Buildings of Theseus

A cyclical assembly and disassembly of non-standard timber structures with timber joints

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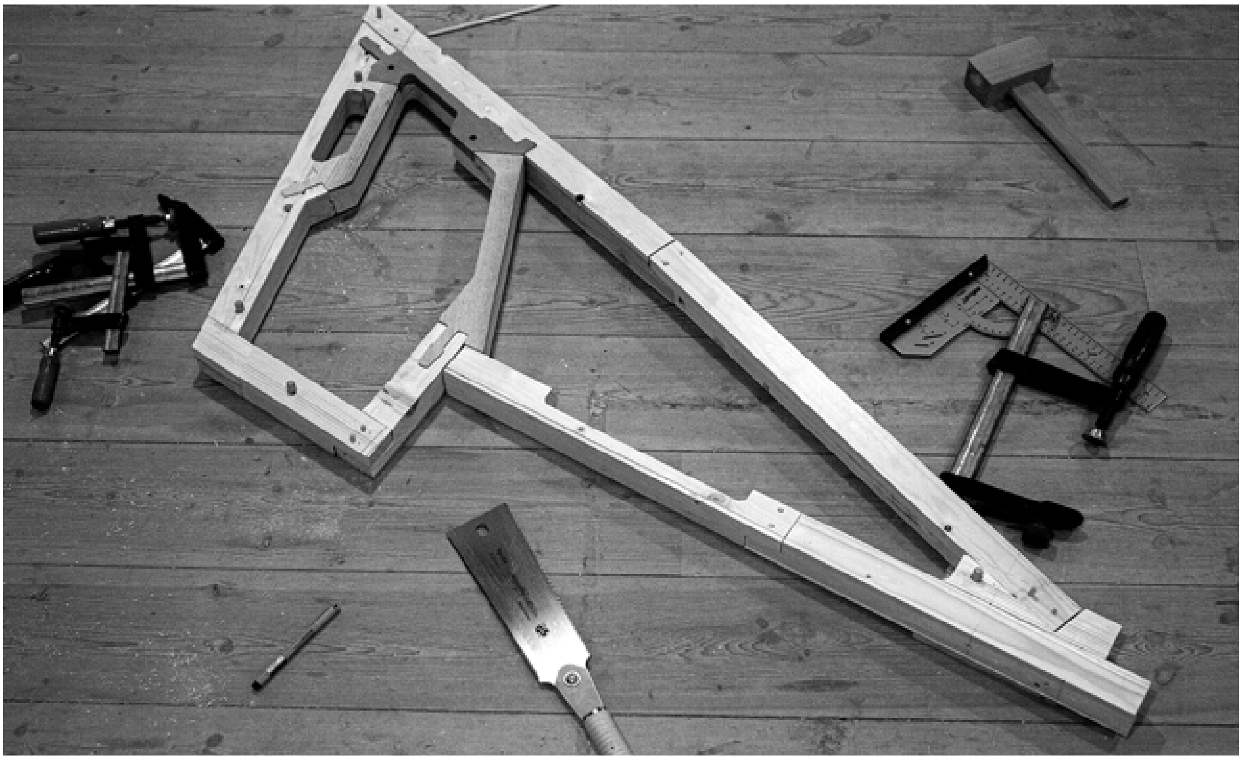

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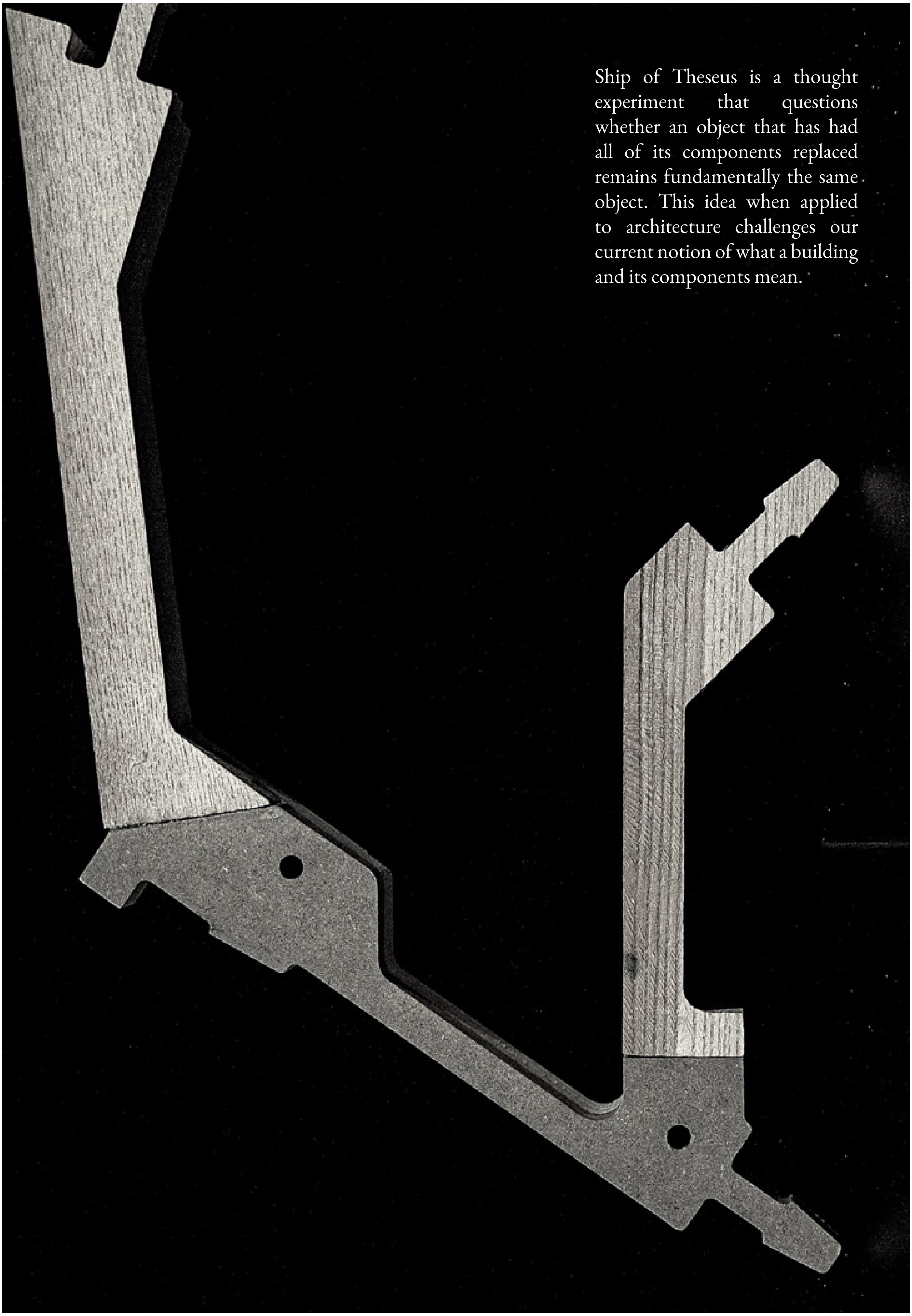
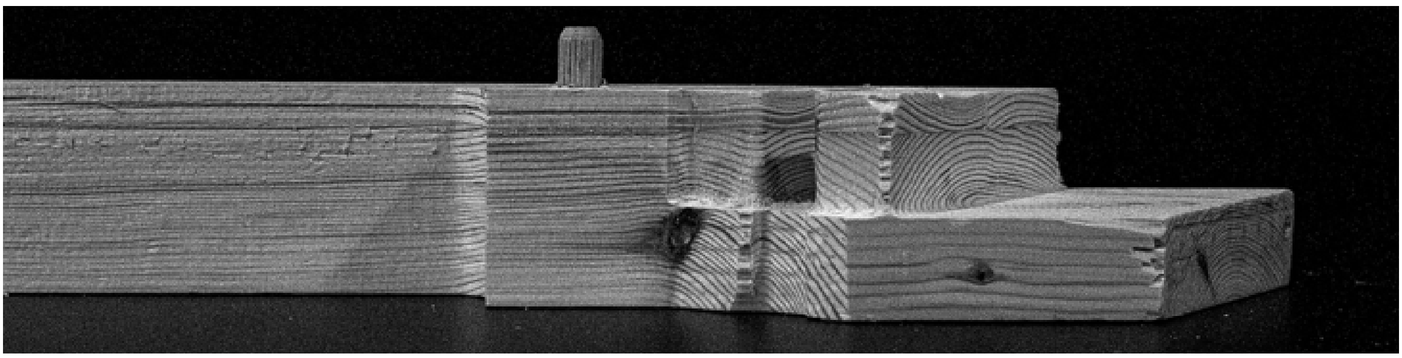


Ship of Theseus is a thought experiment that questions whether an object that has had all of its components replaced remains fundamentally the same object. This idea when applied to architecture challenges our current notion of what a building and its components mean.

