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Three experiments in wood and computational design

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Abstract

This article focuses on the relationships among material-oriented design, digital technologies, and environmentally-responsible construction. It argues that computational design methods and digital manufacturing have the capacity to open new opportunities for design and lead to more sustainable practices. Through an analysis of three experiments in design and construction, the research seeks solutions that use the inherent material properties and behavior of wood to replace toxic chemicals, metal connectors, and energy-intensive processes. Offering an alternative to design processes that begin with theory and representation, this paper proposes a different approach, beginning with experiments in materiality. This approach involves methods based on rational reasoning rather than intuition.

Keywords

Wood, Material-oriented design, Digital manufacturing, Design methods.

Introduction

The architectural profession is facing increased pressures posed by emerging environmental problems and quickly developing digital technologies. These pressures require changes in design practice. Previously subordinate design considerations are now at the fore. These include construction technologies, materials, and environmental analysis. This is a radical departure from design practices founded on Modernist and Classical approaches in which ideas dominate over matter and pragmatic considerations. New approaches are inherently countercultural in the discipline of architecture, opposing well-established hierarchies and the accepted order.

This research focuses on the relationships among material-oriented design, digital technologies, and environmentally-responsible construction, asserting that computational design and digital manufacturing have the capacity to unlock latent potentials in materials. This capacity is demonstrated through an example of wood shaping and connections informed by material properties and behavior rather than external agents.

The following discussion argues for an alternative approach to design, one that asserts a material-oriented design process, where real environmental benefits can be sought as a result of using digital technologies. Through the discussed examples, *material agency* is considered as a critical aspect of the design process, where some design responsibility is ceded to the material. This process is not meant to disrupt design, but to contribute to more sustainable practices.

Methodological approach

Although not perceived as the mainstream approach to design today, a material-oriented design approach was prominent in the history of architecture, and the roots of this thinking can be found in the making and crafts of the Middle Ages. This history can be traced through the writings and works of Philibert de l'Orme (1514-1577), Carlo Lodoli (1690-1761), Viollet-le-Duc (1814–1879), Auguste Choisy (1841–1909), Adolf Loos (1870-1933), Frank Lloyd Wright (1867-1959), and Louis Kahn (1901-1974). Although these architects laid a foundation for material-oriented design, they did not provide a working method for it. Their notion of culturally conditioned material agency was based on “metaphors ... very difficult to use ... as a basis for a more operational understanding of the form-material relationship” (Sandaker 2008, 24), and “not generally robust to the point of promoting an inventive interaction with materials” (Fernandez 2006, 9). As a result the concept of *truth to materials* is rendered irrelevant today, on the one hand by emerging fields of material science, such as nanotechnology, where materials are seen as the objects of design, and on the other by the course of decontextualization of materials, related to the processes of globalization (Moravánszky 2000).

A more systematic approach to material-oriented design was presented by architect-engineers of the 20th century. Frei Otto (1925-2015) and Heinz Isler (1926–2009) who integrated the scientific method based on experiments and cause-and-effect explanations with their working process. Both Otto and Isler developed various form-finding methods using membrane models, suspended nets and cloths, soap films and bubbles, glue, paper, sand, or the wool thread machines, with an objective to rationalize the design process and optimize structures. Their methodology, based on logical reasoning, lends to being reproduced or improved. Most importantly, Otto and Isler succeeded in constructing structures that achieved impressive spans while minimizing the use of

material. Their projects resolved the problem of form respecting material's self-organizational capabilities, while achieving real savings in material, time, and energy.

Despite these achievements, the process that integrates design and the scientific method could be criticized for being reductionist, since it is based on a single objective optimization. As such, Otto and Isler's design methods are not capable of informing a design method that could be generally applied in architecture, which is concerned with systemic problems (Kotnik 2011, 27-29). This criticism defines a starting point for this research, where the emphasis is shifted from form-finding an efficient shape to environmentally-responsible process-finding for a single component. The component then dictates the assembly logic, which can be used in a structure derived by a different process.

