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Joinery Solver for Whole Timber Structures

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ABSTRACT: This paper presents a digital joinery generation method for whole-timber structures using wood-wood connections. The research is based on a collaboration with a local timber company located in a mountain area [1]. In this context, there is a need to explore available round-wood stock to increase its use and apply it to the local construction. The inspiration is taken from joinery generation methods [2,3] and applied to round-wood timber assemblies. The joinery solver considers: available stock of timber, its natural characteristics (i.e. irregularity in section, length, curvature, forking), low-poly digital representation and digital fabrication (CNC, Robot tool-path). First, round-wood is scanned and point-clouds are processed to get the central-axis and radii. Second, trunks are oriented to a design space. Third, the joinery solver creates connections. This method is based on a tiling process when a group of polylines are scaled, sheared and translated to a connection zone. The joinery library is collected from existing literature and classified i.e. side-side, side-end, end-end types. The research shows that it is possible to automate joinery generation while examining variability of timber and digital fabrication constraints. The joinery solver is validated by physical tests using 4.5 CNC and 6-axis ABB robot.

KEYWORDS: Whole-timber, Round-wood, Joints, Connections, Robotic Fabrication

1 INTRODUCTION [1 2 3]

Raw-wood joinery fabrication requires a highly skilled manual process for machining techniques of irregular raw-wood [4, 5, 6, 7, 8]. The role of the craftsmanship changed when the industrial robot arms [9, 10, 11, 12, 16, 17, 18, 19, 22] and CNC machines [14, 15, 18, 20, 21] were introduced in research and timber fabrication companies [23] of whole timber structures. Most of the references reflects on specific project cases and digital fabrication technology. However, there is an absence of automated geometry generation of timber joints considering the irregular timber shapes. The goal of the paper is to gather the knowledge of raw-wood connections and develop a work-flow that could be applied for building with raw-wood.

1.1 MINIMAL MODELS

The digital representation of the raw-wood joints follows a minimal model where a tree-trunk is represented as a central curve with a series of circular cross sections shown in Figure 1b. The round section must have an orientation following the curve tangent axis. The rotation of the frame has to be defined too for transformation of beams to machining space. The connection is commonly displayed as polygonal primitives that are subtracted from beam elements Figure 1c. This model does not include natural characteristics such as cracks, knots or bark, because it is used for a fast computation time and tool-path generation.

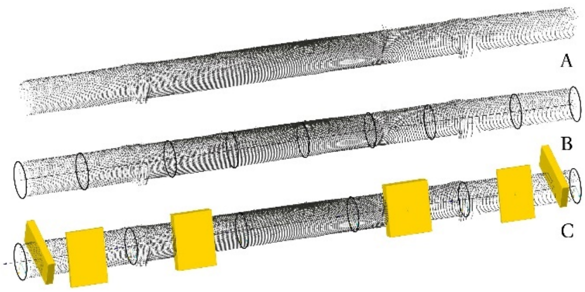

Figure 1: *Minimal Model acquired from a scanned beam using an industrial robot arm ABB IRB 6400 and Faro S 150 Laser Scanner. A – Point-cloud, B – Cylinder Fit, C – Oriented curve axis and joint cuts.*

The subtraction volumes of joints have to be scaled to a local radius of wood with respect to current and adjacent beam. Often a machining tool-path has partial cuts not touching the timber to compensate the irregularity of timber versus safety of a robot or CNC machine [11]. Otherwise, a beam could be milled to precise geometrical shapes such as mechanical rounding, but this takes a long processing time [15]. Notably, the surface mesh or point-cloud data is not directly used to define connection geometry due to slow display and large memory for example a point-cloud in Figure 1 is 24.573 mb in size. Consequently, a set of minimal information is used the connections both for display and fabrication. The section 2 describes such data-structures in detail.

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1.2 CLASSIFICATION OF JOINTS

Raw-wood connections could be classified by a connection topology. Whole wood could be connected end-to-end, side-by-side, side-to-end or using extra fasteners with or without combination of wood-wood connections. The material type of such joints varies from timber attachments, bio-degradable threads to metal fasteners and engineered steel plates. While mechanical fasteners became a standard practice for jointing timber assemblies due to their ease and predictable performance, Robotic Fabrications has a potential to explore the development of complex wood-wood connections inspired by traditional Japanese joinery [16].

1.2.1 END-END JOINTS

End-end joint is a connection following a grain orientation of wood. A scarf or a tenon-mortise joint is a classical connection type [11,15]. These joints commonly have detachable fasteners such as dowels, keys or bolts to reduce traction forces by compression and friction [17]. This type would only work when beams are near to parallel orientation shown in Figure 2.

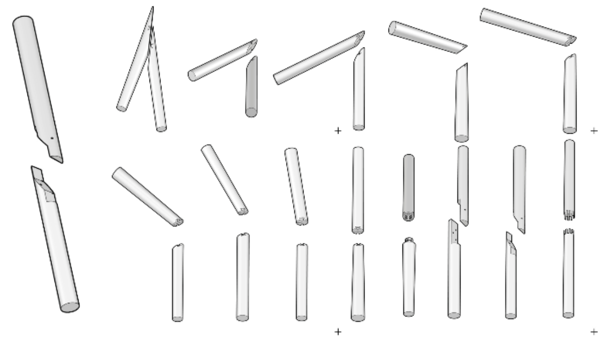

Figure 2: *End-End Joints could be applied when beams are parallel to each other.*

1.2.2 SIDE-END JOINTS

Side-end joint is often applied for in-plane nodes i.e. Truss, Reciprocal or Zollinger systems. Depending on the assembly sequence, these joints may have sub-categories of finger, feather or tenon-mortise see Figure 3. It is necessary to have a maximum connection area which is trivial to obtain for curved surfaces. A minimal area is could be defined by not less than 2/3 of a section [24] or employing bent timber [19].

