

BackToBack

A bio-cybernetic approach to production of solid timber components

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This paper investigates the potential and implications of using naturally occurring material phenomena as a connecting mechanism for solid timber components. Proposed and discussed are connections based on anisotropic shrinkage and geometrical variability of trees. Using the notion of material agency in design, following the bio-cybernetic and biomimetic frameworks, solutions are devised to reduce energy usage, environmental pollution and utilise low-processed material. Finally, consequences of the fusion of the natural (analogue) and the digital realms are discussed, with an example of a workflow integrating inherent material traits with digital manufacture.

Keywords: material-oriented design, computational design, wood properties

Most material innovation emerges not in the making of new materials but in transforming the way in which we handle them.

(Schröpfer 2011)

INTRODUCTION

We propose to use naturally occurring material phenomena as a connecting mechanism for solid timber components. In the presented experiments we look at the anisotropic shrinkage of wood on drying and geometrical variability of trees as a potential that could become a basis of an alternative, more sustainable joining method. We identify a *fusion* of the material and digital domains as the key component of our approach. We set out our theoretical framework and its consequences, before we describe the experiments in more detail and discuss the project's implications and further development.

THEORETICAL FRAMEWORK

Background

Wood in industrialised production. Wood has lost market shares as a raw material for mass production processes as a result of its individualised characteristics and difficult to predict behaviour. Variation and heterogeneity of timber are seen as disadvantages in construction, traits more and more dominant as increasing number of trees are characterised by small sizes and greater variability. Today, remanufacture of timber, i.e. the production of timber derived sheet components and glulam beams, is a way to meet the needs of modern economy. That is not without an impact on the environment. Processing a material means energy expenditure and may have an impact on health risks posed by this material, and also on its recycling: *The higher the degree of processing, the lower the potential for quick and unproblematic decomposition* (König 2011).

Solid timber in construction and its sustainability today. Contemporary solid-wood building technology, primarily represented by cross-laminated timber (CLT) must still be considered a recent invention, although it has matured since its appearance on the market in the early 1990s. CLT production involves cross-lamination of planks or boards by means of polyurethane glue. Polyurethane is a synthetic polymer and as such it is non-biodegradable. CLT building systems rely on metal connectors for assembly e.g. self-tapping screws, brackets, plates and bolts, what is problematic for the three reasons mentioned below:

1. Metal fasteners 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.
2. Metal fasteners penetrating wooden beams in unheated rooms rust where their galvanised coating has been damaged by abrasion upon entering the wood and the surrounding wood rots due to condensation on the cold metal. These processes are delayed by using toxic, chemical wood preservatives (Graubner 1992).
3. 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).

For all these reasons, when the entire lifecycle of the composite element is considered, eliminating the need for non-biodegradable chemicals and metal connectors would substantially lower its environmental impact by reducing pollution and the amount of energy used in the process and improving recyclability of timber components.

Construction as interaction of matter, energy and information

The tectonic quality of architecture emerges from the interplay between various factors, ranging from cultural and environmental to relating to technology and materiality. In order to systematise the field, as well as to position our research, we follow a methodology that renders construction as the interaction of matter, energy and information exchanges, based on systemic and cybernetic models. Using this methodology, Christoph Schindler, architect, designer and researcher, proposed a periodization model for wood construction that integrates fabrication with manual, industrial and information technology. His model brings out the way in which the manufacturing technology radically reshapes the production of buildings, as well as their construction, tectonics and appearance (Schindler 2009).