The following examples focus on this component logic, and computational design and digital manufacturing are investigated to access and harness phenomena already existing in wood.

These experiments should be viewed as indicators of a direction rather than fully developed solutions. They were conducted as part of a wider research in order to illustrate a theoretical and philosophical position. While this broad context of the research is beyond the scope of this paper, the presented aspect of the research is sufficient to discuss the computational implications of the approach. The experiments were not designed and carried out as engineering studies, and as such were not subject to strict technical scrutiny. Notwithstanding the lack of technical standards and testing, they prove the potential of the approach and open way for further replication, development, and improvement. In this light, except of being illustrative, they should be seen as early prototypes of possible technological solutions.

To this end the methodology of the experiments is based on the scientific method. In order to produce comparative results the number of variables in the experiments (1) BackToBack and (2)

Swelling Vault were minimized to one: the geometry of the incisions in BackToBack and the pattern of wood blocks in Swelling Vault. Other parameters, such as the wood species, moisture content in wood, geometrical constraints of the pieces, and environmental conditions were kept constant in order to test the effect of the change of this single variable. The experiment (3) Y-timbers tested the feasibility of digital technologies in dealing with naturally grown shapes of wood, and was not based on the scientific method. The methodological approach aim was to compare variants and indicate possible directions for development and more rigorous testing.

Three material experiments

(1) BackToBack

Aim of the experiment

The aim of the experiment was to demonstrate an alternative method of connecting solid timber members for producing cross-laminated panels. The solution avoided glue and metal connectors by working with forces existing in green wood as it dried.

Precedents

Cross-laminated timber (CLT) is still considered a recent invention in wood building technology although this technology has matured since its appearance on the market in European Alpine countries in the early 1990s. Its production involves laminating wooden planks by means of polyurethane glue, a non-biodegradable synthetic polymer. CLT panel construction systems rely

on metal connectors for assembly. These solutions are problematic when the entire lifecycle and recycling of the component are considered¹.

An alternative path of development has been shown by Julius Natterer, German engineer and professor of wood construction at the École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland, who has worked with stacked-plank panels since the 1970s. His system, called Brettstapel², avoids toxic adhesives and allows all-wood components in production, using dry beech dowels that swell by drawing moisture from the elements that they connect.

A similar principle is employed in the production of NUR-HOLZ³ (timber-only) elements, produced by the firm Rombach in Austria since 2009. The durable panels can be used as walls and floors. Instead of glue (or dowels, as in the case of HOLZ100 system) the layers of timber planks are connected by means of hardwood screws. The system does not exploit the behavioral potential of the material, like swelling, but it achieves an adhesive-free bond to yield a commercially viable product.

Additionally, an Interlocking Cross Laminated Timber (ICLT) system has been developed at the University of Utah. ICLT avoids the use of adhesives or metal connectors in the manufacture of panels by using dovetail-joints. The panels are designed to make use of waste wood, beetle-kill

¹ Metal connectors, e.g. self-tapping screws, brackets, plates and bolts, are problematic for three reasons: (i) They impede recycling of wooden components due to the difficulty with parting-out in a demolition process, thus only about 0.03% of industrial wood comes from recycling (calculations based on Addis (2006)). (ii) Metal fasteners penetrating wooden beams in unheated rooms rust where the galvanized coating has been damaged by abrasion upon entering the wood, causing the surrounding wood to rot due to condensation on the cold metal. These processes are delayed by using toxic, chemical wood preservatives (Graubner 1992, 6). (iii) During a fire, metal fasteners become red hot after only 15 to 25 minutes causing structural failure of the joints and quick collapse of the building: *the wood-to-wood joints guarantee burning buildings a longer resistance than do metal-to-wood joints* (Graubner 1992, 4-5).

² See <http://www.brettstapel.org>.

