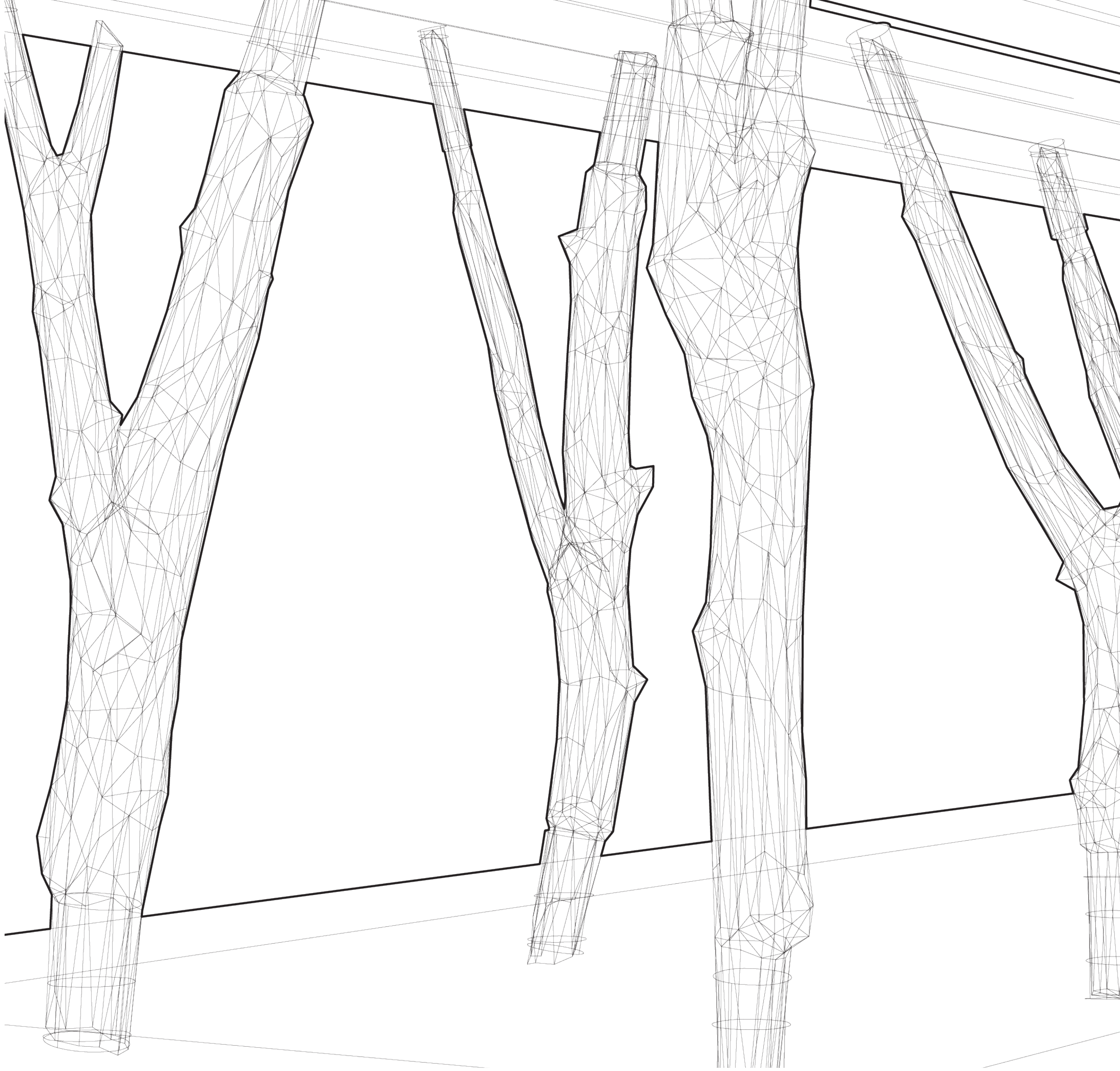

Marcin Wójcik

REFRAMING WOOD CONSTRUCTION

Innovation in architecture through activating material properties with the use of digital technologies

Arkitektur- og designhøgskolen i Oslo
The Oslo School of Architecture and Design

PhD thesis

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ABSTRACT

This thesis focuses on the relationships between ***material-centred*** design, digital technologies and environmentally-responsible practice with respect to wood construction. It argues that computational design methods and digital manufacturing have the capacity to ***reframe wood construction***, open new opportunities for design, and lead to more sustainable practices.

Wood is the building material that frames this research. The long tradition of using wood in construction and its cultural connotations, as well as its heterogeneous structure and its often-unpredictable behaviour, make it a case in point for ***material-centred*** design. Today, the predominant approach to wood construction is adaptation to industrialised processes that suppress individual material properties. The thesis proposes to ***reframe wood construction*** in order to offer an alternative design method that uses material properties and behaviours as valid design factors.

The monograph comprises two main parts: (i) Experiments, and (ii) Perspectives. (i) The first part describes three experimental projects with wood in which inherent material properties and material behaviours are used as a starting point, and computational design techniques and digital fabrication are the main methods. The goal of the experiments is to advance environmentally responsible construction. These experiments are illustrative and form a base for discussion, rather than represent fully developed technological solutions. (ii) The second part theorises the approach presented in the experiments. It comprises three perspectives: (1) design methodology, (2) design theory, and (3) design and technology. (1) The methodological perspective outlines the proposed framework of innovation in wood architecture. (2) The theoretical perspective positions the proposed approach within discussion surrounding relationships of form and matter in the history and theory of architecture. (3) The technological perspective discusses the development of technology related to wood architecture and its impact on design and construction. Together, the three perspectives form a discussion of the approach to ***reframing wood construction***.

The ultimate goal of the thesis is to reorient architecture towards sustainable construction methods. The initial question in Part I is whether there are more efficient and effective ways of using wood as a building material. The working

hypothesis used to set up the experiments is that by applying digital design and manufacturing methods, individual material properties can be used as generative means of design.

Part II of the thesis begins with a study of the method of innovation in wood construction presented in Part I. It identifies that innovation is often triggered by a new combination of already existing components. A hypothesis is proposed that repositioning a problem and changing frames of references is key in design innovation. This leads to formulating the notion of ***reframing*** based on a new conceptualisation of materiality.

This new conceptualisation of materiality is first investigated in relation to design theory surrounding the relationship of form and matter in the history of architecture. The central hypothesis is that material perspective is countercultural to mainstream architectural theory and practice. Architectural history and theory are analysed from the perspective of philosophical formulations of the relationship of form and matter. The form-matter opposition is put into question. As an alternative a new conceptualisation of wood is proposed, one in which wood is no longer seen as a passive “material” but where its individual properties and behaviours actively take part in the generative processes. Finally, the proposed ***reframing*** is contextualised against the historical development of wood construction and digital technologies in design and manufacturing. The thesis identifies that digital technologies have not yet embraced materiality and that digital advances in architecture provide an opportunity for including material parameters as valid design factors. This thesis proposes that digital technologies have the potential to access various latent and palpable potentialities of the material that can deliver design solutions with lower environmental impact.

Chapter 1: Introduction

Motivations

This thesis began as a study of curvilinear wood structures. A comparison of two projects distanced by three decades brought an interesting observation: development in timber technology does not always lead to more energy and material efficient construction.

The two projects in question were the *Multihalle* in Mannheim built in 1975 by Frei Otto and Carlfried Mutschler and Partners (Figure 1), and Centre Pompidou in Metz built between 2003 and 2010 by Shigeru Ban Architects (Figure 2).

Figure 1

Frei Otto and Carlfried Mutschler and Partners, 1975, *Multihalle* Mannheim.

Figure 2

Shigeru Ban Architects, 2003-2010, Centre Pompidou in Metz.

The roof of *Multihalle* in Mannheim is a gridshell made of western hemlock pine. With a curved wood surface of 9,500 m^2 it covers an area of 7,400 m^2. The overall dimensions of the building are 160 x 115 x 20 m, with a maximum lateral span of 60 m and a maximum longitudinal span of 85 m. The primary structure consists of 4 layers of 50 x 50 mm laths laid out on a 500 x 500 mm square grid. The total length of these hemlock laths is 72,000 m and their volume amounts to 180 m^3 (*Multihalle* Mannheim is also discussed on p. 173).

In comparison, the roof of Centre Pompidou in Metz is a free-form surface supported on a hexagonal grid of softwood glulam girders. The roof area is 8,500 m^2, and the total floor area of the building is 10,660 m^2. The building is 60 m long and 35 m high with a 77 m tall spire and the roof maximally spans 40 m. The primary structure of the roof consists of 6 layers of continuous 140 x 440 mm softwood glulam girders laid out on a hexagonal grid with 2.9 m sides. This structure consists of 1790 pieces made from 45,000 individual strips of wood. The total length of these beams is 18,000 m, and it is 1,100 m^3 of wood.

While comparison of these two projects may not be sufficient to draw any long-reaching conclusions, one observation became a catalyst for the direction of this thesis: despite using much more advanced technology in its construction, and despite the much higher environmental awareness in the mid-2000s than in the mid-1970s, the project in Metz used 6.5 more wood per square metre of roof structure, while it spanned approximately half the distance. This realisation became a starting point of inquiry into the ways in which wood is used in construction, and whether there exist other and more effective ways of using the material.

Objects of study

The thesis in its broadest sense discusses the part of design theory concerned with implications of material characteristics used in construction. This theory is investigated through the history of architecture and its interactions with philosophy and technology.

Wood is the building material that frames this research. The long tradition of using wood in construction, its cultural connotations, as well as its heterogeneous structure and often unpredictable behaviour, make it a case in point for ***material-centred*** design. This is a method of design linked to particular properties, traits, and behaviours of materials; one that uses these as a primary design factor with a design goal of harnessing and leveraging their properties (see p. 138).

The thesis is derived from three material experiments with wood that were carried out in order to investigate an alternative method of wood design; one that can be characterised as ***material-centred*** design. These experiments guide the theoretical investigation. The experiments were not developed into full-blown design solutions. The thesis is not technical but theoretical, it deals with metaphysical rather than practical aspects of materials and design. The main body of the thesis consists of theoretical perspectives on the proposed ***reframing of wood construction***.

The widest context of the thesis, and the goal of ***reframing of wood construction***, is more sustainable architectural practice. It is understood that the role of design thinking is not merely to produce an aesthetic value, but also to provide for the sustainable environment (see p. 88). Therefore reduced use of toxicants, energy-intensive processes, and waste quantity became benchmarks against which the proposed approaches were validated. However, as mentioned earlier, it is beyond the scope of the thesis to discuss environmental benefit technicalities of the proposed ***reframing of wood construction***.

Contribution to the investigated field

The thesis makes a contribution to design and architectural theory. This contribution is to provide a new theoretical framework, one that integrates ***material-centred*** design with existing design theory. It strives to provide a new perspective, i.e. ***reframing***, within which a new approach to design and new design methods can be developed. Development of these methods is not the primary focus of this thesis.

Chapter 2 of the thesis describes three material experiments with wood. These experiments, in addition to being instrumental in the development of the main argument, also strive to fill the gaps between the main focus areas of existing approaches to material- and performance- oriented design. The themes of these projects, based on the main identified gaps:

- focus on possible low-tech execution methods,
- focus on application of unprocessed material,
- expand potential applications of the techniques used by material- and performance- oriented designers,
- focus on environmental benefits of devised techniques, i.e. reducing the use of chemicals, energy, time, and waste quantity; enabling recycling; increasing volume yield of timber; providing healthy living environments.

The thesis in Chapter 4 discusses existing design theory as based on a hierarchical relation of form (idea) and matter (material), where the former achieves a higher status than the latter. This relation leads to particular design approaches and methods where material properties and behaviours are often supressed, rarely leveraged, and almost never seen as actively form-giving. The ambition of the thesis is to develop a new theory based on non-hierarchical, or symmetrical, relation of form and matter and discuss its implications. In order to do so, it identifies forerunners for the proposed framework in the history of architecture, design, and engineering. These forerunners are instrumental in constructing the argument for ***material-centred*** architecture in Chapter 4. Contextualising these forerunners against the new theory is another contribution this thesis makes to the existing body of architectural theory and history.

Why wood?

Because the primary motivation for the study was to identify more effective design methods for wood construction, it was important to investigate the advantages of using wood at all as a building material.

Outlined below are the key advantages of using wood in construction.

Wood is strong and durable

Wood is unusually strong for its weight. The most significant but not the only factor determining wood strength is its density. The composition of wood's internal structure at different scale sizes also contributes to its strength. The molecular structure and ultrastructure of wood by mass comprises cellulose – the primary component of the cell wall (softwood 42%, hardwood 45%), hemicelluloses (softwood 27%, hardwood 30%), lignin (softwood 28%, hardwood 20%), and extractives (softwood 3%, hardwood 5%) (Dinwoodie, 2000). Wood's strength results from this composite structure, with the cellulose contributing mainly to the tensile properties, and the hemicellulose and lignin contributing to the compressive strength and elasticity (Lyons, 2014, p.127). Further the high compressive and tensile strength of wood is a result of the orientation of cellulose fibrils in an amorphous, three-dimensional matrix of lignin and hemicellulose (Wagenführ, 2008).

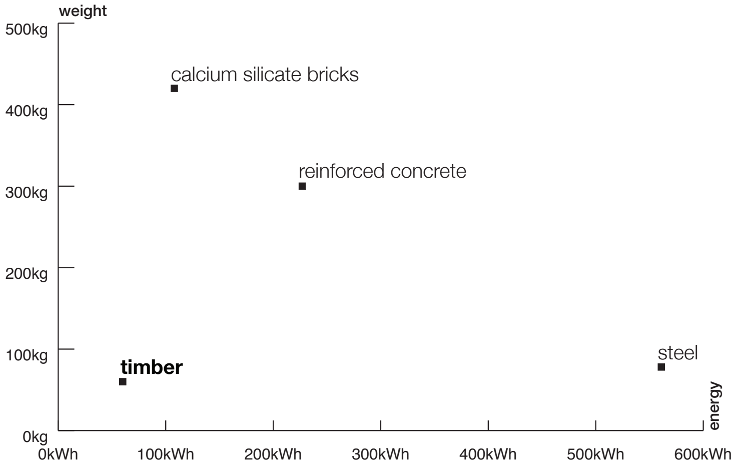

Figure 3

Comparison of weight and energy requirements for producing a 3m high column carrying the same load (after J. Kolb Systems in Timber Engineering (2008)).

Thanks to its good weight to strength ratio, timber is much lighter compared to other building materials when performing the same structural task as a building component (Figure 3).

Figure 4

St Andrew’s church at Greensted, UK, 11th century.

Figure 5

Hōryū-ji temple in Nara, Japan, 7th-8th century.

While wood is commonly considered a perishable building material, when properly detailed and maintained it can survive several hundred years. The earliest wooden building in Europe still standing is the church of St Andrew’s at Greensted, UK (Figure 4), which has been dated to between 1063-1100 using tree-ring analysis (Tyers, 1996). The oldest known existing timber building in the world is the Hōryū-ji temple in Nara in Japan (Figure 5), which was built of cypress in 607 (Berge, 2009, p.173), burnt down in 670, and rebuilt in 711 AD. However, a scientific examination with use of x-ray photography and dendrochronology methods indicated that the Japanese cypress (*hinoki*) trees used for construction were felled in 594 AD[1].

