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A DIGITAL FRAMEWORK FOR ROBOTIC PROCESSING OF RECLAIMED TIMBER

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ABSTRACT: Reusing timber elements in construction is a promising path toward extending their lifecycle and easing the pressure on the forest resource. The direct use of elements from disassembled timber buildings in new construction offers the path of least energy expenditure. However, it presents challenges due to material degradation, variation in form, and existing cutouts for joints or other features. This research prototypes a digital framework that leverages 3d laser scanning and robotic fabrication to detect geometric variations, cutouts, and material inconsistencies in reclaimed timber elements, and integrates them into the design process of new timber buildings through a digital mapping of resource-to-model. The resultant framework demonstrates an adaptive and surgical approach to processing reclaimed timber elements, mitigating the challenges of their reuse and increasing the number of components that can be included in new construction.

KEYWORDS: Reclaimed Timber, Laser Scanning, BIM, Robotic Fabrication, Timber Joinery

1 – INTRODUCTION

1.1 REUSE OF TIMBER STRUCTURES AND MATERIAL INCONSISTENCY

Timber construction has been identified as a key pathway towards reducing CO_2 emissions from the construction sector. A unique aspect of timber as a construction material is its cascading use, which allows coproducts from primary processing to be used for secondary and tertiary products [1]. The shift towards a circular economy in construction has prioritized reclaiming and reusing timber elements, thus slowing their downcycling through the cascade, and retaining as much of their value for as long as possible [2]. In this way, the high-value usage of wood as a construction material is primarily retained instead of being lost to downstream processes. For this reason, reuse has the highest priority among all cascading scenarios, as it maximizes the total material value. [3]

Structural components comprise most of a building's weight and volume, making the greatest use of wood's mechanical properties, and are therefore the primary focus for reuse. However, they are the most challenging to replace, due to their function as the primary load-bearing framework, upon which all other building components depend. Various assessment methods are available to detect mechanical and biological damage on structural timber components, and several studies have already investigated the influence and effects of aging on their mechanical properties [4]. The Materials Testing Facility in Vancouver, Canada by Busby + Associates Architects and Fast + Epp is an example of locally reusing timber members for the same purpose and structural typology. It consists of two external trusses taken from a demolished warehouse [5]. Similarly, in the construction and subsequent deconstruction of the KEVN pavilion in Eindhoven, Netherlands, by Superuse Studios, the trusses were processed so the purlins could be made from an old chicken shed [6]. The Swan Kindergarten by Lendager in Gladsaxe, Denmark reused wooden trusses from the old school on-site, in the new orangery area and the entrance, reinforced with steel brackets. They have developed and implemented the processes needed to map, recover, upcycle and reuse building materials directly on site. These cases show the potential for the reuse of timber structures.

Design for Deconstruction (DfD) is a design approach that makes taking products and assemblies apart easier so that their constituent elements can be reused or recycled [7]. Despite its potential to increase the reuse of timber elements, the number of components that can be reused

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after years and between different systems is limited. Most timber houses built in the last few decades have not been purposed for deconstruction and reuse, nor are most of the timber buildings built today that will be disassembled in the future. Moreover, there is a lack of quality and quantity of reclaimed materials, prohibitive building regulations, and design standards, making the reuse of timber more complicated [8]. While reusing wood means less virgin wood is needed, reclaimed timber presents challenges for new construction due to inconsistent properties, degradation, the effects of long-term combined mechanical action, and variable climate exposure. These may result in geometric deformations and other changes in shape. Traditional reclaimed timber elements often feature cutouts and notches for joints, which can limit their capacity for reuse since these are usually removed entirely in their reprocessing, thus shortening the usable length of the timber element, or they otherwise severely lower their effective stiffness due to the local reduction in cross-sectional area.

1.2 PREFABRICATION IN TIMBER CONSTRUCTION

Modern timber construction can be characterised by prefabrication and off-site construction approaches for large-scale and modular buildings. Offsite construction is an approach that seeks to minimize on-site construction through the extensive use of automation technology to, help minimize misalignments, and enable corrective action. In typical prefab panel construction, elements are assembled in factories and then the finished assemblies are installed on-site [9]. The work environment is therefore much more controlled, leading to higher quality, higher precision, and a reduction of rework [10]. Timber construction possesses a notable competitive edge over other types of prefabricated systems due to its lightweight nature and ease of workability [11]. Such an integration makes paradigms like mass customization possible, opening up opportunities for leaner and more flexible timber production environments. While such approaches are widely used for the construction of new buildings and the manufacturing of components from new and precisely dimensioned materials, the geometric variance and increased complexity of reused timber stock creates barriers for their deployment in reclaimed timber construction.