³ See <http://www.nur-holz.com>.

pine, a sub-standard timber material abundant in North America after a longhorn beetle infestation. Boards are CNC-milled to form interlocking elements that provide bonding action for the panel. Similarly to CLT, the ICLT panels can be manufactured in many variants with different numbers of layers and corresponding thicknesses for different structural and physical parameters. Two experimental buildings have been constructed in Utah using the technology (Smith 2011).

These precedents frame the context for the first material experiment for which the main objective was to test the viability of CNC machining for producing a connection based on wood shrinkage.

Materials sourced

This project used halved wood logs with the cut faces as the finish, while the raw round backs were directed to the inside and used for connection. The connection was based on the material behavior of wood, whose anisotropic shrinkage was activated when green wood dried.

Anisotropic shrinkage is where wood shrinks at different rates tangentially, radially and longitudinally to the log axis (Figure 1).

Norway spruce was chosen for the experiment. The acquired roundwood was frozen and processed while still green. Our test pieces indicated 5% tangential shrinkage⁴ after 2 weeks of keeping the wood at room humidity and temperature⁵.

⁴ For Norway spruce, depending on the sources consulted (Dinwoodie 2000, Falk 2010), tangential shrinkage amounts to between 4–7.8%, radial to 2–3.6% and longitudinal to <0.1–0.3%.

⁵ Approximately: relative humidity = 30-40%, temperature = 20-22°C.

Figure 1. Anisotropic shrinkage of Norway spruce. Photograph by the author.

Description of the experiment

The BackToBack method aims to provide a permanent bond using an all-wood joint. The joint components are assembled using only manual labor. The permanent bond was created by connecting green wood, which becomes inseparable after drying.

Two design paths were followed:

Figure 2. BackToBack, two design paths. Drawing by the author.

(i) *Dry-in-wet*. The connection mechanism was based on green wood tightening on dry wood while shrinking. Dry wood inserts were fitted into the receiving incisions in green wood.

(ii) *Wet-in-wet*. The connection mechanism was based on green wood's anisotropic shrinkage. Special incisions were CNC-cut to harness the tangential shrinkage on the active side of the panel, which then causes tension on the passive side⁶:

⁶ The active side of the panel is the part that shrinks, while the passive side is the part that does not shrink.

Figure 3. Tangential (T) and longitudinal (II) shrinkage as connection mechanism (orange lines indicate sizes after shrinking). Drawing by the author.

(i) Dry-in-wet

This project tests and demonstrates how green wood shrinkage activated through drying can be harnessed to create tight connections between wood components.

A series of linear 20 mm incisions were cut at various angles to the halved-log axis on the bark side (Figure 4). Dry pine boards 20x120 mm were used as inserts. The resulting interstitial spaces between the boards could be used for thermal insulation, e.g. by means of injecting cellulose fiber insulation.

This experiment was based on the assumption that the oblique orientation of the incisions would harness the tangential shrinkage in green components and tightened on the dry inserts. The research interrogates the distribution, geometry and dimensions of these incisions and inserts by testing multiple variants.

Figure 4. BackToBack dry-in-wet. Photographs by the author.

(ii) Wet-in-wet

This experiment demonstrates and tests how anisotropic shrinkage activated on drying could be used for producing all-wood connections in solid wood panels composed of two interlocked milled logs (Figure 5).

A series of waving incisions were CNC-cut perpendicular to the halved-log axis on the bark side (Figure 6), in order to produce actively shrinking areas of the panel, harnessing the tangential wood shrinkage⁷.

Both hand tools and a CNC milling machine were used in the fabrication process. The use of hand tools was a potentially limiting factor for two main reasons: (i) it did not permit sufficient precision to accurately assess the results, and (ii) as a result of the conical, half-round cross-section and irregularity of the individual logs additional work time was required to readjust the machines.

⁷ See <https://vimeo.com/192351147>.

Figure 5. BackToBack wet-in-wet. Photograph by the author.