Wood is abundant

In 2015, British scientist and ecologist Thomas Crowther (b. 1986) estimated that there were approximately 3.04 trillion trees on Earth and 5 billion trees were cut down each year. A tree was defined as ‘s a plant with woody stems larger than 10 cm diameter at breast height’ (Crowther et al., 2015, p.201). It can also be estimated that over a million tonnes of potentially utilisable wood is produced every hour (11 billion tonnes per year based on Nimz et al. (1999, p.2)).

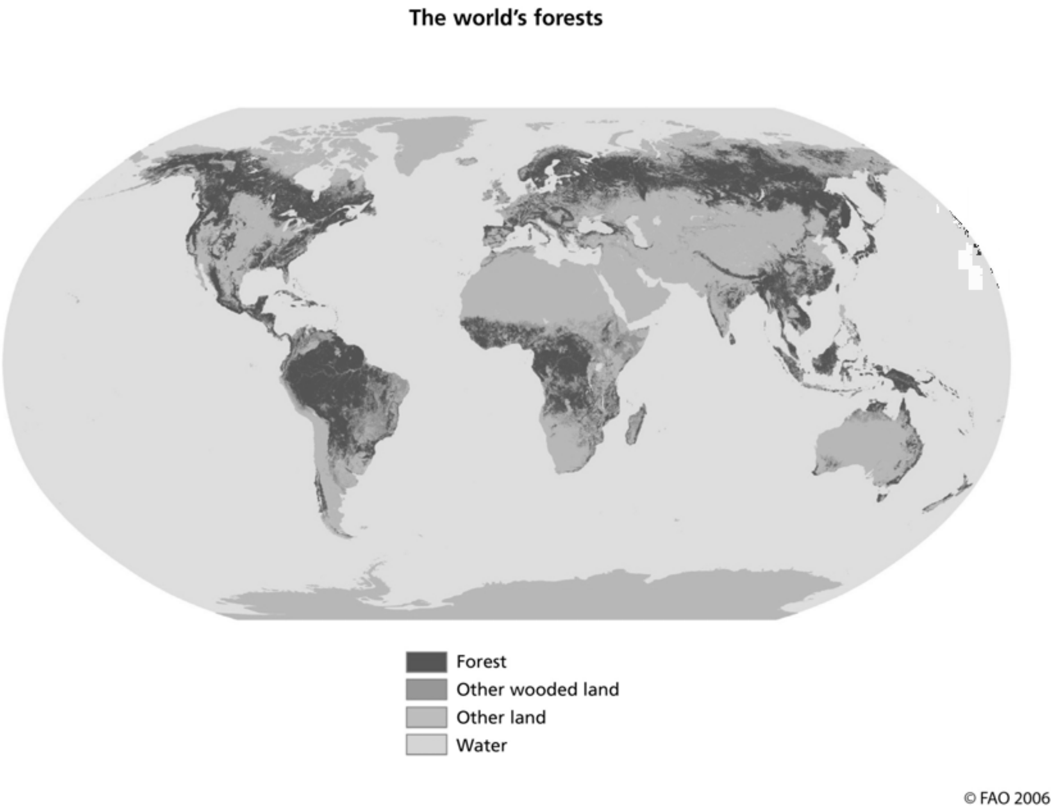

Figure 6
According to FAO the world’s land surface is in approximately 30% covered by forest.

In 2015, according to the Food and Agricultural Organization of the United Nations (FAO), 45.9% of Europe’s area and 30.7% of the world’s area on average was covered by forests (Figure 6). In 2005 wood constituted 42% by weight and 68% by volume of the world’s raw materials consumption[2] and

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[1] https://web-japan.org/trends00/honbun/tj010330.html

[2] Other considered materials include cement, steel, plastics, and aluminium.

47% of that was used in manufacturing an array of wood products (calculation based on Shmulsky and Jones (2011)). Out of 3.8 billion cubic metres of round timber consumed in 2017 almost equal amounts of 1.9 billion m^3 were used as fuel and as industrial wood (FAO, 2019, p.82, 90, 101). Relatively small amount of industrial wood comes from recycling. For instance in the UK half of timber waste, which totals to approximately 4.1 million tonnes yearly, comes from construction and demolition sites. 2.8 million tonnes of this timber was recycled, half of it was used to produce particleboard, and a quarter as a biomass fuel; while the remainder was used for animal bedding and horticultural products (Lyons, 2014, p.175-176, Addis, 2006, p.65).

It is estimated that about a third of the annual worldwide timber harvest is used in construction (Lyons, 2014, p.123). In the case of Germany, as of 2011, a third of the annual wood harvest would suffice to build all the new buildings constructed that year in the country out of timber (Wegener, 2011).

Wood is harmless to the environment

Timber uses less energy in its production than other construction materials such as brick, steel, plastics, and particularly aluminium (Figure 3); and contrary to these materials it absorbs carbon dioxide and releases oxygen into the atmosphere. The mechanism of photosynthesis converts solar energy into matter and at the same time generates oxygen, which is essential to human and animal life on earth. To produce a cubic metre of wood, nature needs 9,500 MJ of solar energy, 0.9 tonne of CO_2, 0.5 tonne of water and various nutrients – nitrogen, phosphorus, potassium, magnesium, and calcium (König, 2011, p.20).

Development, methodology, and structure

The thesis was initially developed as a series of academic presentations and papers that were converted into this monograph. The papers are presented in the Appendices in chronological order. The decision to rewrite the papers as a monograph was driven both by the need to add more material to the still developing argument and the overall readability of the thesis.

The thesis is divided in two main parts. Part I presents three experimental projects related to the theme of the study. Part II presents analytical and theoretical perspectives through which the thesis is investigated (Figure 7). This sequence reflects the thesis' process of development. The projects are tentative, of modest scale, and not developed into full-blown technological solutions as their role was conceptual and illustrative. They became part of the method through which the argument in Part II could be developed.

Part I of the dissertation describes three experimental projects which test aspects of ***material-centred*** design, digital technologies, and environmentally-responsible construction, in relation to wood material properties serving as key design factors. The investigated material properties include static and dynamic traits of wood. Static traits are understood as geometrical features – the naturally grown shapes of wood, and the material internal structure. Dynamic traits are understood as material behaviour – shrinkage on drying from green and moisture induced movement. The tested aspects include how these traits can be harnessed in order to produce architectural artefacts where the principle is using the material in its raw form. The strategies involved digital fabrication as well as computational design and simulation techniques. The three experimental projects were described, summarised, and synthesised using the same procedure.

Part II of the dissertation consists of three themed chapters each presenting three analytical and theoretical perspectives on the experimental projects presented in Part I. The perspectives use various interpretative ideas of the projects forming the main body of the thesis.

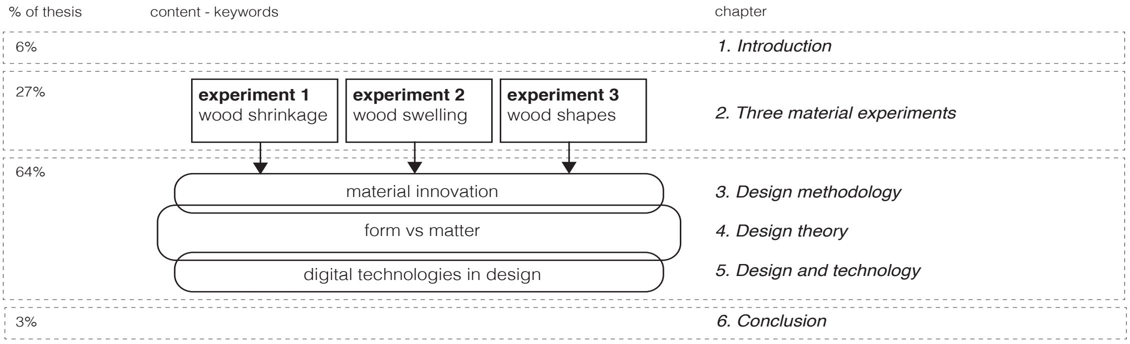

Figure 7
Diagram of thesis structure and methodology.

The thesis is based on an investigation method described[3] by the English philosopher and professor at Rice University in Houston, Timothy Morton (b. 1968). Morton used the metaphor of “mines” and “factories” to explain the method and process of constructing a thesis. “Mines” are archives, theories, and concepts which are being researched. These are compared to the ore from which valuable material can be extracted. “Factories” are chapters of the thesis, where this extraction process is carried out by means of hypotheses. Hypotheses are built to test the material, or “ore”. A hypothesis can be proven or disproven, but it results in “thesis”.

Morton advises that a thesis chapter should be composed of one central “mine/archive”, which is investigated through a few “factories/hypotheses”. The archives are different databases that map the area. Hypotheses convert this material into dissertation material, which can be used to explore the topic. The hypotheses are tested by methods, which should be devised in accordance with the researched material.

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[3] http://ecologywithoutnature.blogspot.ie/p/phd-advive.html

MINES	**HYPOTHESES**
processes and methods of innovation	innovation in design is most often triggered by a new combination of already existing components, repositioning of a problem, and changing frames of reference are key in design innovation
material agency in architecture	the material perspective in architecture is countercultural to the mainstream architectural theory and practice
hylomorphism in philosophy (matter vs form)	getting past the dualities such as form-matter, digital-material, architecture-engineering, etc. can result in design innovation
biomimetics - biological vs technological systems	conceptual transgression of the role of material in design has a potential to deliver solutions with lower environmental impact
biocybernetics - periodisation of wood construction	digital technologies have not yet embraced materiality, the digital turn in architecture provides an opportunity for including material parameters as valid design factors

Figure 8
The “mines/archives” to be investigated through the “hypotheses” in the thesis.

In my construction of the thesis, the mines are defined as existing design theories in architectural history presented with their wider cultural context. The factories, in turn, are hypotheses based on these theories (Figure 8) and proposed in relation to my own material experiments presented in Part I. As such, the thesis construction can be seen as horizontal; that is, it strives to adapt, combine, connect, and fill the gaps between already existing theories. This stands in contrast to another mode of constructing a thesis that can be characterised as vertical, which focuses on a relatively small area of knowledge and investigates it in great detail.

In Chapter 3 the mines are the theories surrounding design methodology, and the main hypothesis is that innovation in design is most often triggered by a new combination of already existing components. The proposed hypothesis is that repositioning a problem and changing frames of references are key in design innovation. This leads to formulating the notion of reframing based on new conceptualisation of materiality.

In Chapter 4 the mine is the development of design theory surrounding the relationship of form and matter in the history of architecture. The central hypothesis is that the material perspective in architecture is countercultural to mainstream architectural theory and practice. To investigate the hypothesis, architectural history and theory are analysed from the perspective of the philosophical formulations of the form-matter relationship. Further, another hypothesis is proposed that getting past dualities such as form-matter, digital-material, architecture-engineering, etc., can result in design innovation. It is proposed that many of the dualities in architectural theory are based on false oppositions. In this light, a method of innovation is proposed based on the notion of reframing from Chapter 3. The method involves material conceptual transgression. The method, applied to the subject matter of the thesis, has capacity to reconceptualise wood: acknowledging that it has a structure on its own, allows it to be seen no longer as material, where “material” implies passivity in the form building process. Another hypothesis is proposed that this conceptual transgression has potential to deliver solutions with lower environmental impact.

In Chapter 5 the mine is the theoretical backbone of the architecture and technology relationship, where the main interests are digital technologies. The technologies are contextualised against the role and use of material properties in design. Two existing design periodisation models are presented on which a proposed further development is discussed. The guiding principle for this development is based on the bio-cybernetic perspective. The main hypotheses are that digital technologies have not yet embraced materiality, and that the digital advances in architecture provide an opportunity for including material parameters as valid design factors.

The thesis concludes with a summary of the key ideas and discussion surrounding the future consequences of the presented approach.

PART I: Experiments

Chapter 2: Three material experiments

This chapter provides a description of three material experiments with wood construction focused on the relationships among ***material-centred*** design, digital technologies, and environmentally-responsible construction. These experiments were performed at an early stage of the dissertation development and formed a basis for discussion in the following chapters. In this discussion they were used as lenses through which various aspects were observed and fleshed out. Before reaching a conclusion, the experiments were presented and discussed at various conferences, in a scientific journal, and as a book chapter (Appendices 2, 3, 6, 7, 8).

The structure of this chapter reflects the sequence in which the experiments were conceived and performed. Before planning the particular experiments, a study of material characteristics that could be used as design strategies was carried out (see p. 31). Then the experiments were performed in the presented order, where each consecutive experiment was informed by the previous. The (1) *BackToBack* experiment (see p. 43) was a simple response to the observed potential of wood shrinkage on drying from a green condition. This approach did not affect the form-giving process. The (2) *Swelling Vault* experiment (see p. 53) was devised to produce form by using the expansion force of wood with changing moisture content. The (3) *Y-timbers* experiment (see p. 66) looked at properties of wood, other than kinetic properties, which focused on structural and formal applications of naturally grown shapes of wood.

The departure points for the experiments focused on the processes that seek environmentally-responsible production methods of architectural components. These methods investigate how to access and harness phenomena already existing in wood through computational design and digital manufacturing techniques.

In order to produce comparable material for further study, the experiments followed a quasi-scientific methodology and rigour. They are presented using one template, under the five headings: (i) precedents, (ii) aim of the experiment, (iii) materials sourced, (iv) description of the experiment, and (v) results. Further to that, the number of variables in the experiments (1) *BackToBack* and (2) *Swelling Vault* were minimized to one each: the geometry of 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 changing 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 aim of the methodological approach was to compare variants and indicate possible directions for development and more rigorous testing.

These experiments should be viewed as direction indicators rather than fully developed solutions. They 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 a way for further replication, development, and improvement. In this light, except for being illustrative, they should be seen as early prototypes of possible technological solutions.

MATERIAL CHARACTERISTICS OF WOOD AS POTENTIAL DESIGN RESOURCES

Before performing the experiments, a study was carried out on material characteristics in order to find potential design resources and drivers. Outlined below are the four identified wood characteristics with this potential: anisotropy, heterogeneity, taxonomic variety, and naturally grown shapes.

Anisotropy of wood

In physics, an anisotropic object or substance possesses a physical property which has a different value when measured in different directions[4]. Wood's strength in tension and compression, movement, shrinkage, thermal conductivity, elastic modulus, etc., are dependent on the fibre direction (Figure 10). The degrees of anisotropy are further dependent on the tree species and the way the log was converted, which results in the orientation of fibres in a piece of timber (Figure 9). More specifically, wood is considered as an orthotropic material, that is symmetric about three mutually perpendicular planes. These planes are related to the longitudinal, radial, and tangential directions in the tree, assuming that the tangential faces are straight and not curved and that the radial faces are parallel and not diverging (Dinwoodie, 2000, p.108).

