

Tree Fork Truss

Geometric Strategies for Exploiting Inherent Material Form

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Abstract

Most recent developments in architectural geometry pursue formal complexity through non-standard building components that are digitally defined and fabricated from standardised material. An alternative approach is proposed in which non-standard materials are used a priori by exploiting their inherent geometric forms through metaheuristic optimisation placement techniques. The rationale for this approach is that the diverse characteristics of near-site material can be exploited directly without wasteful industrial processing to first standardise and then add variation back to the component geometries.

This proposition is tested in the Wood Chip Barn project completed by Design + Make at Hooke Park, in which a series of strategies allowed the inherent natural geometries of forked wood to be exploited. The application of 3D-scanning, evolutionary optimisation of the placement of each discrete component within a structurally determined arch, and customised robotic fabrication are presented as enabling an alternative conception of material form in which inherent irregular geometries are actively exploited by non-standard technologies.

Keywords:

natural material, inherent form, 3D-scanning, fabrication, robotics



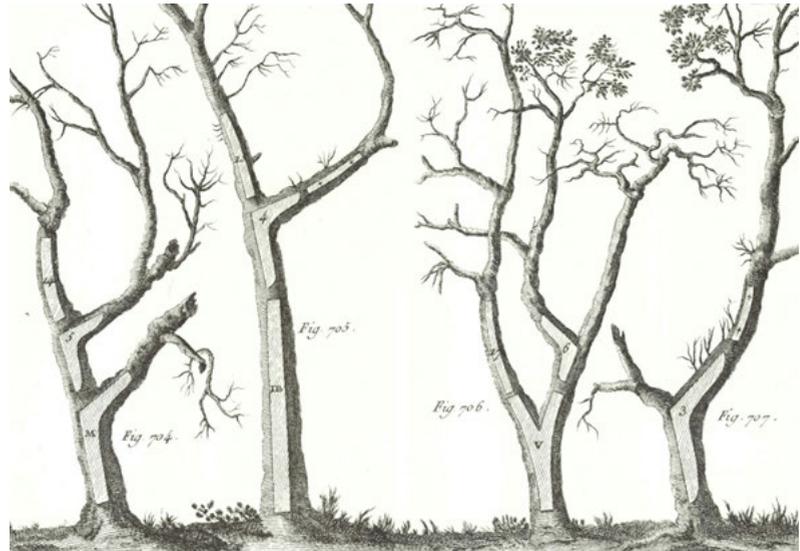
Figure 1. The Wood Chip Barn's arching truss.

1. Introduction

While wood has seen a resurgence as an advanced architectural material, the complex and organic forms pursued are generally not attributable to the inherent geometric and anisotropic structural properties of wood. Instead, subtractive digital fabrication processes are often used to create complex components from standardised and homogenised wood products that have been glued together to ensure consistency (Self 2016, 1). However, before processing, trees and other organic materials already present what digital tools are commonly employed in pursuit of: a non-standard series (Carpo 2011, p. 105). Thus, a wasteful redundancy becomes apparent in which material is processed two or more times to achieve characteristics that may already be present in the original material. Analogous to the intuitive assembly of a dry-stone wall from irregular rocks or the application of specifically curved timbers in traditional ship building, alternative conceptions of design and fabrication process have recently been proposed (Monier et al. 2013; Stanton 2010; Schindler et al. 2014) which address this redundancy.

In a standing tree the naturally occurring branching forks exhibit remarkable strength and material efficiency, able to carry significant cantilevers with minimal material. The Wood Chip Barn project revisits the traditional methods that used curved and forked timber sections in the fabrication of wooden boat hulls in the 17th and 18th centuries. In need of a range of non-linear components, ship-builders selected appropriate materials based not only on the geometric form of pieces of wood but also an understanding of the strength of their grain. By aligning the grains of these branched members which had grown in response to

Figure 2. A plate from the *Encyclopédie Méthodique* (1782) which illustrates various naval timber components traditional boat-builders sought from curving and branched trees.



specific loads they had carried while standing into their designs, boat-builders were able to construct stronger vessels (Matthew 1831, 15).