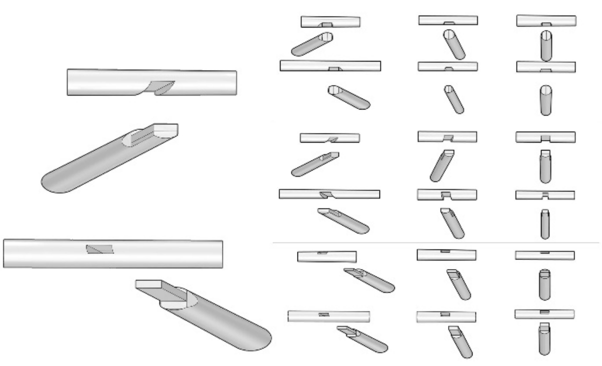

Figure 3: *Side-End Joints and possible sub-categories.*

1.2.3 SIDE-SIDE JOINTS

The side-side joints could be used for doubly curved discrete grid-shells, reciprocal structures [13] and planar assemblies such as wall, slab systems [21]. The geometries of cross-lap (half-lap) joints are commonly calculated at intersection nodes of beam axes see Figure 4. The axes give the orientation of the joint by local curve tangent. Each joint has to be customized to the skeleton intersection angle and the local radii. The cutting method often employs milling and saw-blade processes.

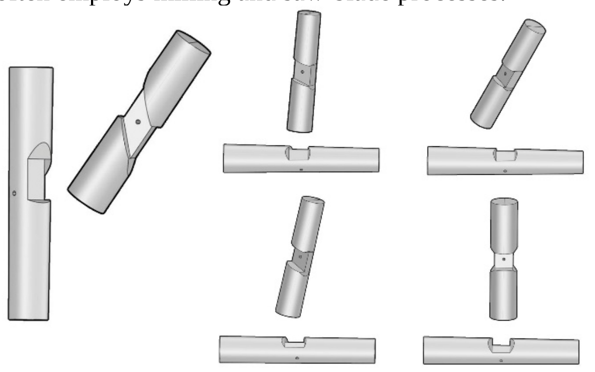

Figure 4: *Side-side joint differences depending on the angle.*

1.2.4 JOINTS FOR FORM-FOUND SURFACES

The need to develop a joinery is due to design process when it is not clear what type of connection could be used or whether it is possible to apply different categories of joints within one structure see Figure 5a. Moreover, boundary conditions at the edges and foundations may require another topology of joints that could be trivial to implement for each model. The design scope is primary tessellated surfaces employing pair-wise connections. In this context, curve surfaces have a direct relation to eccentricity between elements, therefore form-finding process could be employed to have a desired connection area see Figure 5b.

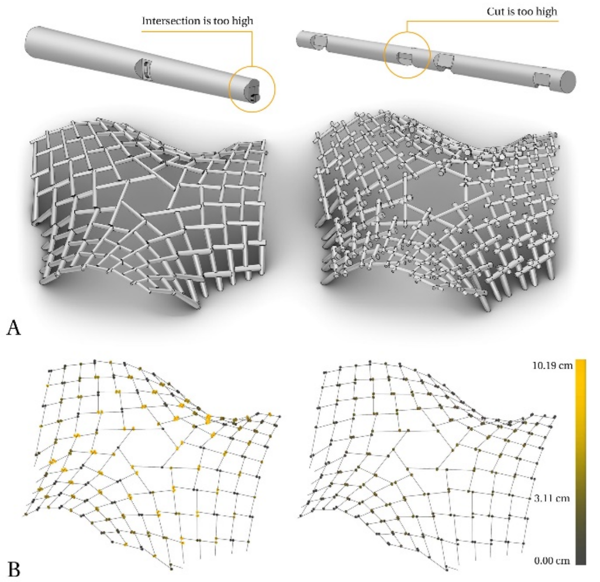

Figure 5: *Relation between joint and section area. A – End-end joint and Side-side joint. B – Eccentricity reduction using a dynamic relaxation for ~ 15 cm diameter round sections.*

1.2.5 FASTENERS

The design of efficient raw-wood joints is challenging because of shrinkage, juvenile wood, minimal connection area, cost and fabrication [26] therefore external fasteners are usually employed alongside timber joint. Raw-wood beams may require additional fasteners ranging from timber dowels [15, 17, 19], screws [13], textile threads [26] to engineered metal plates [25]. The current study cases emphasis wood-wood connections with minimal amount and complexity of external connectors such as timber dowels, threads or metal bars see Figure 6.

Figure 6: *A set of side-side joints with timber and metals fasteners.*

1.3 RESEARCH SCOPE AND ADDED VALUE

Commercial practices that employ raw-wood in construction utilize a standardized fabrication that requires a minimal skilled labour to complete projects by local workers such as Unilog / TTT (New Zealand) and FEEL (Japan). Crooked timber is applied in practice as well i.e. WholeTrees with a manual carpentry and stationary scanning i.e. Faro Focus. Moreover, raw-wood could be machined using robot cells i.e. Balmer Systems (Canada) along with scanning Mobic SA (Belgium). A collaboration is built with the later enterprise to employ a scanning application with a robot controller that could gather point-clouds within 4-5 min and start fabrication process directly after a point-cloud is processed and aligned with the tool-path. Currently, there is a lack of reliable point-cloud processing tools for crooked wood because the current practices do not consider such timber as a valuable resource. Small radius straight, tapered, bent and forked beams has a strong structural advantage and low economic value, thus could be exploited locally in closed circular economies within the proposed workflow of architectural design, fabrication and forest companies.

2 JOINERY SOLVER

The joinery solver is developed to identify beam connectivity and generate joints in-line with a machining tool-path. The solver also addresses irregularities of raw-wood. First, a tree-trunk axis is expressed as a curve and not a straight line with a changing radius along its axis. Second, the stock of available wood is highly relevant, as a result assignment method are included. Third, connectivity of beams has to be stored. Fourth, joint geometry generation needs to be connected with fabrication and assembly sequence (if relevant). Consequently, the joinery solver has to adapt to these local conditions.

2.1 DATA TYPES

The joinery solver is composed from five main data-structures see Figure 7: a) Tile, b) Beam, c) BeamJoint and d) Solver that interprets the joinery data (BeamJoints) on the curved elements (Beams) to model the connections and output e) fabrication tool-path and display geometry (Cut). The purpose of a connection is three-fold: a) display the joints, b) get the machining tool-path and c) track the connectivity of beams. The data-structures are based on the geometry processing library RhinoCommon (Rhino 6) and the robot control is based on Unity software.