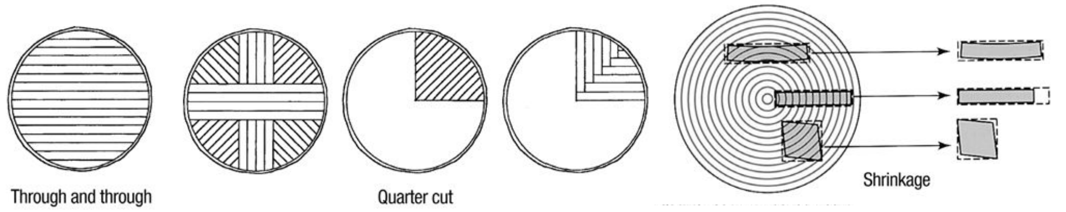

Figure 9
Methods of conversion of timber and their effects on shrinkage.

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[4] https://en.oxforddictionaries.com/definition/anisotropic

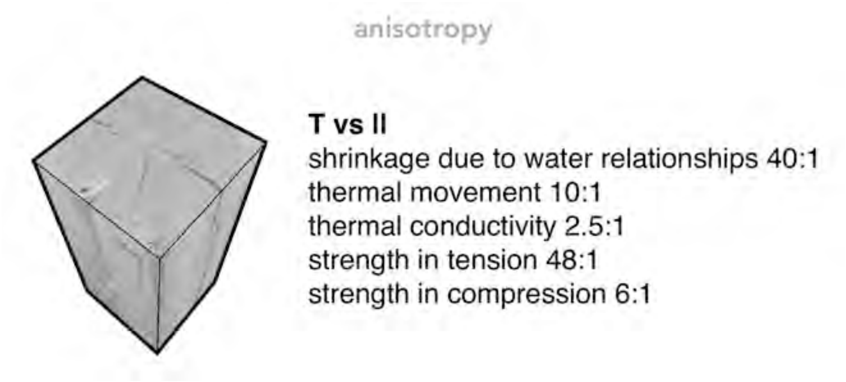

Figure 10
Anisotropy of wood: T – transverse, II – longitudinal direction (Author).

Softwood cells have tracheids playing supporting and conducting roles, while hardwood cells have small amounts of tracheids, fibres for support and storage, vessels (pores) for conduction, and parenchyma for storage. At the microscopic level, 90% of cells in softwood and 80-95% of cells in hardwood are aligned in the vertical axis, along the tree trunk (Figure 11). The remaining percentage is aligned in the horizontal planes and comprises parenchyma for storing food material. Anisotropy present in timber results from this alignment, as well as from the orientation of the microfibrils in the middle layer of the secondary cell wall (Dinwoodie, 2000, p.9-13). The degree of longitudinal and transverse anisotropy of timber shrinkage due to water relationships amounts to approximately 40:1, in regard to thermal movement it is about 10:1, and for thermal conductivity it amounts to 2.5:1. Elastic behaviour of wood is highly direction-dependent, and the elastic modulus is 40 to 60 times higher measured longitudinally than measured tangentially. The permeability, or flow of fluids and gases in wood, is approximately 10^4 times greater longitudinally than tangentially. The ratio of transverse to longitudinal strength in tension averages to 48:1, and in compression to 6:1 (ibid., p.58-61, 65-66, 75, 108, 161-162).

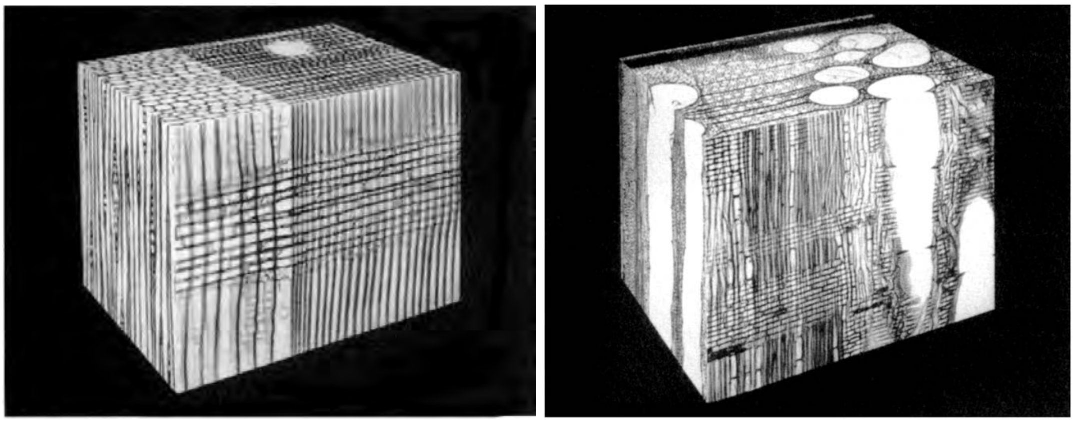

Figure 11
Cellular arrangement. Left: In a softwood. Right: In a hardwood.

Timber is hygroscopic, attaining moisture content in equilibrium with the water vapour pressure and temperature of the surrounding atmosphere. Strength and stiffness of timber decreases with the increase of moisture content; above 20%[5] moisture content, timber is susceptible to attack by fungi. For these reasons, moisture is removed from commercial timbers by air-seasoning or drying in kilns.

Due to its hygroscopic character, wood is not dimensionally stable. It expands and contracts under changing moisture content in relation to its environment. The pressure force of moisture-induced swelling of wood amounts to over a tonne per square centimetre. This property was already known in the ancient Egypt, and was used there for splitting large blocks of stone (Rowell, 2012, p.87-89). Applied knowledge about this movement, i.e. expansion and contraction in timber, was also a frequent motif in traditional construction. At the scale of a building component, movement in timber is measured in millimetres and occurs between seasons and even between times of the day. It was accounted for by traditional detailing, such as lapped joints or dovetail keys, giving the wooden element leeway to expand or contract. Today the main strategy of the construction industry is focused on minimising the problematic effects. For instance, manufactured wood products (Figure 12, Figure 13) are developed and produced with a goal to offset the dimensional instability of wood by randomising its material behaviour.

Figure 12
The array of manufactured wood products: plywood, chipboard, MDF, OSB, and CLT.

The array of these products is vast and widely used, e.g. plywood (developed in ancient Egypt and reintroduced in its modern form in the 1830s), glued laminated timber - glulam (developed in the 1860s and introduced in the 1900s), chipboard (introduced in the 1930s), medium-density fibreboard - MDF (introduced in the 1960s), oriented strand board - OSB (introduced in the 1970s), and cross-laminated timber - CLT (developed in the 1970s and introduced in the 1990s). Other strategies involve application of various oil-based or alkyl-based finishes, heating the timber for short periods of time to very high temperatures (250–350°C), or chemical treatments (Dinwoodie, 2000, p.64-65, 240-243). The common trait of all the strategies is their extensive use of external energy and chemicals, including toxicants.

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[5] Moisture content of newly felled, or green timber, varies between 60% and 200% (Dinwoodie, 2000, p.52).

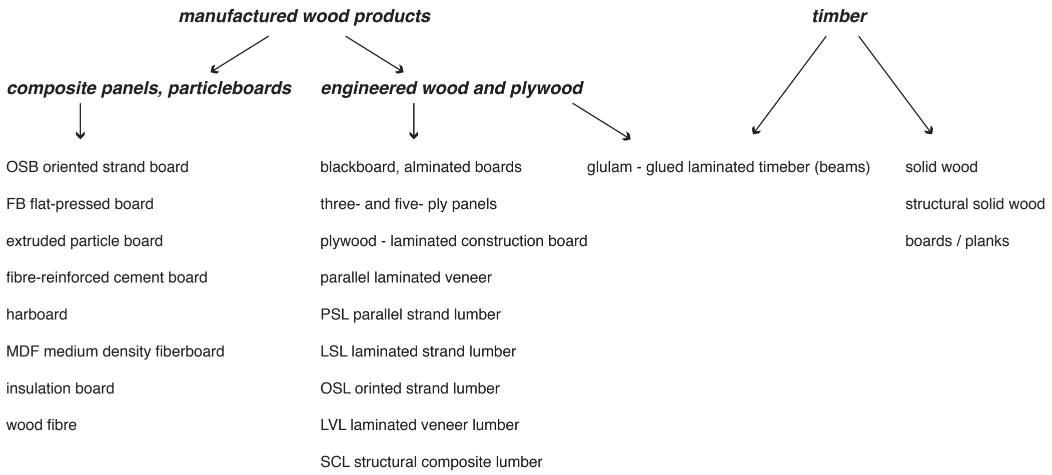

Figure 13
Classification of wood products.

Anisotropic shrinkage on drying from green is used in the *BackToBack* experiment (see p. 45). Movement – anisotropic dimensional instability due to water relationships in wood, is used the *Swelling Vault* experiment (see p. 33).

Heterogeneity of wood

Wood structure is highly heterogeneous; phenomena such as reaction wood and spiral growth result from environmental conditions of tree development (gravity, wind, sloping site, and competition for light and nutrients). Spiral growth has been a persistent feature for many millions of years; thus, it is unlikely a defect as it would have been eliminated by evolution. This phenomenon can be observed for most tree species. Studies confirm that spirally grained trees are better suited to meet extreme wind and snow loads (Harris, 1989) as spiral growth increases stiffness, stability, and minimises the use of material in trees (Wagenführ, 2008).

Spiral grain in wood is seen by some wood scientists as the most serious single defect in softwoods. While wood with spiral grain has no abnormal shrinkage, spiral patterns in sawn timber affect the entire length of a piece. Spiral grain in sawn timber combined with change in moisture content causes a warp type called twist. Spiral grain induced twisting in transmission poles can amount to 50° and break the transmission lines. Additionally, the strength in tension, and to a lesser degree in compression, decreases as the slope of the grain in timber increases. Machining and bending of such wood are difficult. For all these reasons spiral grain reduces log value. The actual cost of wood wastage due to spiral grain is difficult to assess, but at times the rejection rate of the crop may amount to 50% (Harris, 1989).

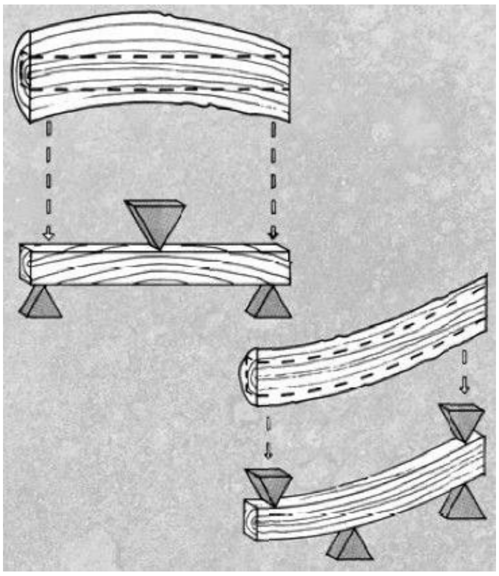

Figure 14

The grain orientation serving as an asset in Japanese traditional woodworking, and helping to resist central and cantilever loads.

Figure 15

Twisted stack of timber after drying.

Japanese traditional woodworkers treated irregularities in grain as an asset (Figure 14) to resist certain loads (Brown, 1989, p.57). In the Scandinavian boatbuilding tradition ‘to ensure that the planking in the prow of a boat swept, sloped, in the right direction, it was suitable to choose a clockwise twisted log for the starboard planking, and an anticlockwise twisted log for the port planking’ (Säll, 2002, p.29). In the 18th and 19th centuries, trees with left-handed spiral grain were sought out for the curved mouldboard section of the wooden plough. Large hardwood trees with pronounced left-hand spiral grain were greatly prized for the strength of the curved surface. Spirally grained poles also give warning of failure, as they fail progressively by splitting, which makes them favourable for pit-props and mining timbers (Harris, 1989). Andre Wagenführ (b. 1959), a professor at the Institute of Wood and Paper Technology (Institut für Holz- und Papiertechnik) at the TU Dresden, experiments with wood with spiral grain. He takes advantage of the interdependence of the fibril angle, stiffness and toughness – the shallower the slope of the fibrils, the smaller the force required for the deformation of the material (Wagenführ, 2008).

The photograph (Figure 15) depicts a twisted stack of timber as a result of the twist in the same direction in all the individual boards due to spiral grain. This demonstrates how double-curved shapes can be achieved using the energy released during wood drying. In order to control this process, the phenomenon of twist must be understood and the resultant movement in the stack predicted. It is known that twist is caused by three main factors: (1) annual ring curvature – the closer a piece of wood is sawn to the pith the more prone it is to twist, (2) spiral grain angle – the higher the spiral grain angle the larger the twist, and (3) change in moisture content – the drier the pieces the more severe the twist (Bäckström et al., 2004, p.I-3). That implies that the twist in a piece of timber can be predicted by a combination of measuring the grain angle and controlling the way wood is sorted, converted, and dried. Wood with left-handed spiral grain, which is particularly prone to twist, should be sorted out early in the supply chain. Spiral grain angle should be measured using a non-invasive technique. Several techniques exist for providing the internal image of a tree: tracheid effect using a laser beam to map the grain curvature (Grönlund et al., 2007), computed tomography (Sarigul et al., 2003), automated scanner systems, electromagnetic wave scattering (Gjerdrum and Bernabei, 2009), X-ray density measurement, ultrasonic Sylvatest, and vibration measurement (Ranta-Maunus, 1999). All these methods are already in use or may find industrial application in the near future. Information acquired this way can be used to predict twist during drying (Säll, 2002) and employed in a digital form-finding simulation process to spontaneously achieve forms otherwise difficult and expensive to achieve. For this process, integration of non-invasive, quick and reliable gradation methods of wood with digital tools capable of simulating behaviour of material systems, or assemblies of multiple twisting components are necessary.

Taxonomic variability of wood

In Northern Europe approximately 35 species of trees exist, of which about 2/3 are suitable for construction. In general, there are about 30 times more hardwood than softwood species. Moreover, hardwoods are on average twice as heavy and 3 to 4 times as strong as softwoods, thus have a better strength to weight ratio (Wright, 2005, p.17). Despite that, only two species of softwoods: pine and spruce are widely used. For instance, in the UK softwood accounts for approximately 80% of timber used in construction. This industrial preference for softwoods results in a monoculture forestry, which leads to acidic soil and increased soil erosion. It affects the entire ecosystem, including reduction of pH level in the rivers, and threatens many species of plants and animals (Lyons, 2014, p.129, Berge, 2009, p.165-168). However, using some hardwoods more extensively would encourage more biodiverse forestry. One research suggested that using more hardwoods in buildings, according to their strength, could reduce the quantity of structural timber needed by 25% (Bunkholt as cited in Berge (2009, p.167)).

