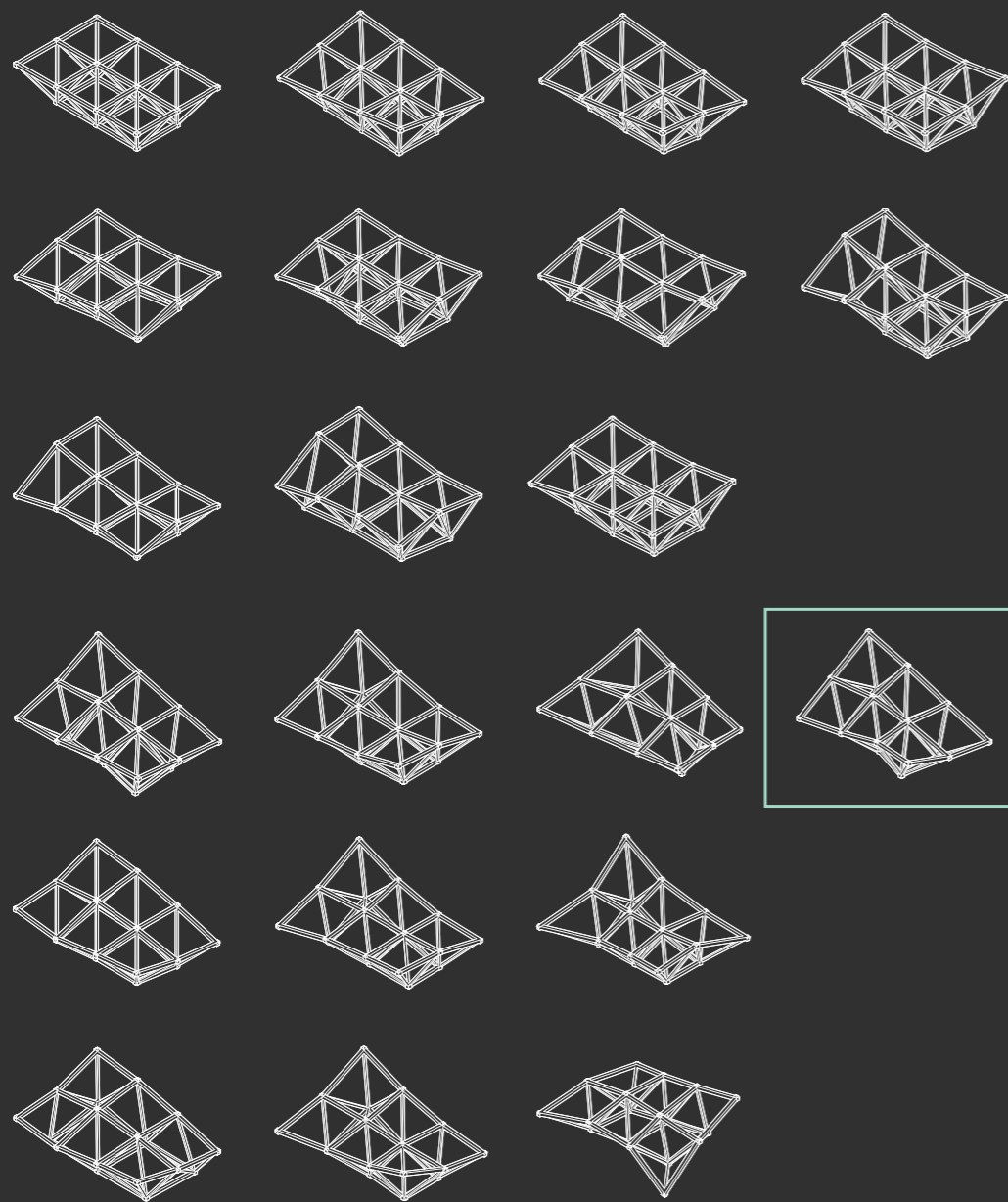


Figure 135: Design series 2

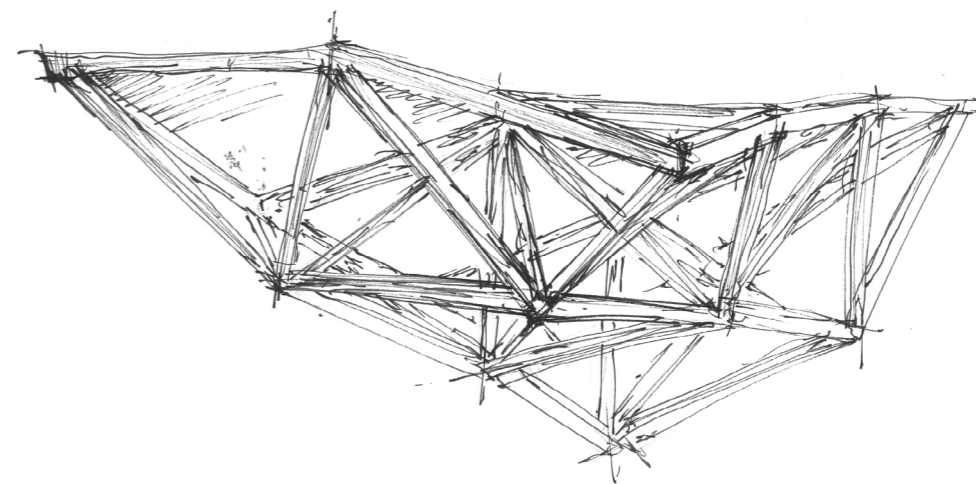


Figure 136: Sketch of design option 2

The second series of designs adopt the 1x1x0.7 grid from the first series and reduce the structure's size by one full bay. This and the following series comes after a two-week delay in material delivery, meaning a loss of a significant portion of the available fabrication time and resulting in a push for a structure with fewer members and cuts. This begins with a 2x3 meter modifier, which is more heavily manipulated than the previous series and rebuilds the undulated modifier with irregular grid subdivisions.