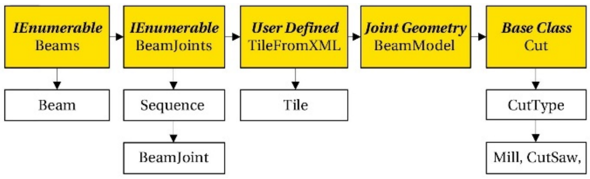

Figure 7: *Data-type of the Joinery Solver*

2.1.1 Beam

A Beam is a data-type that contains information about a central-axis of a tree trunk, radial parameters, orientation, indexing and cuts from a beam. Firstly, it was thought that the round-wood section does not need an orientation because it is circular but physical experiments showed that the initial orientation is needed to define a machining path and a beam insertion vector. Additionally, Beam contains geometry transformation methods to orient its properties to (i) a machining space or (ii) from a scanned tree stock to a design space. Differently to beams, forks have to be represented as a group of Beams with its orientation plane see Figure 8b.

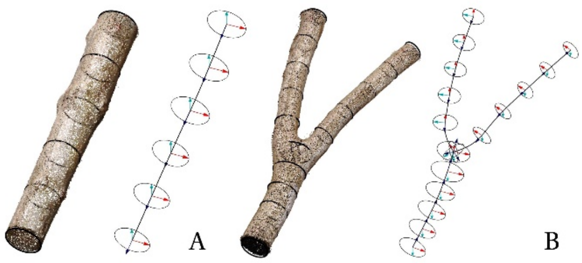

Figure 8: *Point-cloud and Beam data-structure.*

2.1.2 BeamJoint

The BeamJoint stores a) a joint name b) indexing information to know the connectivity between beams, c) position where joints have to be positioned on a curve, d) and a number of cuts a joint contains. The indexing of connected beams could be made in several ways i.e. a) following global shape such as a mesh topology, b) proximity search using curve-curve intersection, c) manually drawing points and lines that point to connected elements. The example of a BeamJoint is show in Figure 10a.

2.1.3 Tile

The abstraction of a joint is made by a Unit Tile represented by a series of polylines. The tile has to be named and assigned to one of the given categories: a) end, b) end-end, c) side-end, d) side-side, e) custom-cut. Afterwards, the solver generates the joint geometry within a beam pair. Lastly, the tile is transformed using shear, scale Figure 8 a1-a4 and plane-to-plane matrices and oriented to the connection area see Figure 8 b1-b2.

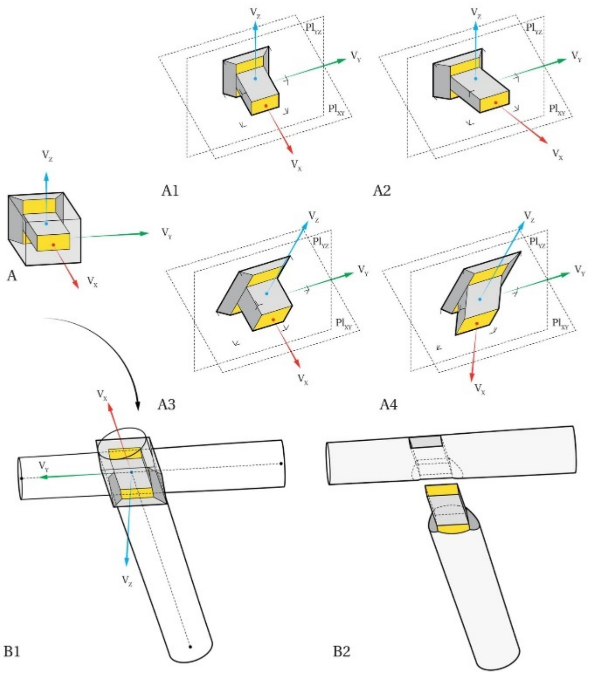

Figure 8: *A joint is representation as a Unit Tile.*

2.1.4 Cut

Cut is data-type that represents a joint located on a beam. The Cut could be is as a collection of properties such as CutType, Plane, ToolR and Polylines. The visualization of the connection is a negative form needed to be subtracted from a conical shape using Boolean difference operations see Figure 1c. Additionally, the Cut has sub-categories such as milling, drilling, saw-blade that inherit from the base Cut class. Machining types are dependent on a tool-path generation as well as the movement of a Robot or CNC. It the main output of the Joinery Solver used for joinery machining and display see Figure 9.

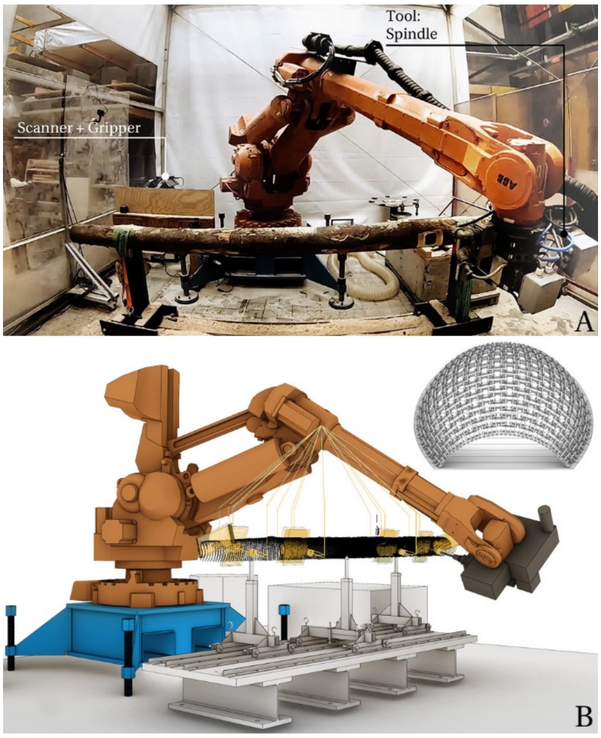

Figure 9: *A – Milling machining operation following B – tool-path aligned to a point-cloud.*

The display of joints in round-sections vary depending on computation speed: a) pairs of polylines, b) BRep volumes constructed from polylines, c) beams with cut joints using boolean operations see Figure 10 b-c. The polyline display is the fastest and boolean operations cut take 0.2-3 sec depending on complexity of joint and number of them.