The list below (adapted from Berge (2009, p.166-167)) outlines northern European wood species suitable for construction, as well as their areas of use:

- Alder, common (*Alnus glutinosa*) – piles, gutters, plywood, internal cladding
- Apple (*Malus pumile*) – wooden screws, dowels, thresholds
- Ash, common (*Fraxinus excelsior*) – flooring, plywood, internal panelling, stairs, internal structural details
- Aspen (*Populus tremula*) – flooring, plywood, suspended ceilings, smaller structures, cladding, piping for water and gutters, piles
- Beech, common (*Fagus sylvatica*) – flooring, balustrades, smaller structures, plywood, internal panelling, tar, vinegar

- Birch (*Betula pubescens* and *Betula pendula*) – flooring, stairs, internal panelling, plywood, chipboard, bark for damp proofing, smaller structures
- Douglas Fir (*Preudotsuga menziesii*) – structures, flooring, cladding
- Grey Alder (*Alnus incama*) – internal panelling, veneer
- Hazel, common (*Corylus avallana*) – wattle walling in timber framework
- Holly (*Ilex aquifolium*) – plywood
- Juniper, common (*Juniperus communis*) – cladding plugs
- Larch, European (*Larix decidua*) – structures, flooring, doors, windows, roofing
- Lime (*Tilia cordata*) – smaller structures (used for log buildings in the Carpathians), internal panelling, plywood, fibre for woven wallpaper and rope
- Maple (*Acer platanoides*) – flooring, balustrades, stairs, plugs
- Oak, English (*Quercus robur*) – structures, flooring, windows, doors, thresholds, plugs, cladding, roofing
- Plane (*Platanus hybrida*) – plywood
- Plum (*Prunus domestica*) – plywood
- Rowan or Mountain Ash (*Sorbus aucuparia*) – wattle cladding on external walls
- Scots Pine (*Pinus sylvestris*) – structures, flooring, cladding, windows, doors, tar, roofing, foundations below ground level, plugs
- Sitka Spruce (*Picea sitchensis*) – joinery, cladding
- Spruce, European (*Picea abies* and *Abies alba*) – structures, cladding, laminated timber, fibreboard
- Sycamore (*Acer pseudoplatan*) – flooring
- Walnut (*Juglans regia*) – plywood
- Western Red Cedar (*Thuja Plicita*) – exterior cladding, roofing
- White Willow (*Salix alba*) – veneer, wattle cladding on external walls
- Wild Cherry (*Prunnus avium*) – flooring
- Wych Elm (*Ulmus glabra*) – flooring, balustrades, piles, stairs, panelling, internal structural details

Commercial timbers are defined as hardwoods or softwoods according to their botanical classification rather than their physical strength (Lyons, 2014, p.127). This misleading distinction dates back to the medieval timber trade, and it is not in reality related to the actual softness or hardness of the wood (Butterfield, 2003, p.30).

The density of timber is related to the relative proportions and wall thicknesses of various types of cells. Timber density ranges between 120-1200 kg/m^3 in general and between 400-950 kg/m^3 for the wood species occurring in Europe (Figure 16). The density of the actual cell wall material is constant for all timbers with a value of approximately 1500 kg/m^3. Variability in mechanical properties of wood is related to cell wall thickness and distribution of cell types (Dinwoodie, 2000, p.30). In general, the density of hardwoods is higher than that of softwoods. However, balsa with density below 200 kg/m^3 is a hardwood; while yew, over 3 times denser, is a softwood. As strength and durability of timber are related to density, these properties are also species-dependent. Further to that, woods of different species vary in the amount of moisture movement.

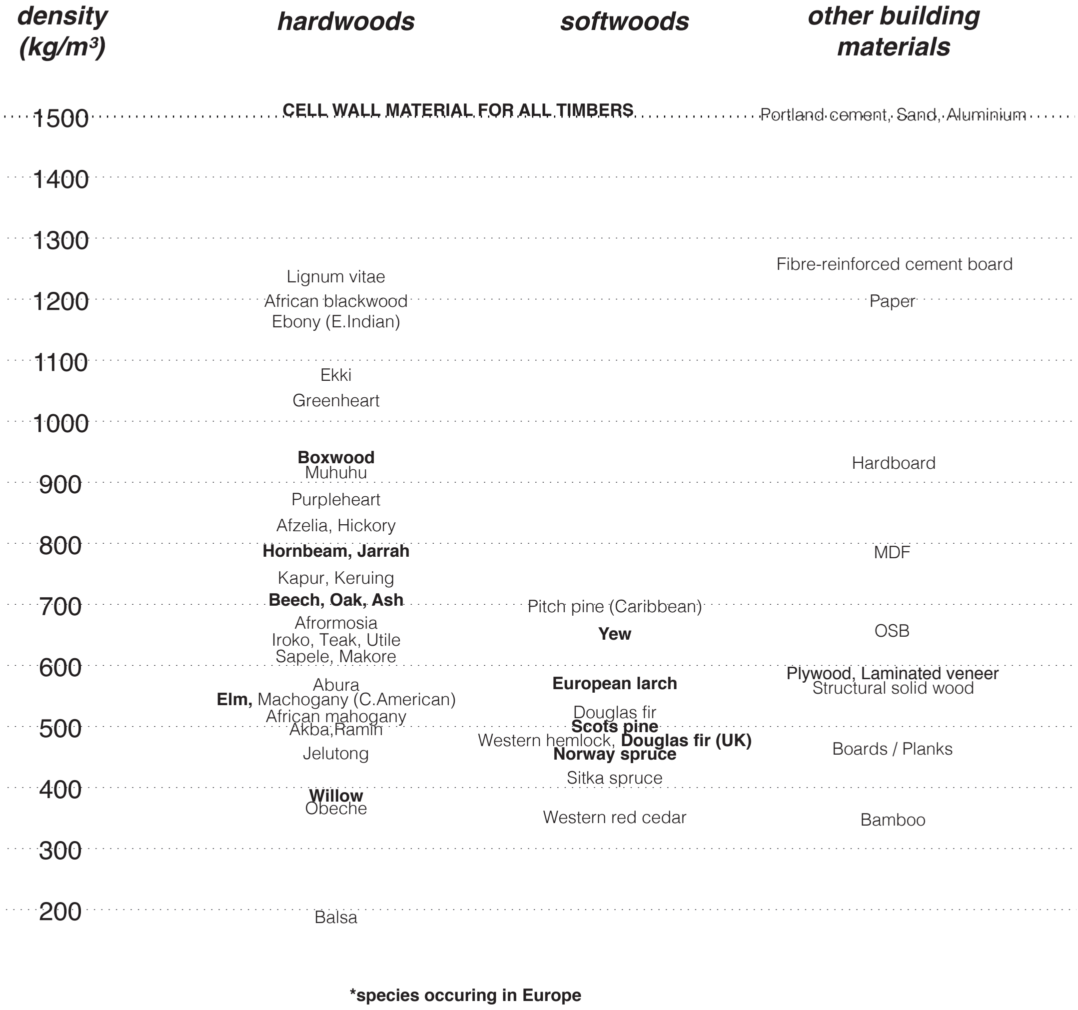

Figure 16
Densities of various species of wood compared to other building materials.

Some wood species are more resistant to fungi, insect, and rot attack than others; and as such they could potentially be used in construction without additional treatment. This feature is often related to toxicity of the wood: yew (*taxus baccata*) and black locust (*robinia pseudoacacia*) are well known examples. There are rare cases of architectural applications of yew for its properties. Some of the 16th-18th century wooden churches in Slovakia: mainly in Hervartov (Figure 17), and partly in Točany and Kežmarok, were constructed of yew wood (Zwerger, 2012, p.34). More recently the Albisgüetli forestry operations centre in Zurich, designed by Fahrländer Scherrer Architekten and completed in 2013 (Figure 18), featured cladding with three layers of untreated yew shingles (Schindler, 2014).

Figure 17

Church in Hervartov (Slovakia) from 16th century made of yew.

Figure 18

Fahrländer Scherrer Architekten, 2013, Albisgüetli forestry operations centre in Zurich, yew shingle cladding.

Species-specific wood properties were traditionally used in vernacular construction. Before the introduction of structural iron and steel, builders often applied hardwood dowels in softwood structural elements for replacement of mortises, notched and scarf joints, for their greater strength, for the ability to connect elements with more ease, and for saving time (Steurer, 2006, p.148). This approach, where woods of different species are used in one project according to their properties and performance, had been famously utilised by the American entrepreneurs-engineers Henry J. Kaiser (1882-1967) and Howard Hughes (1905-1976). The Hughes-Kaiser HK-1 (later renamed to H-4 Hercules after Kaiser's withdrawal from the project) was an aircraft developed between 1942 and 1947 when, due to World War II, materials such as aluminium were rationed. The largest aircraft ever built (Figure 19), it was constructed almost entirely out of wood. Originally birch was chosen as a material, but due to a shortage in supplies fir, cottonwood, maple, and balsa were used (ibid., p.82) in different parts of the airplane according to their species-specific properties. The HK-1 was designed with the variant performance of the unique material characteristics of wood from various tree-species.

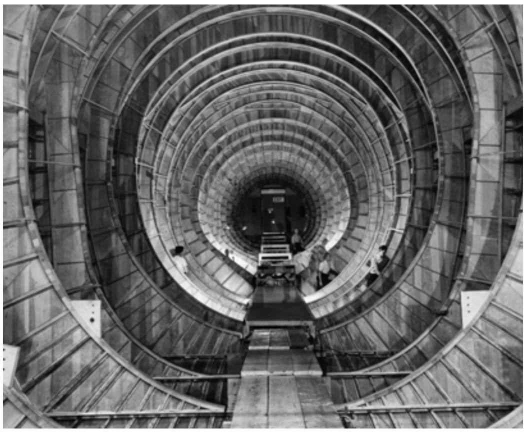

Figure 19

Interior of HK-1, October 1945.

Figure 20

HILDEBRAND, formerly known as Blue Architects, and Rubrecht Architekten, 2008-2012, Sports Centre Sargans, interior.

The Swiss Federal Laboratories for Materials Testing and Research (EMPA) conducts investigations into the behaviour of indigenous wood types. The wide scope of research projects, including biological and bio-mechanical studies, led to improvements to laminated timber construction. The research project *Laminated Beech Wood Structures*, carried out at the ETH in Zurich, paved a way for the use of beech in construction. Beech, being the country's most important hardwood, was not used in load bearing structures due to its tendency to bend; however, its strength is superior to spruce, the most commonly wood used in glulam construction.

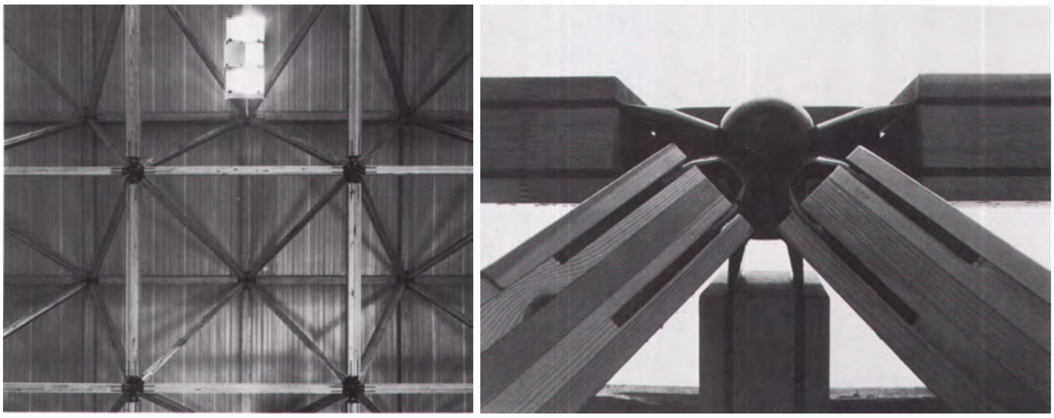

Figure 21

Architect Plinio Haas, timber engineers Wälli AG and ETH Zurich, 1984, Seeperksaal building in Arbon. Left: Beech glulam beams. Right: 8-way connectors.

The Seeperksaal building in Arbon (Figure 21) was a pilot project developed by architect Plinio Haas together with timber engineers Wälli AG and ETH Zurich in 1984. It included spans of 27 x 45 metres that could not be executed maintaining the slender cross-sections of 180 x 180 mm in spruce. Utilising beech, a much stronger wood than spruce, and utilising the custom-made compact 8-way metal connectors both contributed to the feasibility of this project. Similarly, the Dörfli Bridge in Eggiwil, designed by timber engineer Hans Vogel Bern and ETH Zurich and constructed in 1984, uses beech glulam components. It was not possible to build this road bridge out of softwood given the limited height of the structure (Steurer, 2006, p.60-63).

Timber hybrid components that involve laminating wood with other materials such as fibre-reinforced polymers, steel, or textile fabrics are beyond the scope of this research. However, another class of hybrid components combines laminated layers of softwood with layers of higher strength grade timber, laminated veneer lumber (LVL), thermally modified timber (TMT), or compressed laminated wood. The idea to replace the top and bottom layers in glulam beams, where the tension and compression forces are the greatest, with wood of higher load-bearing capacity has been tested since the late 1970s. For instance, in Switzerland, glulam beams with beech laminations top and bottom already received technical approval. In the Swiss Sports Centre Sargans (designed and built in the years 2008-2012 by HILDEBRAND, formerly known as Blue Architects, and Rubrecht Architekten) spruce and ash woods were used according to their specific characteristics and roles in the building (Figure 20). The ash glulam beams used in the gymnasium can be characterised as hybrid components, reinforced with steel and combined with concrete, achieving slender 140 x 500 mm cross-sections spanning 10.65 m (Jeska and Pascha, 2015, p.29-31).

Naturally grown shapes of wood

Vernacular joiners and carpenters must have always faced the problem of putting irregular timber to good use. For instance, in medieval English joinery slightly curved trees were split in half to make rafters and joists, where the split was used as the straight surface to which other elements could be attached. More considerably curved trees were longitudinally halved, then the two matching mirror-image halves were placed symmetrically in a frame as tie beams, braces, or crucks (Figure 23)(Harris, 1979, p.17-19).

Figure 22

Crooked Forest, Nowe Czarnowo, Poland.

Figure 23

English cruck frame, tithe barn, 14th century, Bradford-on-Avon, Wiltshire, UK.

The pre-industrial carpenters took advantage of existing shapes of trees in order to achieve superior strength and reduce labour. Integrating naturally grown wood shapes into the design was a typical feature of pre-industrial architecture; for instance curved or elbowed oaks were used for arched types of roofs in the 14th to 16th centuries (Mark, 1993, p.183, 194). Schindler cites a German forest administrator and author from the turn of the 18th and 19th centuries, Karl Friedrich Viktor Jägerschmid (1774-1863), as saying in 1828 that crooked trunks are very useful for waterwheels and for shipbuilding, and that curved wood often costs more than straight wood (Schindler, 2009, p.103). Evidence of this practice can be found in manuals for loggers and shipbuilders from various countries from that period of time (Figure 24, Figure 25, Figure 26).

Figure 24
Encyclopédie méthodique marine, 1798, France.

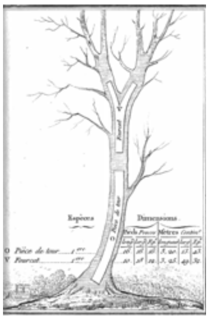

Figure 25
Manuale ad uso degli agenti dei boschi e della marina, 1807, Italy.