The present work tests the premise that the integration of digital tools including 3D-scanning, parametric control modelling, and robotic fabrication enable sophisticated exploitation of the inherent qualities of natural materials such as wood. The building's primary structure is an arching truss consisting of 20 discrete beech forks that were 3D-scanned and optimally configured for structural performance before receiving robotically machined connection geometries that define their relationship to each other. The inherent geometric forms and structural potential of naturally grown tree forks (Slater & Ennos 2015) from Hooke Park's forest were deployed to create a long-span structure with minimal machine processing.

In this paper four key strategies are elaborated: the development of a precise geometric referencing system to ensure consistent placement of each component independent of its irregular surface features; the photographic and photogrammetric techniques deployed to identify and 3D-scan appropriate tree-forms to build a database of available geometries; the metaheuristic evolutionary optimisation of the placement of each discrete component within the structurally determined arch form; and the strategies employed in the robotic tool path generation for the connection fabrication to ensure overall dimensional precision independent of the local material irregularity.

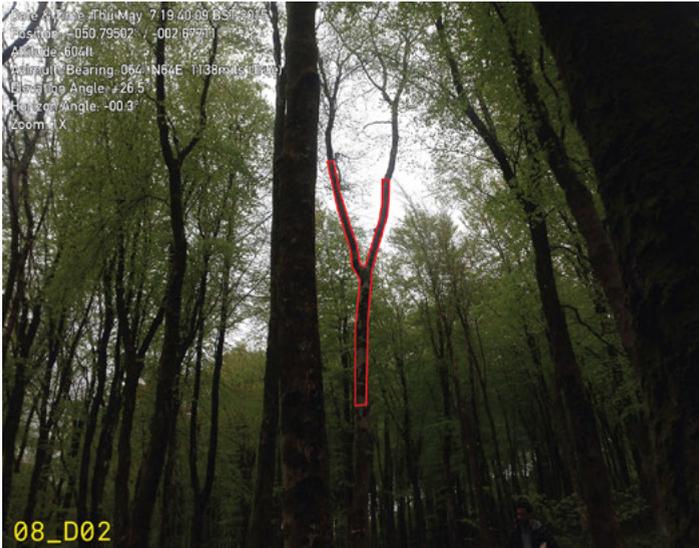


Figure 3. Approximately scaled 2D outlines were generated for each of the 204 forks photographically surveyed.

2. Methods

2.1 Establishing a Database

Historically, shipbuilders travelled into the woods equipped with a set of templates describing the specific forms they required to construct various components. The introduction of digital tools in this project allowed the use of a wider range of geometric forms as the eventual structural form was derived from the specific character of each component found rather than finding forms which would fit within a predetermined design. Two databases of tree-fork geometries were established. First, a photographic survey of 204 standing beech trees provided approximate two-dimensional fork representations with enough detail to make informed decisions on which trees to cut down. Following the harvesting of 25 selected trees, a second more detailed 3D-scan of each fork was carried out which allowed for the development of the final truss configuration from these forks' specific geometric forms.

For the two-dimensional survey, a scaled polyline outline was generated by tracing a photograph of each fork, then correcting for parallax error according to the photograph's inclination angle and distance from the tree. An analysis of this database gave an understanding of the variations in the geometric characteristics such as the included angle between branches and minimum diameters, and, by extracting GPS location data, patterns within the forest with the aim of identifying forest compartments with the most promising forks. From this analysis a short-list of 40 forks to be considered for felling was generated based on geographic proximity to each other, as well as a minimum angle of opening and minimum