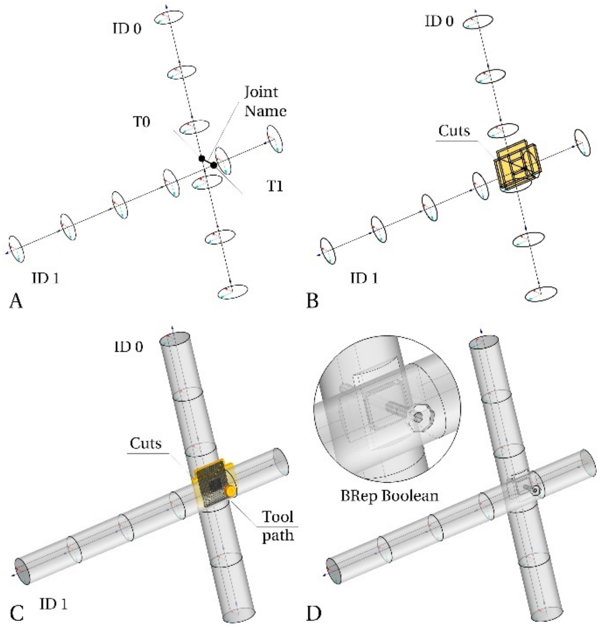

Figure 10 *A – BeamJoint representation (red line) and its parameters: a) JointName, b) Position on beams exes T0-T1, c) Indexing of beams ID0-ID1. B – Cuts positioned for a Half-lap joint, C - BRep volumes, D – Beam geometry after Boolean operation.*

2.1.5 Solver

The Solver combines a collection of Beams, BeamJoints and Tiles to generate connections named Cuts see Figure 10b. Firstly, beam indices are extracted from BeamJoints, male-female index is assigned, male-female radii, position and curve parameter of a joint on a beam axis. Secondly, parameters are passed to geometry generation methods based on a connection category i.e. side-side, end-end, end-side. Thirdly, the outputs of the methods are gathered for each Beam in a form of polylines pairs representing a volume needed to be removed from a Beam. Following chapters are equivalent to the methods to generate joints employed in the Joinery Solver.

2.1.6 End-End

The end-end joint could be divided into two sets: joints that are parallel and not parallel joints. When beams are not parallel, it is only possible connect linear elements by additional fasteners and the beam itself is cut using bisector planes. The End joint has sub-categories such as Scarf, Tenon-Mortise, Scarf-Step, Finger joints with additional fasteners. The current implementation considers following types: "ScarfBisector", "ScarfStep, "ScarfZigZag", "ScarfTenonMortise", "Scarf", "KeyButterfly".

The geometry generation is as follows Figure 11. First, Planes are oriented towards the end axes see Figure 11.1.0. Second, a bisector-plane is constructed see Figure 11.1.1: a) Y-Axis is a cross-product of Z_M, Z_F and if the axes are parallel V_Z is taken, b) X-axis is a sum of male and female Plane Z-Axes (Z_M and Z_F) and if the axes are parallel a cross-product is taken from Y-Axis and Z_M. Third, planes are oriented towards each beam end see Figure 11.1.2 and their XY axes are switched to ZY. Four, the beam tiles are sheared using tangent vectors of the curves see Figure 11.2.0 and the scale of the beams is taken from the biggest radius of the both elements see Figure 11.1.3. It is also possible to align these planes by the user input if it is given see Figure 11.2.1 for a rotation between Figure 11.2.0 and 11.3.0.

While the geometry representation relies on BRep Boolean intersection between pipe-like elements and closed tile elements. it must correspond with the tool-path see Figure 12. The tile geometry representation is the input for cutting such as pair of rectangles for saw-blade cuts or closed contours for milling. The orientation of these polylines must be considered too. Each point is a Plane with assigned speed value. If the Boolean operation and tool-path simulation is successful the Tile is good to use. The check is made visually by testing distinct cases of angles and whether the robot or CNC could run without a collision.

2.1.7 Side-Side

The Side-side joint also known as a half-lap joint is composed of two elements whose intersection forms the joint. Half of the intersection is cut from one beam and another half from the other beam. Angled cuts are added to the design of the joint to compensate for the irregularities of wood. For planar assembly cases such joint can be inserted into each other using one insertion vector but for curved cases the overlap cut has to be angled since the insertion direction is problematic [21]. In such cases beams are connected using additional fasteners or they interlock each other in a larger assembly sequence.