MATTER: material-oriented design - a historical discussion. The approach to wood in construction today is still affected by the spirit of the Scientific Revolution and the Enlightenment. Spanish ship constructor Jorge Juan y Santacilia (1713-1773) wrote in 1771: *Toward the end of the last century (...) The Construction of Vessels was abandoned to mere Carpenters; and it was not considered that NAVAL ARCHITECTURE was based on a constant application of Mechanics and Geometry, which are the most difficult branches of Mathematics* (Ferreiro 2007), expressing what Manuel de Landa, Mexican-American artist and philosopher, calls the disregard for the *linguistically unarticulated knowledge* of craftsmen about complex material behaviour (de Landa 2001). De Landa's observation is based on the notion expressed by James Edward Gordon (1913-1998), British pioneer of material science, of *reducing design to a routine* with the invention of homogenised building materials that *facilitated the dilution of skills*, where *manufacturing can be broken down into many separate stages, each requiring a minimum of skill or intelligence* (Gordon 1988). The *mere carpenters*, diminished by Santacilia, took advantage from the existing shapes of trees or irregularities of grain in order to achieve supe-

rior strength and reduce labour. Accordingly, curved wood could be more expensive than straight wood up until the 19th century. This approach was only possible given the condition of *unarticulated knowledge* of the craftsmen, transmitted through experience and not codified in a form required by industrial production. The turning point in the wood construction was the development of the Balloon Frame in 1830s when *the skilled carpenter* was replaced by *the unskilled labourer* (Giedion 1967). Late 18th century inventions of steam powered circular saws and rapidly cut nails from sheets of iron allowed *a man and a boy (...) attain the same results, with ease, that twenty men could on an old-fashioned frame* (G. E. Woodward in 1865 as cited in Giedion (1967)). As a result, American cities like Chicago or San Francisco have arisen from little villages to great cities in a single year (Solon Robinson as cited in Giedion (1967)). Beyond the obvious economic gains, mechanisation and standardisation of construction and developments in material science resulted in a shift of focus to *a more rational, abstract and analytically driven understanding* of construction in structural design, e.g. *iron provided the physical basis for a mathematically oriented formulation of design, thoroughly justified by science* (Rinke 2010). Not surprisingly the manual craftsmanship came to a standstill. As a side effect, *by 1930 (...) wood had been squeezed by manufacturers of all its design potential* (Giedion 1967). That is reflected, for instance, in the writings of Le Corbusier (1887-1965), criticizing in 1931 the use of *heterogeneous and doubtful materials*, both from the position of economy: *Natural materials, which are infinitely variable in composition, must be replaced by fixed ones. (...) The laws of Economics demand their rights: steel girders and (...) reinforced concrete, are pure manifestations of calculation, using the material of which they are composed in its entirety and absolutely exactly; whereas in the old-world timber beam there may be lurking some treacherous knot, and the very way in which it is squared up means a heavy loss in material* (Le Corbusier 1986), as well as the design potential: *wood, being a traditional material, limited*

the scope of the designer's initiative (Ngo and Pfeiffer 2003).

Modern Movement in architecture had a double-sided approach to materiality. One lineage, that allowed the material agency in design, can be traced to Viollet-le-Duc (1814-1879) who in opposition to the Classicism saw architectural composition in relation to *the material made use of and the processes that can be applied to it* (Viollet-le-Duc et al. 1990). In this vein, some Modernist architects allowed the material to inform their design concepts: Adolf Loos (1870-1933) arguing that each material has its own *Formensprache* (language of forms), Frank Lloyd Wright (1867-1959) talking about *the meaning of materials*, Louis Kahn (1901-1974) asking *what do you want, brick?*, or Alvar Aalto (1898-1976) who saw wood *viable for psychological and biological reasons*. However, all of them used a vague or soft notion of a culturally conditioned material agency, *metaphors (...) very difficult to use (...) as a basis for a more operational understanding of the form-material relationship* (Sandaker 2008). In other words they failed to provide any working method for material-oriented design. The second lineage, stemming from the Classical notion of form as independent of matter, verbalised by Bruno Taut (1880-1938) as *the ultimate dematerialisation of form*, found its most famous expression in the 1924 Schröder House by Gerrit Thomas Rietveld (1888-1964): *a messy hybrid of timber, steel, masonry and reinforced concrete, but visually it appears to be composed entirely of coloured planes* (Weston 2003). Peter Eisenman's (b.1932) notion of the *cardboard architecture* as an *antimaterial statement* symbolically marked the final stage of the negation of materiality by the modernist architects in the 1970s. Since then until the 1990s the architectural discourse problematized history and philosophy rather than materiality. In the 2000s with rising ecological concerns on the one hand, and the *post-postmodern need for realism and post-digital need for quantifiable techniques and evaluation* (Borden and Meredith 2012) on the other, the focus was shifted towards *the real*. Under the banner of *digital materiality* substantial effort has been