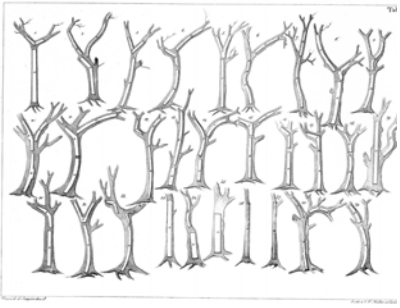

Figure 26
Handbuch für Holztransport- und Floßwesen, 1828, Germany.

Woodlands were regarded not only as hunting preserves, but also as precious resources. They not only provided timber, but also allowed for producing – to a certain degree – desired shapes, either straight or curved. Therefore there is evidence for legal protection of forests in the Middle Ages (Mark, 1993, p.186). A 20th century example of this strategy is the so-called Crooked Forest in Nowe Czarnowo in Poland (Figure 22). In this forest, a few hundred pine trees planted in the 1930s have been unnaturally curved; it is believed those trees were intentionally deformed in order to provide curved timbers for carpenters.

Naturally grown forked shapes of wood are used in the *Y-timbers* experiment where this characteristic and its use are exhaustively described (see p. 66).

BACK-TO-BACK

Precedents

Application of metal connecting plates and brackets, nailing, bolting, screwing, and gluing are the main methods of connecting solid timber members today. Yet, some wonders of wood engineering up until the 19th century were based on all-wood connections. The Mormon Tabernacle at Salt Lake City (Figure 27) was built in the 1860s by Henry Grow (1817-1891) and William H. Folsom (1815-1901) and still exists today. It has a vault spanning almost 50 metres that was, for long time, the world's largest; while all its joints were made by wooden pegs and cowhide lashing (Wright, 2005, p.23).

Figure 27

Henry Grow and William H. Folsom, 1864-1867, The Mormon Tabernacle at Salt Lake City. Jointing made by wooden pegs and cowhide lashing.

Figure 28

19th century log construction, Norsk Folkemuseum, Oslo.

Log construction is one of the oldest methods of building with wood (Figure 28). As the character of wood logs and simple tools allow a limited variety of possible cuts, similar methods of construction based on arranging logs horizontally developed independently in different parts of the world. The oldest remains of log huts were found in excavations in the village of Buch near Berlin and were dated to c. 1200-800 BC. The builders of traditional log huts not only used all-wood connections, but also in some cases took advantage of wood shrinkage. A common practice was to use green wood in construction, which required a period of at least a year for a house to dry and settle before windows, doors, and other elements could be set. Descriptions of this practice can be found in traditions coming from various cultures. The shrinkage of a wall could be significant and was described as amounting to 3-5 cm per metre (Norway) or 1/2" per log (Canada). In the process, the logs would be 'bedding more and more firmly together', and making the building tight (Mackie, 1972, p.8, Falk, 2002, p.28, Drange et al., 1992, p.154, Berge, 2009, p.217).

Cross-laminated timber (CLT) (Figure 84, Figure 85, p. 136) 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 (PUR), 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 considered (see p. 51).

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. Natterer has worked with stacked-plank panels since the 1970s. His system, called *Brettstapel*[6] (also known as "Dowellam"), avoided toxic adhesives and allowed all-wood components in production, using dry beech dowels that swell by drawing moisture from the elements that they connect. The connected softwood posts of fir or spruce are at 12-15% moisture content, while the beech dowels are at 8%; as the moisture content equalises, the beech dowels swell, thus locking the posts together. In some cases, diagonal dowels are applied to avoid potential delamination. This method allows for producing elements up to 600 x 8000 mm in size and 80-300 mm thick (Lyons, 2014, p.174-175).

A similar principle is employed in the production of NUR-HOLZ[7] (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 the HOLZ100 system), the layers of timber planks are connected by means of hardwood screws. The system does not exploit the behavioural 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 coming from beetle-kill 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. Similar 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).

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[6] See http://www.brettstapel.org.

[7] See http://www.nur-holz.com.

Aim of the experiment

The aim of the *BackToBack* 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. The method involved harnessing the material behaviour, i.e. shrinkage, as a connecting mechanism. Secondly, it attempted to accommodate two contradictory needs: to yield as uniform and smooth a component as possible, and to minimize processing of the material. Boles of trees were longitudinally split and the straight cut faces exposed, while the unprocessed backs were used to connect the pieces.

The experiment set out to test the viability of CNC machining for producing a connection based on wood shrinkage. To this end, one method (*dry-in-wet*) involved comparing the results of working the material using conventional carpenter tools with using CNC machining, and the other method (*wet-in-wet*, see p. 48) was based on incision patterns very difficult to achieve by conventional tools. By completing this experiment, the viability of CNC machining precision was put to test and showcased.

Materials sourced

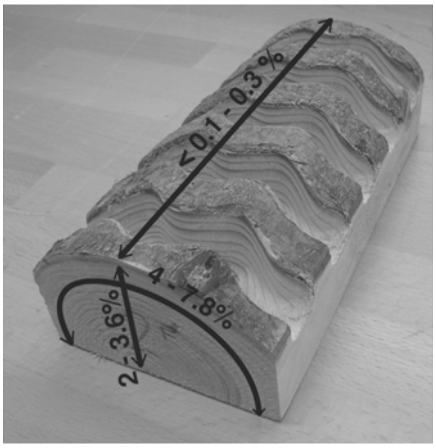

Figure 29

Anisotropic shrinkage of Norway spruce.

Figure 30

BackToBack, wet-in-wet system.

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 behaviour 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 29, Figure 31). Norway spruce was chosen for the experiment. The acquired roundwood was frozen and processed while still green. The test pieces indicated 5% tangential shrinkage[8] after 2 weeks of keeping the wood at room humidity and temperature[9].

Description of the experiment

The *BackToBack* method aimed to provide a permanent bond using an all-wood joint. The joint components were assembled using only manual labour. The permanent bond was created by connecting two pieces of green wood, which become inseparable after drying.

Two design paths were followed (Figure 32):

(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 caused tension on the passive side. The active side of the panel is the part that shrinks; the passive side is the part that does not shrink.

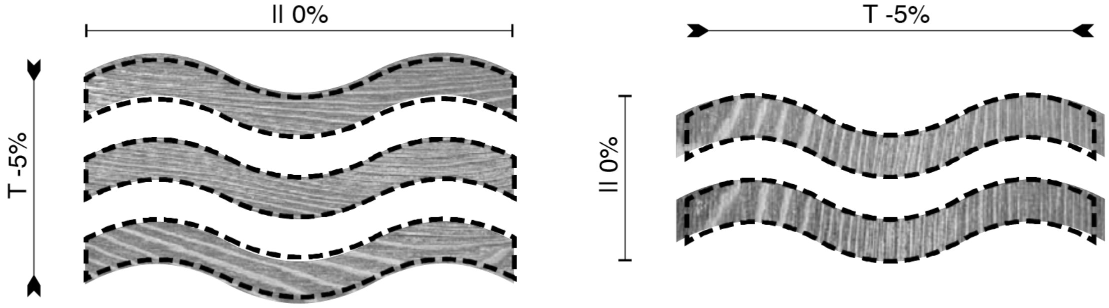

Figure 31

Tangential (T) and longitudinal (II) shrinkage as connection mechanism (dashed lines indicate sizes after shrinking). Left: Incisions along the grain. Right: Incisions across the grain.

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

[9] Approximately: relative humidity = 30-40%, temperature = 20-22^{0}C.

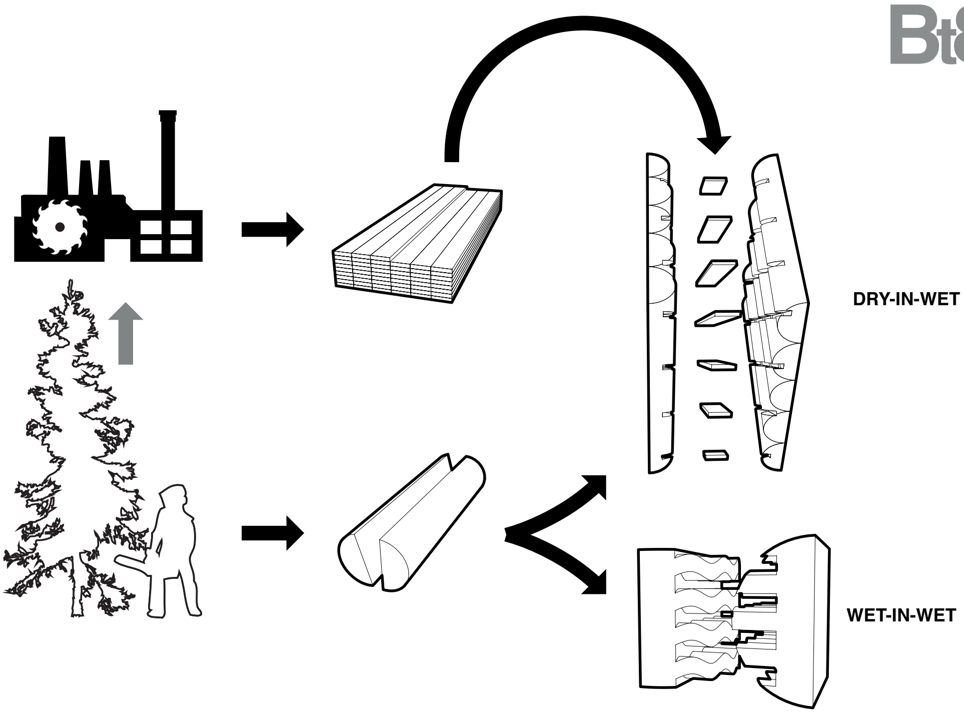

Figure 32
BackToBack, two design paths.

Dry-in-wet

This project tested and demonstrated how green wood shrinkage, activated through drying, could be harnessed to create tight connections between wood components.

Figure 33
BackToBack, dry-in-wet. Left: Connection detail. Right: A series of dry pine boards inserted into parallel incisions .

A series of linear 20 mm incisions were cut at various angles to the halved-log axis on the bark side (Figure 33). Dry pine boards 20 x 120 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 fibre insulation.

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

Wet-in-wet

This experiment demonstrated and tested 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 30, Figure 34).

Figure 34

BackToBack, wet-in-wet. Left: Connection detail. Right: Pieces with various incision patterns.

A series of waving incisions, 20 mm wide and 20 mm apart, were CNC-cut perpendicular to the halved-log axis on the bark side (Figure 36) in order to produce actively shrinking areas of the panel, harnessing the tangential wood shrinkage[10]. According to our estimation, based on literature review, their width after drying should shrink to 18.5-19 mm and tighten on the receiving ribs, resulting from identical incisions cut parallel to the log axis on the corresponding passive elements of the panel (Figure 34). This strategy was based on the anisotropy present in wood shrinkage: While the active incisions, cut perpendicular to the log axis, shrink; the passive incisions, cut parallel to the log axis, remain dimensionally stable.

The waving pattern of the incisions and resulting ribs have been proposed in order to maximise harnessing tangential shrinkage, and prevent the corresponding pieces of wood from sliding. Its precise geometry, size, and proportions remain subject to further research and development.

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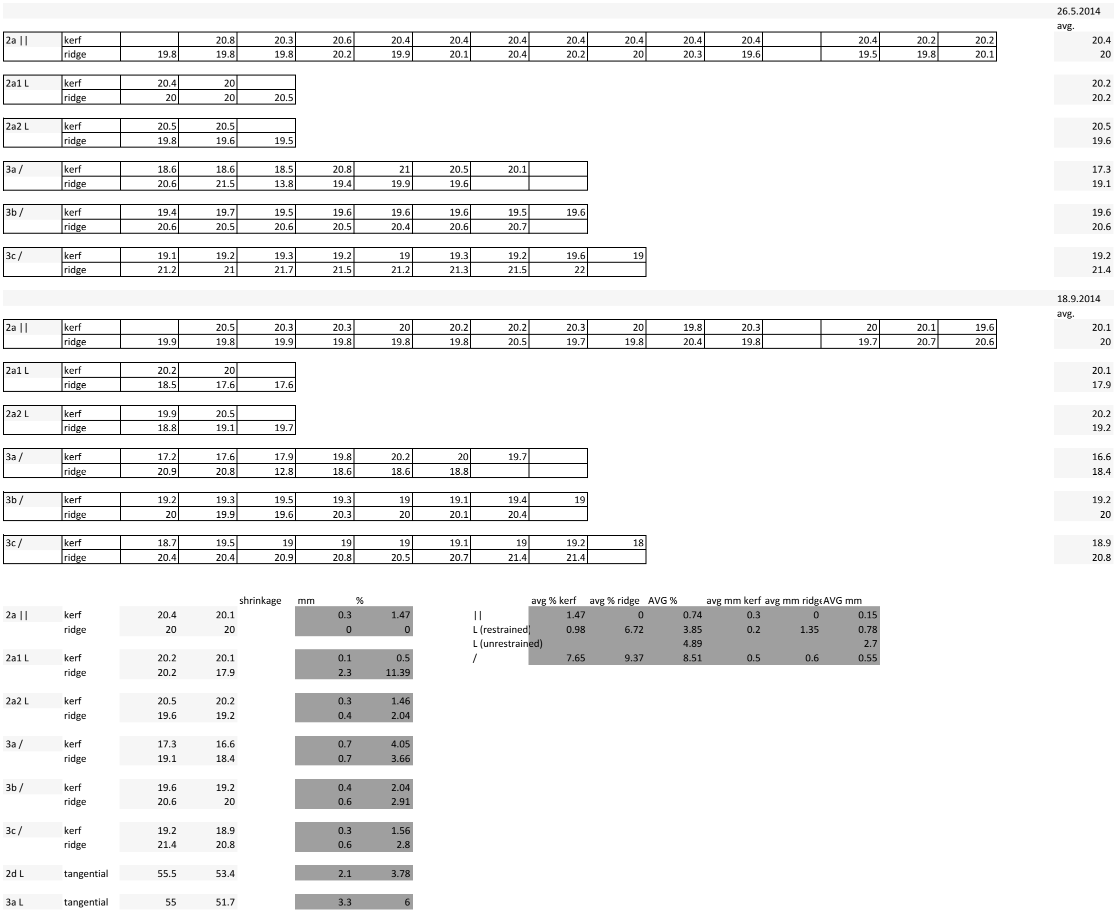
[10] See https://vimeo.com/192351147

Results

The wood and incision shrinkage were measured with callipers and recorded over a period of 4 months (Figure 35). As expected, the width of the incisions shrank after drying and tightened on the receiving ribs, resulting from 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.