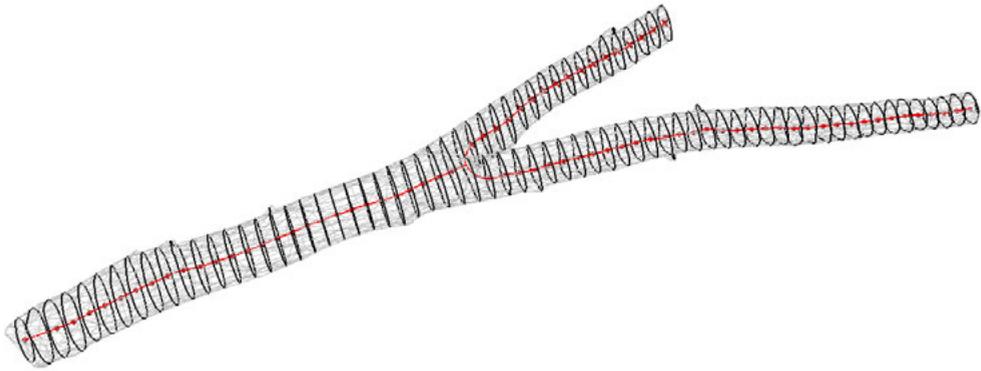


Figure 4. Medial curve generation from best-fit transverse circles.

diameter which were determined in working with engineers from Arup based on early iterations of the truss form. Of these, 25 beech forks were successfully harvested. Once transported back to the yard, a detailed photogrammetric 3D-scan was made of each in order to capture their complex forms. The resulting surface mesh geometry was used as the basis of centre-curve and diameter approximations that informed the subsequent placing of the components.

Traditional timber framing methods include the projection of straight centrelines and axes onto irregular pieces of wood. Measurements are then taken outwards from this arbitrarily introduced centre geometry to ensure that variations in the tree's form have no bearing on the overall organisation. For this project, rather than straight centrelines, centre curves were defined using a polygon-based method in which transverse sections were cut through each fork at regular intervals to obtain the outer profile of their geometry and then local best-fit diameters and centroids calculated for each profiles' section which were interpolated to generate the medial curves.

Throughout the project, a fundamental consideration was how to ultimately achieve construction precision when the original material exhibited complex irregularities. The whole workflow – from standing tree to standing building – was organised around a consistent system of geometric reference (in physical and digital realms) to ensure precision in the location of the components, and thus the relative position of the fabricated surfaces, even though the actual natural form was not precisely known. This referencing system simply consisted of three points that were physically created on the tree fork components by drilling three reference holes to define a local origin point, orientation axis and plane

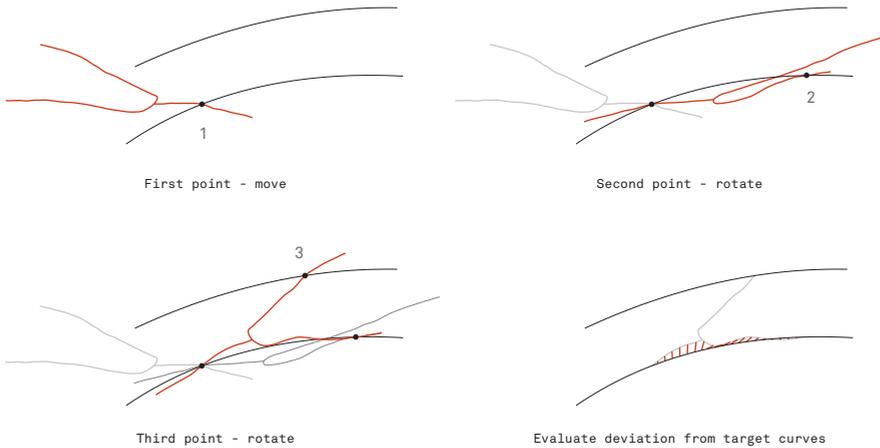


Figure 5. This image illustrates the transformations each fork underwent in being oriented to the truss target curves. Once placed, its deviation from the target curve was evaluated as a fitness parameter.

analogous to a local construction plane in 3D-modelling software. These holes were picked up in the 3D-scanning process so that they could be incorporated in the digital modelling processes and ultimately transferred back to the physical realm by being used as the supporting points when the fork component was mounted in the robot cell.

2.2 Metaheuristic Component Organisation

The tree forks are employed within a Vierendeel-style¹ arching truss, whose global geometry was determined to take account of the initial analysis of the available forks. The Vierendeel configuration exploits the structural capacity of the fork junction that provides the rigid moment connection that enables the construction of a non-triangulated truss. The arch structure is composed of two planar inclined arched Vierendeel trusses whose lower chords are connected by lateral elements. The structure lands at four points, the front slightly wider than the rear, with four inverted tripod legs supporting the robotically fabricated mid-section.