2 – BACKGROUND

This paper describes an individual thesis project completed in two semesters as part of the Computation in Architecture Masters programme at the Centre for IT and Architecture (CITA) at the Royal Danish Academy in Copenhagen, Denmark. The project takes as its starting point the challenges associated with reusing reclaimed timber beams from old timber buildings in a new construction, and proposes a digitally augmented design and production workflow for overcoming these barriers. To this end, it proposes three main points of intervention: the digitization and analysis of reclaimed timber beams to determine their shape, unique features, and existing joint cutouts; the strategic allocation of reclaimed timber elements from a digital material library to a building information model of a new construction, aligning their geometry and unique features with the newly designed beam geometries; and the consideration of tolerances and strategies for adapting timber joints to be more amenable to automated production and robotic assembly.

2.1 LASER SCANNING

Laser scanning has widely been used in an architectural context to digitally reconstruct individual construction elements or entire building environments. It enables the recovery of observed surfaces from point cloud datasets and the subsequent generation of boundary representation of the scanned surfaces [12]. These datasets can hold detailed information about material characteristics in the existing environment, including geometrical, physical, visual, and spatial information [13]. Such digital feedback from the physical environment can provide crucial information about the state of a task, the location of items or obstacles in the workspace, and potential discrepancies between a designed geometry and its actual physical form. This information can provide valuable inputs into the architectural design process, steering design decisions and further planning.

2.2 TIMBER INFORMATION MODELLING

The development of large construction projects typically employs the Building Information Modelling (BIM) approach. This method aims to collect and relate all information relevant to a project throughout its development and lifecycle in a shared environment between all stakeholders. The building model is iteratively augmented from various inputs – design, engineering, costing, and so on – and this data is exchanged and accessed as necessary by the involved parties, thus connecting the various stages of development and production with a common informational platform. In the context of reclaimed timber, this type of digital platform, therefore, creates the opportunity to connect the building model with specific

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information on reclaimed timber stock that might be used in its construction.

In the new timber museum in Reutlingen, by wulf architekten, geometry and component data were extracted from a central model using Rhino.Inside and integrated into Revit. Revit plans provided quantification, cross-sectional assignments, and component placements, while knot references were managed in a central Excel file [14]. The combined data and digital model allowed communication between engineers and the timber construction company's final workshop planning. Other research focuses on the modeling of timber behavior and predicting its mechanical properties through the analysis of X-ray computed tomography (CT) scans of reclaimed barn timber. Properties such as stiffness are estimated through numerical models that incorporate material orientation derived from the density gradient of the scans, suggesting the possibility of new non-destructive scan-based timber grading methods [15]. The derived geometry and properties can therefore be further integrated into other digital processes and BIM models of new constructions.

2.3 TIMBER JOINERY FOR ROBOTIC ASSEMBLY

Since this project focuses on elements reclaimed from old timber buildings, the automated reprocessing of these elements must confront existing joinery details and other features borne from their roles in the previous construction. Joint details and cutouts are typically entirely removed from reclaimed elements in order to obtain elements with full cross-sectional areas, albeit shorter in length. However, these existing cutouts can potentially be reused if they are strategically placed in the new construction and reprocessed to fit their new purpose. If the approach of using integral joints in the new construction is to be retained, then specific considerations need to be made for adapting them to automated assembly strategies. Integral joints typically have tighter tolerances than face-to-face nailed or bolted connections. Surfaces must meet precisely to effectively transfer loads between elements and achieve enough rigidity in the structure.

The inconsistency of the reclaimed beam geometry further affects the accuracy of the insertion trajectory. Using a robot for joint insertion that requires predicting and interpreting the insertion forces and adjusting the trajectory makes the task even harder. Research in this area has looked at easing the rigidity of the connections and the ease of assembly for the robot by modifying key geometric features in through-tenon joints with chamfer and offset parameters [16]. By angling the contact faces of the joints, a higher tolerance is achieved at the outset of the joint insertion, gradually shrinking as the elements are brought together. Therefore, the possibility of creating joints that feasibly allow automatic assembly rests on the close management of variable tolerances throughout the insertion process.