																	26.5.2014 avg.
2a ||	kerf		20.8	20.3	20.6	20.4	20.4	20.4	20.4	20.4	20.4	20.4		20.4	20.2	20.2	20.4
	ridge	19.8	19.8	19.8	20.2	19.9	20.1	20.4	20.2	20	20.3	19.6		19.5	19.8	20.1	20
2a1 L	kerf	20.4	20														20.2
	ridge	20	20	20.5													20.2
2a2 L	kerf	20.5	20.5														20.5
	ridge	19.8	19.6	19.5													19.6
3a /	kerf	18.6	18.6	18.5	20.8	21	20.5	20.1									17.3
	ridge	20.6	21.5	13.8	19.4	19.9	19.6										19.1
3b /	kerf	19.4	19.7	19.5	19.6	19.6	19.6	19.5	19.6								19.6
	ridge	20.6	20.5	20.6	20.5	20.4	20.6	20.7									20.6
3c /	kerf	19.1	19.2	19.3	19.2	19	19.3	19.2	19.6	19							19.2
	ridge	21.2	21	21.7	21.5	21.2	21.3	21.5	22								21.4

																	18.9.2014 avg.
2a ||	kerf		20.5	20.3	20.3	20	20.2	20.2	20.3	20	19.8	20.3		20	20.1	19.6	20.1
	ridge	19.9	19.8	19.9	19.8	19.8	19.8	20.5	19.7	19.8	20.4	19.8		19.7	20.7	20.6	20
2a1 L	kerf	20.2	20														20.1
	ridge	18.5	17.6	17.6													17.9
2a2 L	kerf	19.9	20.5														20.2
	ridge	18.8	19.1	19.7													19.2
3a /	kerf	17.2	17.6	17.9	19.8	20.2	20	19.7									16.6
	ridge	20.9	20.8	12.8	18.6	18.6	18.8										18.4
3b /	kerf	19.2	19.3	19.5	19.3	19	19.1	19.4	19								19.2
	ridge	20	19.9	19.6	20.3	20	20.1	20.4									20
3c /	kerf	18.7	19.5	19	19	19	19.1	19	19.2	18							18.9
	ridge	20.4	20.4	20.9	20.8	20.5	20.7	21.4	21.4								20.8

				shrinkage	mm	%
2a ||	kerf	20.4	20.1		0.3	1.47
	ridge	20	20		0	0
2a1 L	kerf	20.2	20.1		0.1	0.5
	ridge	20.2	17.9		2.3	11.39
2a2 L	kerf	20.5	20.2		0.3	1.46
	ridge	19.6	19.2		0.4	2.04
3a /	kerf	17.3	16.6		0.7	4.05
	ridge	19.1	18.4		0.7	3.66
3b /	kerf	19.6	19.2		0.4	2.04
	ridge	20.6	20		0.6	2.91
3c /	kerf	19.2	18.9		0.3	1.56
	ridge	21.4	20.8		0.6	2.8
2d L	tangential	55.5	53.4		2.1	3.78
3a L	tangential	55	51.7		3.3	6

	avg % kerf	avg % ridge	AVG %	avg mm kerf	avg mm ridge	AVG mm
||	1.47	0	0.74	0.3	0	0.15
L (restrained)	0.98	6.72	3.85	0.2	1.35	0.78
L (unrestrained)			4.89			2.7
/	7.65	9.37	8.51	0.5	0.6	0.55

Figure 35

Table with recorded shrinkage of wood and change of size of incisions over q period of 4 months.

The main task of the prototypes was to promote an approach that makes use of material properties and behaviour instead of attempting to overcome them. Log processing time and effort were minimized by only halving and sometimes debarking the logs, instead of sawing on four sides prior to cutting the incisions. By utilizing properties already present in the material and without any external bonding agents, the connection eliminated toxic and composite connections, making the panel biodegradable and recyclable. In this case, the tests performed demonstrate that it is possible to construct a behaviour-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 by attempting to separate them manually. 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%).

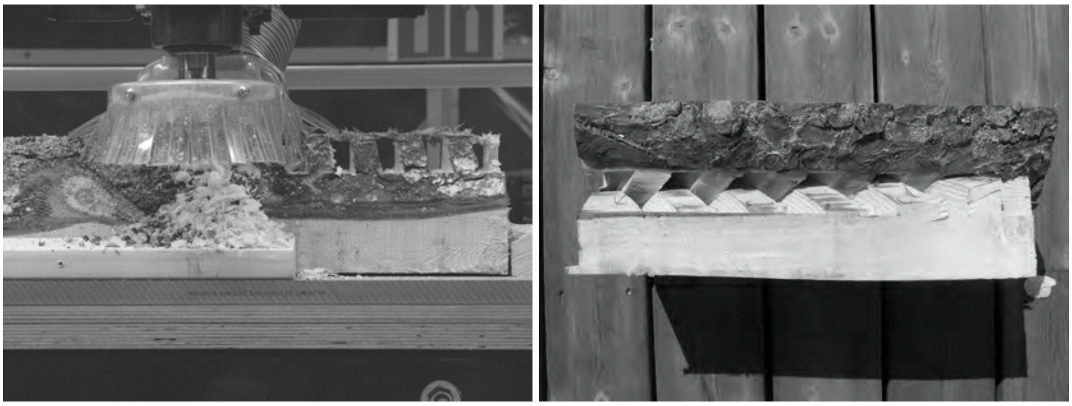


Figure 36
BackToBack, wet-in wet. Left: CNC-cutting. Right: Two parts connected.

For comparison, 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 three main reasons: (i) it did not permit sufficient precision to accurately assess the results, (ii) additional work time was required to readjust the machines as a result of the conical, half-round cross-section and irregularity of the individual logs, and (iii) it limited the possible geometries of incisions to straight linear shapes.

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 rpm[11] produced very smooth surfaces, where no manual work was required. A standard flat tip milling bit was used as a cutting tool.

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

Discussion

Advantages of the BackToBack system

If the *BackToBack* method succeeded, one could foresee large reductions in the use of chemicals, energy, time, and waste generation. Production of the polyurethane glue (PUR) used in the CLT panels involves high temperatures, fossil fuel based raw materials, and chemical additives.

Further to the environmental benefits, the *BackToBack* method would result in a construction technique free from harmful volatile organic compounds (VOC's). VOC's can be dangerous to human health, and both the USA and EU regulations restrict their use and caution against exposure to them.

Using all-wood connections has potential to improve fire safety of structures. CLT panels or glulam beams can delaminate and lose its loadbearing capacity, due to heat exposure weakening the glue. As it burns, PUR produces toxic fumes that can cause respiratory diseases. 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: all-wood connections guarantee burning buildings a longer resistance than metal-to-wood connections. Further to that, metal fasteners penetrating wooden beams in unheated rooms rust where the galvanized coating has been damaged by abrasion upon entering the wood. This causes the surrounding wood to rot due to condensation on the cold metal, a process that is delayed by using toxic, chemical wood preservatives (Graubner, 1992, p.4-6).

Recycling timber components mixed with glue and containing metal connectors, e.g. self-tapping screws, brackets, plates, and bolts is problematic. Metal connectors impede wooden component recycling due to difficulties with partying-out in a demolition process; also, the glue is difficult to separate from the wood. Waste material from CLT production is typically processed into wood pellets. The process of converting this waste into energy requires special filters and high temperatures to ensure the destruction of pollutants emitted from burning the contained PUR.

The volume yield of raw logs for production of timber for standard CLT panels can be roughly estimated at about 50%. One study estimated the yield of small diameter logs, i.e. logs of a maximum diameter below 185 mm, to be often below 45% (Fredriksson et al., 2015, p.1477). As the *BackToBack* system utilises almost entire logs, it could allow for an estimated doubling of raw log yield for the production of wall panels.

Applications

The *BackToBack* project is currently at an early stage and various paths of further development can be considered. The presented panels are designed to be used as structural elements and double as exposed surface. This approach saves energy, production time, and money potentially spent on additional finishes. It would be difficult to meet the present-day thermal requirements using only wood 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.

The incisions pattern

It is necessary to perform rigorous structural testing of various incision patterns in order to develop the *BackToBack* method further. The geometry, sizes, and proportions of the incisions must factor into the structural behaviour 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.

THE SWELLING VAULT

Precedents

A new generation of researchers and designers, working at the intersection of computer science and physical materials, is beginning to explore the potential of using material behaviours as design strategies. In the 2010s the director of the MIT Self-Assembly Lab, Skylar Tibbits (b. 1985), popularised the terms "4D printing" and "programmable materials". These concepts can be characterised as intelligent assembly systems, and are based on producing customised, smart materials by multi-material printing. This means putting together independent parts or components, that by sensing and reacting to their environments, are able to transform and change shape over time, finding their structures and functionalities without further human or machine guidance. However there has already been extensive research in the area of self-assembly. The novelty of this approach lies in the focus on applications in large-scale structures, where substantial reductions can be sought with respect to the energy, cost, and time consumption during the construction of buildings and infrastructure (Tibbits, 2011, p.343). For the field of architecture, one logical consequence of this new conceptual framework is that some aspects of the notion of "smart materials" can be extended onto all building materials, where any material property or behaviour that results in dimensional change can be used as design, or forming strategy, as long as it can be predicted and harnessed[12].

The research into "4D timber construction", carried out by the Institute for Computational Design (ICD) at the University of Stuttgart, is a direct application of these ideas to wood construction (Wood et al., 2016). Under the direction of Achim Menges (b. 1975), the team identified that the major scale limitation of the current research in self-forming and self-assembling systems (based on materials such as shape memory alloys, heat curling carbon fibre composites, or phase- or state-changing polymers) is caused by the immense quantity of required external actuation energy. Wood's ability to shrink and swell with high force in response to the energy-neutral change of moisture content in its environment presents an opportunity to develop large-scale, self-constructed timber surfaces. The team develops bending methods for timber surfaces based on the principle of bilayer-responsive material systems, where the curvature results from combining layers with different coefficients of expansion. The method harnesses wood's anisotropic moisture-induced movement by combining active with restrictive elements, or layers using opposing fibre orientations. The resultant curvature is controlled by the orientation, length, thickness, and initial configuration of the elements

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[12] It is understood that most building materials cannot be seen as "smart materials" as defined in material science, see discussion on p. 187.

(Figure 37). The system behaviour is determined by integrated simulation, visualisation, and computational design methods.

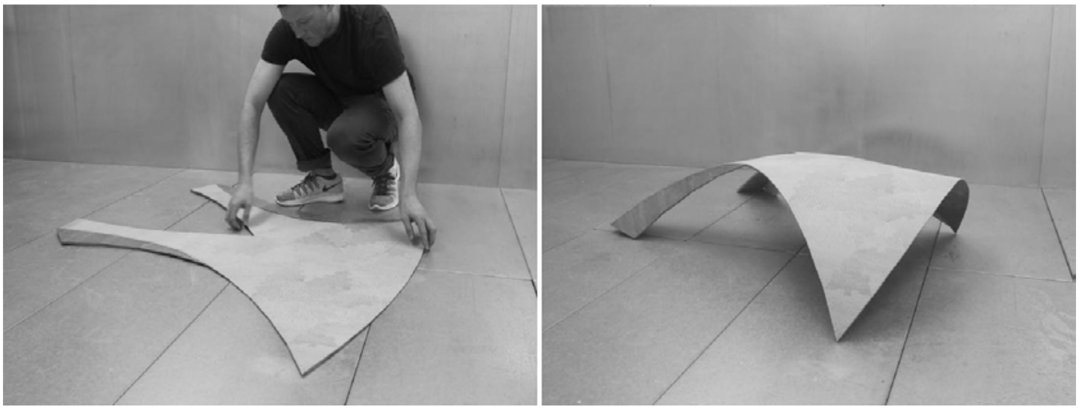

Figure 37

ICD University of Stuttgart "4D timber construction" prototype: self-constructing surface from flat (left) to double-curved (right).

In 2019, the "4D timber construction" method was used by the University of Stuttgart ICD/ITKE team to construct a 14 m tall Urbach Tower for the Remstal Gartenschau event (Figure 38).

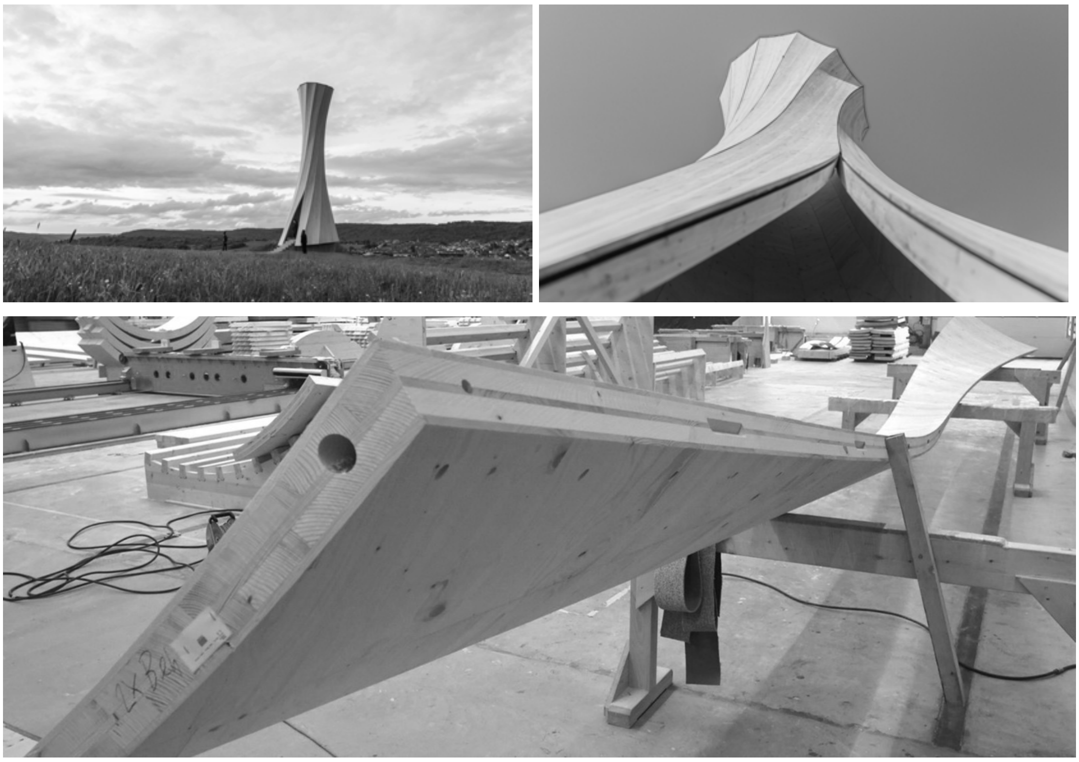

Figure 38

ICD University of Stuttgart, 2019, Urbach Tower Remstal Gartenschau. Top Left: Tower completed. Top Right: View of tower from entry. Bottom: Twisted component in factory.

The components for the tower were manufactured in a flat state and assumed predicted curved shapes while the wood shrunk with decreased moisture content. Spruce wood with a high moisture content was sourced from Switzerland and was used to produce 5 x 2.4 m bilayer CLT panels that were dried using a standard industrial drying process, during which the parts curved. The parts were laminated together and overlapped to form larger curved components, spanning up to 15 m with a radius of 2.4 m and thickness of 90 mm. The components were 5-axis CNC cut and detailed before they were preassembled in groups of 3 components including a water barrier and cladding made from larch wood[13]. These components were assembled on site.

The problem of double-curved wooden shells

Double curvature is a shape with surfaces that curve in two directions, such as the shape of domes or spheres. These shapes, unlike those of cones or cylinders, cannot be wrapped with a sheet of paper without creasing it. In other words, they cannot be unrolled without approximation.