The Grasshopper plugin for Rhino was used to develop an organisation procedure capable of dynamically placing forks within the truss' target curves. An individual fork was located within the truss through a sequence of three transformations: (1) moved to an assigned point on the lower target curve; (2) rotated 3-dimensionally such that its stem contacts this same curve at a second point; (3) a second rotation performed using these two points to define an axis allows the branch to find its third point along the upper target curve. This placing logic was repeated for every component in each iteration of the optimisation.

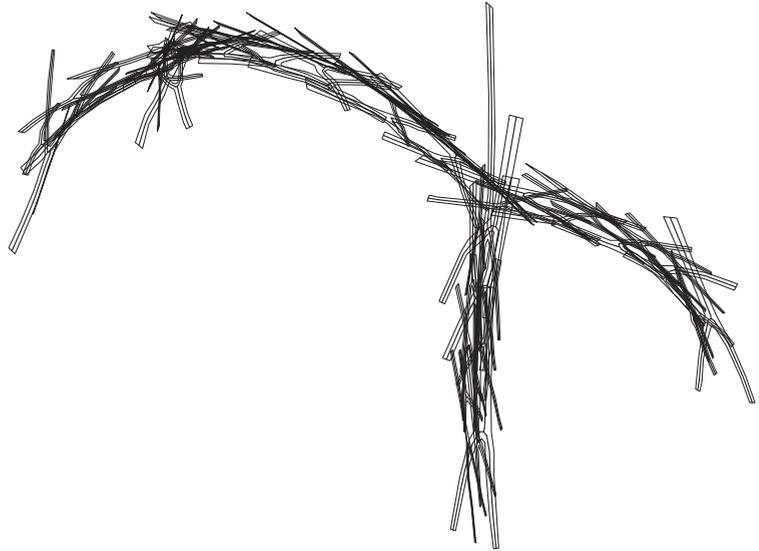


Figure 6. An early test of the optimisation scripting using 2D outlines of forks and their respective centrelines.

The procedure followed in organising the tree forks was to initially define the ideal ('target') inverted-catenary curves for the truss chords, and then to seek the optimum arrangement of the forks, in terms of their location within the structure and their exact local positioning, so as to best satisfy structural requirements. To minimise non-compression forces throughout the arched truss, the primary parameter evaluated in optimising the truss was the total deviation ('offset') of all 20 forks' root and stem curves from the target curves. As the placement script became more developed, a number of secondary parameters were added which addressed specific material and fabrication requirements of the truss. For example, conditions were added to ensure a minimum 300-mm gap occurred between connections as well as controls to ensure that forks which had to pass by each other did not clash.

Within the organisation process, forks were allowed to move both globally (occupying different positions within the truss) and locally (shuffling within that position) with the aim of minimising the summed offset dimension. In order to allow the truss' fitness to be optimised for the stated parameters in a controlled manner, a series of 20 integers were used as index values for selecting forks from the database of available geometries. Because the harvested forks were each longer than their required size, the individual forks were allowed to slide between the two points that define their position, to find the location where they best match the arch chord curve. The overall optimisation process was governed by 56 separate variables that would result in approximately 1×10^{59} possible solutions. In order to address this very large search space, metaheuristic processes were implemented in an effort to find appropriate solutions through