put to integrate digital or robotic fabrication into the design process, and it is legitimate to say as of 2014 that *robotic fabrication in architecture has succeeded (...) in the synthesis of the immaterial logic of computers and the material reality of architecture where the direct reciprocity of digital designs and full-scale architectural production is enabled* (Gramazio et al. 2014). However, the post-digital discussion about materiality has been dominated by mass-customisation and the part-to-whole relationship, where material traits played a secondary role. In our view, a question that remains a challenge for today stems from Viollet-le-Duc's notion of the form as a synthesis of *the material made use of and the processes that can be applied to it*, posed in the context of the 21st century developments. Is our technology mature enough to embrace the material complexity? What kind of framework and working methods could be applied today, in order to harness material potentials? What can be learned from the *mere carpenters*, how a fusion of the analogue matter and the digital information processing can be achieved? Our project, taking on board wood -- the ancient, heterogeneous and endlessly variable material, is an attempt to take part in this discussion.

ENERGY: technological vs biological types of management. Despite the fact that *architecture and engineering are just two aspects of one thing* (Heinz Isler as quoted in Larsen and Tyas (2003)) the two disciplines take into account different criteria and systems of values. Therefore the notion of performance has two different meanings for them. For engineering performance is a quantifiably measured efficiency, expressed as the highest load-bearing for the lowest weight, whereas for architecture the notion is more elusive and consists of a wide range of design approaches (for more in-depth discussion see (Sandaker 2008)). Moreover, strategies orientated towards minimising cost, maximising performance or the performance to cost ratio yield different design trajectories and solutions (Russell and Gero 2014). In order to establish a value system for our project, we adhere to a principle, where a design goal could be

formulated as maximising the project's effects and affects, objective and subjective aspects, while minimising time, material and energy expenditures. In this view, in currently prevailing approach to wood construction, formal and performative requirements conflict the material efficiency and manufacturing logic.

In our proposed approach, we understand the act of making as a negotiation between material potentials and fabrication constraints. In order to establish a theoretical framework to that end, we propose to look at natural systems through the lens of bio-cybernetics and biomimetics.

Frederic Vester (1925-1983), a German bio-chemist, ecologist and an originator of *networked thinking* that is based on systemic and cybernetic approaches, opposes constructivist against evolutionary types of management. In the former the system is produced at great expense of material and energy, in the latter it emerges spontaneously at little expense. The 4th rule of his eight basic rules of bio-cybernetics outlines the strategy: *exploiting existing forces in accordance with the ju-jitsu principle rather than fighting against them with the boxing method* (Vester 2007). That in turn resonates with the comparison of biological and technological systems as presented by Julian Vincent, professor of biomimetics at the University of Bath (Vincent et al. 2006). Vincent argues, that our technology *kills the information* of raw materials, by *reducing, melting, dissolving, homogenising*, thus achieving *random material with no intrinsic information*, further *moulded, cast, turned, joint* with a substantial expense of energy to make the material *ordered with imposed shape and structure* for the final product. Conversely to technological systems, biological systems use information rather than energy to solve technical problems. In live organisms information, stored in DNA, is used to drive specific reaction at the cellular level and *self-assemble* structures. Conversely to nature, where *shape is cheap but material is expensive*, in engineering, *material is cheap and shape (resulting from energy-intensive processing) is expensive*, says Vincent, and points to our ability to

tap abundant and cheap fossil fuels during the Industrial Revolution as a key turning point in our relationship with nature.