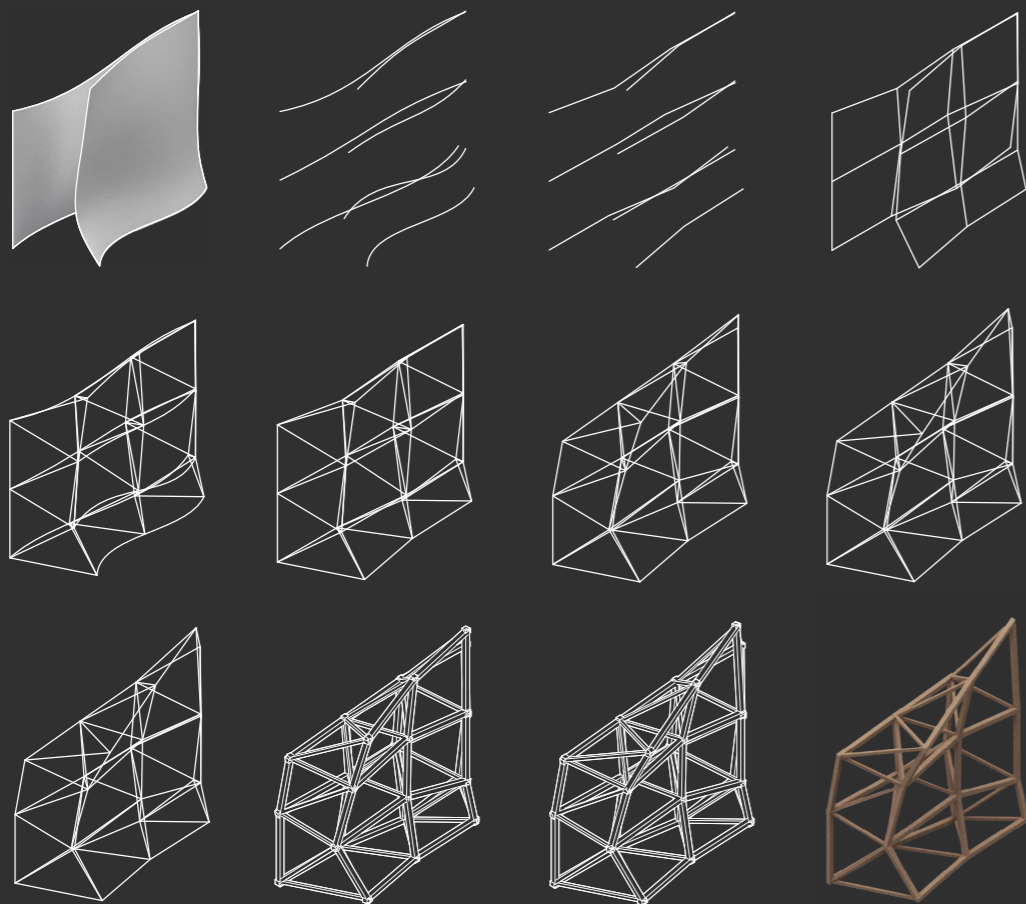


Figure 137: Design series 3

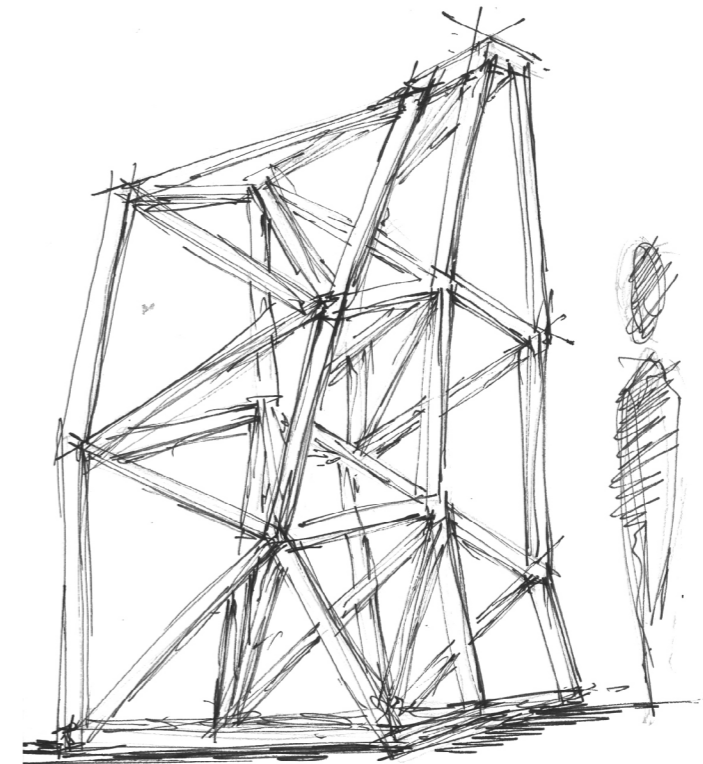


Figure 138: Sketch of design option 3

The final design iteration has a very similar structural makeup to the previous series; however, this shifts the paradigm from roof to wall. The space frame scripting and design drivers are still existent; this paradigm shift merely allows the structure to be something that an audience could observe from up close. The lack of structural testing would make it challenging to hang a roughly 140kg spaceframe above the presentation space – not that it cannot support its own weight, but more that it has not been tested to destruction, and therefore would have created several issues with receiving health and safety approval. This design would also be self-supporting and use a relatively small portion of the total allocated display space, while the previous two require feet or mounting points to suspend.

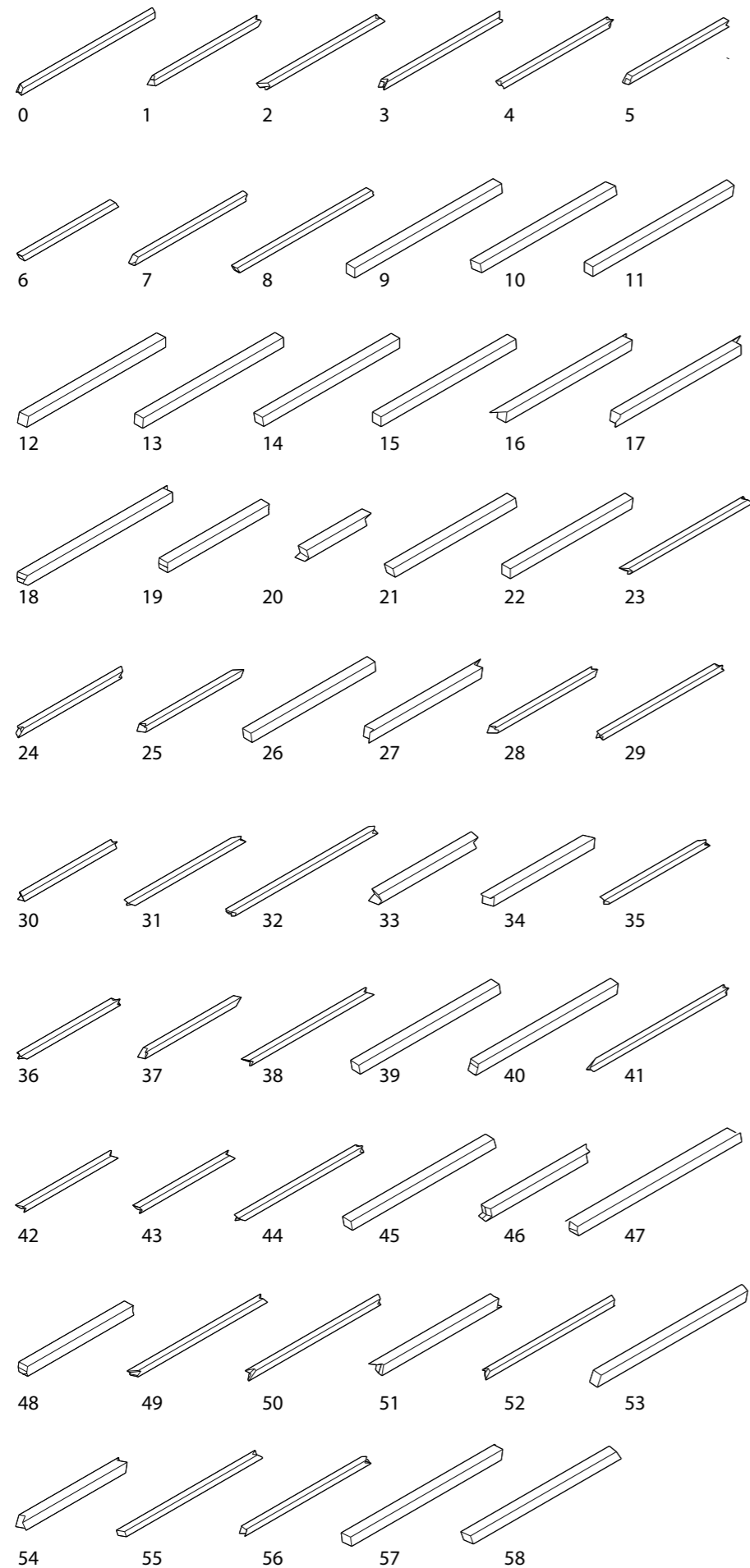


Figure 139: Part catalogue, sorted by model index

6.2

DESIGN

59 unique pieces
573 cutting faces

2.649 m width
1.194 m depth
2.789 m height

Due to the limitations of only having a single robotic arm with a fixed base point, robotic assembly was not available for this structure. This meant that all parts required labelling to identify where they belong in the structure.

The lack of input from digital aids (robotic assembly) also results in the construction sequence needing to be governed by gravity rather than the simplest arrangements of connections. The complicated three-dimensional angular relationship every piece has to its corresponding parts means clamping is not possible during the glue curing, hence the requirement for gravity to be put to use.