3 – PROJECT DESCRIPTION

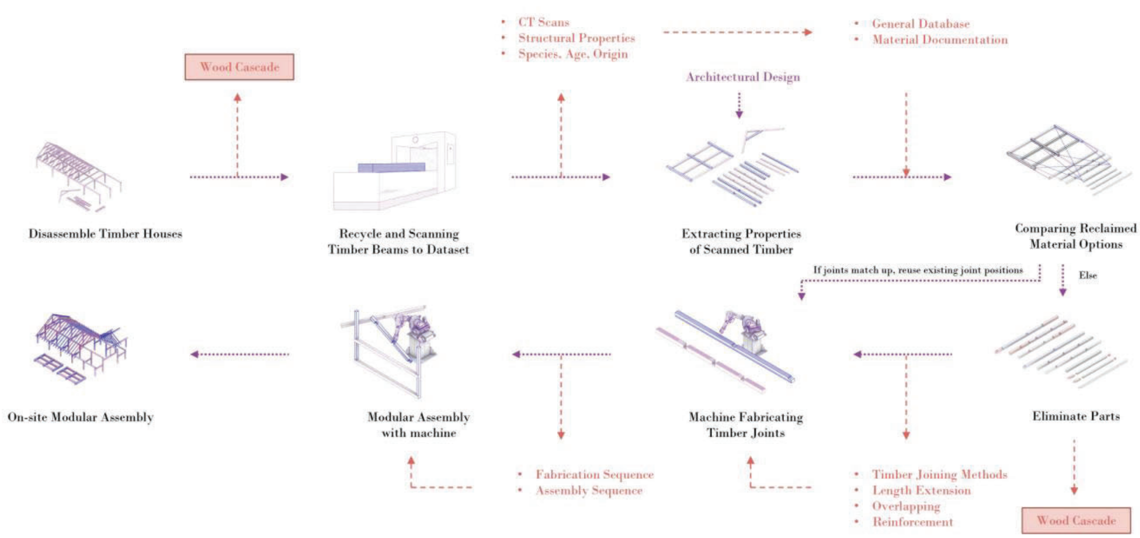

Figure 1. Digital information to prototyping framework

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The project proposes a digital framework for prefabricating reclaimed timber beams within a controlled environment into parts or modular units while retaining as much of their existing joint features as possible. The framework encompasses the detection of existing joints in reclaimed elements, the collection and management of their data into a database for later querying, their allocation in various configurations to a new design, and the evaluation of these configurations by comparing the amount of waste material produced (Fig. 1). The application of this framework is demonstrated by reusing a selection of reclaimed timber beams from a demolition site to design new timber trusses.

3.1 DIGITIZING RECLAIMED TIMBER

The first step in addressing material inconsistency and pre-existing cutouts in reclaimed barn beams is achieved through laser scanning the overall beam geometry. The scanned data is then analyzed to capture the element geometry and to identify existing joints and other geometric features, which are indexed and sorted. The sorted elements are saved in a material library as indexes and geometrical data to match scanned barn beams to a digital building model of a newly designed structure.

3.2 ALLOCATING MATERIAL

A digital framework is prototyped to track and map the features acquired from scanning to a digital model by comparing the size of the joint and beam, proposing alternative options for reusing reclaimed timber that minimizes material waste. The original joints tracked on the reclaimed beam can be reused and evaluated first, so less wood is being removed when producing a new joint. An algorithm is developed to compare the amount of waste wood used and cut off for a newly designed structure. An option with the best solution is chosen for robotic handling and re-machining of these beams into new building elements. This allows developed design solutions that adapt to these beams' unique characteristics and extend the use of the reclaimed timber beam.

3.3 REFABRICATING JOINTS

To demonstrate the use of digitized information during fabrication, a simple joint on a reclaimed timber beam is robotically fabricated. It uses a lap joint with chamfered edges that ease robotic insertion. The processed data from the laser scan and the sorting algorithm is crucial for later stages of robotic fabrication and assembly. These data includes the geometrical deformation of the beam, which affects the orientation of the joints; dimensions of the joining beams, which affect the joint size; depth of the joints, finding beams that are possible to mill on. The milling paths are auto generated from the digitally aligned model, pointing towards a scaling-up and potential for industrialization. Experiments focusing on joint geometries and assembly tolerances that are more amenable to robotic handling and production are conducted.