INFORMATION: fusion of the analogue and the digital. However it would not be easy for us to trigger reactions at the cellular level in wood, our project is a test-bed through which we attempt to investigate what role information plays in the design process when the focus is shifted towards the dynamic material behaviour. This approach calls for different information transfer than traditional architectural methods. Neither two- or three-dimensional representations are capable of capturing and communicating processes and changes in time, nor the state-of-the-art Building Information Modelling (BIM) programs could be helpful in this regard. BIM, *a shared knowledge resource for information about a facility forming a reliable basis for decisions* [1], has been introduced in order to provide a platform for data exchange between stakeholders and is fine tuned to the standard design process, where a change of material state in time is of little importance to the design decisions. As our standard methods of representation are lacking content regarding change, sequence and tolerances, equally *the building culture is unlikely to be able to fill in the gaps with experience* (Schröpfer and Lovett 2011), result of our earlier described divorce with craftsmanship. We face a similar challenge to that of the Jørn Utzon's (1918-2008) Sydney Opera House (completed in 1973) or the Frank Gehry's (b. 1929) fish-shaped canopy for the 1992 Olympic Village in Barcelona, where the two-dimensional representations were more complicated than the shapes themselves, what triggered the integration of associative software in the design process. In an attempt to find a reference for information transfer in other form than two- or three-dimensional representation, our approach takes inspiration from the traditional Japanese joinery methods. *The attempts to graphically describe many of the primary connections in Japanese joinery in the Western method of orthographic projections (...) fall short of being able to convey the complexity of the sequence of operations re-*

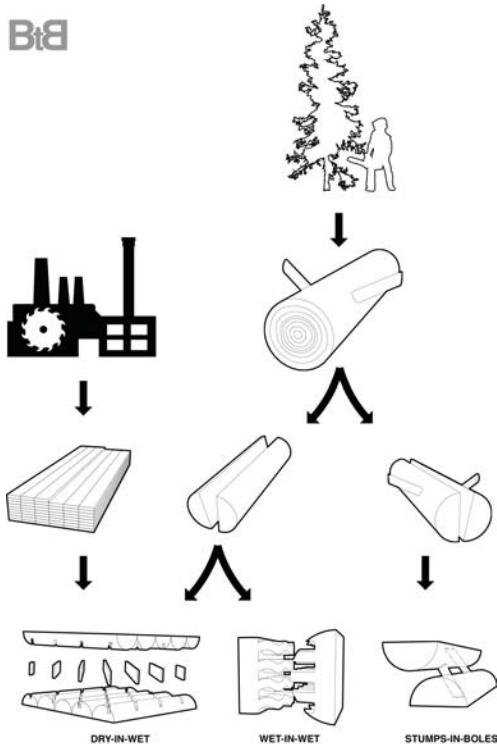
quired to perform these joints. (...) The personal instruction given to carpenters during their training allows for the transfer of a body of three dimensional and processional information that flattens out in the form of two-dimensional drawings (Schröpfer and Lovett 2011). Similarly, the details of our connection, the precise dimension of the incisions, were not executed based on a fixed set of drawings, but in a process of determining digital machining paths, resultant of the tool (shape, radius, feed speed, rpm etc.) and material parameters, verified through physical testing. These paths could neither be reused for another connection nor fully prepared in advance. Even if the same tool setup was preserved, the material parameters would constantly change in time, resulting in different incisions, cut for instance in wood of different density or moisture content. In case of wood, where no two pieces are alike, all pieces vary at all structural levels, what results in impossible to compute behaviour, a question of tolerances becomes highly relevant as well. Trying to make the elements snugly fit, we strived to leave the necessary tolerances allowing for an easy push-in and catch-in - only possible to determine by a physical trying and error process.