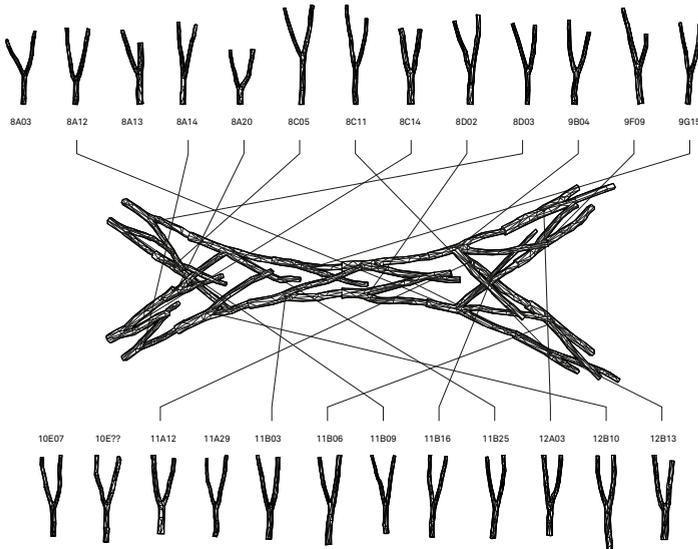


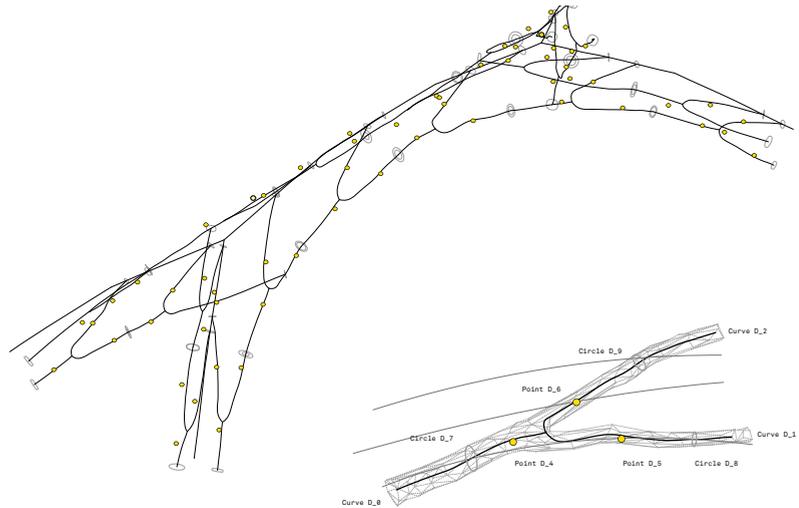
Figure 7. The Wood Chip Barn's arching truss.

partial searches rather than truly optimal solutions. Within the Galapagos component developed by David Rutten for Rhino-Grasshopper, both the Evolutionary and Simulated Annealing solvers were used. The role of the human operator remained significant, and a number of strategies were implemented in order to aid the solving algorithms, as discussed below.

The allocation of real physical stock within a structure presents a particular challenge to optimisation processes. Whereas adjustable variables within an optimisation typically refer to abstract quantities or proportions and building components are later derived a posteriori from a final geometry, in this case selected discrete integers refer to actual objects. As such, in order to select 20 forks to populate the truss, a list of 20 unique, non-repeating reference integers must be generated as forks cannot be in two places at once. The difficulty lies in avoiding duplication while allowing each position to select a value with equal priority. One option would be to null any iteration in which a selection is repeated but the permutations for selecting 20 objects a list means that only about 0.001% would be admitted and thus too inefficient computationally. Another option would be to randomly assign shuffled sequences of fork objects in each iteration but this would lose any correspondence between iteration cycles, resulting in an overly stochastic search.

The strategy that proved most successful was to assign the forks to locations sequentially, accepting that the first location that was populated was likely to have better fit success than latter locations that have a smaller set of remaining available forks to choose from. This was used to our advantage by dictating that queuing sequence according to which positions within the truss were more

Figure 8. The final wireframe drawing output from the optimisation scripting. All of the digital fabrication information was developed from these geometries.



difficult to populate than others, thus requiring more specific or uncommon fork geometries (examples include those which cross each other). These positions were placed higher within the selection queue, allowing them to take priority over those positions that might be more easily filled.

A related strategy that was found to help improve the metaheuristic search was to sequence the discrete set of available forks according to their geometric similarities. This helped the optimising solver because it meant it was presented with variables in which there was a correspondence between variations between forks and their position in the integer sequence that indexed them. To generate this sequence, a script was written which, by comparing each fork's three centre curves, was able to rank the remaining 24 forks in a logical order by their geometric similarity to the first. While this 'similarity' represented a significant simplification of these complex 3-dimensional forms, it was observed that this reordering increased the ability of the solver to generate meaningful truss configurations. Although with just 25 forks the steps between them remain quite significant, it is presumed that a larger database would with surveys of enough forks begin to result in a smooth progression of geometric forms and thus enable a less stochastic search.