The abovementioned problems resulted from the CNC-machining process as well, though these could be more easily overcome by using a different software and hardware setup. It has been noted during the experiment that CNC machining of green timber requires high spindle speeds. While the pieces machined at 6,000 rpm required a great deal of post-processing (sanding), increasing the spindle speed to 18,000 rpm⁸ produced very smooth surfaces, where no manual work was required. As a cutting tool a standard flat nose milling bit was used.

The width of the incisions shrank after drying and tightened on the receiving ribs resulting from the identical incisions cut parallel to the log axis on the corresponding passive elements of the panel. The incisions along the log axis were passive, as the longitudinal shrinkage ratio is negligible.

⁸ In FabLab's milling machine setup, 18,000 rpm is available as a standard (Shopbot PRS Alpha with HSD 4HP spindle).

Figure 6. CNC-cutting. Photograph by the author.

Results

The main task of the prototypes was to promote an approach that makes use of material properties and behavior, instead of attempting to overcome them. Log processing time and effort were minimized by only halving and/or debarking the logs, instead of sawing on four sides prior to cutting the incisions. The connection utilized properties already present in the material without any external bonding agents thereby eliminating toxic and composite connections, making the panel biodegradable and recyclable. In this case the tests performed demonstrate that it is possible to construct a behavior-based wood connection, opening the way for further study.

Laboratory structural testing was beyond the scope of this experiment, so the connection of the pieces was only examined by measuring shrinkage, and manually, by attempting to separate them. These tests indicated that the *wet-in-wet* method is more promising and worth pursuing. All samples, regardless of the patterns and initial fit, produced a bond after drying that was inseparable by manual force. The *dry-in-wet* method also produced a connection after drying,

however not as strong as the wet-in-wet method -- it was possible to manually separate the pieces by applying strong force. The measured shrinkage of a 20 mm kerf was 0.3-0.7 mm (1.5-3.5%).

If this method succeeded one could foresee large savings in the use of chemicals, energy and time. Further to the environmental benefits, it would result in a construction technique free of harmful volatile organic compounds (VOCs). VOCs can be dangerous to human health, and both the US and EU regulations restrict their use and caution against exposure to them.

(2) The Swelling Vault

Aim of the experiment

The main goal of this material experiment was to devise a method for harnessing phenomena resultant from kinetics of material behavior, and thus to extend the notion of material-oriented design in wood. This approach creates the potential for emergent phenomena where form is produced through interaction between small components, while the meaningful properties of the form are not exhibited by the components themselves.

Parquet buckling, an inspiration for the project, is a well-known and undesired phenomenon caused by increased moisture content in wood. The aim was to replicate it and to test how the buckled shape had been affected by various block patterns, and how the emergent shapes could be predicted by digital simulations.

Precedents

This project does not have direct precedents; the swelling of timber has not been used as a forming technique. However, tangentially related are research projects that investigate the design potential of wood in response to environmental humidity. One such example is HygroSkin

Meteosensitive Pavilion⁹, FRAC Centre Orleans, by Institute of Computational Design, Universität Stuttgart (Achim Menges, Oliver David Krieg, Steffen Reichert; 2013). The pavilion contains apertures that open or close based on curling of the wood skin induced by changes of humidity in the surrounding air.

Materials sourced

The raw material used in the experiment was oak parquet blocks, 20 mm thick, by 100 mm wide, and 900-1,000 mm long, with a moisture content of 8%.

In order to compare results, two identical 1,700x1,900 mm oriented strand board (OSB) bases with edge constraints were constructed. It was decided to lay two different patterns: *checkered*, using 100x100 mm square blocks laid with alternating grain orientation; and *herringbone*, using 1,000x100 mm elongated rectangular blocks. The edge blocks had to be cut to fit in the base.

Figure 7. The Swelling Vault, checkered and herringbone block patterns. Drawing by the author.

⁹ See <http://www.achimmenges.net/?p=5612>.

The patterns were as anticipated to be the most extreme cases for comparison within the limits of our available material; the herringbone pattern consisted of the largest possible blocks and the checkered the smallest, given the 100x100 mm module. Connections between the blocks used the Lamello Joining System (biscuit joint) and no adhesives were applied.