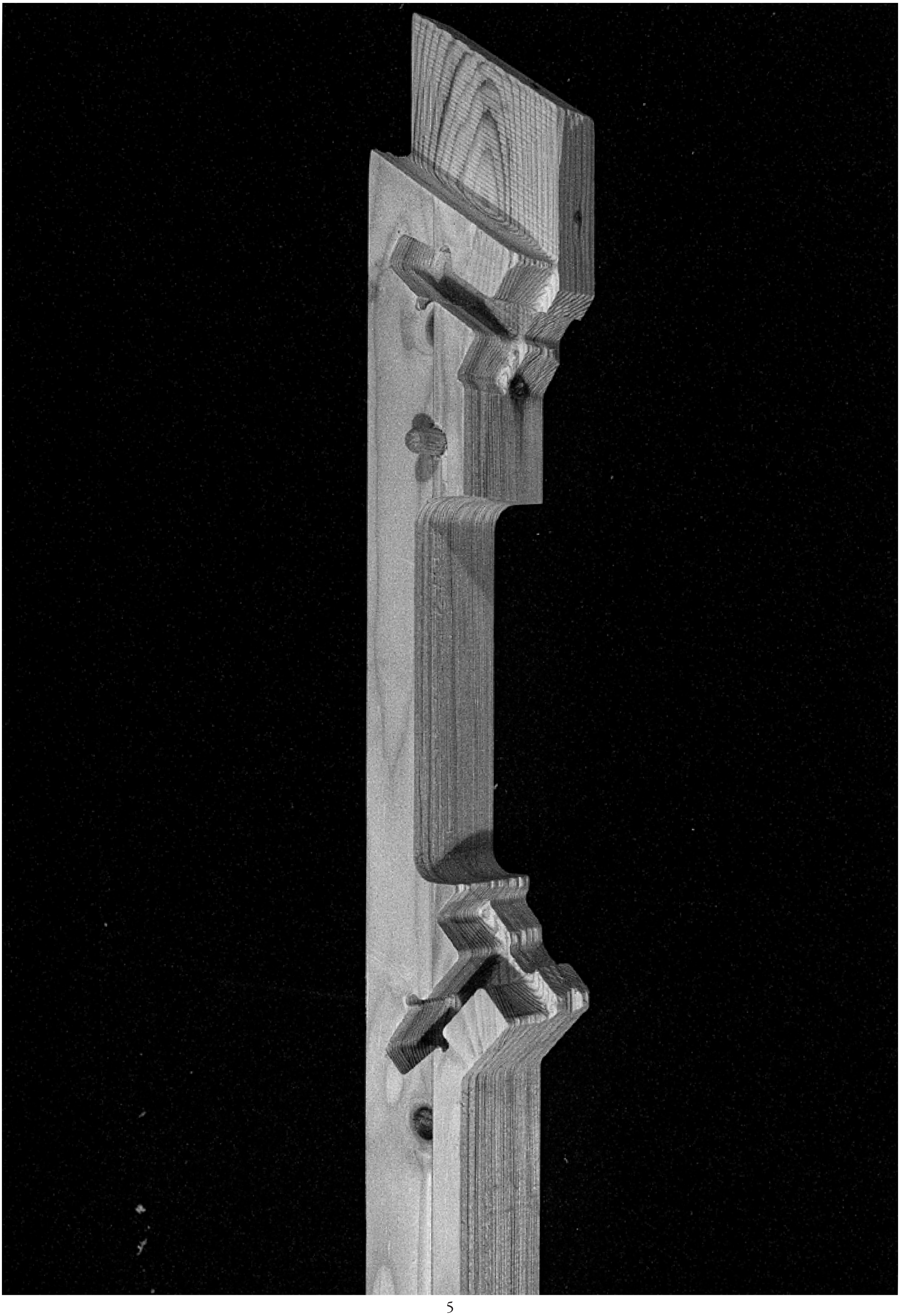
I. Abstract

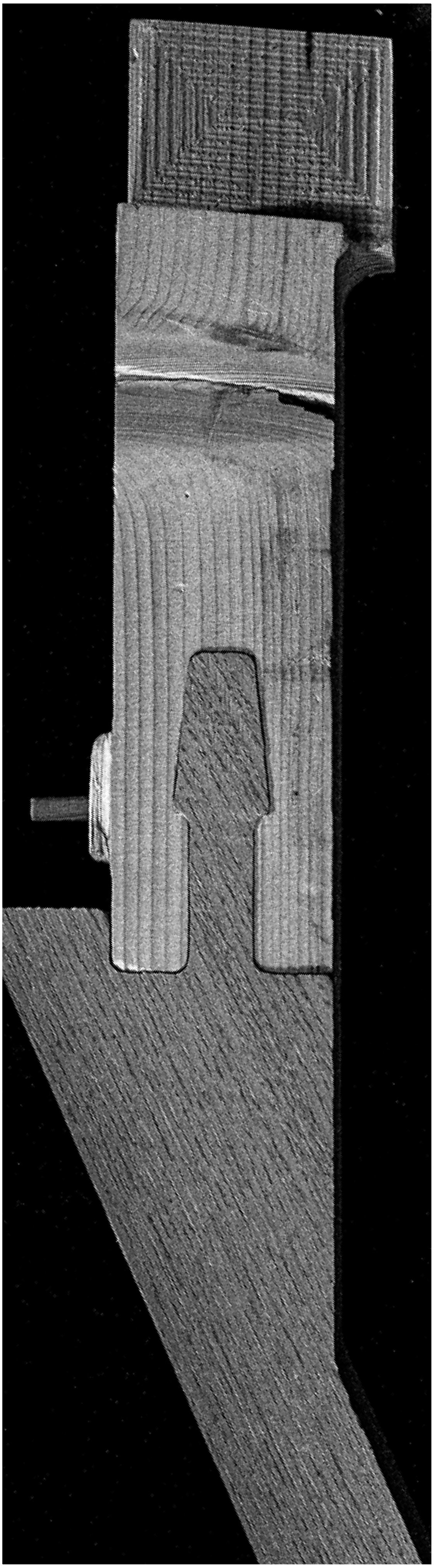
The research described in this dissertation explores a novel computational design method for the multiple reconfiguration of timber structures to extend its material life cycle. The construction sector produces 37% share of global CO_2 emissions. With the growing concern for the impact the built industry has on the environment, we need to re-evaluate our architectural practices by looking at the life cycles of our materials and how they can be reused. Timber offers the possibility to reduce the sector's carbon footprint as it is a renewable resource. Modern timber construction has already been highly integrated with automation and prefabrication (Construction 4.0) which could potentially increase the viability of timber disassembly. The benefits of using timber joints without nails allow the structure to be assembled and disassembled in a different site, context, and time. Traditional joints, however, pose two main challenges for automation of assembly. Firstly, traditional joints must be precise for it to function and fit well. Secondly, the aforementioned tightly fit joints require large frictional forces to be overcome during insertion. I will investigate how computation can prolong the life cycle of timber structures by designing for multiple stages of reconfiguration. This research project would also address the current limitations of designing for disassembly. With the utilisation of computation it would expand the potential of timber assemblies and speed up its adoption in the construction industry. The proposed process targets factory based prefabrication and robotic assembly of bespoke timber elements with modular joints. The key research objectives are: (1) explore the use of computer vision, CNC and automation to track, evaluate and machine timber elements to prolong its material life cycle; (2) explore timber joints that are adapted to automated fabrication, reconfigurable and multi-functional; (3) design a work flow that incorporates timber elements that can be reused in multiple cycles of construction.

Keywords: disassembly – timber joints - prefabrication - life cycle



II. Content





1. Background

The construction sector is recognised as one of the main culprits of CO_2 emissions in 2020, with a 37% share of the global emission. This mainly comes from the manufacturing of the building's construction material such as steel and concrete (UNEP 2021). The practice of building permanent structures that would last forever but only to tear them down when it no longer meets the demands of society is a huge drain on our natural resources.

How can we challenge the existing paradigm of a building's life cycle?

Design for Disassembly (DfD) responds to the growing weight of embodied energy in the materials and the sequential renovation cycles over the building's lifetime (Crowther 2009). DfD takes into account the possible technical barriers to successfully recover and reuse materials and components from existing buildings. Current construction practices view assembly of material as a linear process which severely limits the end-of-life options of a building. A more cyclic view of the built environment needs to be considered during the design stages. This thesis will explore these cyclic processes of timber structures at the scale of materials, components, and structure.

What are the challenges of disassembling timber structures?

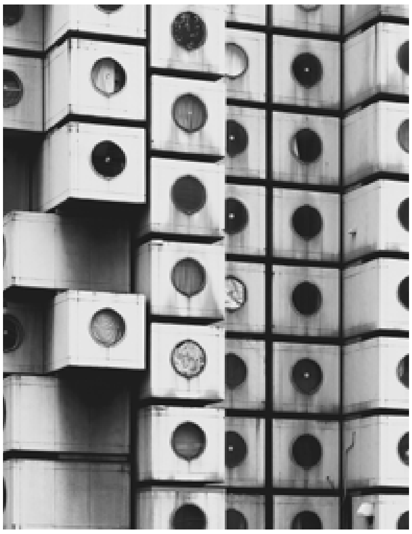
Wood is an anisotropic material that shrinks and expands non-uniformly due to changes in moisture content, and these changes need to be accounted for during the design (Rogeau et al., 2020). Any misalignment could lead to improper connection and separation.

How can digitalisation and automation aid in these cyclical processes?

As the construction industries move towards digitalisation and automation (Construction 4.0), automation could potentially increase productivity in construction (Sawhney et al., 2020). Digitalisation offer opportunities to enable DfD through adaptive work flows and managing complexities.

2. Architectural intention

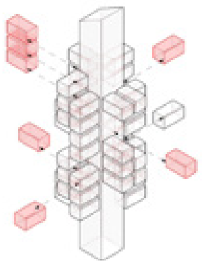
Disassembly in architecture

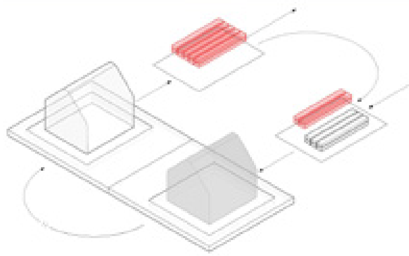


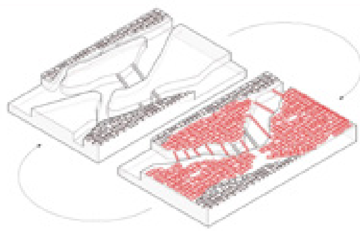
1972 - Nakagin Capsule Tower

4BCE - Ise Grand Shrine

Kumbh Mela in Allahabadhabad







Disassemblable architecture has been designed in many places around the world. In Japan, the Nakagin capsule tower built in 1972 utilises modules that can be disassembled from a central core, and the Ise Grand shrine goes through a process of renewal every 20 years, moving between neighbouring sites. This process retains some of the usable timber elements between iterations. In India, Kumbh Mela is a festival that happens every 4 years when the river water level recedes far enough for levelling and foundations to be constructed, a disassemblable city is assembled. At the end of the festival the city is disassembled and the river floods again. These examples of disassembly strategies at different scales showcase the potential cyclical nature of architecture.

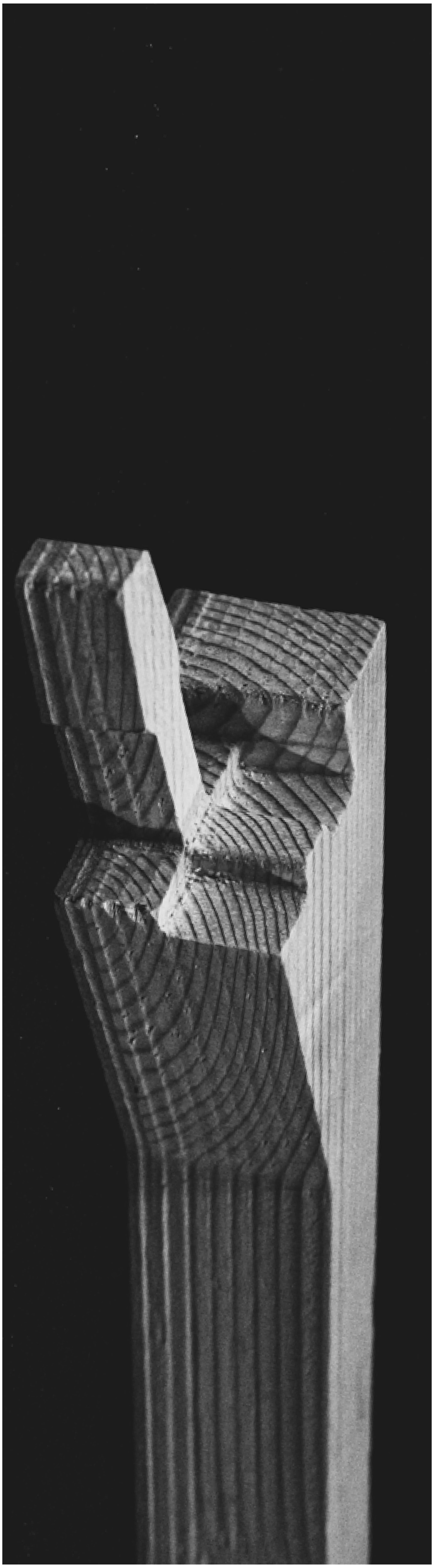
Some key concepts of DfD :

1. Use mechanical connections rather than chemical ones

2. Use modular design

3. Use construction technologies that are compatible with standard building practice and common tools

4. Provide realistic tolerances to allow for manoeuvring during disassembly



3. Timber

Timber in architecture provides a good starting place for designing for disassembly.
Firstly, much of timber architecture revolves around modular elements and traditional timber joints that are made for disassembly already exist. This enables a faster adoption of DfD.
Secondly, timber is a renewable resource. When lumber is harvested from the forest, carbon is sequestrated in the wood. This effectively means that timber buildings are carbon sinks (Churkina et al., 2020).
Wood as a grown material has properties that vary greatly across different growth conditions, species and the internal structure within a tree (Hoadley, 2000). Wood is an anisotropic material that shrinks and expands non-uniformly due to changes in moisture content, and these changes need to be accounted for during the design process(Rogeau et al., 2020). In most cases, joints are made with tolerances. However special care needs to be taken when multiple joints need to come together simultaneously as a slight misalignment would prevent the proper insertion (Apolinarska et al., 2021).