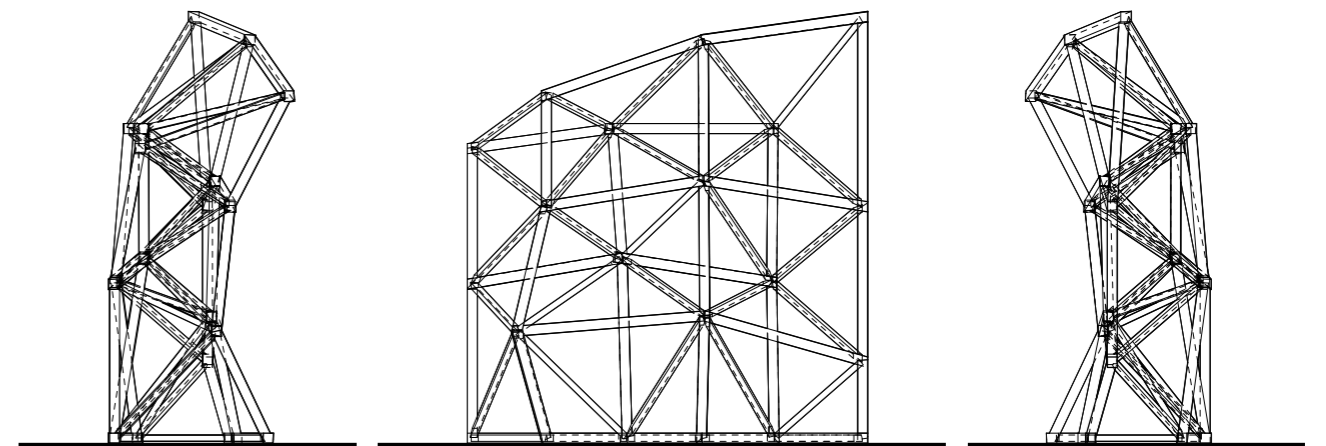


Figure 140: Front, side elevations, 1:20

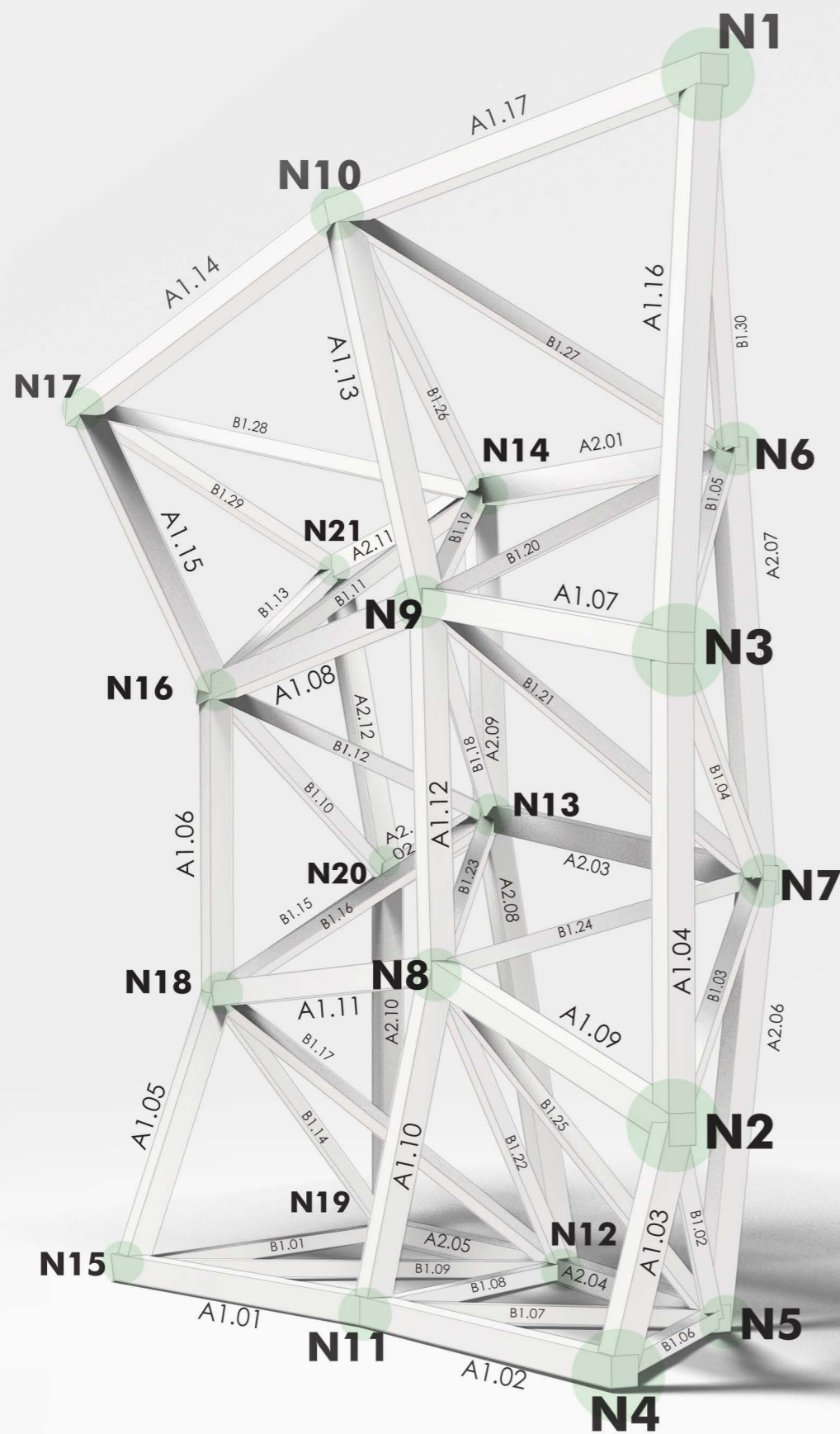
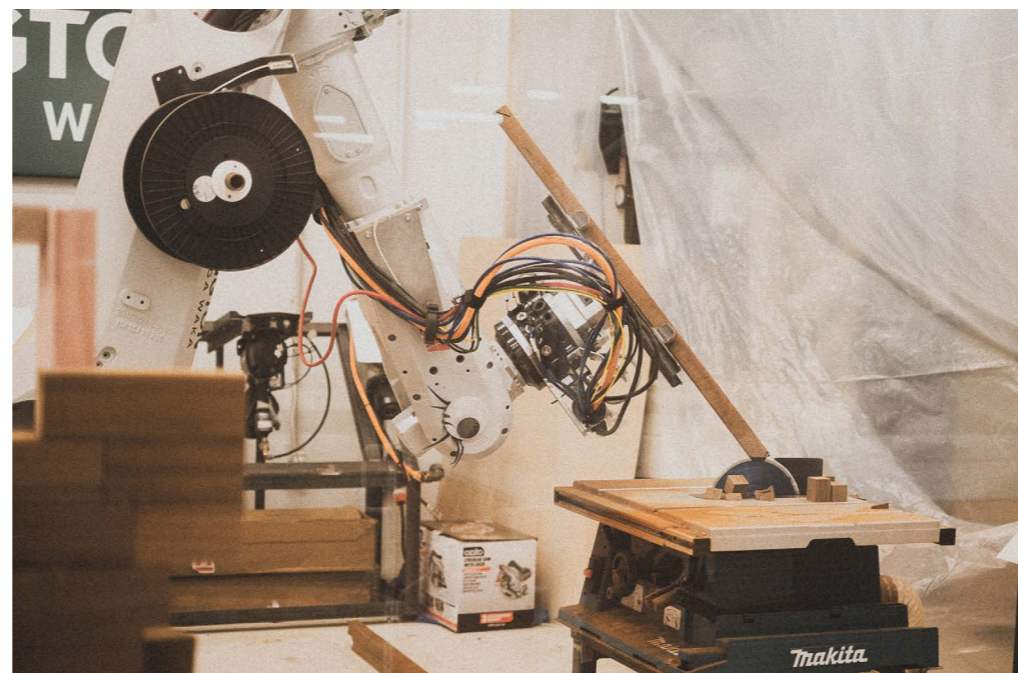
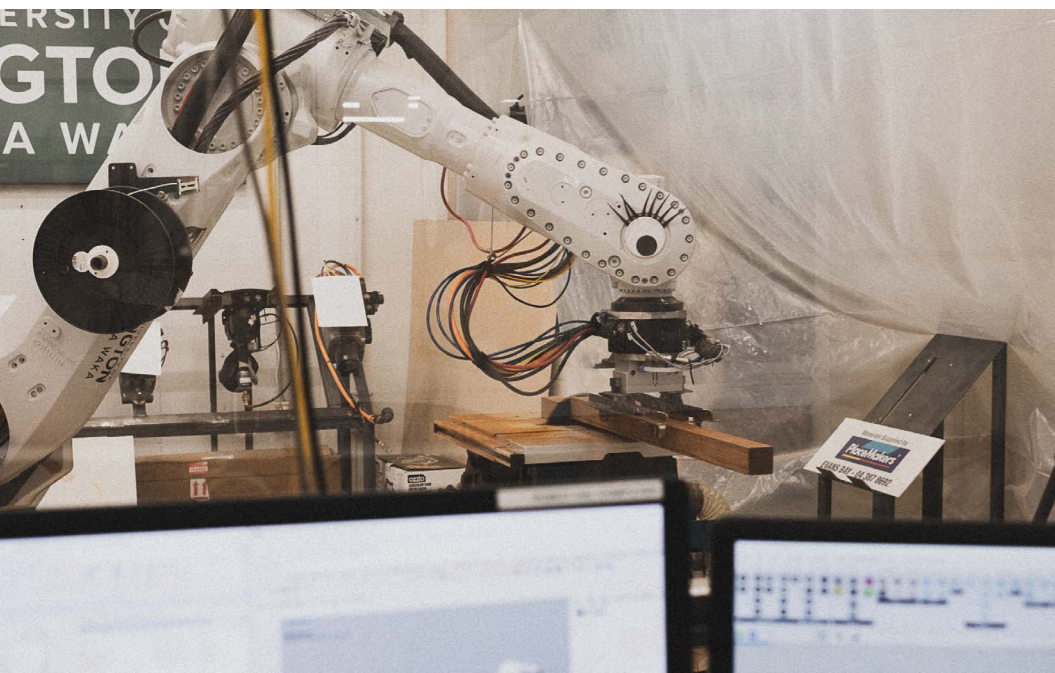