A double curved shell shape may be advantageous for several reasons[14]. The main benefit of using double curvature in construction is that through the spatial leap from two to three dimensions a superior structural strength is achieved, so that less material can be used to perform a given structural task. A synergy of material properties and form is accomplished. This strategy is not without a pitfall, which can be described as the problem of "structural vs technological efficiency". The contradiction occurs when a material-saving design implies a higher complexity of structural forms and further the cost to achieve in a way that is not justifiable, both financially and in terms of material, time, or energy. (Sandaker, 2008, p.57-59).

Wood comes from trees, so its shape is determined by the geometry of the trunk: it is long, narrow, and often straight. Manufactured wood products, on the other hand, are made into sheet form. The geometrical and physical properties of the material are problematic when used for forming double curved shell structures. In the pursuit of curved wood shapes, the key strategies can be divided into two groups of techniques: subtractive and transformative. The processes in first group are based on carving out the material from solid blocks, and in the second on bending techniques.

The main disadvantage of subtractive methods in wood forming is the excessive production of waste. The portions of the material that are removed are turned into sawdust[15]. Sawdust can be remanufactured into another

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[13] https://icd.uni-stuttgart.de/?p=23336

[14] While its possible architectural applications are beyond the scope of this discussion, it is important to mention that double-curved surfaces are structurally efficient, effective for improving room acoustics, and also may be used for creating interesting light effects, or for aesthetic reasons.

[15] Centre Pompidou in Metz (2003-2010) by Shigeru Ban Architects is a good example where advanced design strategies were used to minimise wastage resulting from subtractive wood machining. The double curved roof of the Centre is supported by approx. 1800 individualised curved glulam beam segments. The engineers involved in the project (DesignToProduction, SJB Kempter Fitze, Holzbau Amman) devised strategies based on pre-bending these segments in order to approximate the curvatures prior to milling. Wastage was minimised by

product; however, this operation involves a series of energy and chemical intensive processes, causing an impact on the environment. Further to that, as usually the best quality wood is used for the production of double curved components, it is not economically viable to further remanufacture this material.

Bending may be seen as a more efficient method of producing curved wood components; however, as a 2-dimensional operation it is technically not suitable for double curved surfaces. The main argument for bending wood is saving labour and material. This delivers a curvature of superior strength without compromising wood grain. Yet, working out double curvature through bending requires breaking the surface into smaller parts and approximating the shape by flat, single or double curved panels, which significantly complicates the process. In the case of curved panels, a separate mould has to be manufactured for each piece; so the cost of this method is responsible for the fact that still very few large freeform structures are in existence (Pottmann et al., 2008, p.21).

When bending a piece of wood, the fibres on the outside of the curve stretch, while the ones on the inside compress (Figure 39). As the cellular walls of wood compress more easily than they stretch, splitting on the outside of the curve is the most common failure during bending (Benson, 2008, p.16). Several methods have been devised to make the material more pliable over the 5000 years of wood bending history (Sandberg and Navi, 2007, p.17-63)[16]. The agents used as plastifiers include temperature, moisture, and chemical treatments[17].

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integrating the wood grain direction with the beams' shapes (Jeska and Pascha, 2015, p.64-69, Schittich, 2010, Scheurer, 2010).

[16] The Kalvträsk skis from c. 3200 BC are the oldest known example of using plastifiers for bending wood - their front tips were probably curved with heat from open fire (Sandberg and Navi, 2007, p.17), see also http://www.vbm.se/en/se-and-gora/utstallningar/skidutstallningen.html.

[17] More methods for bending wood exist. Laminated and kerf bending use the fact that the bending radius is dependent on the thickness of the material. Compression bending is based on changing the wood structure by compressing it along the grain while preventing it from buckling, so that the fibres become like a bellow and are easier to bend.

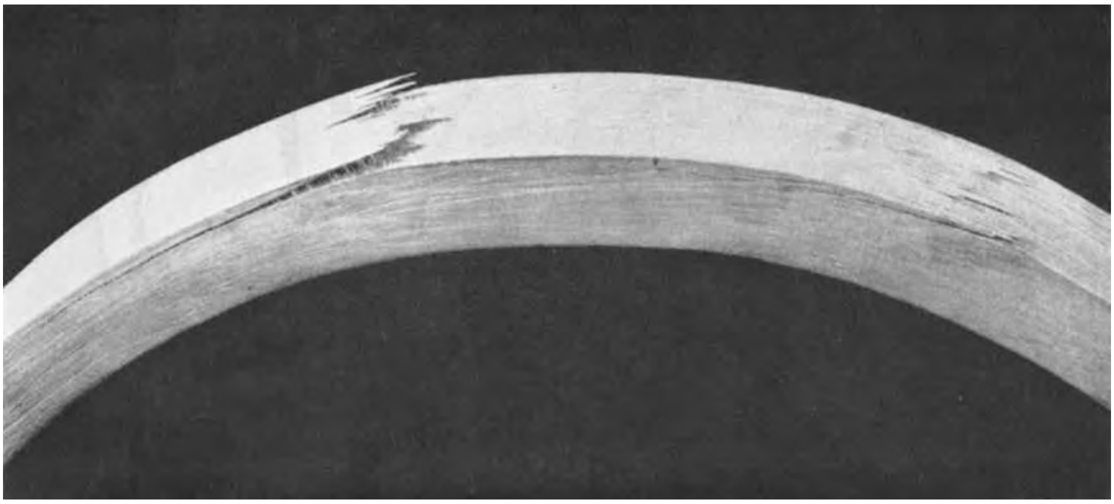

Figure 39
Splitting on the outside of the curve during wood bending.

Overview of wood bending techniques in the 20th century

The precedents discussed below outline the prevailing approaches to forming wood into double-curved shapes, rather than techniques that harness the response to environmental humidity. The most advanced techniques in forming double curved surfaces from wood were developed by the aircraft, boat, and furniture making industries in the first half of the 20th century.

Just before World War I, a new fuselage design called the monocoque[18] appeared in the aircraft industry. The earliest construction attempts were based on a very laborious process of layering extremely thin plywood sheets glued and nailed to a circular wooden frame[19]. The French Deperdussin Racers (1912-1913) and the German *Albatros* fighters (1917-1918) were the most famous examples of this early method. In 1918 the Loughead Aircraft Manufacturing Company[20] improved this method by introducing a technique of forming half-shells, based on forcing layered spruce veneers into concrete moulds by means of an inflatable rubber bladder (Figure 40). After the casein glue cured, the half-shells were joined over a light skeletal framework (Figure 41). This process was employed in a series of very successful airplanes in the 1920s and 1930s (Jakab, 1999, p.915-916).

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[18] A monocoque is an aircraft or vehicle structure in which the chassis is integral with the body (https://en.oxforddictionaries.com/definition/monocoque).

[19] Bending laminated wood in two directions was first patented by the cabinetmaker John Henry Belter (1804-1863) in the USA in 1858.

[20] Today Lockheed Martin Corporation.

Figure 40
Forming Loughead monocoques in concrete moulds.

Figure 41
Loughead S-1 Sport biplane from 1920.

The short supply of steel during World War II inspired further development of methods for making wooden monocoque hulls for boats and airplanes. This progress led to a new technique called hot moulding. The technique required large autoclaves, pressure vessels and moulds, as it was based on adhesives dependent upon heat (approximately 150°C) and pressure (approximately 75 PSI). After the end of World War II, this technique was still used for production of boat hulls; however, it could not compete against new materials such as fiberglass, developed in the late 1930s and 1940s. In the early 1950s new adhesives came onto the market that did not require heat and pressure. As the expense of autoclaves and pressure vessels was eliminated, hot moulding gave way to cold moulding. Since then, even boats as big as 65 m were built using the cold moulding method (Gougeon, [1979] 2005, p.35-41).

Figure 42
Eames leg splint from 1942.

In the early 1940s the American designers Charles (1907-1978) and Ray (1912-1988) Eames were experimenting with wood-moulding techniques. This led to a commission from the US Navy to develop plywood splints (1942), which were used successfully in World War II (Figure 42). The splints were moulded under heat and pressure to achieve double curvatures, mimicking the shape of the human leg (Scott and Eames, [1943] 2015). This experience contributed greatly to the development of the LCW and DCW chairs (1946), which are bent plywood design classics (Eames, [1953] 2015). The most copied chair in the world, the Model 3107 (1955) by Danish architect and designer Arne Jacobsen (1902-1971), can be seen as the culmination of the use of pressure moulding (Figure 43). Since the 1950s, only relatively small improvements were made to the technology, and the need for aluminium moulds has not been eliminated.

Figure 43

Comparison of pressure moulded chairs. Left: Eames' LCW chair from 1943. Right: Jacobsen's Model 3107 chair from 1955. Jacobsen was the first to achieve the seat and back of chair from one piece of plywood.

Aim of the experiment

This research seeks solutions for achieving double-curved wooden shells by reframing the problem rather han developing existing techniques further. The techniques outlined in the previous section seek to overcome wood's natural material properties, such as stiffness, by applying energy and chemical intensive processes. The proposed approach assumes that inherent material characteristics and behaviours exist that could be harnessed in order to form curved surfaces with a minimisation of external agents. One such behaviour is wood movement induced by changes of its moisture content. Harnessing this behaviour could potentially lead to a solution that would avoid the pitfall of the "structural vs technological efficiency problem" (see p. 55). While the presented experiments with "4D timber construction" (see p. 53) used state of the art technology, i.e. CNC milling or industrial robots, as well as manufactured sheet wood products; this project used low-tech carpentry techniques and unprocessed solid wood.

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

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

Materials sourced

Architect and professor at the MIT MediaLab, Neri Oxman (b. 1976), observed that ‘the extent to which anisotropy is explored, as a generative means to create form, is still rather limited and unexplored’. Oxman proposed to utilise anisotropy directly as a design strategy, and posed a question: ‘If one were able to model anisotropy in the digital space – as part of the form-generation process – what would it look like?’ (Oxman, 2012, p.92).

Oxman’s question defines the departure point for this project. Can the force and directionality of wood movement be used to form double curved shells? Moisture induced parquet buckling is an everyday phenomenon that suggests wood swelling produces 3-dimensional forms from flat patterns of wood blocks, and these forms may result from the individual block shape and orientation.

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

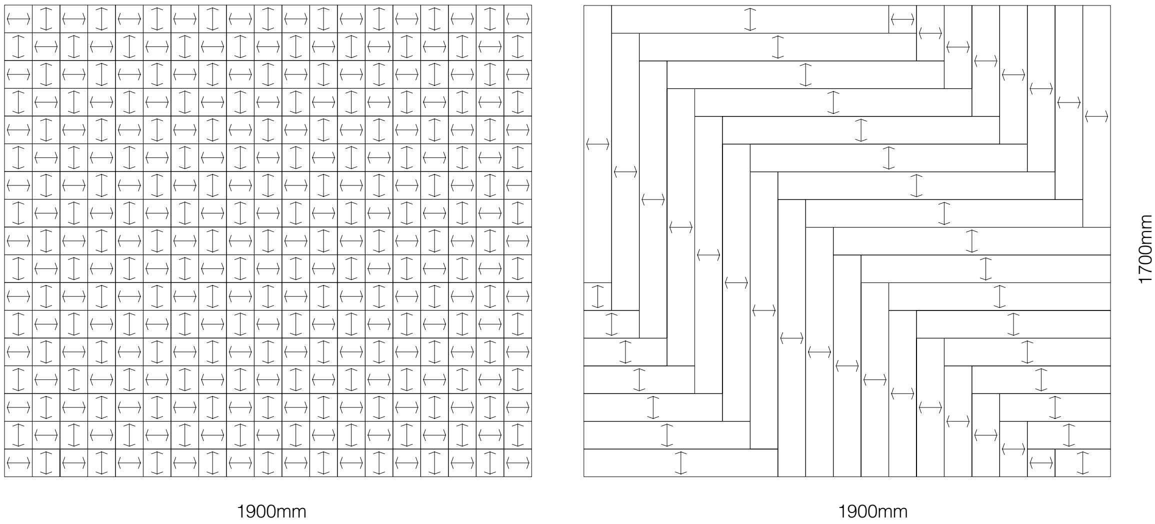

Figure 44

The Swelling Vault, chequered and herringbone block patterns.

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

The patterns were those predicted 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 chequered the smallest (Figure 44). Connections between the blocks used the Lamello Joining System (biscuit joint) and no adhesives were applied.

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 (Figure 46) to accommodate the connecting oval-shaped wooden biscuits. The parquet blocks were laid on the OSB bases with foil sheeting (Figure 45), and the edge constraints and ratchet straps were applied.

Figure 45
The *Swelling Vault*, laying the parquet blocks.

Figure 46
The Lamello Joining System.

It was estimated that about 15 litres of water per system would increase the moisture content of the wood up to approximately 30%. Warm water was poured on the systems with a watering can (Figure 47). Both pieces were covered with foil and left for some time to soak in water and swell.

Results

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

Figure 47

The *Swelling Vault,* increasing the moisture content in wood.

Figure 48

The *Swelling Vault*, chequered pattern bulging.

The chequered 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 opposite direction at the 120 mm measurement. The shape of the surface was regular and domed (Figure 48, Figure 49 right).

Four people weighing approximately 280 kg could step on the 3.2 m^2 system causing slow flexible movements with the Lamello biscuits operating as articulated joints.

Figure 49

The *Swelling Vault*. Left: The herringbone pattern bulging. Right: The chequered pattern bulging.

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 49 left).

Comparison of the empirical results and analytical estimates

In parallel with the material experiment, a digital simulation model was devised to compare the results with empirical tests. The simulator was built in the 3D software Rhinoceros with Grasshopper and Kangaroo plugins[21]. 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, as estimated based on literature review. The system of springs was set in motion by the Kangaroo physics engine, deflecting the flat pattern and assuming a 3D shape[22].

Wood swelling 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 – fibre saturation point

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, p.59). As “through-and through”, the most common conversion method of timber, yields pieces with a mixture of grain orientation from tangential to radial, an average value of 5.75% was assumed. Therefore:

$$SV = 0.0575$$

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

$$CMC = 0.19$$

The fibre saturation point at 30% is based on an average value for oak for most practical applications (Ross et al., 2007, p.24):

$$FSP = 0.3$$

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

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

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[21] 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).

[22] See https://vimeo.com/192333690 and https://vimeo.com/192333694.

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 sagitta[23] (Figure 50).

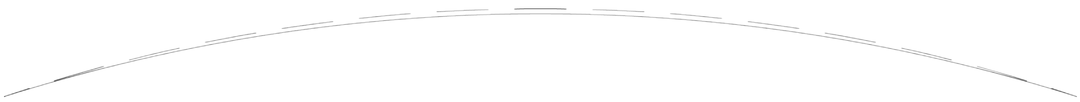

Figure 50
The *Swelling Vault*, the bulged curvature and discrepancy between the simulated (dashed line) and observed (solid line) elongation of the surface.

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.

Discussion

The aim of the experiment was to demonstrate an alternative method of achieving double-curved shapes from wood. The solution minimised machining and waste by using dimensional instability of wood induced by changing its moisture content. While it was demonstrated that the achieved shapes could be predicted, the range of these shapes is restricted, both by the limited ability to constrain the system and the limited amount of wood swelling.