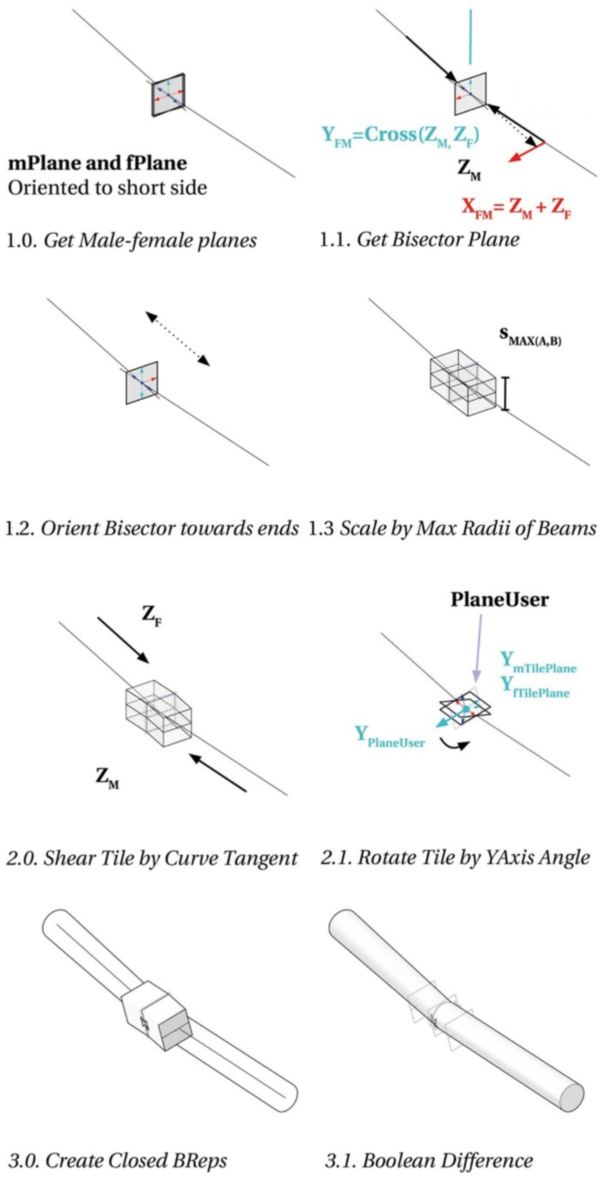

Figure 11: *End-end joint geometry generation.*

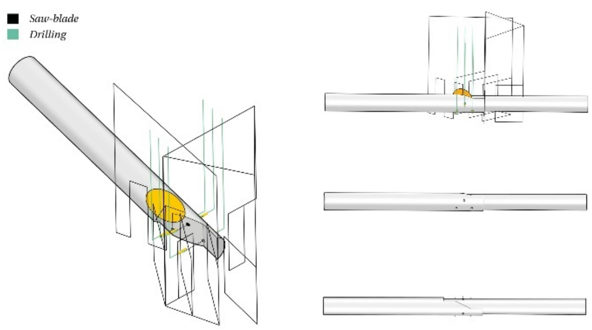

Figure 12: *Tool-path example of end-end joint.*

The geometry generation is as follows Figure 13. First, the planes (P_{mPlane} and P_{fPlane}) of beams are retrieved at the intersection zone see Figure 13.1.0. Second, beams can have eccentricities when their intersection is not a point but rather a small distance. As a result, an overlap distance is computed see Figure 13.1.1. The overlap distance is a measure between two spheres that represents a radius of beams at the joint point. The calculation is simplified to 2D circle method to determine where they intersect. There are four possibilities of intersection: beams are not touching, beams intersect at the same point with the same radii, beams are inside of each other and beams overlap (for more detail see Figure 15.1.5). The spherical overlap gives an average joint plane: a centre of the overlap is the plane origin, the Z-Axis is the distance between the most distant sphere points. Third, the sphere plane is used to project a plane derived from cross-product of curve tangents. The projected plane is also rotated 90° to get a correct tile shear transformation see Figure 13.1.2. Four, the projected planes are translated to joint positions and named as $P_{fTilePlane}$ and $P_{mTilePlane}$ see Figure 13.1.3. At this step planes point to the same direction. Five, planes are flipped from the canter of the intersection see Figure 13.2.1 and 13.2.2. The bisector cuts are positioned at curve points $P_{mTilePlane}$ and $P_{fTilePlane}$ while the other cuts are positioned the center at planes $P_{mTilePlaneMid}$ and $P_{fTilePlaneMid}$. Six, the overall scale of the beams is the smallest radius of both beams see Figure 13.3.0. The S_X is 1 if the male radius is smaller than the female, else it is a division between R_{Male} and R_{Female}. The S_Y is an inverse value of S_X. The S_Z depends on the overlap distance. When beams are inside each other the biggest radius is taken divided by the minimum radius. The algorithm could position a joint on a curved and tapered beam, but the user needs to specify the scale tolerance to have the full overlap of the cut and the Beam see Figure 13.4.0. Lastly, the tile is created and sheared by a female plane ZAxis on the male and $P_{fTilePlaneMid}$ and $P_{fTilePlaneMid}$ see Figure 13.4.0. At this step, the fabrication process is considered: the pyramid saw-blade cuts, milling and drilling tool-paths see Figure 15. When the result is tested visually in regards to the Boolean-difference see Figure 13.4.1 and tool-path, the joint is prepared to use.

2.1.8 End-Side

The End-Side Joint is a joint with male and female elements forming a letter T. This is the most common joint for Truss, Nexorade or Zollinger. The structural applications may result in eccentricities between beam i.e. in-plane or out-of-plane connection forming eccentricities between elements. Ideally the end-side joint would form a tenon-mortise joint, but it viable only with planar structures such as slabs with parallel arrangements of its members. Otherwise, End-Side with dowels, screws or threads, Half-Tenon-Mortise, Butt could be applied, which are not the strongest joints but allows to assemble discrete curved surface [11,19].

The algorithm starts by identifying which beam is male and female. This is determined by measuring sub-domains of the curve. The beam that has a larger domain length difference is the male. Afterwards the geometry generation starts as follows Figure 14.