Figure 8. Lamello Joining System. Photograph by the author.

Description of the experiment

The blocks were planed and cut to the desired shapes. In all the pieces, special mortises were cut with a Lamello joiner to accommodate the connecting oval-shaped wooden biscuits. The parquet blocks were laid on the OSB bases with foil sheeting, and the edge constraints and ratchet straps were applied.

Figure 9. The Swelling Vault. Laying the parquet blocks. Photograph by the author.

It was estimated that about 15 liters of water per piece would increase the moisture content of the wood up to approximately 30%. Warm water was poured on the pieces with a watering can. Both pieces were covered with foil and left for some time to soak in water and swell.

Figure 10. The Swelling Vault. Increasing moisture content in wood (left) and the checkered pattern bulging (right). Photographs by Sebastian Kraft.

Results

After a few days, the bulging was significant. The measured moisture content amounted to approximately 26-28%.

The *checkered* pattern bulged to 120-132 mm (depending on the measurement direction). The 132 mm measurement was recognized as more accurate because the OSB base buckled in the direction that yielded the 120 mm measurement. The shape of the surface was regular and domed (Figure 10 right).

Four people weighing approximately 280 kg could step on the 3.2 m² piece causing slow flexible movements with the Lamello biscuits operating as articulated joints.

The *herringbone* pattern bulged to 108-113 mm (depending on the measurement direction). It buckled mainly along the central joint line, forming a conical, almost ruled surface that was much more stable than the dome.

Figure 11. The Swelling Vault. The herringbone pattern bulging. Photograph by Sebastian Kraft.

In parallel with the material experiment, a digital simulation model was devised to compare the results with the empirical tests. The simulator was built in the 3D software Rhinoceros with Grasshopper and Kangaroo plugins¹⁰. In the program 2D block patterns were drawn with the swelling direction of each block programmed as a compressed spring. The rest length of the spring was specified as the width of the block after swelling, estimated based on literature review. The system of springs was set in motion by the Kangaroo physics engine, deflecting the flat pattern that assumed a 3D shape¹¹.

Swelling of the wood was estimated using a formula based on an equation from Covington and Fewell (1975):

$$DC = OD \times SV \times CMC / FSP$$

Where:

DC – dimensional change,

OD – original dimension,

SV – shrinkage value from green to oven dry moisture content,

CMC – change in moisture content,

FSP – fiber saturation point.

¹⁰ Grasshopper is a graphical algorithm editor integrated with Rhinoceros (<http://www.grasshopper3d.com>), while Kangaroo is a physics engine for interactive simulation with Grasshopper (<http://kangaroo3d.com>).

¹¹ See <https://vimeo.com/192333690> and <https://vimeo.com/192333694>.

For our case:

Each block measures 100 mm across the grain, so:

$$OD = 100 \text{ mm}$$

For European oak (*quercus robur*), tangential shrinkage from green to 12% moisture content amounts to 7.5% and radial to 4% (Dinwoodie 2000, 59). As the most common conversion method of timber (through-and-through) yields pieces with a mixture of grain orientation from tangential to radial, so an average value of 5.75% was assumed. Therefore:

$$SV = 0.0575$$

The average measurement of the final moisture content equaled to 27%, while the initial to 8%, thus:

$$CMC = 0.19$$

Fiber saturation point at 30% is based on average value for oak for most practical applications (Ross, Mettem, and Holloway 2007, 24):

$$FSP = 0.3$$

Substituting the above values in the formula yields a 3.6 mm elongation of a 100 mm wide oak block:

$$DC = 100 \times 0.0575 \times 0.19 / 0.3 = 3.6 \text{ mm}$$

Comparison of the simulated elongation of the surface (1,730.6 mm) to the empirical (1,726.7 mm) yielded only 0.2% discrepancy, and resulted in approximately 6% discrepancy between the measured 132 mm and simulated 140 mm for the sagitta¹².