From the optimisation script, a series of possible truss iterations were output, and geometries provided to the engineering team for analysis and comparative quantification of the structural performance.

By automatically drawing these lines to layers based on local fork diameters, the performance of the truss could be accurately and swiftly evaluated by the engineers for a large number of iterations. In working with the engineers, one of



Figure 9. Development of the mortise and tenon connection.

these iterations was selected and this arrangement further refined. With a final truss geometry confirmed, the optimisation script was used to output a model with all of the geometry needed to derive the necessary digital fabrication information – 60 curves, 60 points, 60 radius circles, and 20 meshes.

2.3 Connection Definition and Fabrication

The strategy for the connections between the truss components was to maximise the use of compression transfer through timber-to-timber bearing and to use steel bolts and split rings to provide tension and shear capacity where needed. The connection bearing surfaces were all formed by milling using a router spindle on a six-axis robot arm. Additionally, the router was used to drill pilot holes and make locating marks for the steel hardware, and to drill further geometric reference holes for the truss assembly. Three categories of connections were fabricated. Firstly, a set of 36 axial connections between components along the truss chords were formed by milling matching planar end-faces on the pair of meeting components, which were tied together using pair of steel cross-bolts. These two planar faces, on two different pieces of irregular wood, needed to be precisely positioned and oriented 3-dimensionally so that the compression force would be transferred evenly.

Secondly, an oblique through-bolted mortise and tenon connection was used to connect the end of the branch elements to the top chords. The timber interface geometry for this connection became relatively complex as a consequence of needing to provide sufficient compression area whilst allowing for diversity in the position of the surrounding wood surface and also having a geometry that could be formed within the access constraints of the robot arm. A form similar to a truncated elliptical cone was found to best satisfy these criteria. A further subtlety was that while the compression-bearing surface was precisely milled as a smooth surface, the non-loaded surface was best milled as a series of contour

Figure 10. The robot arm machining one of each fork's two bearing surface.



steps. Thirdly, a simpler set of planar 'seat' surfaces were defined and milled, to which smaller reinforcing timber truss members were screw connected.

To create the connection geometries, a pair of corresponding 'subtraction volumes' was defined for each of the pair of elements meeting at a given connection. These subtraction volumes – co-planar on their shared faces – consisted of geometric primitives (cuboid, cylinder, truncated cone) and represented the volume of the wood material to be removed to leave the required connection surface in its correct precise position. Intentionally, these subtraction volumes were oversized when compared to the actual pieces of wood (i.e. larger the fork's local diameter) to allow for irregularity in the wood's surface and thus ensure that all of the existing wood would be removed as required. In other words, there was always some 'milling of air' to provide tolerance for inaccuracies of the surface scan. This was one of the fundamental strategies for achieving connection precision whilst allowing for variability in the surface of the irregular natural material.

The output of the fork placement optimisation process was a 3D-model comprising sets of points, curves, and meshes that defined the component positioning, centre-curves, and surfaces, respectively. The spatial location of each fork component was defined using the three reference points from the original scan that defined its local coordinate system. A further three nodes defined the intersections of the centre-curves with the truss chord curves for each element; these nodes are shared with neighbouring elements and locate the connection geometries. At each of these connection nodes a set of vectors was defined that represented the local tangent directions of the two or three incoming elements' centre-curves.



Figure 11. The front half of the truss being assembled within the Big Shed. In this image, all ten forks are loosely braced together before any connections have been made.

This set of minimal information for each connection – the three direction vectors and the xyz coordinate of the connection node – was the input for the generation of the connection surface geometries. Notably, the surface mesh data was not used directly in defining the connections; it was only used to check that the connection milling volumes would wholly capture the available wood. These subtraction volumes were geometric primitives defined relationally from surrounding nodal and vector information. Once defined, these volumes were populated with routing toolpaths defined using Grasshopper.

The robotic fabrication cell consisted of a fixed-position 2.7 m reach 6-axis robot arm carrying a routing spindle, and an adjustable 'trolley' that carried each fork for machining. Three vertical steel dowels, located in a horizontal plane, supported the fork at its reference holes, ensuring correct positioning of the fork within the robot workspace. The trolley itself was able to move longitudinally, acting analogously to a seventh-axis rail and enabling the robot to access the various parts of the tree for fabrication.