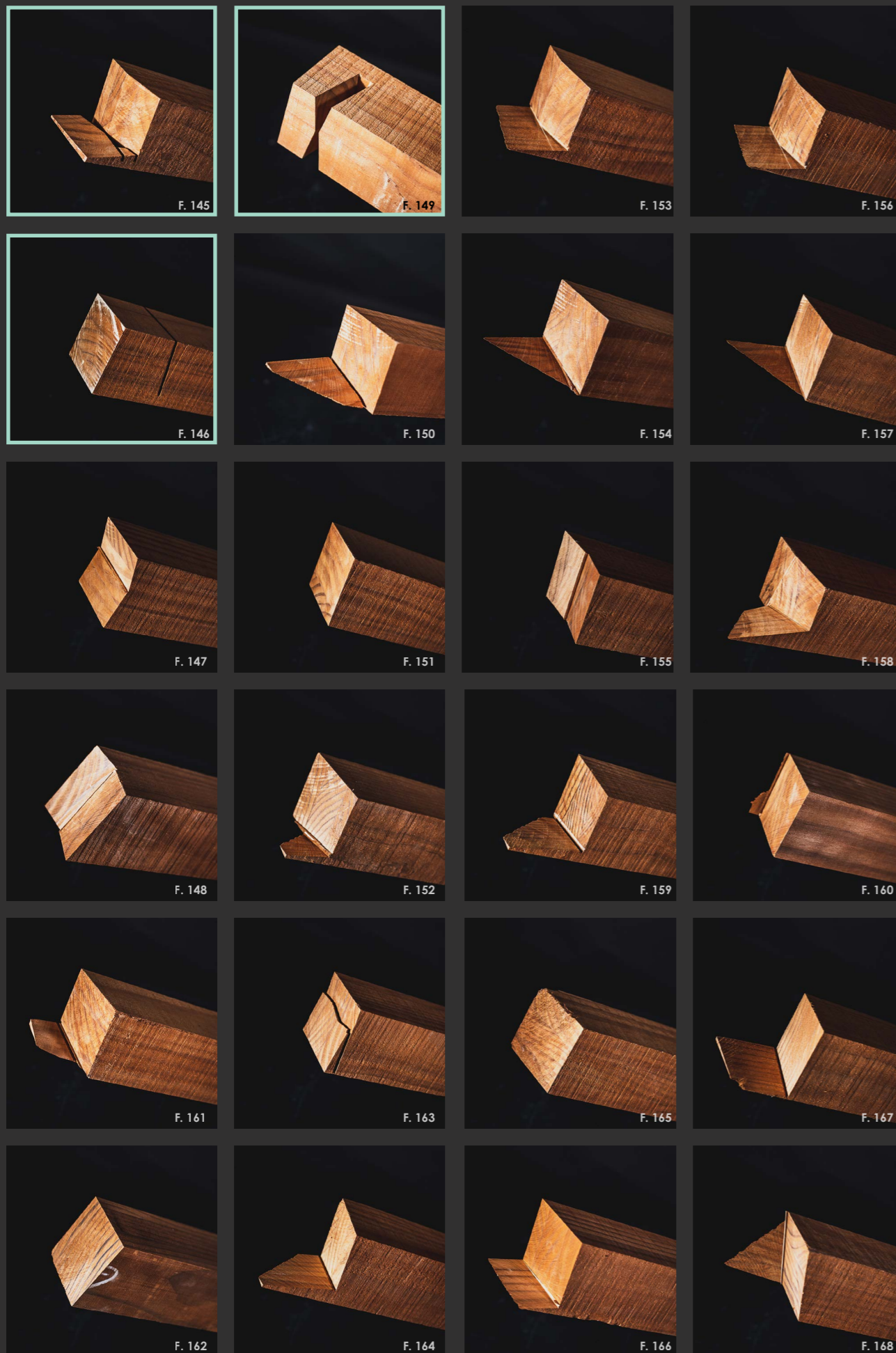
Figure 141: Structure schematic

Category Key		Timber length	Size	Model Index	Node 1	Node 2				
A1	A1.01	1067.9	65x65	46	N11	N15	N1	A1.17		B1.07
A1	A1.02	1078.4	65x65	33	N4	N11		A1.16		B1.08
A1	A1.03	518.5	65x65	54	N2	N4		B1.30	N12	A2.04
A1	A1.04	947.7	65x65	47	N2	N3	N2	A1.04		A2.05
A1	A1.05	785.6	65x65	34	N15	N18		A1.09		A2.08
A1	A1.06	846.0	65x65	48	N16	N18		A1.03		B1.08
A1	A1.07	1086.8	65x65	13	N3	N9	N3	B1.03		B1.09
A1	A1.08	1093.6	65x65	45	N9	N16		B1.02		B1.17
A1	A1.09	1112.3	65x65	39	N2	N8		A1.16		B1.22
A1	A1.10	834.1	65x65	51	N8	N11	N4	A1.07	N13	A2.03
A1	A1.11	1258.5	65x65	40	N8	N18		A1.04		A2.02
A1	A1.12	910.5	65x65	12	N8	N9		B1.04		A2.08
A1	A1.13	954.8	65x65	58	N9	N10	N5	B1.05		A2.09
A1	A1.14	1168.3	65x65	53	N10	N17		A1.03		B1.12
A1	A1.15	812.1	65x65	21	N16	N17		A1.02		B1.16
A1	A1.16	1214.8	65x65	57	N1	N3	N6	B1.06		B1.18
A1	A1.17	1172.2	65x65	20	N1	N10		A2.06		B1.23
A2	A2.01	1127.7	65x65	10	N6	N14		A2.04	N14	A2.01
A2	A2.02	1057.1	65x65	26	N20	N13	N7	B1.06		A2.11
A2	A2.03	1088.7	65x65	15	N7	N13		B1.02		A2.09
A2	A2.04	1049.8	65x65	22	N5	N12		B1.07		B1.11
A2	A2.05	1035.0	65x65	27	N12	N19	N8	B1.25		B1.19
A2	A2.06	1045.5	65x65	18	N5	N7		A2.07		B1.26
A2	A2.07	1019.1	65x65	19	N6	N7		A2.01		B1.28
A2	A2.08	1170.0	65x65	14	N13	N12	N9	B1.30	N15	A1.01
A2	A2.09	781.8	65x65	11	N13	N14		B1.05		A1.05
A2	A2.10	940.9	65x65	9	N20	N19		B1.20		B1.01
A2	A2.11	957.7	65x65	17	N14	N21	N10	B1.27		B1.09
A2	A2.12	919.6	65x65	16	N20	N21		A2.06	N16	A1.06
B1	B1.01	1041.8	42x42	55	N15	N19		A2.07		A1.08
B1	B1.02	840.5	42x42	28	N2	N5	N11	A2.03		A1.15
B1	B1.03	942.2	42x42	23	N2	N7		B1.03		B1.10
B1	B1.04	929.9	42x42	30	N3	N7		B1.04		B1.11
B1	B1.05	884.6	42x42	29	N3	N6	N12	B1.24		B1.12
B1	B1.06	775.5	42x42	0	N4	N5		B1.21		B1.13
B1	B1.07	746.0	42x42	52	N5	N11		A1.09	N17	A1.14
B1	B1.08	873.2	42x42	25	N11	N12	N13	A1.10		A1.15
B1	B1.09	1063.1	42x42	31	N12	N15		A1.11		B1.28
B1	B1.10	980.6	42x42	32	N16	N20		A1.12		B1.29
B1	B1.11	829.0	42x42	41	N14	N16	N14	B1.22	N18	A1.05
B1	B1.12	776.3	42x42	42	N13	N16		B1.23		A1.06