The experiment indicated that the flat layout pattern of wood blocks dictates the bulged 3D shape when the blocks swell, and this shape can be predicted by means of digital simulation. This method can be used to form curvilinear wooden elements without using wasteful and energy intensive processes.

(2) Y-timbers

Aim of the experiment

The aim of this last experiment was to investigate the implications of designing with naturally grown shapes of wood: what design and fabrication techniques are required. The motivation was to challenge existing design logic. In mainstream design practice, materials are selected after the design of architectural form. This experiment used an opposite logic where natural shapes of the wood sourced for the design dictated the type and form of the designed elements.

Precedents

The project made use of the naturally forked branching shape of trees. This shape offers innate strength, knowledge of which was exploited by vernacular builders in the past, but was not convenient for industrialized production. For the efficiency of modern construction methods it is more important to use uniform material profiles than to take advantage of the strength of an

¹² Sagitta: the distance from the midpoint of an arc to the midpoint of its chord (<http://www.merriam-webster.com>).

irregularly grown form. Such natural forms cause problems as they are incompatible with standard machinery, difficult to address in design when no two branching pieces are exactly alike, and do not lend themselves easily to structural performance calculations.

Yet in vernacular construction and boat building, naturally branching shapes were frequently used to save time and labor, and occasionally to achieve superior structural strength. Examples of historic construction systems that used the innate strength of branching timbers include the Polish strut frame, *konstrukcja sochowa* (Ruszczyk 2014, 16) and Norwegian bent construction (cross frame), *grindverk* (Drange, Aanensen, and Brænne 1992, 145-149).

The geometric configuration of branching trees was scientifically investigated for the first time during the Renaissance. Leonardo da Vinci (1452-1519) formulated mathematical rules for the development of the branched tree form. Also significant, in the 1920s, biologist Cecil Murray applied rules developed for arterial networks to plant stems that described the angles of branching and their relationships (Ball 2009, 133-134). The first algorithmic model for computer simulation of branching patterns employing the concept of *cellular automata* was proposed by a Polish-American mathematician Stanisław Ulam (1909-1984) in 1966 (Prusinkiewicz and Lindenmayer 1990, 51).

While these mathematical models focus on the geometry of branching, more research is needed to develop accurate models to assess the strength and structural performance of forked timbers. In the 2010s, the US Forest Products Laboratory in collaboration with the WholeTrees Architecture & Structures¹³ performed testing and analysis to establish the structural parameters of branching timbers. This enabled the WholeTrees group to design and build large structures using forked timbers, including the Festival Foods Grocery Store in Madison, Wisconsin (2014-2016).

¹³ See <http://www.wholetrees.com>.

Figure 12. WholeTrees Architecture & Structures, Festival Foods Grocery Store in Madison, Wisconsin. Architect: Bark Design Architects; contractor: Tri-North Builders. © WholeTrees Architecture & Structures.

While the above project demonstrates the viability of forked trees in the construction industry, the problem of how to integrate naturally grown wood shapes into the design process was discussed by Norwegian architects Helen & Hard in their Ratatosk Pavilion at the V&A Museum in London in 2010. The project breaks from the conventional design process in beginning design by first finding, scanning and digitally modelling ash trees. The digital material became a starting point for design, where material agency achieved a prominent status. Material idiosyncrasies -- organic shapes, knots, holes and fibers -- led the design and construction. As a result, it was not possible to develop the design in a conventional way through sketching: “*[the] forms were dictated largely by the shapes of discarded branches, and therefore could never have been predicted in a preliminary sketch*” (Stangeland and Kropf 2012, 172-179).

Figure 13. Helen & Hard, Ratatosk Pavilion, V&A Museum, London. © Helen & Hard.