How can we account for dimensional shifting in wood within the design process when producing timber joints that work in different environmental conditions?

3.1. Timber construction

2008 - Centre of Pompidou Metz

2016 - La Seine Musicale

2019 - Swatch Headquarters

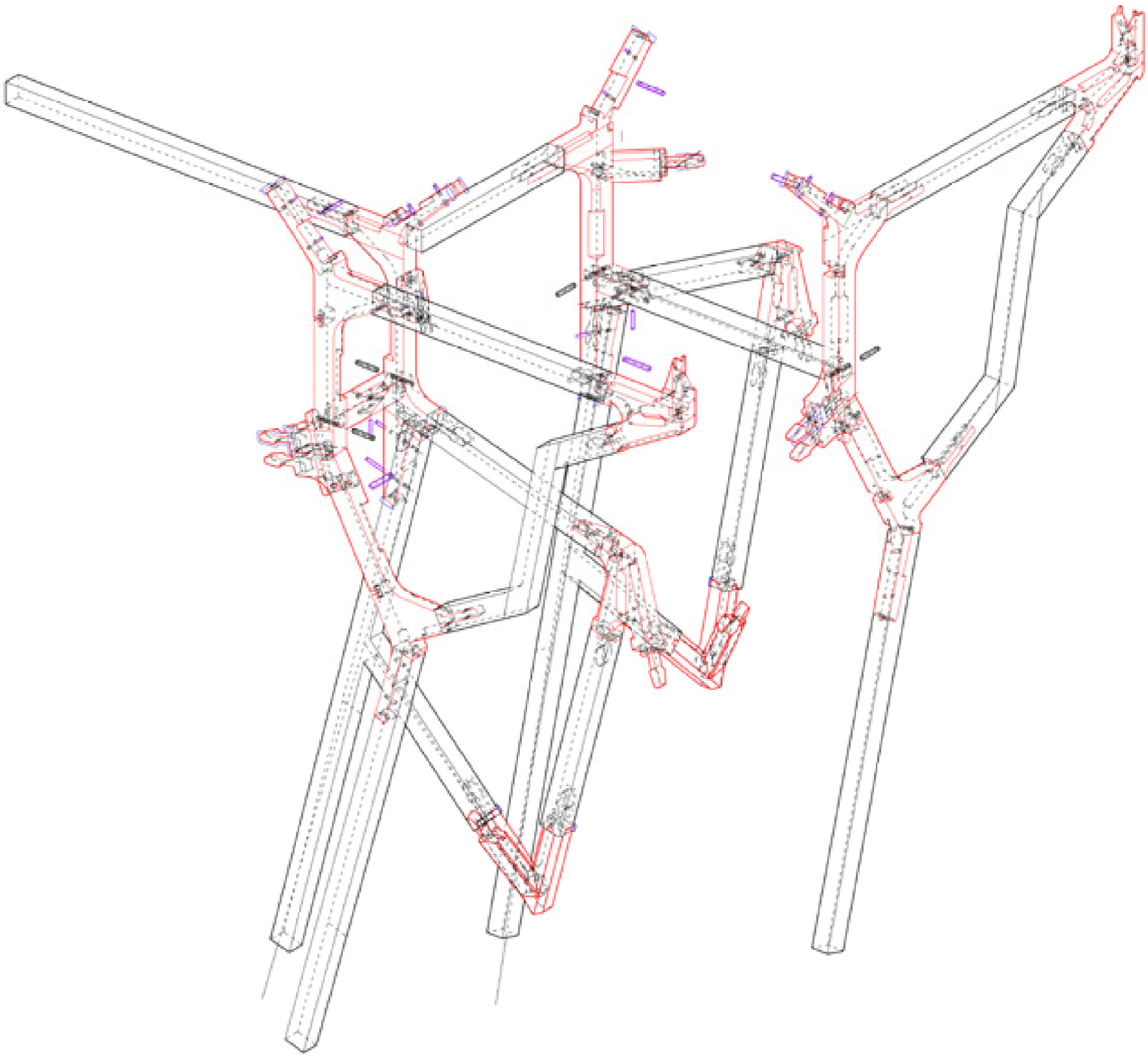
Timber construction and technology has been improving over the years. At a building scale, from Pompidou Metz to La Seine Musicale to Swatch Headquarters, timber elements have increased in complexity driven by prefabrication to allow for ease of assembly on site by humans.
On a parallel track at a smaller scale at the DFAB House by ETH, developments have been made to adapt robotic arms for assembly of standard timber elements. Similarly, modules are prefabricated and assembled on-site.

This research project explores the area between these fields to find a solution that would enable DfD to be adapted for the timber construction industry by involving intelligent design of timber elements for disassembly and automation to handle the ever increasing complexity and demand of timber construction.

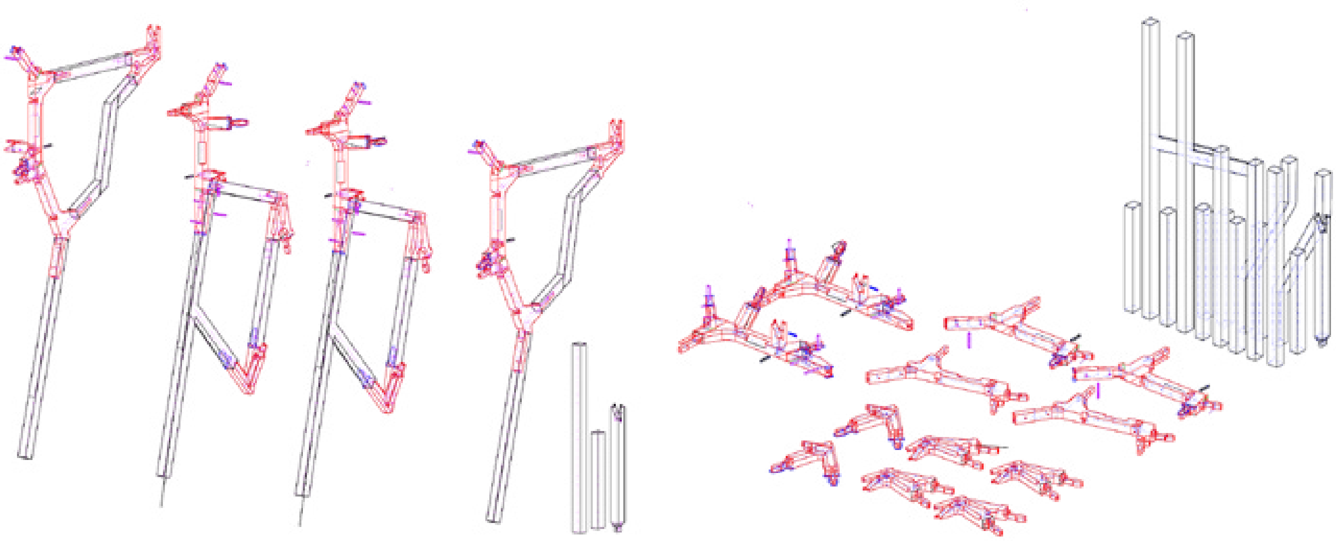
Intelligent timber elements for disassembly
+
Automation to increase productivity at a larger scale

2019 - ETH DFAB House

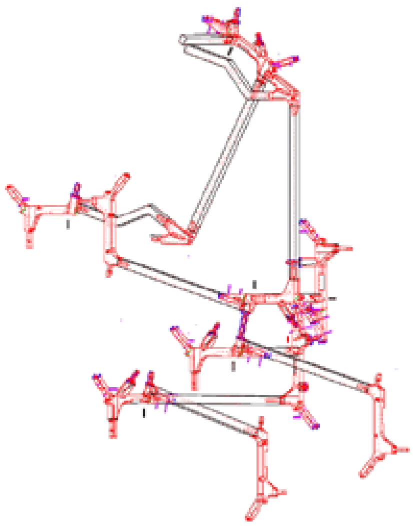
4. Architectural vision



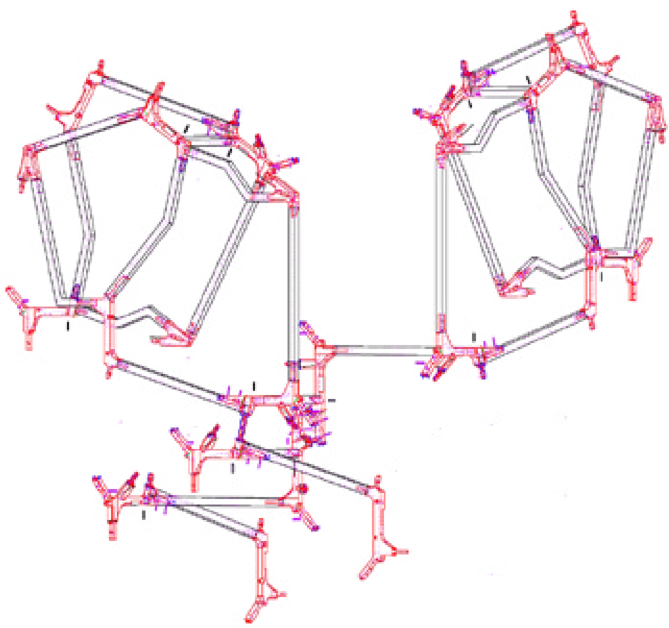
The research focuses on the modularity of nodal connections to produce highly adaptable timber framed structures. It delves into how automation and digitalisation enables the ideas of DfD. This research project will explore 3 scenarios of disassembly: (1) deconstruction, (2) reconfiguration and (3) addition. Deconstruction explores how a structure is disassembled. Reconfiguration investigates the new functions and spaces with existing elements. Addition studies how new elements can be added to existing structures. This project will investigate the intersections of these scenarios and interactions with the structure's inhabitants during these processes.