Another problem we faced was the amount of information necessary to efficiently deal with the material and to be able to compute the machining paths. While trying to capture geometrical characteristics of our pieces we realised that the contact 3D scanner with an articulated arm suits our purpose better than the non-contact active 3D scanner. The type of information required to establish the important geometric features for our connections could be boiled down to a few numbers (boles and stumps diameters and coordinates of two axial points for each stump), as opposed to thousands of coordinates in the point cloud. Keeping the information to minimum was the only strategy enabling successful computation of the machining paths.

THE BACK-TO-BACK SYSTEM

Project description

The proposed connecting system attempts to accommodate two contradictory needs: to yield as uniform and smooth component as possible and to minimise the processing of the material. For the whole boles of trees are longitudinally split and the straight-cut faces exposed, while the unprocessed backs are used to connect the pieces.



Three design paths were followed (Figure 1):

1. *Dry-in-wet*. The connecting mechanism based on green wood tightening on dry wood while shrinking. Dry wood inserts were fitted into the receiving incisions in green wood.

2. *Wet-in-wet*. The connecting mechanism based on green wood anisotropic shrinkage. Various incisions were CNC-cut to test how the tangential shrinkage on the active side of the panel would tighten on the passive side.
3. *Stumps-in-boles*. The connecting mechanism based on scanning stumps and inserting them into corresponding CNC-drilled holes in the opposing bole. Stumps are crushed to separate the fibres and increase their flexibility prior to inserting them into the holes. As greenwood dries the holes should shrink thereby increasing the connection strength.

For paths (1) and (2) Norway spruce, and For path (3) birch wood, were used. In all cases wood was processed while still green.

Dry-in-wet

This project demonstrates and tests how the green wood shrinkage activated on drying could be used for tightening on dry wood elements.

Various series of incisions were cut at a 45° angle to the halved-log axis on the bark side. As the inserts dry pine boards were used (Figure 2). The resulting empty space inside of the panel could be used for thermal insulation, e.g. by means of injecting cellulose fibre insulation.

It has been assumed that the oblique orientation of these incisions would harness the natural shrinkage in green components and make them cling on the dry inserts. In order to investigate the distribution, geometry and dimensions of these incisions and inserts various variants were tested.

Wet-in-wet

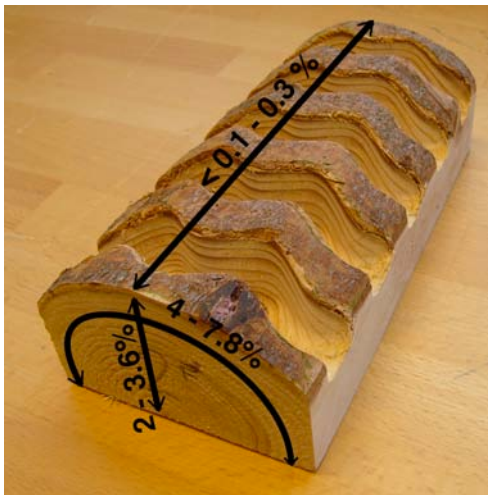
This project demonstrates and tests how the anisotropic shrinkage activated on drying could be used for producing all-wood connections in solid wood panels. In Norway spruce, depending on author, tangential shrinkage amounts to between 4% (Dinwoodie 2000) - 7.8% [2], radial to 2% (Dinwoodie 2000) - 3.6% [2] and longitudinal to <0.1% (Dinwoodie 2000) - 0.3% [2] (Figure 3).

Figure 1
Three BackToBack
design paths

Figure 2
The BackToBack
dry-in-wet concept



Figure 3
Orthotropic
shrinkage in
Norway spruce



Various series of waving and straight incisions were CNC-cut perpendicular and at a 45° angle to the halved-log axis on the bark side, in order to produce the active elements of the panel. Their width after drying should shrink and cling on the receiving ribs resulting from the identical incisions cut parallel to the log axis on the corresponding passive elements of the panel (Figure 4).

Various patterns of the incisions and resulting ribs have been manufactured in order to test their shrinkage and resulting connection.