The Woodchip Barn (2015-2016) designed and built by students of the Design & Make program at the Architectural Association School of Architecture in London strives to explore the boundaries of applications of this material at full architectural scale¹⁴. The structural spine of the project is formed by a truss composed of interconnected forked beech trees. In order to produce a database of available material, trees from a local forest had been 3D scanned prior to harvesting. Based on the criteria of the structure 25 forked trees were selected and felled. A customized computer script was used to find the configuration of the trees in the truss and to translate this information to a robotic arm for milling the connections between the pieces.

¹⁴ See <http://designandmake.aaschool.ac.uk/woodchip-barn/>.

Figure 14. Architectural Association School of Architecture, The Woodchip Barn, Hooke Park near London. © Architectural Association School of Architecture.

In each of these projects, digital technologies were used to analyze the material in both the design and construction phases. In both cases, digital technologies enabled work with wood in its natural form, and allowed it to be designed as a structural system in its raw form rather than merely a product to be processed into a uniform and passive material.

Materials sourced

The material of choice for the experiment was birch in the shape of Y-shaped branches, which was collected in the forest. The material was cut to 40cm length using a bandsaw. All ends of the branches were rounded with a tenon cutter (Figure 15). A typical tenon cutting blades set consists of sizes 8, 10, 12, 15, 20, 25, 30 and 35 mm so the branches were cut with the closest matching blades. The collected material ranged from 12 to 30 mm in diameter. All branches and the diameters were marked for identification after scanning.

Figure 15. Y-timbers. Tenon cutter. Photograph by the author.

The horizontal slabs were made out of polyurethane, for its low weight and ease of CNC milling. This material was suitable for a first prototype that investigated the geometric implications of using forked trees in construction, but it would not be possible to use it for structural performance testing.

Description of the experiment

The goal the Y-timbers project was to produce a 1:10 model of a construction system using forked timbers as columns with connecting horizontal beams or slabs. The joint between the column and the beam was based on mortise and tenon techniques.

The main geometric problem was that the top of a Y-shape does not lend itself to being inserted into a horizontal beam or slab. To this end, a design strategy was devised that resolves the problem by connecting two beams on top of a Y-shape.

Figure 16. Y-timbers. Connection problem. Drawing by the author.

Analysis of the precedents indicated that digital technologies used in both design and manufacturing are a viable method to deal with irregular, naturally grown wood. The Y-timbers project required digitization of the found material geometry, assembly of the components into a meaningful whole by means of 3D CAD modelling, and drilling holes using 5-axis CNC milling. a desktop size robotic arm AL5D with an Arduino microcontroller¹⁵ was used. The arm was programmed with a custom made forward and inverse kinematics script written in Grasshopper. For obtaining the geometric information of the branches a handheld Artec 3D scanner was used that is capable of producing a 3D mesh model from a physical object (Figure 17). The model was imported to Rhinoceros and manipulated to reduce the face count from approximately 150,000 to 500 per branch and cylinders were added at the tenons to even out the scanned ends (Figure 18).

¹⁵ Arduino is a do-it-yourself microcontroller kit for prototyping digital devices (<http://www.arduino.org>).

It was then possible to lay out the branches accordingly to the design intent and locate the mortise positions and orientations in the slabs.

Figure 17. Y-timbers. 3D scanning. Photograph by Jan Strumillo.

Figure 18. Y-timbers. Rhinoceros 3D model. Drawing by the author.

Finally, an industrial Motoman robotic arm was used to mill the oblique holes in the polyurethane slabs¹⁶.

Figure 19. Y-timbers. Robotic milling (left) and final model (right). Photographs by the author.

Results

The model was assembled without problems and all the mortises corresponded well to the tenons. The final form was stable, yet easily demountable.

The project demonstrated that using Y-shaped timbers as structural members demands precision and versatility of 3D scanning and 5-axis CNC milling. These requirements complicated the process, but produced a very accurate result. The devised process minimized processing of the material and may also benefit in finding use for the innate strength of the naturally grown forked shapes of timbers.

¹⁶ See <https://vimeo.com/192430402>.