4 – EXPERIMENTAL SETUP

4.1 SCANNING RECLAIMED TIMBER BEAMS TO DATASET

In total, four beams were obtained from two sources: two from an old timber frame warehouse undergoing deconstruction and renovation, and two from a nearby recycled wood yard. Old beams and columns were being replaced with fresh timber. However, some beams were in good condition and were sent away for reuse. The reclaimed timber beams brought back from various sources displayed different properties, including dimensions, species, color, joints, cracks, dents, and rotten parts.

A primary scanning test is done for smaller wooden sticks, with a desktop laser scanning instrument placed at various angles around the joints. The output point clouds are used for plane segmentation to return mesh faces for property extraction. However, the desktop laser scanning poses inaccuracies and difficulty registering and merging points. Terrestrial lidar scanning turns out to be more suitable for acquiring accurate scans for building-sized beams. The reclaimed beam elements are placed edge down to scan all the beam faces. The scans are performed from four corners for beams over two meters long to ensure sufficient point density for a high degree of precision (Fig. 2). Post-processing steps include filtering outliers, cropping the designated areas, checking the intensity values, merging the partial data into an aligned

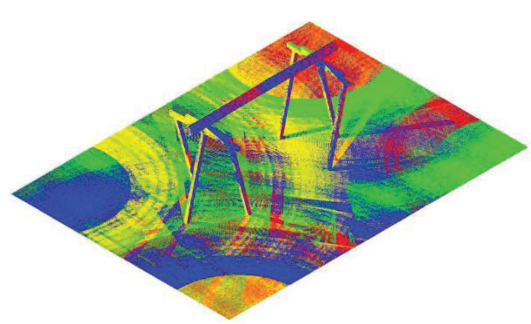

Figure 2. Laser scanning point cloud output

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point cloud of the whole element, and exporting the dataset into a manageable data format. After digitizing the reclaimed beam elements through laser scanning, the subsequent point cloud datasets are analyzed to determine the beam geometry and identify existing cutouts, cracks, or cross-sectional variations.

4.2 EXISTING PROPERTIES EXTRACTION

A computational method in the modeling software is designed to automatically define joints converted from the laser scan output. The output point cloud is separated into clusters by plane segmentation, and the point clusters are converted into meshes for calculation using an open-source library Open3d [17]. The converted mesh is imported into the Rhino3D environment, where the customized method is developed. The first step determines a minimal bounding box aligned to the scanned mesh. The long side of the bounding box is defined as the central axis connected to the beam's two ends. Each segmented mesh is grouped by finding the closest normal to the bounding box face; this way, the meshes that belong to the same face are grouped on the same side of the beam. After all mesh faces are grouped according to the sides of the beams that they correspond to; the next step is to associate the mesh faces to each individual joint. The most prominent face in the group is found and used to determine the height of the joint, and compared to the height of the other faces. If these other faces have a height under a specific value, they belong to a joint. These discovered joint faces grouped by face normal are reorganized into joint geometry by grouping

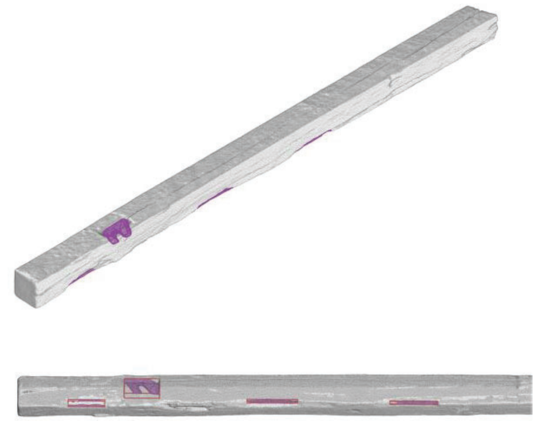

Figure 3. Joint extraction from meshes

them with the closest face. A minimally aligned bounding box is constructed for each joint geometry, using the same orientation as the beam. Other properties, such as depth, width, and length, are related to the orientation of the beam.