B1	B1.13	803.0	42x42	35	N16	N21		B1.24		A1.11
B1	B1.14	955.5	42x42	36	N18	N19	N15	B1.25		B1.14
B1	B1.15	738.6	42x42	50	N18	N20		A1.07		B1.15
B1	B1.16	897.6	42x42	38	N13	N18		A1.08		B1.16
B1	B1.17	1135.7	42x42	43	N12	N18	N16	A1.12		B1.17
B1	B1.18	811.9	42x42	44	N9	N13		A1.13	N19	A2.05
B1	B1.19	781.9	42x42	6	N9	N14		B1.18		A2.10
B1	B1.20	752.0	42x42	7	N6	N9	N17	B1.19		B1.01
B1	B1.21	976.1	42x42	8	N7	N9		B1.20		B1.14
B1	B1.22	1081.7	42x42	49	N8	N12		B1.21	N20	A2.12
B1	B1.23	746.2	42x42	24	N8	N13	N18	A1.13		A2.10
B1	B1.24	741.8	42x42	5	N7	N8		A1.14		A2.02
B1	B1.25	986.0	42x42	56	N5	N8		A1.17		B1.10
B1	B1.26	1032.1	42x42	4	N10	N14	N19	B1.26		B1.15
B1	B1.27	1030.6	42x42	3	N6	N10		B1.27	N21	A2.11
B1	B1.28	1002.9	42x42	2	N14	N17		A1.01		A2.12
B1	B1.29	1076.7	42x42	1	N17	N21	N20	A1.02		B1.13
B1	B1.30	980.6	42x42	37	N1	N6		A1.10		B1.29



<https://youtu.be/8gSHIhR98UM>
Web member fabrication.

Figure 142:
Figure 143:
Figure 144: Fabrication



6.3

FABRICATION

Timber stock and Fabrication:

In order to move away from the issues of bowing and twisting that a lot of the cheaper radiata had been doing, Abodo was approached, who graciously sponsored a significant amount of timber stock. Abodo is still radiata pine; however, through lamination and baking, the product is far less susceptible to twisting and bowing. The stock is not perfectly straight; even in its engineered and chemically modified state, it is still natural. That said, this was far closer to true than what had previously been tested with, and any bows were so minor that the effects are negligible.

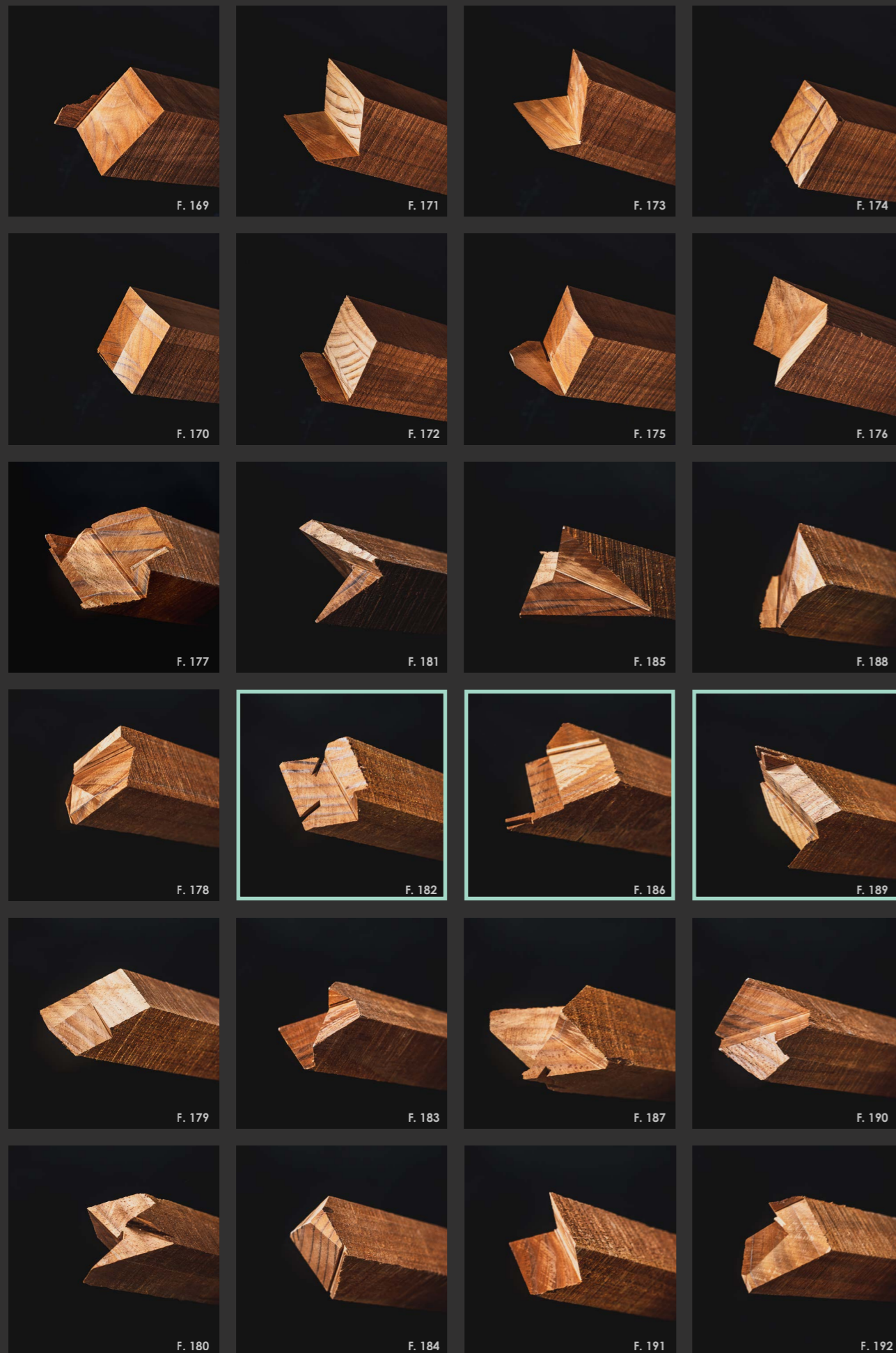
Moving to Abodo also allowed a greater variety of timber cross-sections to be ordered, so while all previous robotic testing had been on 40x40 that was dressed in-house, 50 linear meters of both 65x65 and 42x42 millimetre sections were procured. This not only served as an opportunity to trial the robotic fabrication scripting on larger timber members, but also allowed for a combination of different timber sizes to join together with aesthetic and structural hierarchy.