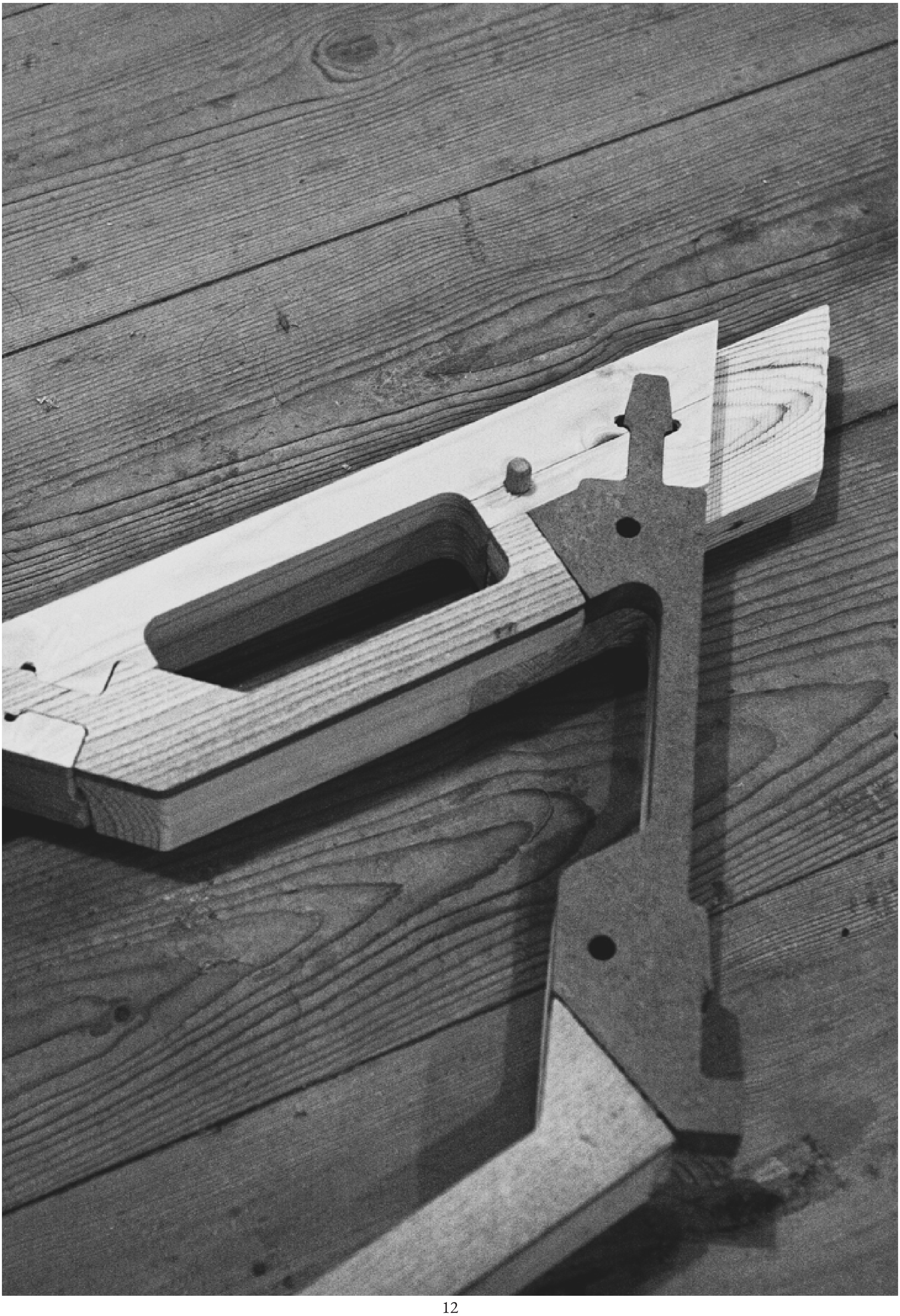
(1) Deconstruction



(2) Reconfiguration



(3) Addition



5. Research question

How can adaptive digital processes prolong the life cycle of timber structures through designing for multiple stages of reconfiguration?

6. Methodology

How can [adaptive digital processes] [prolong the life cycle] of timber structures through designing for [multiple stages of reconfiguration]?

1. Adaptive digital processes

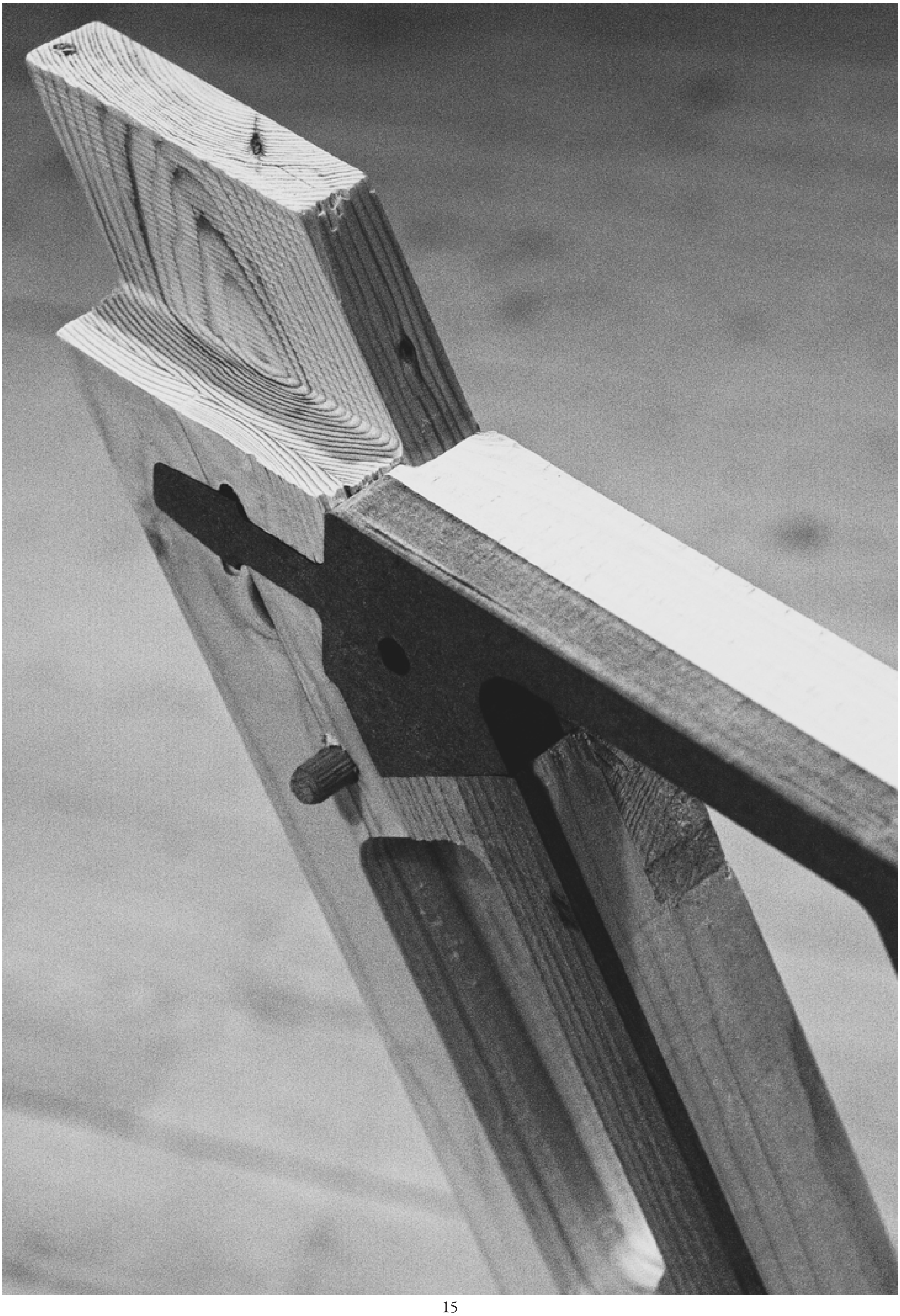
To enable the upscaling and adoption of designing for disassembly, this research project will explore the use of computer vision, CNC and automation to track, evaluate, and machine timber elements.

3. Reconfigurable timber joints

Reconfiguration of timber structures requires joints that can be disassembled. Drawing from the wealth of knowledge on existing timber joints, this research project explores timber joints that are adapted for automated fabrication, reconfiguration, and multi-functionalism.

2. Multi-phase elements

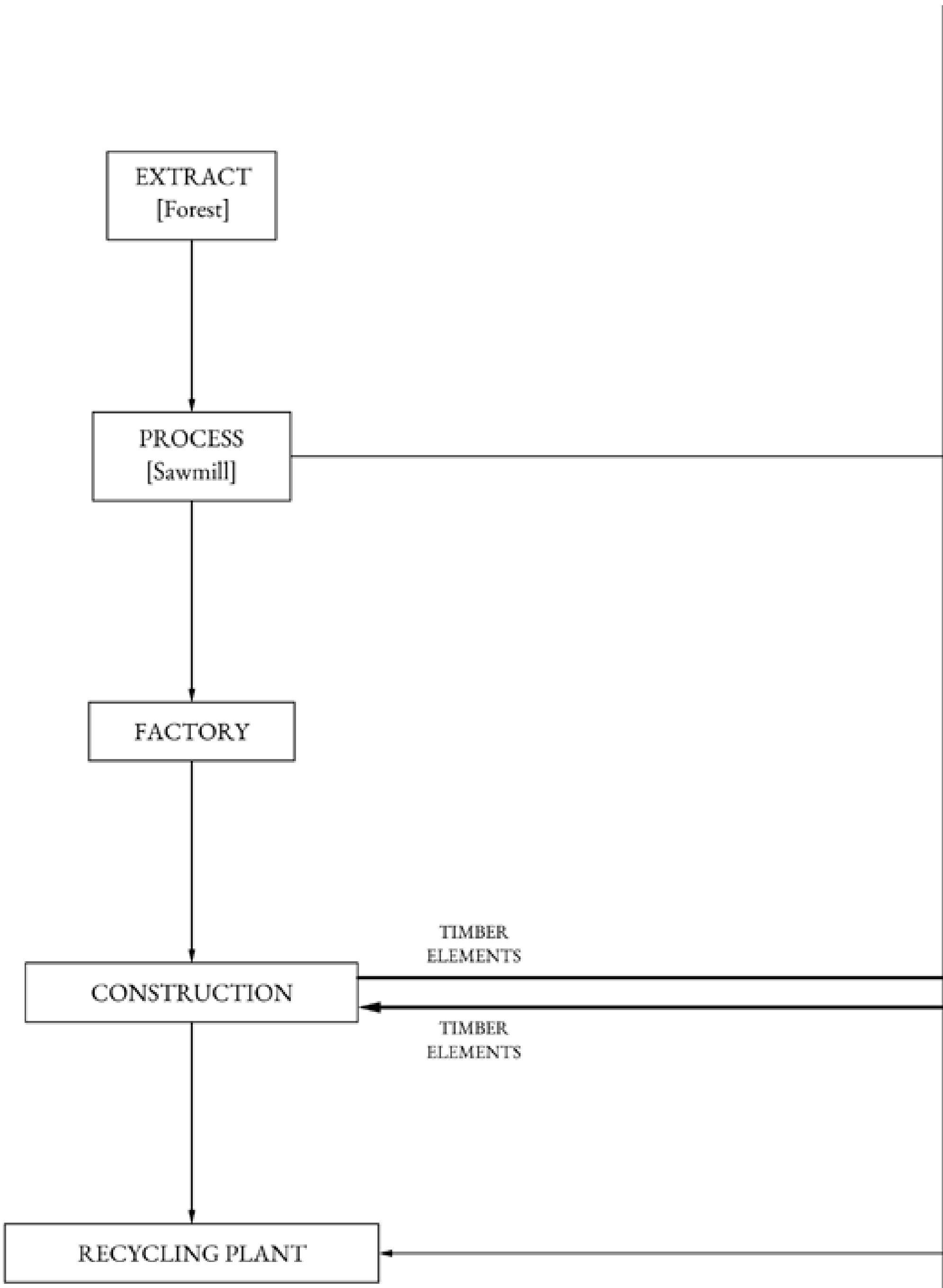
To extend the typical life cycle of timber structures, this research project will explore a design work flow that incorporates timber elements that can be reused in multiple cycles of construction and that allows elements to adapt to its new function each cycle before reaching its end of life due to degradation.