The digital alignment of matching geometries relies on a center curve as a referenced position, such as orienting objects and positioning joints to the new object. Having a center curve also helps keep track of the related position of the properties on the beam and enables the geometry alignment for a new design. For inconsistent geometries like deformed reclaimed beams with joints, contour lines are constructed from the end of the beam to the other. A line connects the center of the contour lines. To identify

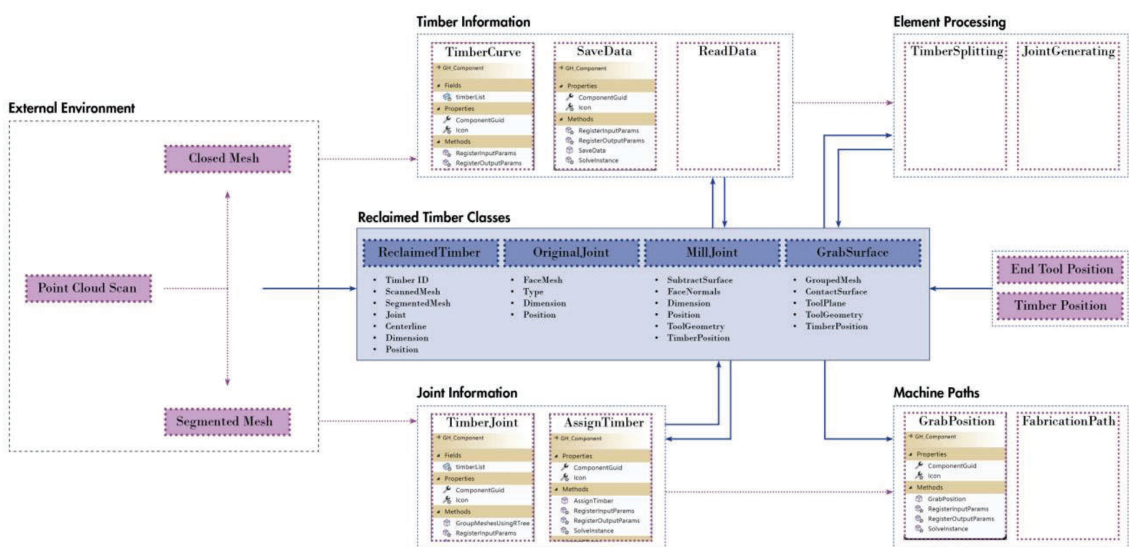

Figure 4. Reclaimed Timber Object used for matching resources and fabrication

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shifted center points caused by contour lines on the joints, we compare each vector to its previous one. If there is a drastic shift in the direction, the point in the query is removed. The remaining points are connected and used as a reference center curve. The method above was applied to reclaimed timber scans, and the results showed that not only were existing joints identified, but other properties, such as dented and rotten parts, were extracted (Fig. 3). Each joint on the timber has its own position and dimension. Using the center curve, we identify the joint dimensions, position, and orientation relative to the beam axis. This ensures that every joint position is recorded along the orientation of the timber beam.

4.3 MATCHING DESIGN WITH QUALIFIED RESOURCES

The constructed data classes that store the geometrical properties and perform calculations use the modeling software API, integrating geometric representations and numerical data. The data attributes include the dimension, position, orientation, and geometry of each reclaimed timber, the joints on the timber, and the new joints and assembled surface nested inside. The data is saved and extracted for future design options (Fig. 4).

The initial aim is to reuse original joints and produce less waste to extend the lifespan of the timber material before letting it enter the wood cascade process, saving the amount of material being cut off. The new and old timber and joint dimensions are evaluated, assigned to the new design, and compared by calculating how much material is being used and wasted. The selection is done through an automated selection sequence. From the timber information class, an automated material configurator sets constraints on material selection, starting from comparing the beam size to joint location on the beam, whether it should be re-machined or cut off, and comparing how much residual wood is produced for each option. The configurator starts by comparing the size of the timber and then separates them into two groups according to whether the beam contains a joint in the middle of the beam. It is easier for beams without joints or only joints that are situated on both ends. As long as they are long enough, they are eligible as a material to reuse.

On the other group with existing joints in the middle, if the existing width and length are enough for the new design, the next phase is to compare joint dimensions on the sides of the beam in each rotation to see if the joint can be re-machined. Then, for each rotation, we check if the beam length between the found joints is enough to reuse. From this selection algorithm, we identify which beams are reusable, and how much material is being used and cut off. After the beam from the selection fits all the criteria, they are automatically aligned from the joints' position plane on the timber orientation to our design model joint orientation, automating the digital alignment process for future fabrication and assembly of the timber joints.