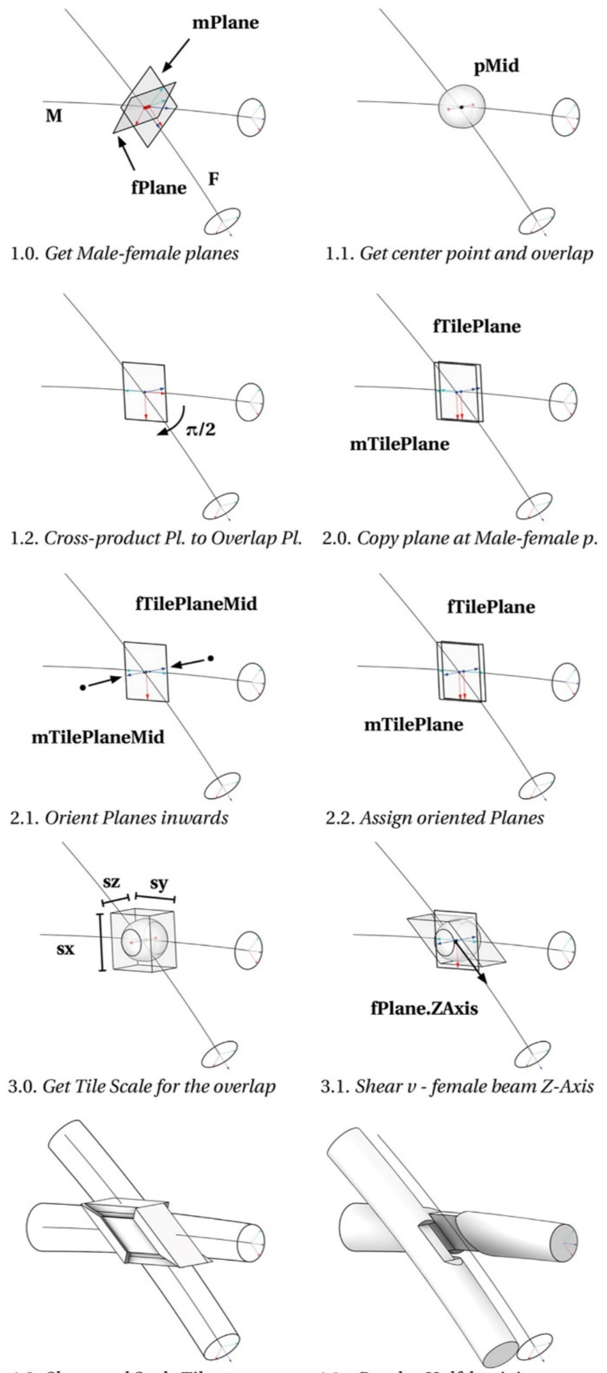

Figure 13: *Side-side joint geometry generation.*

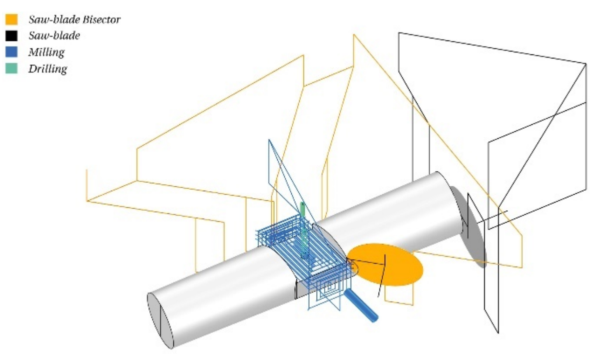

Figure 14: *Tool-path example of side-side joint.*

First, perpendicular beam planes are referenced see Figure 16.1.0. Second, the overlap is calculated to know the joint center-point, overlap distance and conditional check regarding position and radius of beams see Figure 16.1.1. The beams may not overlap, touch only, intersect partially, or one beam could be inside other beam radius. These conditions would result varying joint scale as well as in side-side joint. If the beams are touching the algorithm is continued. Third, a plane $P_{planeCross}$ is constructed at the middle of the overlap where the X-Axis is $X_{mPlaneZAxis}$ and Y-Axis is $Y_{fPlaneZAxis}$ see Figure 16.1.2. Fourth, a plane $P_{planeCommon}$ is constructed whose Z-Axis is formed from overlap direction. The plane $P_{planeCross}$ is projected to $P_{planeCommon}$ to have a correct Tile orientation. Also, it is oriented towards the male beam and rotated by 90° see Figure 16.1.3. Depending on a joint, the plane might by at the center or on each beam see Figure 16.1.4. Five, the joint scale depends on a beam overlap and non-overlap distances S_{ZM}, S_{ZF} and the global joint scale is defined by the smallest beam radii see Figure 16.2.0. Six, the joint shear vector is the female plane Z-Axis see Figure 16.3.0. It is also possible to add fasteners such as screws, dowels or threads. Finally, the tile polylines are converted to cuts for male and female sides and added to their corresponding beam indices. The cuts similarly to previous joint types contains machining tool-path and display geometry see Figure 17.

2.1.9 End and Custom Cuts

There are joints that require customized setups for example the End cut method is created for beams touching the ground or boundary conditions. The End-cut definition is similar to End-end joint but applied for a single beam. Also, elements such as dowels or screws are created in a Custom-Cut method to identify line segments for drilling or milling see Figure 15.

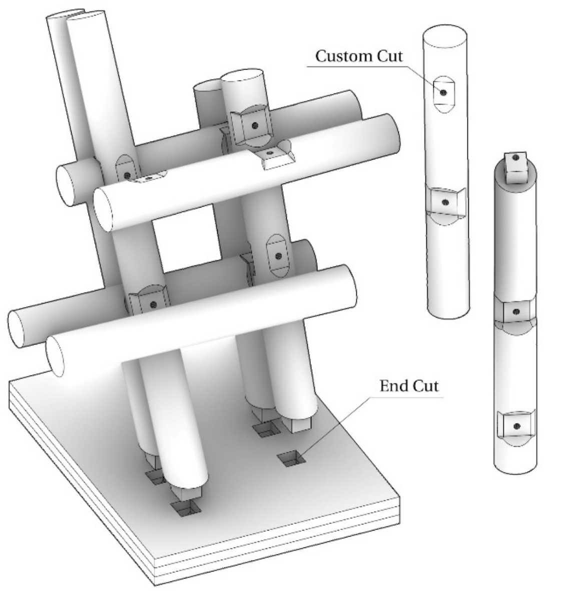

Figure 15: *A small-scale prototype model that contains side-side (half-lap) joints. The drilling holes for dowels are treated as Custom cuts and foundation elements has an End cut for a tenon-mortise connection.*