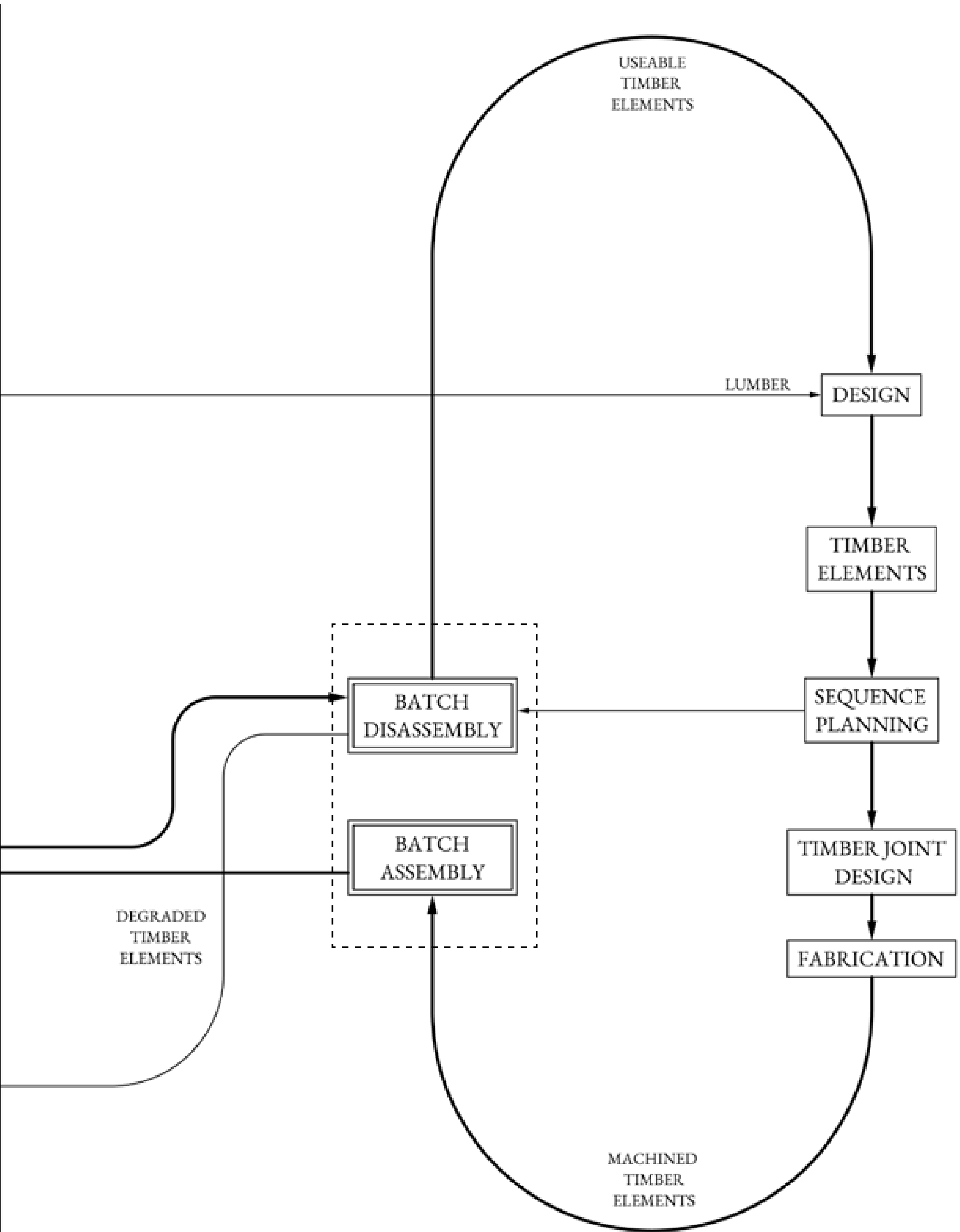


7. Research Scope

The scope of the research focuses on the process from design to construction and the subsequent deconstruction. It looks into how elements can be reused and reconfigured in different contexts, taking advantage of sensors during the production, assembly, and disassembly phases.

The methods explored in this research positions itself around the idea of prefabrication. A factory-based production allows for a more controlled setting to regulate the reuse of existing materials into new products. Elements that are not recycled from other sources can be carefully selected to ensure that they are recyclable, making their end of life a new life (Smith, R. E. ,2010).

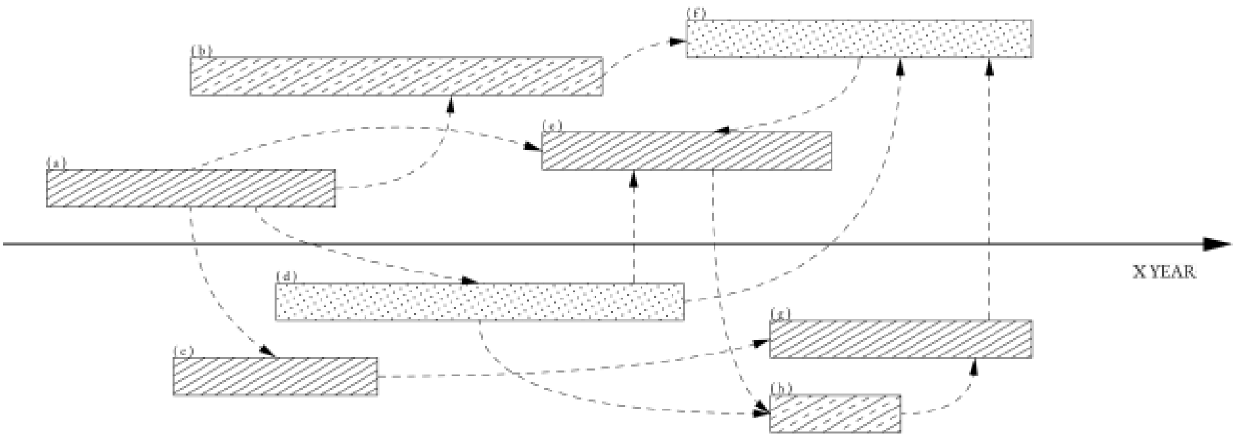




Left: A flow chart showing a conventional life cycle of the a raw material from extraction to a recycling plant or a landfill.
Right: Architectural intervention that enables materials to stay within the system through multiple layers of reuse before finally being removed when it is no longer viable.

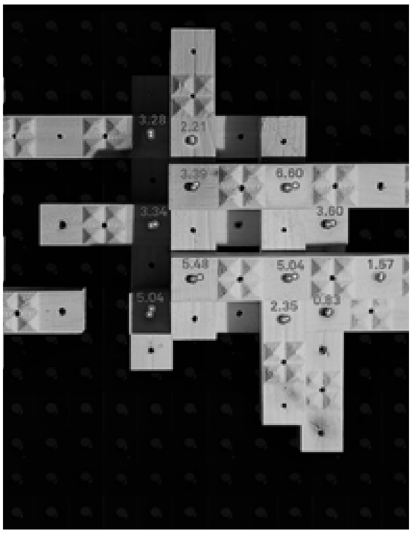
8 Automation and digitalisation

WHY AUTOMATION?

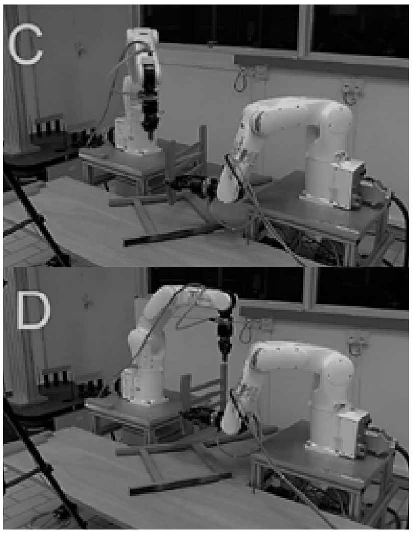


One hurdle for the reuse of timber elements is the complexity of sharing prefab elements between buildings. The diagram illustrates the complexity of buildings being assembled and disassembled over the same period of time (Smith, R. E. ,2010). Automation through tracking larger amount of parts could provide a possible solution to organise these elements and allocate them appropriately based on their functions.
Automation also allows for increased productivity when assembling and disassembling large numbers of intricate timber elements into modules that require high precision.

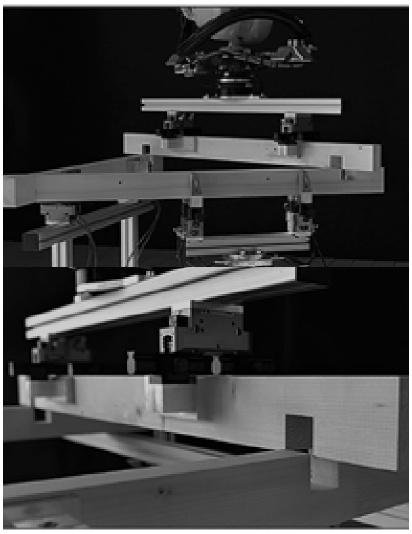
8.1. Sensors



2021 - Cyber-Physical Robotic Process for Re-Configurable Wood Architecture (Anja Kunic)



2018- Can robots assemble an IKEA chair? (Suárez-Ruiz)



2021 - Robotic assembly of timber joints using reinforcement learning (Apolinarska)

Examples above show case the use of computer vision and force gauges as sensors to aid in the assembly processes. This research project will focus on the use of computer vision to capitalise on the unique pattern of wood grains and geometry of timber elements to track and detect any deviation from the digital model.

During the assembly process a significant discrepancy between virtual models and build site could occur. This could be due to differences in joint tolerances from machining or expansion/shrinkage from changes in moisture and self-weight deformations (Rogeau et al., 2020). These gaps and inaccuracies in the joint compounds quickly in larger structures which affect assembly down the line or even cause structural failure.

(1) Traditional joints must be precise for it to function well and have a fixed assembly direction. Any deviation between the physical and digital model would prevent proper insertion.

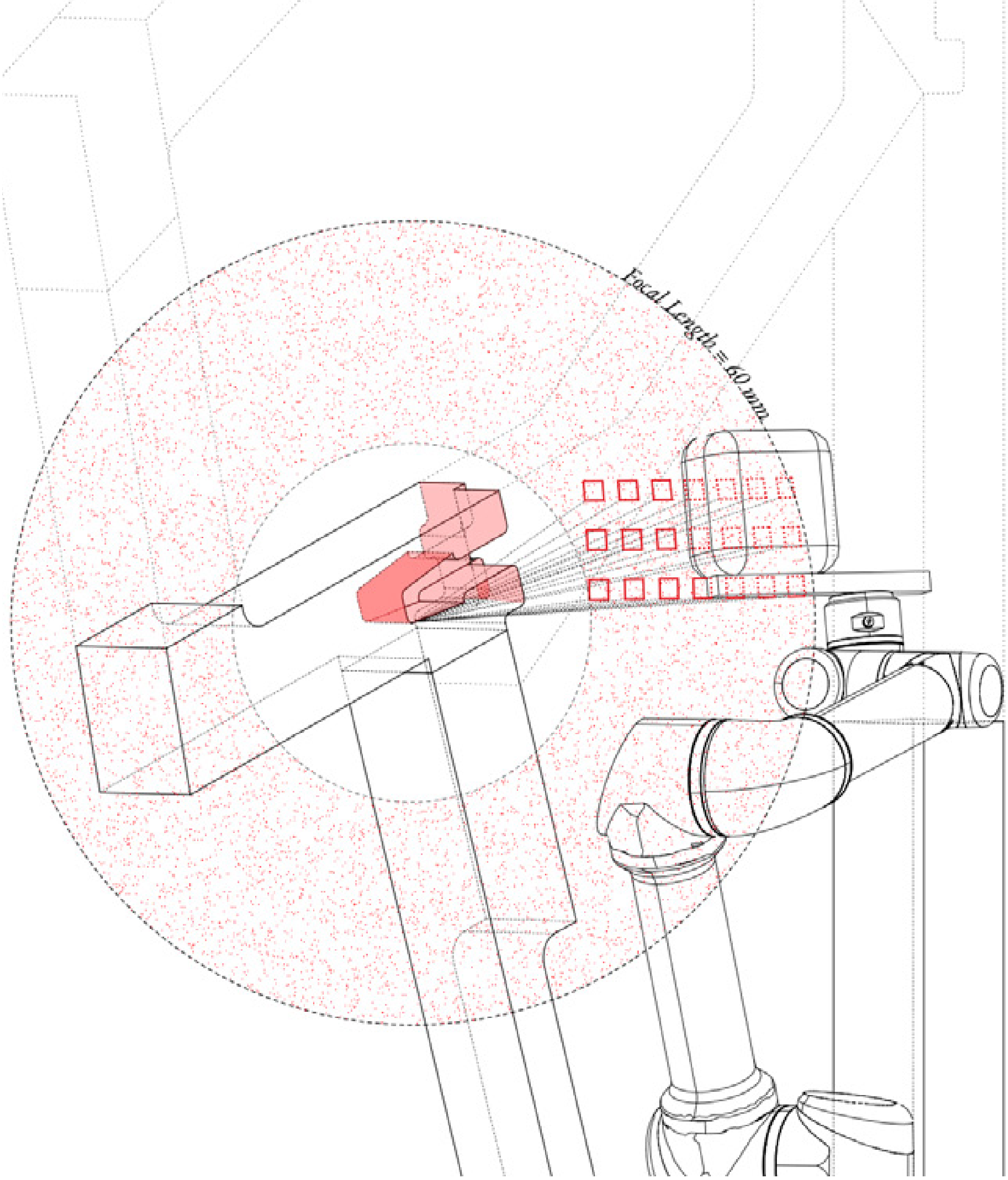
(2) Traditional joints fit tightly and thus large frictional forces need to be overcome during insertion.