A timber frame house is modeled as a case study to test the digital framework for different components. The pieces are evaluated using the customized computational tool developed, and these properties are exposed in the modelling environment (Fig.5). The tool identifies the different types and positions of joint data of the material library, including other reclaimed timber scanned from the source and used to match new designs. An example is shown with a designed truss that requires three different dimensions of timber to build parts of the new trusses (Fig. 6). While manually assigning favorable elements is possible, constructing an algorithm that automatically selects all the elements with applicable dimensions shows the potential of utilizing all the materials in the dataset. The configurator shows results indicating which section of the reclaimed beam fits the material stock layout criteria. This data lets us visualize which part of the reclaimed timber will be used. Allowing

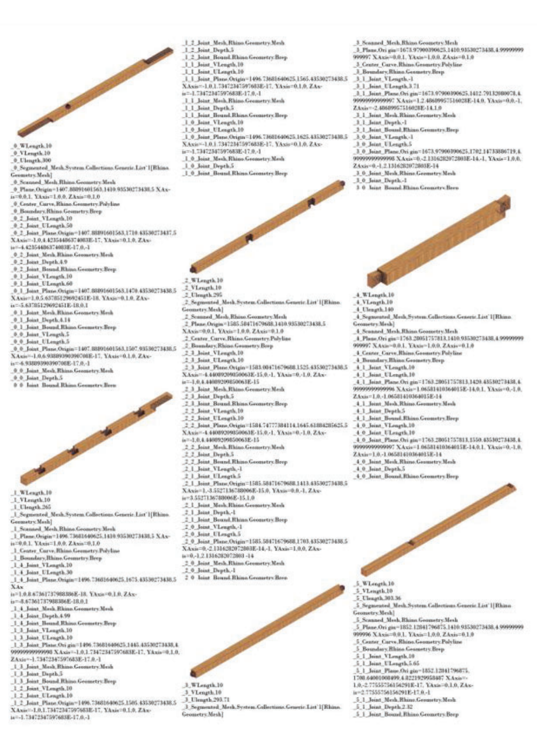

Figure 5. Data for types of existing timber beams

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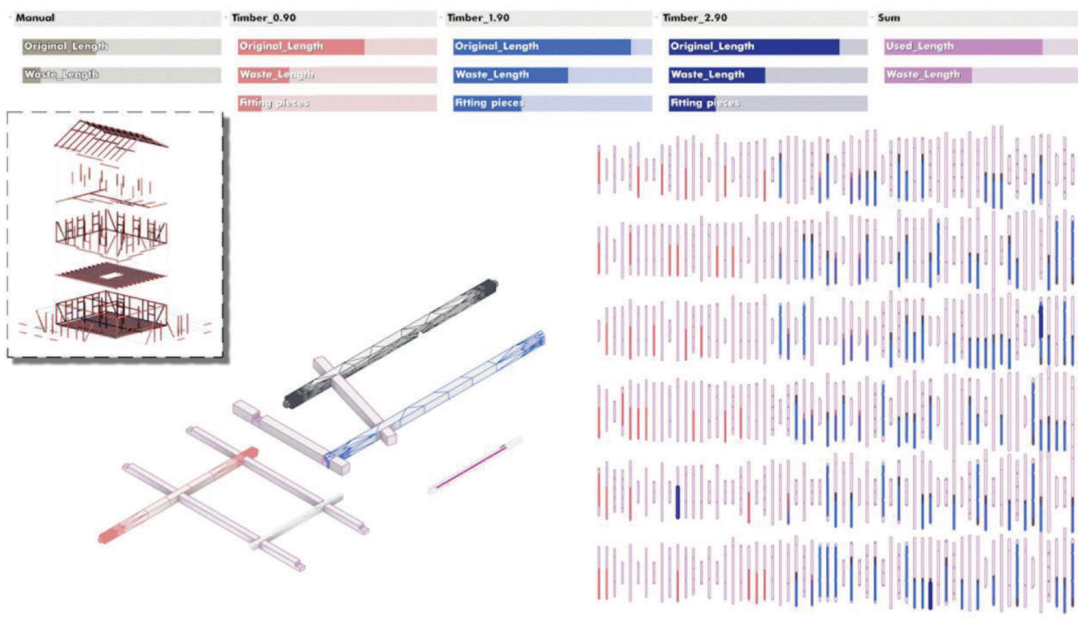

Figure 6. Matching reclaimed timber beams from timber barm elements for a newly designed structure

the calculation of the sum of the used material and the cut-off waste. After a design decision is made, the geometry is transformed to the orientation to apply further fabrication and post-processing for the chosen reclaimed beam.