Different stock sizes meant that the script needed to be calibrated in order to yield the correct results. This brought up issues that were not visible in the previous testing, as the error was not as extreme on them, and the smaller timber size hid some of the issues.

First, the grippers needed modification in order to be able to pick up the bigger section of timber, then the TCP data needed to be calibrated according to the relativity of the end of the grippers to the centre of the timber.

Secondly, the depth at which the grippers were grabbing the timber resulted in incorrect cuts. If they were relatively flat, this resulted in the cuts not being deep enough, while heavily angled cuts would end up in the wrong place altogether. Fortunately, this was a simple calibration fix, and a safe frame was created to set the correct depth after every pickup and timber rotation.

Finally, it became apparent that cuts done on one side of the saw were near exact, while those on the other side had some significant offsets. This was initially thought to be a global error in the scripting, but after recalibrating the saw location in the robotic X-Y-Z world, it was found that the saw was off location by nearly a millimetre.



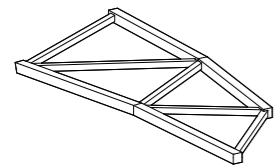
The grasshopper script would occasionally malfunction. Of the 573 cutting faces in the final assembly, on four separate occasions, a cutting plane would be on the correct spot but at a completely random orientation that did not relate to the face at all. The script was pulled apart and rebuilt, and it did not appear to fix it. The processing script that creates the orientation planes was duplicated and run again on a separate file with the same geometry, which solved this issue. This tells that Grasshopper is not flawless and can malfunction when processing large amounts of data. This error only affected less than 1% of the data being processed.

One part (A1.03), was too small to be processed by the robot, as the grippers would hit the saw blade. Under normal circumstances, the design process of the form would have eliminated this geometry. A conscious decision was made to include this part, to achieve the base for the structure to stand, and demonstrate some of the constraints of this construction method.

Further issues did occur, but these all fall on human error (a small number of the cuts had the incorrect number of timber rotations plugged in, so cut on the wrong face) or irregularities in the stock. While the heat-treated Abodo product does not suffer from deforming to any comparable degree to an untreated member, the timber arrived in rough sizes. One or two millimetres off a given dimension on a piece of 65mm timber screening is appropriate for its original purpose. However, digital fabrication methods, as aforementioned, work off precise measurements. Without additional allowances for scanning the stock and altering the scripting geometries to compensate, there is no real way to deal with these issues. Fortunately, the severity of these mistakes tends to be that the cutting depth may be off by up to two millimetres, a relatively easy fix by hand. However, this is something that would need addressing in the case of a real-world production.

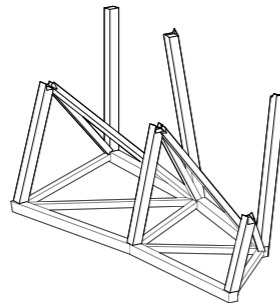
The heat treating of the Abodo members results in a few other side effects. As the chemical structure of the timber is altered in the caramelisation process, the timber becomes far more brittle than in its natural form. This resulted in some of the more nuanced geometry breaking off far quicker than they had done in standard radiata, as they do not have nearly as much give in them before failure.

The stock was also measured with a moisture meter and found to contain 0% moisture content. Each joint had moisture added to ensure the polyurethane based adhesive would be able to create a bond, as this reactin requires moisture.



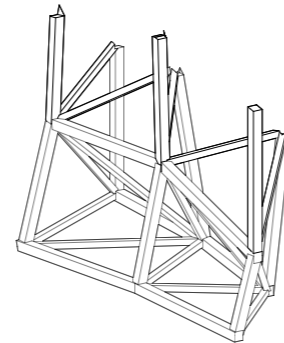
1

A1.01	B1.01
A1.02	B1.09
A2.05	B1.08
A2.04	B1.07
	B1.06



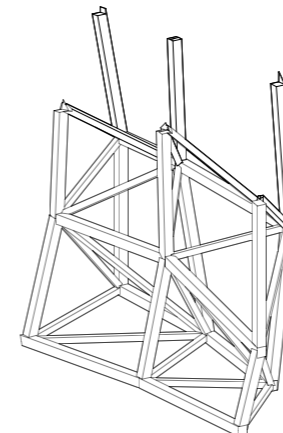
2

A1.05	B1.02
A1.10	B1.25
A1.03	B1.22
A2.10	B1.17
A2.08	B1.14
A2.06	



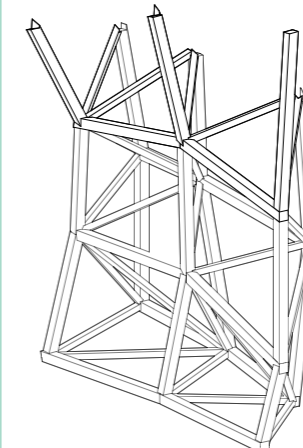
3

A1.11	B1.03
A1.09	B1.24
A1.06	B1.23
A1.12	B1.16
A1.04	B1.15



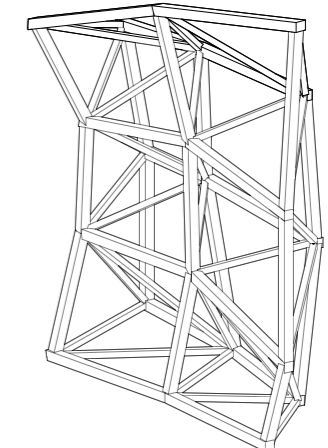
4

A2.02	B1.04
A2.03	B1.21
A2.12	B1.18
A2.09	B1.12
A2.07	B1.10



5

A1.08	B1.05
A1.07	B1.20
A1.15	B1.19
A1.13	B1.11
A1.16	B1.13



6

A2.11	B1.30
A2.01	B1.29
A1.14	B1.28
A1.17	B1.27
	B1.26

Figure 193: Assembly sequence.



Figure 200: First complete 8-member node

6.4

ASSEMBLY

Once all the parts had been fabricated, the assembly process was able to begin. Immediately the following became apparent with the lack of a digitally controlled aid to the assembly.

Even with a detailed itemisation system, the digital model on hand for reference, and a step by step assembly diagram, finding the correct part and orientation was not always as straight forward as desirable; one part was placed in rotated 90 degrees to what it should have been, requiring disassembly. A computationally controlled system would eliminate the constant back and fourth this caused, and remove the risks of human error.

Time was a massive disadvantage – not only in the sense that manually finding, placing and fixing parts was a drawn out process, but curing times for the glue had a number of consequences. One positive consequence was that the curing time allowed for minor adjustments where parts might be positioned incorrectly. This point is of course moot when a robotic arm is assembling, as the robot can position it perfectly in space. Other digital aids like augmented reality could have assisted in this aspect.

The other consequence curing times for glue had was that a timber member could sag from the desired position as the glue set. Upon reflection, this may not be an issue had the method of connecting parts had a tighter tolerance. However, while untested in this research, many other methods of fixing would have a tolerance that allows a degree of rotational discrepancy. The unfortunate side effect is something that was brought up earlier in the research; a tiny error in angle at one end of a member will result in the other end being a way off where it should be.

A robotic arm would be able to hold the part in the exact quaternion location, and if need be, hold the part as the adhesive sets. The consequence of not having that aid was that a number of members did slouch as they set, even where they were resting on their constituents or held in place with strops. While all parts did come together, gaps started appearing as the structure got higher. Over a small-scale prototype like this, it is undesirable, but the structure can still come together. In a real-world context however - say a space frame on a civic building - that kind of dimensional inaccuracy is completely unacceptable and could cause structural failure.