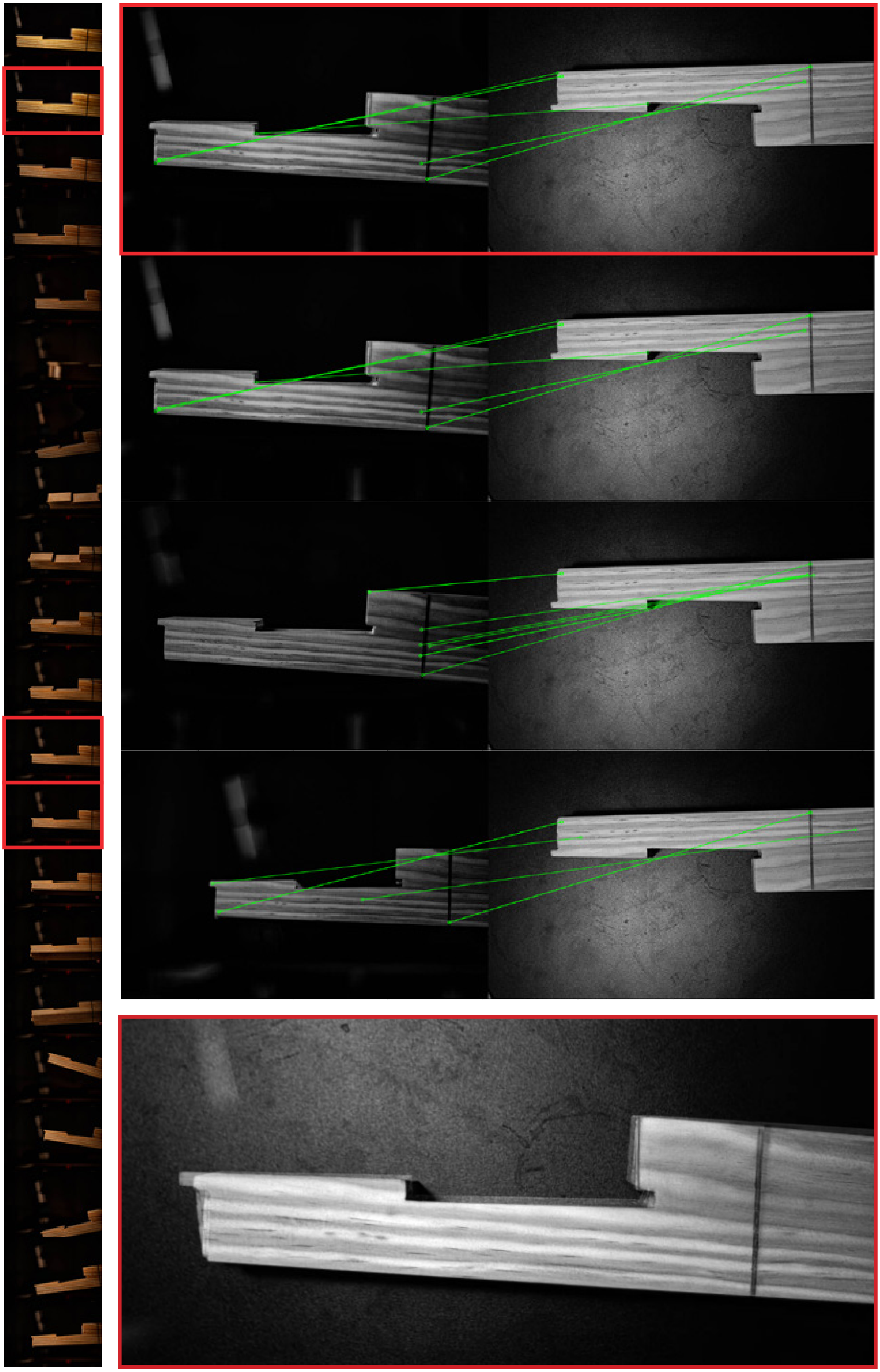
How can sensors be deployed to detect these deviations and where should they be used during the process?

8.1. Sensors

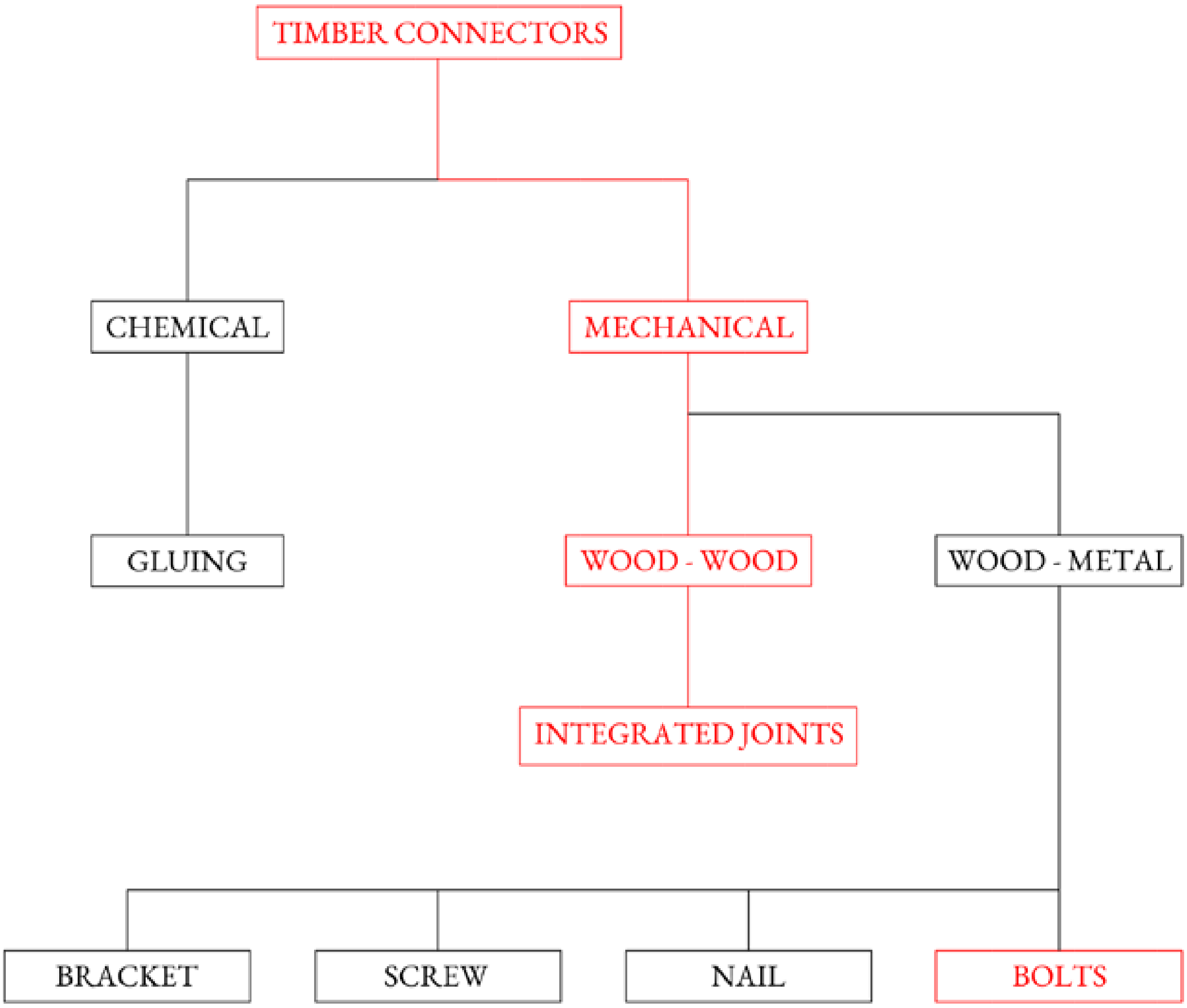
Experiments

An experiment done explores a method to aligning the physical model and digital model in space. This method takes photos of the joint from multiple angles and uses Open CV to determine the orientation of the object with world coordinates. This method takes advantage of the unique grain pattern of wood and geometry to identify and measure dimensional changes.