4.4 DIGITAL ACQUISITION TO JOINT FABRICATION

Since trusses are made modularly in factories today, we propose reclaimed timber beams to be assembled into truss frames for modular assembly. They do not require extra service, membranes, or insulation compared to wall frames. Reclaimed beams consist of various lengths and are suitable for this structure. The design of the truss is broken down into individual beams in the design model and their joint geometries for evaluation. Even though the timber frames are modularized, each component is still unique, and for machine fabrication, we need the geometrical data extracted and generated from the digital scans. Each beam contains profile size and beam length, and connected beams contain joint attributes, such as length, depth, and location on their corresponding beam. Therefore, the customized digital objects containing these properties created through the software API help to integrate geometric representations and numerical data. A fabrication experiment process is conducted after the new timber truss is developed by carefully selecting existing reclaimed material stock, maximizing its material potential. Robotically applicable joints are fabricated after locating a new joint on a reclaimed beam. It is cut to its designed length with a saw and then fixed onto a vice for joint milling. The robot positions the tool point, and the milling path is mapped to the plane position. Then, it is placed on an assembly table for joint assembly. The dowels are inserted for securing the joint (Fig. 7).

The first experiments on robotically applicable joints are tested using a small-scale wood piece. They can be fabricated relatively quickly using a 3-axis CNC machine and assembled by pick and place with a cobot, making it easier to test the possibilities of the timber piece's joint insertion and automatic assembly (Fig. 8). Two sides of the joint are cut off at an angle, and there is less contact surface at the beginning of the insertion. When working

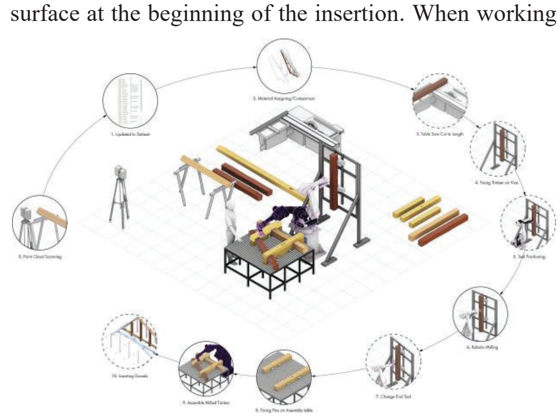

Figure 7. Digital acquisition to fabrication process

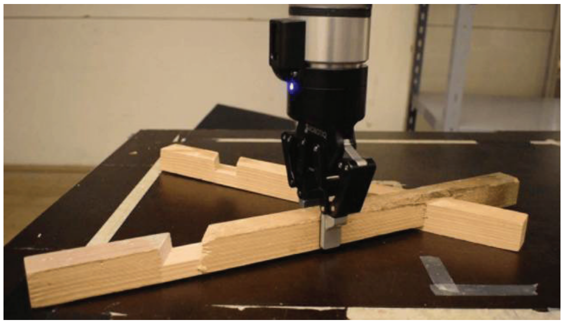

Figure 8. Cobot pick and joint insertion

with an inconsistent wood piece, the angle allows the robot insertion to accept a greater tolerance. Through a series of milling tests and planar assembly with the robot, it is found that the milling smoothness of the angle sides affects the ease and depth of inserting the joint.

The fabrication toolpath for the joint is generated automatically to account for perfect alignments for reclaimed timber with deformations and uneven surfaces. First, the geometry is aligned with the timber center curve property to ensure the geometry is intersecting at the correct position and rotation. A part of the intersecting material on both beams is removed to form a lap joint. To create the angles on the lap joint for easier insertion, the beam length, width, and depth vectors are used to generate the correct beveling direction and angles for the top and bottom joints. Because of the uneven surfaces of the reclaimed timber beam, the edges next to the joint are milled off to fit the shape of the inserted beam to ensure smooth insertion.

For the fabrication of reclaimed timber beams, a milling end tool is connected to an ABB robot. During milling, the reclaimed timber is fixed to a vice fixed to a frame fixed to the ground to ensure stability. The fabrication starts by positioning the tool to the beam. Then, a thin planar layer is milled as a basis plane for the joint alignment. The depth of the lap joint is then milled. The angle on the joint and timber sides for easier insertions is milled last (Fig. 9). Due to the project's time frame and technical resources, the joints were assembled manually to demonstrate that joint insertion could be performed. However, the previous robotic insertion test showed promise in automated joining, the fabricated joints allows a higher degree of tolerance at the outset of insertion.