Discussion

A summary of the three experiments is presented in the table below:

	project	properties of wood used	scale	use of IT	avoidance of	possible application
(i)	BackToBack	shrinkage during drying from green	1:1	CNC precision and repeatability	metal connectors adhesives	solid wood panels all-wood connectors
(ii)	Swelling Vault	anisotropic swelling after increasing moisture content	1:1	digital simulation	wasteful milling steaming chemical softeners	curvilinear panels formworks
(iii)	Y-timbers	strenght of naturally grown forked shapes	1:10	3D scanning CNC versatility	metal connectors wood processing	structural pillars cross-bracings

Table 1. Comparative summary of the 3 experiments.

Role of computational design and digital manufacturing in the experiments

In all three experiments, information technologies were pivotal to the testing, ideation, and fabrication processes. Experiment (1) BackToBack was based on precision and repeatability offered by CNC machine; experiment (2) The Swelling Vault used digital simulation to predict wood shapes resultant from the swelling process; and experiment (3) Y-timbers drew upon 3D scanning and versatility of robotic milling.

While The Swelling Vault experiment did not require digital fabrication, it used computation as a means to control the process. As discussed earlier, bulging of multiple parquet blocks is an emergent phenomenon, in which the final shape cannot be intuitively predicted. Thus the emphasis in this method is focused on devising a digital simulation of the process. The role of the

simulation draws upon Manuel DeLanda's observation that "[digital] simulations are partly responsible for the restoration of the legitimacy of the concept of emergence because they can stage interactions between virtual entities from which properties, tendencies, and capacities actually emerge Simulations can play the role of laboratory experiments in the study of emergence complementing the role of mathematics in deciphering the structure of possibility spaces" (DeLanda 2011, 6). Thus the simulator plays a key role in the process by enabling predictable outcomes to result from interactions of multiple elements not possible to intuitively predict.

Hence this research demonstrates that computation can unlock new capabilities within existing materials, including capabilities that offer a more environmentally responsible future. In the experiments here discussed, wood behavior and characteristics replace metal connectors, toxic adhesives, and forming methods that use extensive amounts of energy. By challenging the industrial paradigm wherein materials are passive and homogeneous, and harnessing the efficiencies of digital technologies, these projects produce much less harm to the environment.

Future development and applications

The proposed methods could be used for producing solid timber panels, double-curved panels or formwork, and bifurcated pillars for construction. The experiments were performed at the scale of an architectural component. Operating at the full scale, or as close as possible to it, was important in order to test both the manufacturing processes and the resultant components' viability. That being said, this research aim was not to scrutinize technological solutions, but to discover potentials and indicate areas for further study. In order to validate the methods, the projects must be further developed. That includes structural performance testing, development of software and

manufacturing methods for industry-size scale, assessment of the environmental impact improvement, and market viability testing.

The necessity to perform rigorous structural testing in order to develop the method further can be exemplified with the BackToBack project. The geometry, sizes and proportions of the incisions must factor into the structural behavior of the panel as a building component. The joint that resists the pulling force perpendicular to the long axes of the logs should also be tested for its ability to transfer shear stress. Providing a shear force resistant connection between the pieces would dramatically increase the stiffness and hence the panel load-bearing capacity.

Impact on design methods

In these experiments, the inherent properties of wood were harnessed for design. In The Swelling Vault wood had a limited capacity to take on various shapes and hence limited possible outcomes; while in Y-timbers, natural shapes dictated the aesthetics of the final form. This methodology suggests that material properties can guide design. In fact, many aspects of form can be dictated by the material's traits, behavior, composition and shape.

In material-oriented design, many of our assumptions about design are challenged. The designer no longer imposes a form upon a material, and this requires rethinking her approach to aesthetics, tolerances, sequences, but also the role that kinetics and time play in design. While this process may sound limiting for the scope and freedom of design, on the contrary, material-oriented design opens new opportunities for architecture guided by rational principles to solve environmental problems. At the same time new methods of assembling structures offer refreshing opportunities for design. By deriving design from material, we can minimize the environmental impact of our buildings and rejuvenate the architectural profession.

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