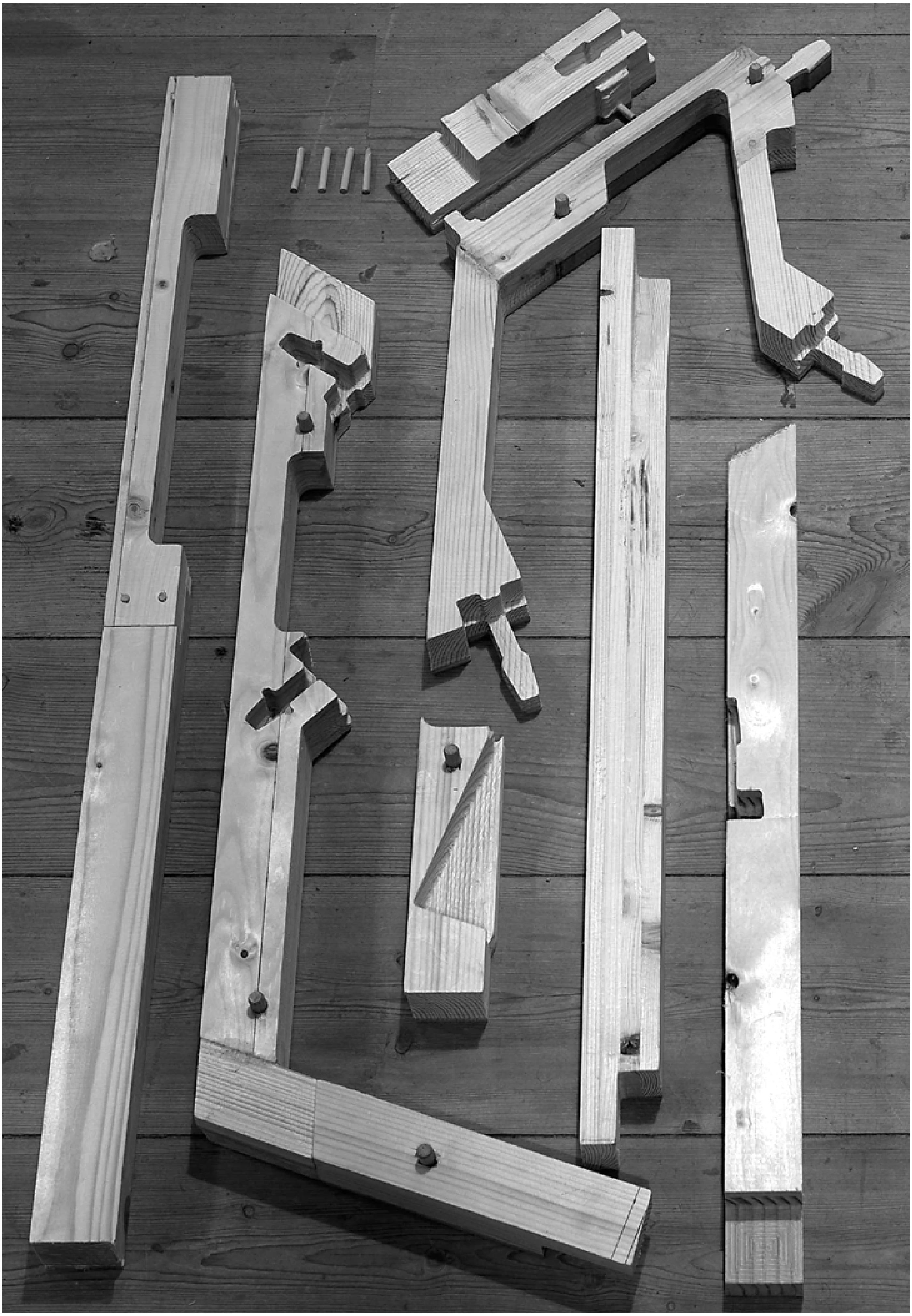
9. Timber connectors



There exist many types of timber connections; however, not all are suitable for disassembly. Some of the common ones are gluing, nailing, screwing, and timber joints (Eversmann et al., 2017). This research project will focus on wood-wood connections of timber joints. This method of connection not only enables disassembly but also reduces the embodied energy of construction by not using metal connections.

Modularity of timber construction

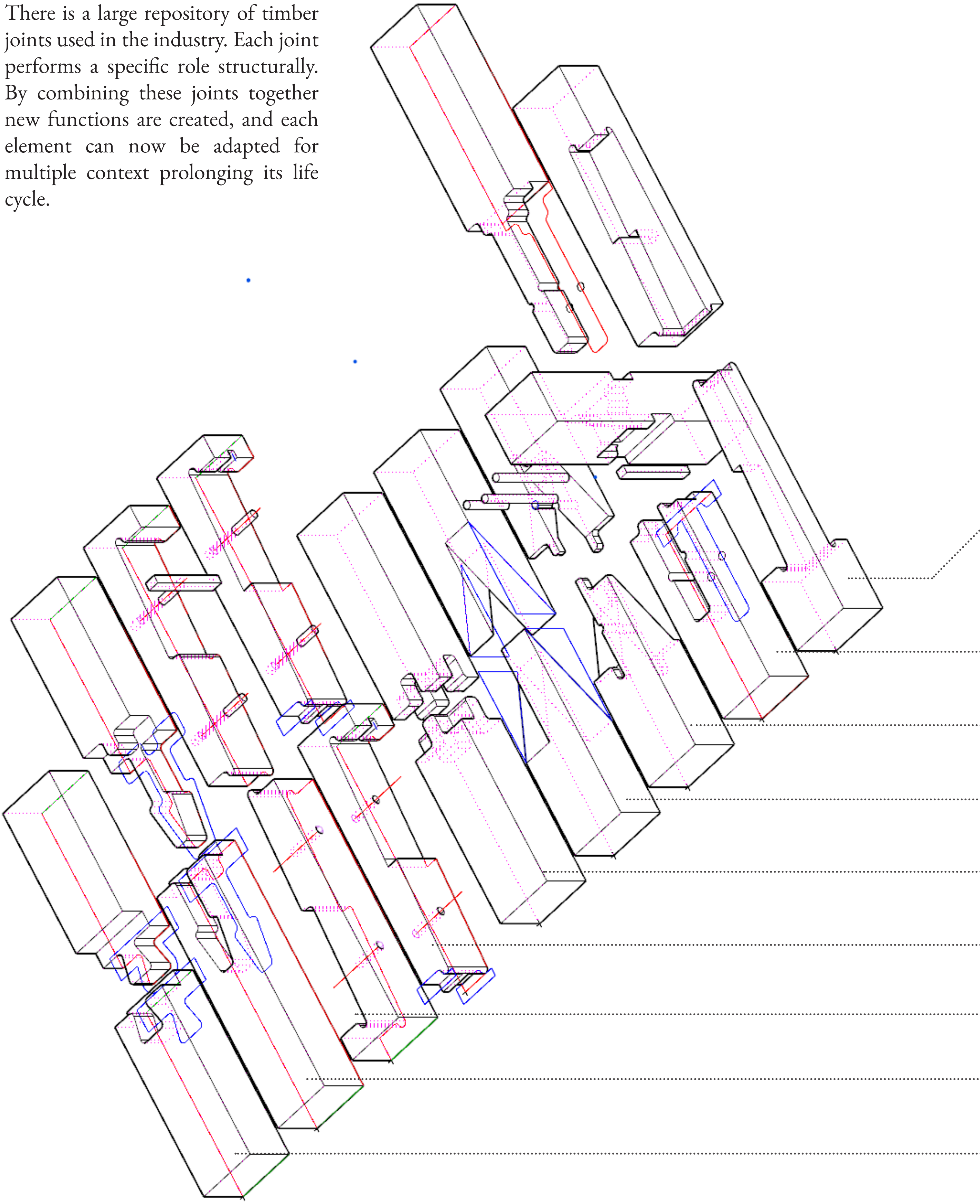
Images above shows some examples of common wood-metal connections. Each of these jointing techniques performs a different role structurally. It can be argued that timber construction can be seen as modular in most cases. The bespoke nature of timber architecture comes from the creative utilization of such joints.

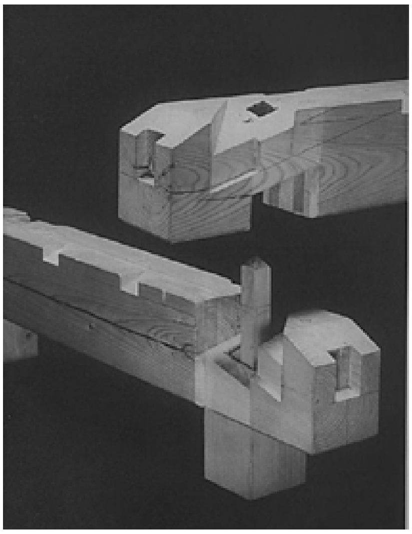


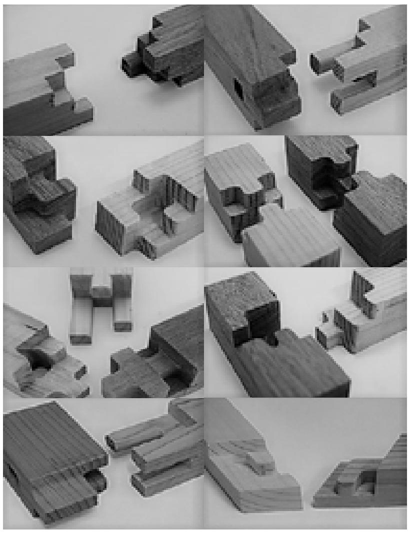
9.1. Traditional timber joints

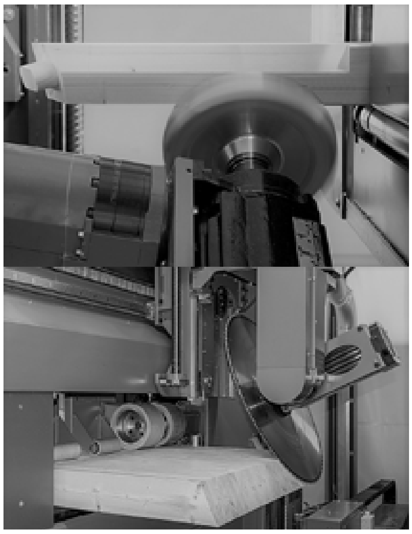
Modularity vs Bespoke

There is a large repository of timber joints used in the industry. Each joint performs a specific role structurally. By combining these joints together new functions are created, and each element can now be adapted for multiple context prolonging its life cycle.




Traditional Japanese timber joints


Tsugite: Interactive Design and Fabrication of Wood Joints


Hundegger's ROBOT-Drive Joinery Machine

With the ease of access to digital tools, there are now new opportunities to look at how labour intensive traditional timber joints/elements can be produced with new technology. Traditional timber joining methods have been adapted for CNC-fabrication in Tsugite (Kanasaki & Tanaka, n.d.). Hundegger's robot used in the industry can further increase the productivity of these joints with its ability to do multiple machining methods in a single pass.

Housed rabbeted oblique scarf splice | Kakushi kanawa
Tension
Uses: Decorative splice for finishing

Pole tenon | saotsugi
Tension
Uses: Connect two beams on opposite faces of a column

Double-faced halved rabbeted oblique scarf splice with key | Isuka tsugi
Compression
Uses: Decorative splice for finishing

Double-faced halved rabbeted oblique scarf splice | Isuka tsugi
Compression
Uses: Decorative splice for finishing

Cross-shaped tenon and mortise splice | Jujui mechiire
Torsion| Compression
Uses: Combined with splicing plates bolted throughout