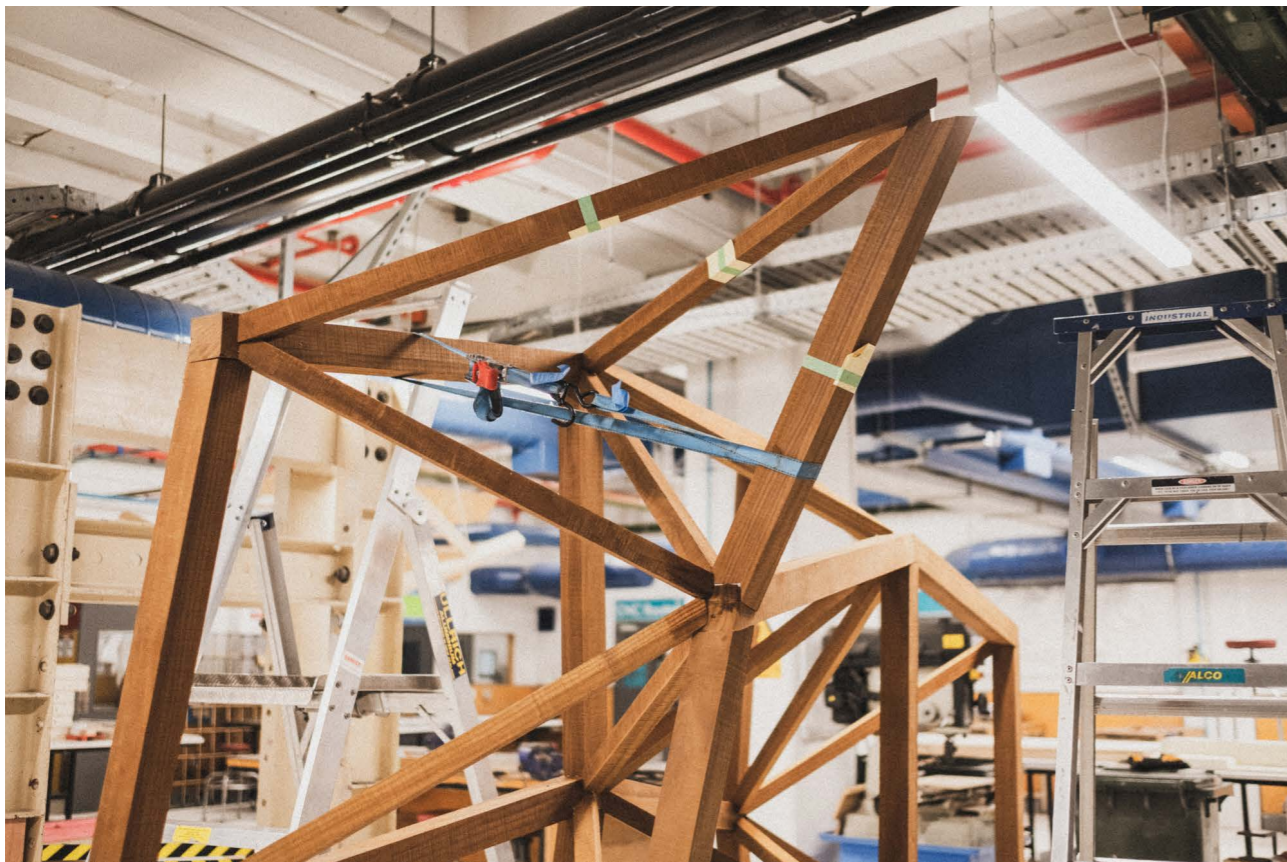


Figure 201: Strap holding timber member in place as adhesive cures.
Figure 202: Structure nearing completion.



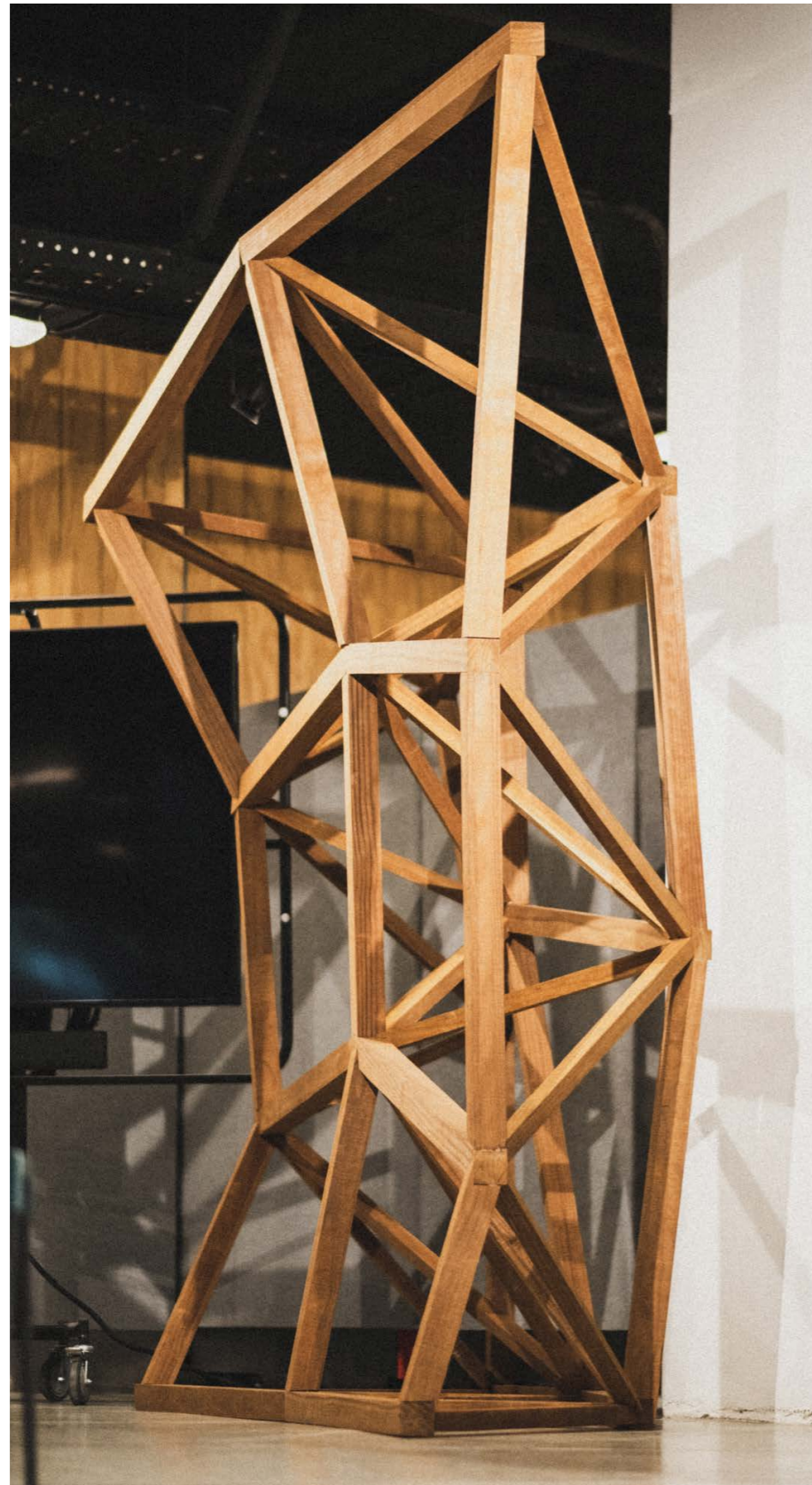


Figure 203: Completed structure.
Figure 204: 8-node.