Machining finished, a large assembly jig made up of CNC'd sheet material and wooden studs was constructed in the Big Shed in order to precisely join together these large and complex building components. The truss was preassembled in two halves – each approximately 8 m x 6 m. This jig needed to allow the positioning of all ten forks in each half with respect to each other precisely and stably, as no connections would be made until all of the components had been loose fit together. In order to allow this, a second three-point reference system was established. The last procedure performed by the robot arm on each fork was to mill a second set of three reference holes - each drilled such that they would

Figure 12. A drone photo of the Wood Chip Barn's primary structure erected on site. Spanning 25 m from front to back and 10 m side to side, the arching truss rises to 8.5 m at its zenith.



be vertically oriented once the fork was properly positioned above the jig's floor. Corresponding to these points, three square pockets were cut into the 18 sheets of oriented strand board (OSB) by the CNC for each of the 20 forks, a simple vertical support then rising from each pocket to allow the reference points to be precisely set out in X, Y and Z.

Forks were lifted into place one at a time and temporarily braced. With ten forks positioned and approximately fitting, the robot-fabricated top chords were lifted in to place. With all of the major pieces held together as a loose system, the assembly team moved around the truss with hammers, straps and a Rhino model, adjusting each piece to as close to its intended position as could be achieved.

3. Results, Reflection, and Conclusion

With the preassembly completed, the two halves of the truss were moved to site where they were craned in to place and connected. The ease with which these large pieces came together is seen to demonstrate the success of the geometric strategies previously described in the processing of inherently non-standard materials. With its scaffolding removed, the truss was left self-supporting – its rigid, naturally formed forked components working together to allow a non-triangulated truss to stand stably. Spanning 25 m from front to back and 10 m side to side, the truss rises to 8.5 m at its zenith. Subsequently roof panels were added and the Wood Chip Barn building completed.



Figure 13. The structure fully loaded with its roof added. The complex form of the truss contrasts with the regular lines of the roof above. Image: Valerie Bennett.

Throughout this work digital technologies were used to convert low-value branched section of trees into complex and valuable building components while using a minimal amount of energy. In combining 3D-scanning, metaheuristic optimisation and customised robotic machining with traditional timber framing practices this has been done without significant increase in production time over a similar structure composed of standardised materials – the fabrication and construction of the building taking place in under 6 months. That the Wood Chip Barn project was realised by a student team using low-cost software and local resources is seen to prove the viability of a design-fabrication workflow in which the inherent geometric forms of materials can be exploited and deployed.

As, we believe, the first full-scale materialisation of these concepts, each of the individual processes within the workflow might be further developed and refined. For example, the survey from which components were selected for inclusion in the structure documented just 204 trees from the Hooke Park estate. A survey of this kind might be expanded to include thousands of available tree forms from a number of forests, and in doing might progress to be capable of allowing an understanding of how variables such as topography and climate affect the development of specific tree geometries for construction purposes. As

well, the optimisation process could be developed to integrate real-time structural analysis as well as a sensitive consideration of wood's unique grain patterns. In allowing the global form to be adjusted in accordance to performance and local material properties, this might allow for a greater degree of design flexibility and a return to the sensitive treatment of material in traditional buildings.

While the Wood Chip Barn project focuses on the exploitation of naturally occurring materials – in this case branched trees – the geometric strategies developed throughout might readily be applied to other materials with inherent form such as recycled industrial building components. In an era in which architects commonly seek to both add geometric sophistication to built forms as well as to reduce the embodied energy of their projects, lessons from the work outlined in this paper have significant implications. The on-site processing of near-site material by a generic industrial robot arm serves as an example of distributed manufacturing processes that fully exploit the potential of new digital tools and technologies. The non-standard aspect of the structure achieved is derived directly from a specific material's inherent forms.

Endnotes

¹ A Vierendeel truss arrangement, more commonly found in steel structures, is one in which the truss gains stability by rigid moment resisting connections in place of triangulation.

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