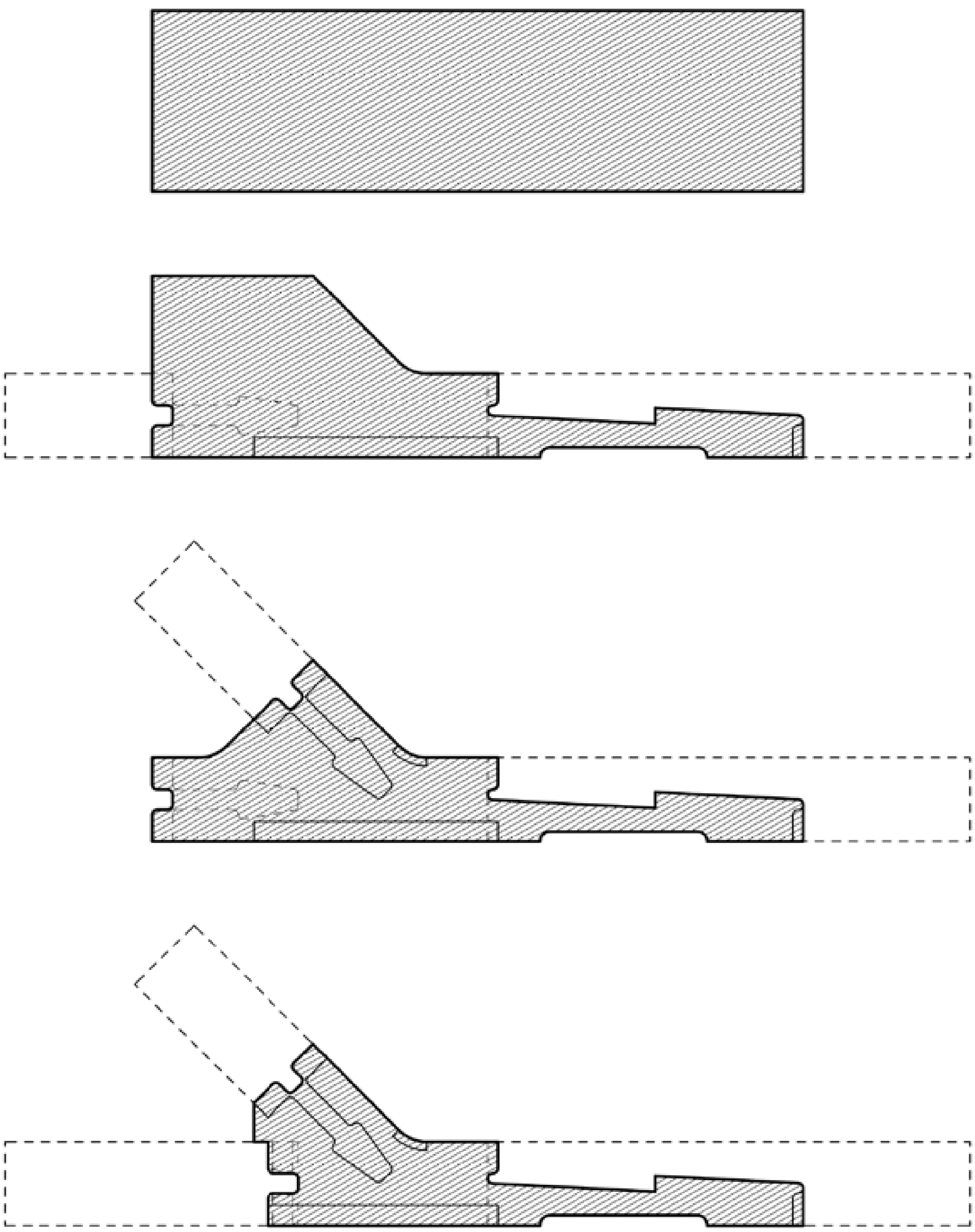
Blind stubbed, housed rabbeted oblique scarf splice | Shiribasami tsugi
Tension
Uses: Join lumber sections, beams

Rabbeted oblique scarf splice | Okkake daisen tsugi
Tension
Uses: Join lumber sections, beams

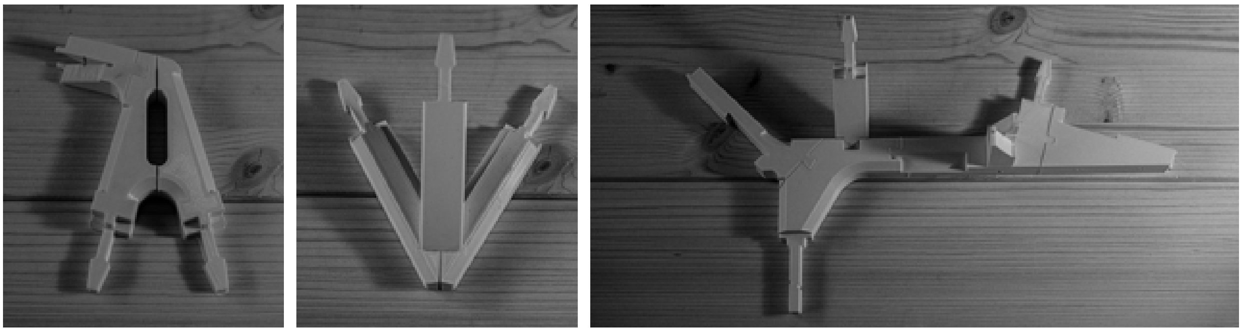
Stepped goose neck splice | Koshikake kamatsugi
Tension
Uses: Ground sills, join lumber sections

Stepped dovetailed splice | Koshikake aritsugi
Tension
Uses: Ground sills

9.2. Re-machining



With the scanning methods mentioned earlier, it is possible to machine these joints again to fit new requirements. By modifying and controlling its degradation the life cycle of each element is prolonged.



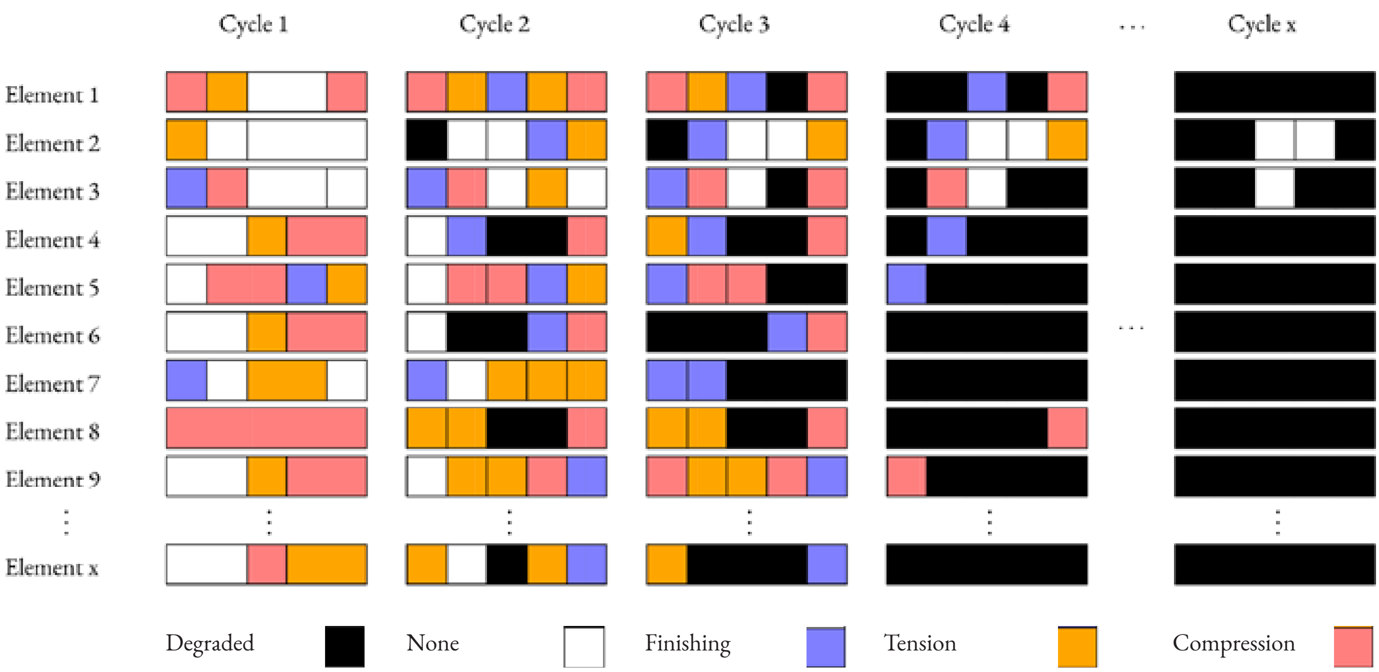
Traditional timber joints for disassembly

Each joint interface can be seen as a modular piece. By designing these joints, interconnected pieces can be simple while still maintaining the possibility of forming highly adaptable structures. After disassembly, these joints can be reconfigured for a different context. Furthermore, by combining multiple of these joints together, the utility of each element increases beyond its current function.

10. Multiple stages of reconfiguration

In order to evaluate the effectiveness of the methods mentioned previously, this research project will design a timber structure that would have multiple life cycles. In each cycle, the timber element would adapt to its new function and demand (below). By building a physical prototype, tactile feedback of material fatigue on the joints can provide a better understanding of DfD for timber structures.

The prototype will also simulate conditions of prefabrication in a factory setting for the reconfiguration of timber elements from and into sub-assemblies. These modules would then be assembled on site with less complex joints. By simulating these conditions, close approximations of potential problems can be studied.

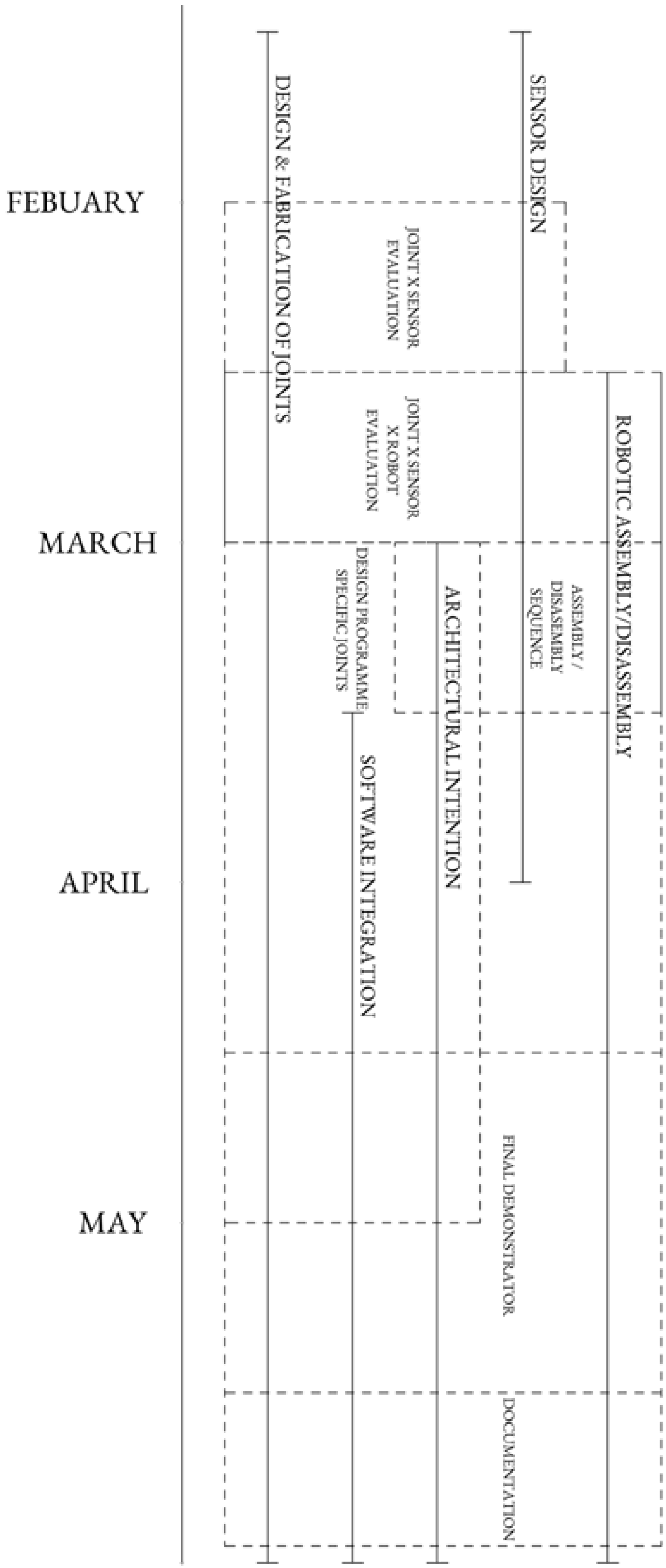


Above: Mapping of joint roles changing over multiple cycles of reconfiguration and re-machining with new functions.

11. Conclusion

This thesis will explore these cyclic processes of timber structures at the scale of materials, components and structures. It establishes a potential solution for extending the life cycle of buildings by giving timber elements multiple functions over time. As the construction industries move towards digitalisation and automation, this research project also showcases how computation can be utilised to enable designing for disassembly in the industry.

III. Timeline



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