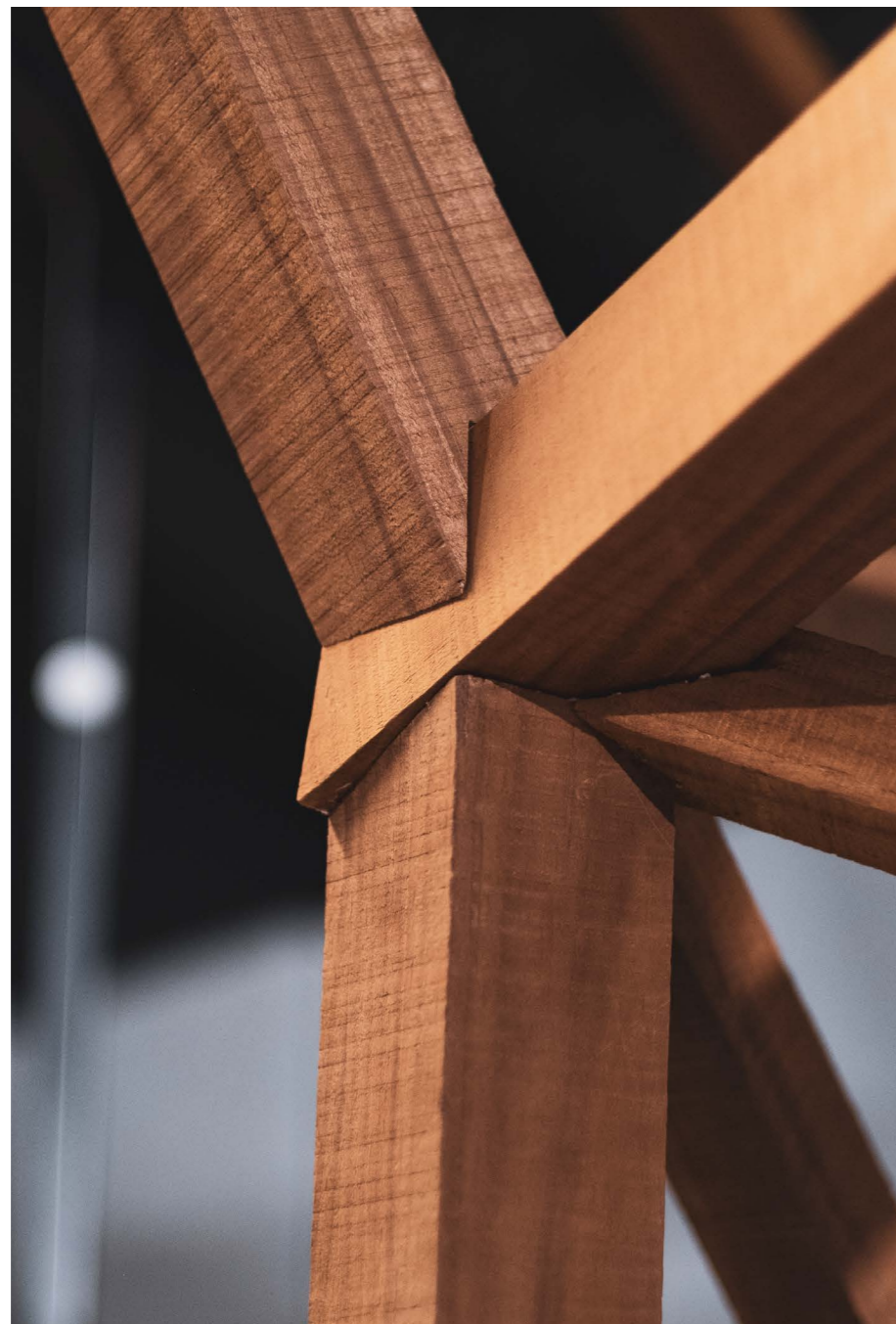


Figure 205: Completed structure.
Figure 206: “





Chapter seven

Figure 207: Timber cuts

CONCLUSION

Using digital design and fabrication methods, can a visual timber spaceframe be feasibly constructed to allow greater choice in architectural freedom?

To give this research question a simple answer, yes. The complexity of such a structure can be dealt with using digital methodologies of designing and building in a fashion that would make the feasibility of said structure far more accessible. That said, that conclusion is oversimplistic, and the answer has far more layers involved in it.

The technologies and processes becoming available to architects have incredible possibilities, allowing “Architects become digital craftspeople, developing new forms, structures, and details that are tailored for computerised fabrication” (Osterlund & Wikar, 2019, p. 135)

Nevertheless, there are still limitations, and a step forward in thinking and approach is required to make use of it. Employing these systems requires implementing a wholistic design strategy that encompasses everything from design concept to assembly. The methods of making need to be engineered towards the desired outcome, while the design outcome needs to consider the processes of manufacture to utilise the possibilities and evolve what architecture could feasibly be.

“Here a shift can be observed, which moves the intellectual activity from the design of architectural objects towards the design of a process of interconnection between digital information, machine and the tool” (Hudert, 2019, p. 130)

This thesis set out to:

- create a design tool that could optimise the process of designing a bespoke timber spaceframe.
- clean up and create all the cutting geometry
- Process the geometry into a robotic manufacturing procedure to be manufactured, and make comparisons with traditional practices.

On a conceptual level, these objectives are achieved, though not flawlessly. Certain areas of the scripting had the correct logic but were bypassed to have the process completed manually, as they became

computationally very intense. A number of the scripting defects were left unresolved due to the time required and the need to complete other aspects of the research. Likewise, even at the optimisation level, the robotic handling script is still prone to failure through human error and does require time for set-up and manually checking and applying safeguards where appropriate.

When comparing the digital method to the traditional, one can make the conclusion that digital has the potential to be far faster than the alternative. A critical factor in whether the digital will be faster is the scale of what is being done and the foundations of any existing workflows. Suppose the set-up time to generate digital design tools and processes is included. In that case, a small-scale structure could conceivably work out faster through traditional ways of making, especially combined with digital documentation, which is at this point accepted as the industry standard. However, in the context of a large project, or a project where the digital processes have already been assembled, there is no doubt that robotic manufacturing could produce the desired results in mere fractions of the time otherwise required.

When the question of financial cost comes in, a similar conclusion can be made to time. Realistically, a production scale establishment would have far greater resources than what was used in this research, at the cost of several hundreds of thousands, if not millions of dollars. Add into that ongoing costs of dedicated manufacturing space, people to operate the machinery, software licensing and maintenance. Without the economies of scale, robotic fabrication suddenly becomes entirely unattainable for the one residential client that wants a boutique architectural feature.

However, with enough production volume, architects could use digital design and fabrication methods to feasibly use these complex, beautiful and innovative assemblies, allowing additional freedom of choice, broadening architectural possibilities.

**The volume of production refers to the amount of manufacturing with robotic arms for the same or similar processes, not the amount of the same structures – these could still be unique forms and systems.*

7.2

WHERE TO NEXT

Following this research, several items could be explored to add further validity. Firstly, jointing options were explored, but physical testing undoubtedly would reveal far more about each method and its feasibility.

Next, the generative script creating structures was derived from taking a fairly standard space frame layout and applying it to any modulated surface, fed into the script. Moving into structural algorithms would open up several new formal opportunities. Like many of the case studies identified in chapter two, this could be anything from striking structural assemblies, to load-path optimisation that achieves the smallest material use.

As mentioned above, full automation of the scripting would negate the need for the vast majority of the set-up time and remove the potential for human error. "Manual tasks, such as creating toolpaths using CAM, exchanging tools, and rearranging workpieces during processing, continue to exist, and solving these issues will truly realise versatile robotic wood processing." (Takabayashi et al., 2019)

The robotic setup used within this research had with it a number of constraints, experimenting with alternative methods of processing with different configurations and tools could open up further possibilities.

Finally, and most critically to successful fabrication, material inadequacies need to be accounted for, It is unrealistic to expect physical, natural materials such as timber to obey computational accuracies, so a process to analyse each piece of stock being processed and compensate the geometries accordingly is required to achieve perfect results.

7.3

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7.4

FIGURES

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