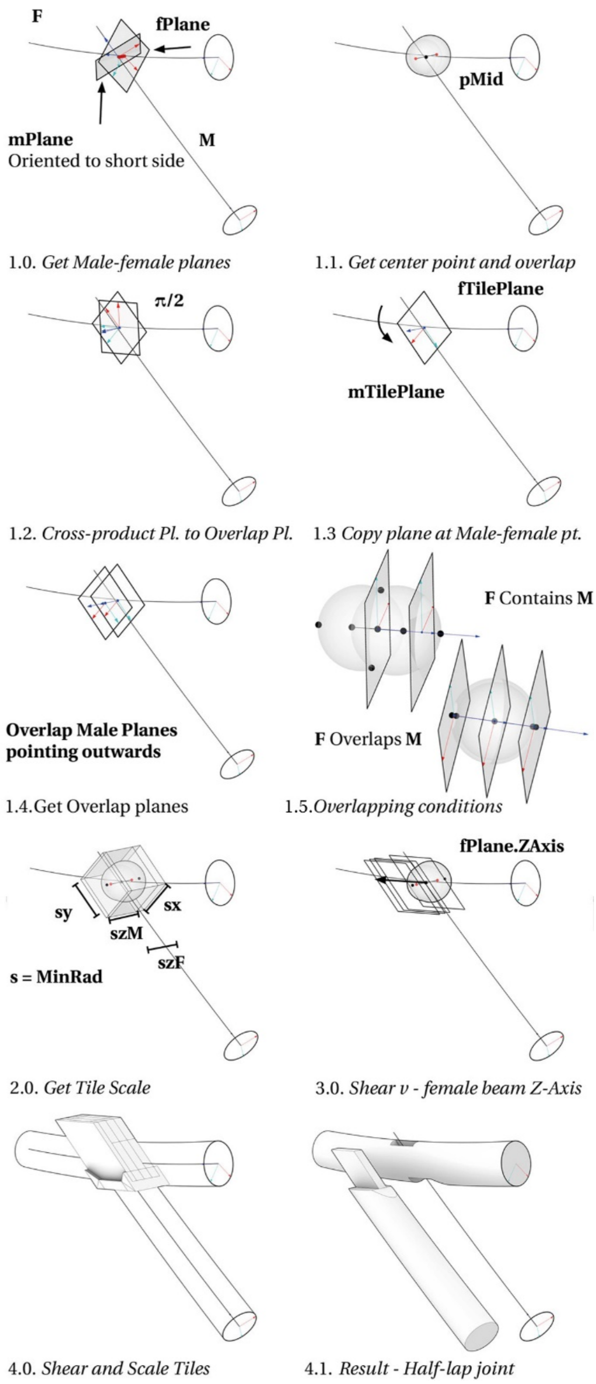

Figure 16: *Side-end joint geometry generation.*

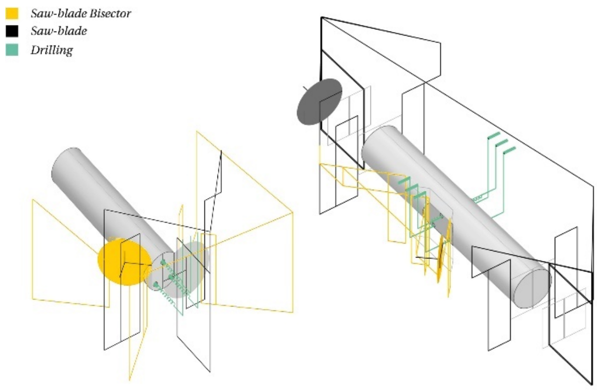

Figure 17: *Tool-path example of side-end joint.*

2.2 INSERTION DIRECTION

Previously, joinery generation was discussed considering two-beam assembly only. Raw-wood beams could be inserted using one insertion vector so that the inserted element would not be blocked by previously assembled beams and their connections. Two prototypes were made to test insertion direction. The blocking could be avoided in by a) the joint geometry itself that allows a large range of insertion see Figure 17, b) or joints could be oriented to one direction see Figure 18. The orientation of a joint could be aligned with the other connections by summing each insertion vector. Additionally, the assembly sequence must be solved beforehand to know already connected elements in a sequence. The insertion is usually limited to an insertion range and most applicable where beams are close to parallel and orthogonal.

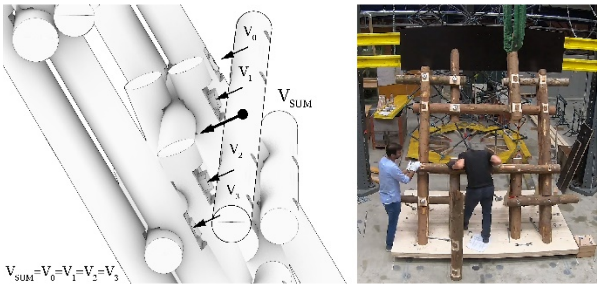

Figure 18: *Insertion vector per beam is equal in all the joints.*

2.3 TIMBER STOCK AND ASSIGNMENT

Raw-wood is unique its geometric properties. This is obvious for crooked wood i.e. when timber is bent or forked. However, it is less clear for small-radius straight trunks. The assumption is made that it is fully irregular and needs to be addressed due to following reasons collected in physical experiments see Figure 20: a) there was a taper along the axis of the examined logs, b) the harvested wood was targeted at 15 cm radii but collected ones varied between 13 - 18 cm, c) small radii wood strongly deviates from the straight-axis, d) length changes as well. Because of these differences an assignment problem is formulated to choose a best fit beam within a design model.

2.3.1 The Assignment Problem

The study case explores a two-layer reciprocal structure see Figure 19. The initial design is altered by a given set of timbers. First, all the beams are scanned in one time and the point-cloud is cropped to individual beams. Second, skeletonization is performed on each point-cloud using a Cylider-fit method [27]. Third, cost is assigned for each beam based on length and radii. Fourth, the assignment is made using a Hungiarian method[4]. When a solution is found, the initial design is updated in relation to the oriented point-clouds. In this study case, the initial beams were too small to overlap or too large at the connection zone. These findings resulted in the global design changes such as reduction of layer thickness, reorientation of conical parameters and better cost estimation per element so that too small or two large beams would not be positioned closed to each other.

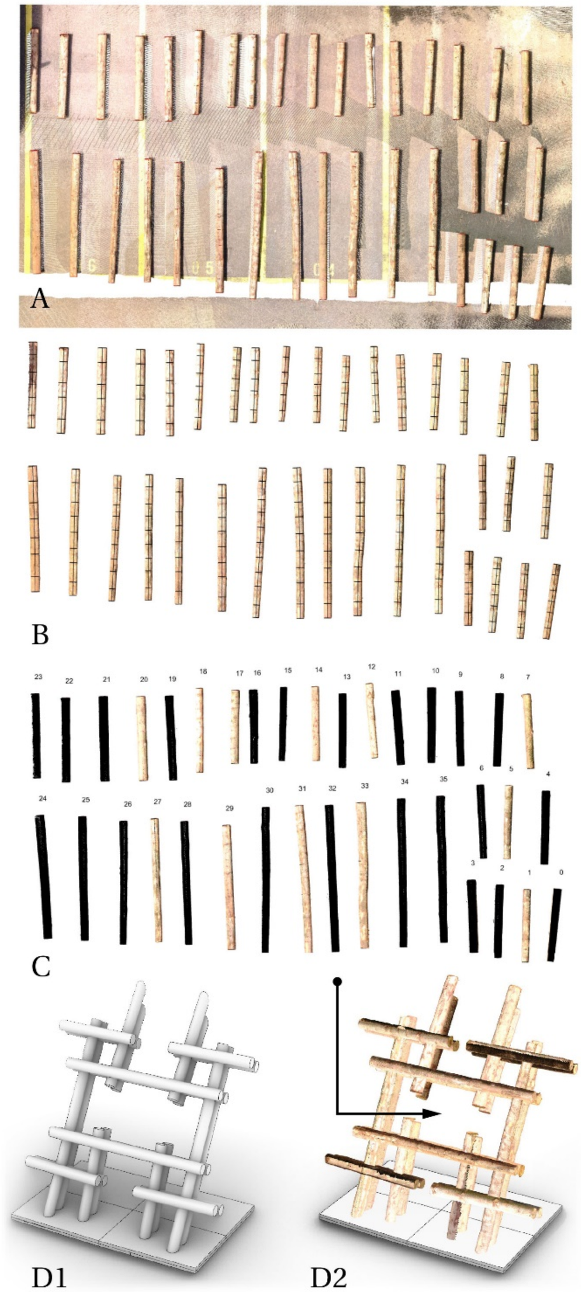

Figure 19: *Beam assignment from real to digital stock. A – Beams are scanning all at once, B – Cropped point-clouds and skeletonization, C – Assignment using a Hungarian algorithm.*