Stumps-in-boles

This project demonstrates and tests how randomly placed stumps of branches could be used to provide connection between opposing layers of halved round timber boles. A birch sample was halved along the longitudinal axis. The sample with a projecting branch stump was 3D-scanned. By means of a computer script this information was subsequently translated into the position and angles of the hole to be drilled in the paired element by a tiltable drill press. The stump was successfully forced into the resulting hole (Figure 5). During the experiment it was determined that since the branch stumps have random spatial angles and possess a significant stiffness it would be impossible to force more than one such stump into a correspondingly inclined hole lest their spatial angles were identical or almost identical. One way to overcome this is to increase the elasticity of the stumps. We achieved this by crushing the stumps in a carpenter's vice. The final result proven to be a failure: as branches shrunk more than the corresponding hole in the bole the connection has loosened its snug fit after some time. This means the solution would only be possible while working with dried material, characterised by a higher modulus of elasticity, thus not providing the sought synergy in the process.



Figure 4
The BackToBack
wet-in-wet concept.
Tests of various
incision patterns.



Figure 5
Stumps-in-boles.
From 3D scan to
tiltable drill press
and assembly

FURTHER DEVELOPMENT

The BackToBack project is currently at its early stage and various paths of further development are considered. Our initial tests indicate that only design paths 1 and 2: *dry-in-wet* and *wet-in-wet* are worth pursuing.

The presented panels are designed to be used as structural elements and double as exposed surface. This biologically inspired approach -- in nature often single material serves multiple functions -- saves energy, production time and money potentially spent on additional finishes. While it would be difficult to meet the present day thermal requirements with wood only without increasing the wall thickness to 40-50 cm, the *dry-in-wet* panel is more suitable for external walls as it provides internal space that could

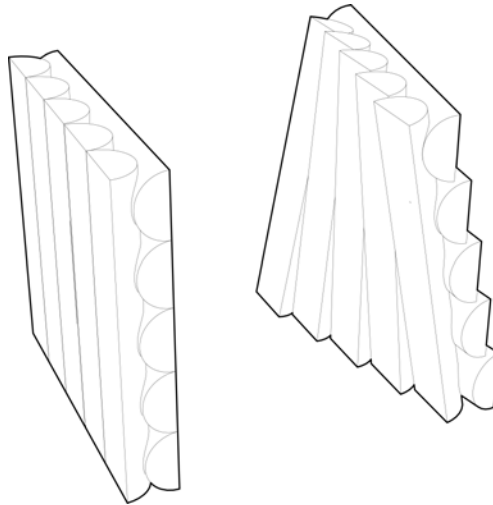
be used for additional insulation. The *wet-in-wet* scenario would be suitable for internal partitions or as a load-bearing leaf of an insulated wall.

All presented examples result in flat panels of even external surface. It remains to be answered how the wood-behaviour based connections could be further exploited architecturally by application of geometry, e.g. for their formal and aesthetical appeal, self-support, sound or light-wave reflection or attenuation.

It would be possible to manufacture curvilinear panels of ruled geometries, controlling the curvature by the geometries of the incisions, not spending more production time, material or energy than while producing flat panels of the same size (Figure 6). This line of thinking opens new prospects: when shape

becomes cheap, to paraphrase Vincent, what would the implication for design and architecture be?

Figure 6
Using the
BackToBack
method production
of both panels
would require the
same amount of
time, material and
energy



Another line of development includes the application of juvenile wood in the form of roundwood thinning material. That -- except of being a byproduct of the forest management -- has several advantages over sawn timber:

- 40% lower embodied energy.
- Self-replenishment over a much shorter period of time.
- Much lower cost.
- The characteristic bending strength of unsorted material may be even double the value of sawn timber.

It is intended to take advantage of the low modulus of elasticity of juvenile wood further bolstered in the green condition. That would allow for bending the material beyond its proportional limit, as featured in the Hooke Park workshop building in Dorset, UK

(Richard Burton, Frei Otto and Buro Happold, 1988). Combined with the BackToBack method it could enable an effective way of producing curved timber panels.

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