5 – RESULTS

The project demonstrated a digital design and fabrication framework that considers the inconsistencies of reclaimed timber, making it more suitable for robotic processing. A laser scanning workflow for reclaimed timber beam detects and extracts the reclaimed timber component's usable features and critical physical information. Automated segmentation methods are applied on reclaimed timber surfaces, producing separate mesh faces from scans to export to a custom joint identification method. Results came out not only identifying existing joints but also other deteriorated parts on the timber beam. A customized digital tool is developed to integrate the scan data into the design process and digital information from the timber scan into our design environment. The analyzed beams are stored in a database, enabling the digital framework to reuse the beams for the truss. The geometrical data used in the configurator assists in positioning and machining new joints on each beam. The digital tool is prototyped to include sorting algorithms for reducing waste and matching qualified resources to the design for less waste. After identifying original joints on the beam, adapting the reclaimed timber data to fabricate new joints, or evaluating the possibilities of re-machining original joints to account for deviated material and detect imprecisions. The robot-compatible joint allows a higher tolerance during assembly, and the prototype is tightly

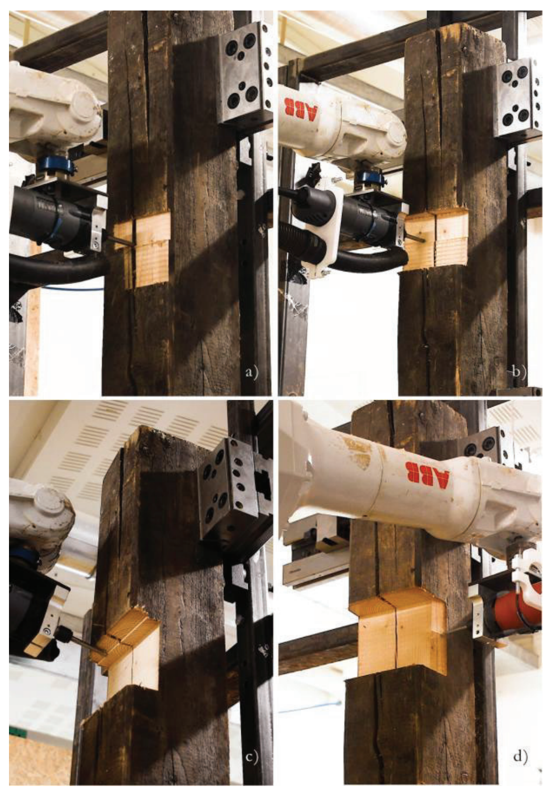

Figure 9. Fabrication of robotic applicable joints. a) Planing flat surface. b) Pocketing joint. c) Insertion angle on the joint side. d) Insertion angle on the timber side.

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assembled. The result is a partial timber truss prototype that successfully demonstrates the application of this framework (Fig. 10). Two out of the four obtained reclaimed beams from the wood yard contained existing joints. If the joints are cut off, the total length would shrink 16% and 12% respectively, providing less use case for a reclaimed beam in designed structures that require longer lengths.

6 – CONCLUSION

The research shows that much of the apparent challenges of reusing reclaimed timber can be identified and mitigated using an integrated digital reclaim-to-design framework and material configurator. Using reclaimed timber is already beneficial, but a more strategic use enhances its value. Robotics and automated digital workflows suggest that this approach can be scaled up and industrialized. Digital tools tracking material properties can automate industrial fabrication and assembly of inconsistent materials. Further steps include scaling up this workflow to accelerate database gathering and developing interfaces to more extensive industrial production environments. The assembly of multiple reclaimed timber beams hasen't yet been tested, which requires precision of joint directions to ensure that beams are assembled at the right orientation. While the digital framework showed that identifying original joints, damage, and rotten parts may be re-machined to improve the reuse of timber beams as load bearing elements, it involves many technical challenges. In the research, the sourced beams are without metal contaminants and reclaimed from wood yards, where we do not have control of the quality. The use of reclaimed timber should begin by identifying reclaimed timber sources. The digital framework should include standardized data over the entire value chain of the product or building, and determine the degradation effects and mechanical quality to ensure the parts that can be used. They should be adaptable to altered regulations or standards or alternative functions. Moreover, from a design and preservation perspective, properties such as species, color, age, and history should also be considered when choosing the timber element. Keeping track and working with data in different design and construction phases increases the precise use of reclaimed timber and helps ease the pressure on the virgin timber resource, prolonging the life cycle of construction timber material and reducing the environmental burden.

Figure 10. Fabricated timber joints and joined partial structure

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