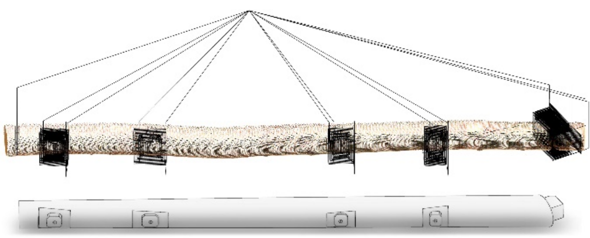

Figure 20: *Deviation between a digital model and physical.*

[4] http://accord-framework.net/

2.4 RIG AND FABRICATION SETUP

Two main methods are employed to cut the irregular raw-wood: a) scanning, b) machining. Before fabrication starts a point-cloud is captured to position a machining tool-path. An automatic tool-changer is used to switch between two hardware options. The fixation of the raw-wood within the machining setup has a high importance because there is a contradictory task: robot must have the largest reachability while timber needs to be fixed firmly. One of the main issues that happened during fabrication tests was the vibration because the work-piece is lifted in the air. The belts and the steel three-point rig proved to be the most stable solution.

Figure 20: *Robotic fabrication and scanning setup employed to cut both straight, curved and forked beams suing 2-rail system and Faro S150 laser scanner fixed to the gripper.*

3 RESULTS AND VALIDATION

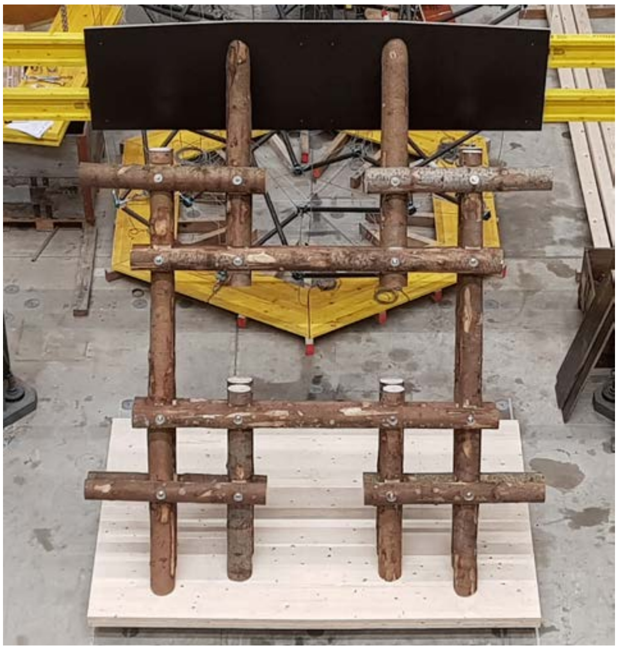

Figure 22: *Prototype of a two-layer reciprocal system.*

The validation of the proposed methodology is based on prototyping. The methodology is designed by learning from the movement and control of the hardware that could help to realize digital models within the raw-wood. The methods affect the result of a physical model including the assignment of beams, positioning a low-poly model within a real tree trunk, joinery and the tool-path generation. A raw-wood reciprocal structure explores small-radii (13-18 cm) tree trunks connected side by side. A reciprocal prototype serves as a study for a doubly-curved shell made from relatively straight tree-trunks. Two models are made to test the half-lap connections a) tightened with ropes and see Figure 15 b) tenon-mortise joinery using metal bars of 20 mm see Figure 22. It was also the first study to analyse the theoretical framework in practice to gather as much information as possible regarding scanning and fabrication. The first 8 beam prototype employed saw-blade cuts and surfacing using a milling bit. While the joint allows a large contact area, the fabrication in 2 sides resulted in high impression value (5-10 mm) and machining time because each beam had to be rotated 180 degrees due to the reachability of the robot. The second prototype is designed with the fabrication constraints by means of simple tenon-mortise joint that could be fabricated from both sides without rotations. The model is designed as two-layer system due to a high span of the structure. Future investigations are planned to improve the joinery further and understand whether the two layers are needed along the full surface of the shell.

4 DISCUSSION

The raw-wood fabrication is possible due to software and hardware developments that helps to transform timber to pre-determined design models. One of the main questions needed to be discussed is how much of irregularity needs to be taken to account and whether it could be ignored. The prototyping showed that even for the straight beams the deviation from a straight axis was up to 6 cm. The straight tree trunks have a considerable curvature because the radii are small. The larger a tree trunk the more regular beam is and this is why the industrial application employs bigger trees even with mechanical rounding. On the other hand, the crooked timber including bent and bifurcated forks should be used more often because currently it has no value in existing forestry while being a valuable structural material. The software and hardware methods could be improved further to increase the fabrication speed by optimizing tool-paths, machining tool-sets, real-time scanning or employing custom build cutting tools such as band and chain-saws. During the fabrication several beams had to be re-cut, questioning the role of the stock and its unique pieces. Furthermore, the stock assignment could be relatively simple for small scale prototypes and pavilions but how one can manage data for hundreds of beams for both machining and design? Nevertheless, the research application shows that such methods could be employed locally without a link with large timber fabricators which proves a local circular economy viable. Future experiments will focus on a truss system employing tree forks to test the methodology within branched tree topologies. Lastly, the framework will be then integrated into structural engineering design developed by Rezaei Rad et al. [28, 29, 30].

5 CONCLUSION

The paper shows a methodology built for a raw-wood fabrication using a laser scanner and an industrial robot arm. There is a close link between the hardware control and the software development to realize the timber joints with external connectors. Currently, the methodology emphasizes the micro scale – joinery to prove the proposed tool-set. The study cases helped to understand what precision is necessary when working with crooked timber and what fabrication tolerances are allowed. Additionally, the workflow is closely linked to the possible movements of the robot and tools it employs that differs from the manual craftsmanship. It also shows that the control of digital tools helps to work with raw-wood with minimal carpenter skills if the setup is already well-defined. Further studies will focus on design methods with irregular raw-wood to understand how the timber stock could influence the design of the global geometry.

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