The main novelty of this approach lies in its low-tech execution method. The computational techniques were only used for simulation of the resultant 3D shapes based on 2D block patterns; while the blocks were made, cut, and laid out using traditional carpentry techniques.

Advantages of the Swelling Vault system

Similar to the *BackToBack* method, if successful the *Swelling Vault* method could lead to reductions of waste, energy, time, and the use of toxic chemicals. The biggest foreseen saving would lie in eradicating the need for moulds, or wasteful milling of the excess material.

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[23] Sagitta: the distance from the midpoint of an arc to the midpoint of its chord (https://www.merriam-webster.com/dictionary/sagitta).

Applications

Due to the limited range of shapes, possible applications of the *Swelling Vault* system are limited. Historically, using curved wood in construction has mostly been motivated by maximising the structural span, by cultural and aesthetic reasons, or by the need to achieve acoustic and light-related performance of undulating wooden surfaces (compare discussion on p. 170). It would be possible to develop the method into a production system of double-curved panels using small pieces of scrap or salvaged wood. Alternatively, these panels could be used as moulds for casting shells with malleable materials.

Y-TIMBERS

Precedents

This project made use of the naturally forked shape of trees. Naturally grown forked shapes of wood offer innate strength; which was exploited by vernacular builders in the past, but was not convenient for industrialized production. For the efficiency of the industrialised construction methods, it is more important to use uniform material profiles than to take advantage of the strength of an irregularly grown form. Such natural forms cause problems as they are incompatible with standard machinery, are difficult to address in design when no two branching pieces are exactly alike, and do not lend themselves easily to structural performance calculations. Nevertheless, the recent developments in digital fabrication, and computational analysis and design methods suggest it may be possible to reverse this well-established logic.

In vernacular construction and boat building, naturally branching shapes were frequently used to save time and labour, and occasionally to achieve superior structural strength. Viking boat- and shipbuilders used naturally curved timbers for stems, keels, ribs, and knees of boats; while tholes and keelsons required forked timbers, selected for the job at hand. Wood for curved components was sourced from isolated oaks, free to grow outwards and produce crooked timbers (Graham-Campbell, 1980, p.50-51, 56-57). Examples of historic construction systems that used the innate strength of branching timbers include the Polish strut frame (Figure 51), *konstrukcja sochowa* (Ruszczyk, 2014, p.16) and Norwegian bent construction (cross frame, Figure 52), *grindverk* (Drange et al., 1992, p.145-149). The Polish strut frame can probably be dated to the Bronze Age (1800-1700 BC). It was based on two posts made from forked trees (*socha*) upon which a ridge purlin (*ślemię*) was supported. The ridge in turn supported hooked rafters (*kluczyna*). The system, based on naturally grown shapes of trees, was used up to the 19th century (Ruszczyk, 2014, p.16). The oldest excavated examples of Norwegian *grindverk* date to the 12th century, but the construction system is much older. It probably developed first in western Norway, where there was a shortage of good quality wood. The technique was a very economical way of using a tree. The trees were longitudinally divided into three parts: bottom, middle, and top. The top parts were used for rafters, the middle parts for wall plates and the bottom parts, usually upside down, as main posts. Because the trees were used as found, the naturally grown tree “knees” often served as braces (Drange et al., 1992, p.145-149).

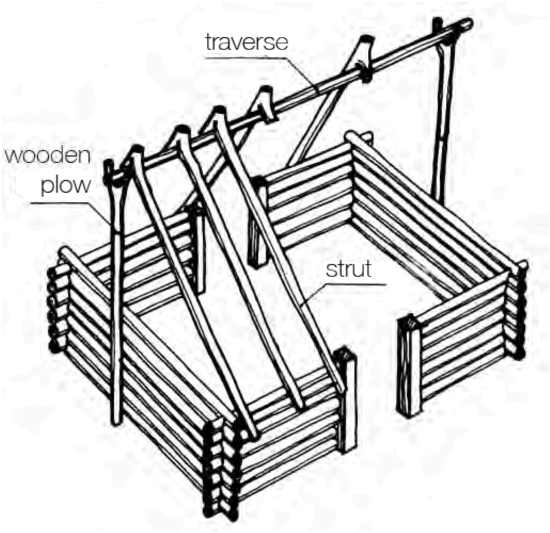

Figure 51
Polish strut frame.

Figure 52
Norwegian bent construction or cross frame (*grindverk*).

The geometric configuration of branching trees was scientifically investigated for the first time during the Renaissance. The Italian polymath Leonardo da Vinci (1452-1519) formulated mathematical rules for the development of the branched tree form. Da Vinci was the first to observe the phenomenon of area-preservation where the total cross-sectional area of a branch before forking is maintained in the branches after forking: 'all the branches of trees at every stage of their height, united together, are equal to the thickness of their trunk' (da Vinci and MacCurdy, [1939] 1955, p.306). Also significant, in the 1920s, biologist Cecil Murray applied rules developed for arterial networks[24] to plant stems that described the angles of branching and their relationships (Ball, 2009, p.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, p.51). In 1971 Japanese biologist Hisao Honda developed a complex algorithm for making tree-like branching structures closely approximating those of real trees. However, Honda's rules are deterministic and do not account for randomness that enters in nature through environmental conditions. Polish computer scientist Przemysław Prusinkiewicz uses L-systems, a different type of

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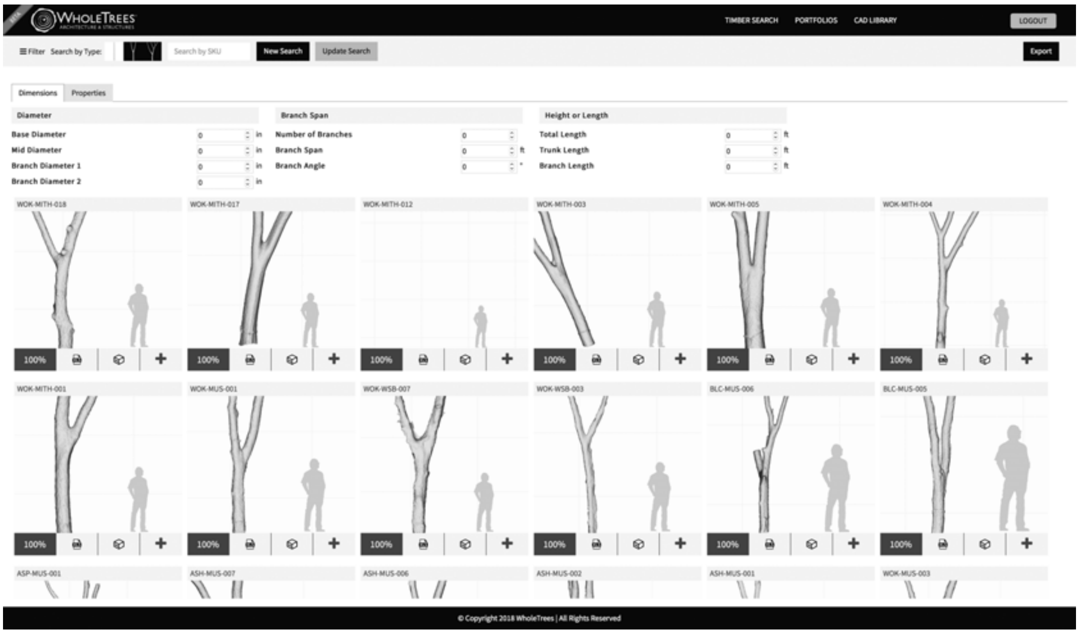
[24] Cecil Murray applied to plant stems some rules developed earlier for arterial networks by the German zoologist Wilhelm Roux (1850–1924) in the 19th century.

deterministic algorithm, to produce branching patterns of plants (Ball, 2009, p.135-137, Prusinkiewicz and Lindenmayer, 1990).



Diameter
Base Diameter 0 in
Mid Diameter 0 in
Branch Diameter 1 0 in
Branch Diameter 2 0 in

Branch Span
Number of Branches 0
Branch Span 0 ft
Branch Angle 0 °

Height or Length
Total Length 0 ft
Trunk Length 0 ft
Branch Length 0 ft

Figure 53

WholeTrees Architecture & Structures, database of 3D-scanned trees.

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 WholeTrees Architecture & Structures[25] 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). It has 86 roundwood wing trusses spanning over 18 metres supported by 12 un-milled ash columns with forked ends (Figure 54). A project of this scale required a more methodical approach than the previous system of cutting down single trees and bringing them to the warehouse for individual scanning and analysis. In 2015, WholeTrees approached Mandli, a company that deals with the design and development of specialised digital imaging, data collection equipment, and operational methodologies. Mandli suggested using Maverick[26], a highly portable mobile mapping system. It combines LiDAR, a high-definition 3D environmental scanning, with 360-degree imaging, and an integrated position and orientation system. A Maverick-equipped car was driven through the area where the trees were being collected. Based on the gathered information a specialised software was used to identify trees that fitted the WholeTrees requirements (Figure 53). The entire process proved to be successful, very quick, and cost-efficient.

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[25] See http://www.wholetrees.com.

[26] See https://www.mandli.com/maverick-by-teledyne-optech/

Figure 54

WholeTrees Architecture & Structures, 2014-2015, Festival Foods Grocery Store in Madison. Left: Construction. Right: Detail of forked tree.

The Madison project (Figure 54) 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, London in 2010 (Figure 56). The project broke from the conventional design process by first finding, scanning and digitally modelling ash trees. This digital material became a starting point for design, where material agency achieved a prominent status. Material idiosyncrasies: organic shapes, knots, holes, and fibres 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, p.172-179).

At the Architectural Association School of Architecture in London, students of the Design & Make program designed and built the Woodchip Barn[27] (2015-2016). In this process, they strove to explore the architectural application boundaries of forked timbers through the integration of 3D scanning, robotic fabrication, and form-finding techniques. These were combined with traditional wood construction knowledge and built at full architectural scale. The structural spine of the project was formed by a truss composed of interconnected forked beech trees. The Y-shaped fork junctions were used structurally, so that the natural strength of these joints was exploited. Analogously to the process applied by WholeTrees and Mandli, trees from a local forest had been 3D scanned prior to harvesting in order to produce a database of available material. 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 trees in the truss and to translate this information for a robotic arm to mill the connections between the pieces.

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[27] See http://designandmake.aaschool.ac.uk/woodchip-barn/

Figure 55
Design & Make programme at the Architectural Association School of Architecture in London, 2015-2016, Woodchip Barn in Hooke Park in Dorset. Left: Roof detail. Right: Robotic fabrication.

The problems of designing with the heterogeneity of naturally grown shapes of wood in the context of digital technologies were also a theme of the *Serial Branches* workshop at The Royal Danish Academy of Fine Arts, School of Architecture in Copenhagen (KADK), led by Christoph Schindler in 2013 (Schindler et al., 2013). Schindler's project took inspiration from Viking boatbuilders and vernacular joinery, where superior strength was achieved by using naturally forked hardwood pieces: 'forked wood can be regarded as a high-tensile and elastic joint of high intelligence' (ibid., p.606). The authors' study revealed that each tree species has a limited range of crotch angles, confirming the branching pattern findings of the above-mentioned researchers. For collected beech samples, the wood of choice and the most populous forest tree in Denmark, the angle differences were within a 20° range. The material was divided into three groups based on variations of "Y-shape", "flatness" (2D-branches) and "uniqueness" (3D-branches) (ibid., p.607). As the result of a trial and error process, a method was devised to minimise the amount of information neccesary to compute the shapes for design: all branches were planed on both sides resulting in two parallel evenly distanced surfaces (Figure 57). Thus, the exact shape of the branch was disregarded as long as it stayed within the defined tolerances. This project demonstrated how designers working today with digital tools, are still 'bound to the heritage of industrialization', i.e. working with measurable geometry, minimal tolerance, and reliable material constraints (ibid., p.609-610).

In each of these projects, digital technologies were used to analyse the material in both 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 (see p. 180).

Figure 56

Helen & Hard, 2010, *Ratatosk* Pavilion, V&A Museum in London.

Figure 57

Schindlersalmeron, 2013, Branch Stool.

Using raw unsawn material brings savings in energy consumption. One study reveals that the embodied energy of roundwood material is 40% lower than that of sawn lumber (Chrisp, Cairns and Gulland as cited in Dickson et al. (2011, p.2)). Another study points towards economic gains while using roundwood (Ranta-Maunus, 1999). The material self-replenishes over a much shorter period of time than that needed for sawn timber (ibid., p.132). In Europe the cost of debarked round timber is roughly half of sawn timber; while the characteristic bending strength of unsorted material may be even double the value of sawn timber (ibid., p.179-180). Bending strength of round timber is higher than that of sawn timber of similar cross-section size, and small cross-sections are known to have relatively higher strength than large ones based on the Weibull theory (ibid., p.12-13).

Small diameter roundwood has been widely used for centuries in such structures as sheds, barns, or fencing – mostly for its convenience in size and where quality was of secondary importance. However, today there are attempts to use the material in engineering structures such as bridges or domes. The 27 m high Observation Tower at Apeldoorn (architect Pieter Huybers, 1995) has been built of 2.5 and 3.6 m long with 12, 15 and 20 cm diameter debarked larch poles. The project employs a design strategy based on a three-dimensional space frame where the short length and small cross-section of the poles are not a disadvantage; using the whole cross-section additionally offsets the problem of weakness of small cross-sections (Ranta-Maunus, 1999, p.167-169).

Projects like the workshop building in Hooke Park in Dorset (see p. 175), by Richard Burton, Frei Otto and Buro Happold, elevate roundwood to highly engineered applications. By combining material behaviour and characteristics with applied geometry, roundwood is pushed to its limits in terms of structural performance.

Figure 58

FT Architects, 2014-2015, Light Sheds in Kanagawa. Left: Construction detail. Right: Working with cylindrical shapes.

Despite all its advantages, roundwood is not commonly used in developed countries as a structural material. This is due to several factors: the lack of design guidelines, readily available and reliable connectors, unavailability of the material through normal commercial channels, and the difficulty when attaching cladding to irregular and round structure (Ranta-Maunus, 1999, p.147, Dickson et al., 2011, p.3). Another reason yet exists for hesitance by architects in turning to roundwood: the material is considered inherently anti-modern and is associated with the primitive, vernacular, and rustic. Its associations make it more prone for a clichéd romanticism rather than any "truly architectural" expression. Especially interesting in this context is a project for a photographic studio Light Sheds in Kanagawa designed by Japanese studio FT Architects and completed in 2014-2015 (Figure 58). While the architects point to the 'symbolic associations of [...] one of the oldest building material[s]' (FTArchitects, 2016), the project at the same time radically departs from this notion, offering an attractive and modern alternative.

Aim of the experiment

The aim of this last experiment was to investigate the implications of designing with naturally grown shapes of wood, in particular which 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 the opposite logic where the natural shapes of sourced wood dictated the type and form of the designed elements.

The presented architectural proceedings used fork shaped timbers as structural members of single-storey hall-type buildings (Figure 54, Figure 55). The ambition of the experimental project was to explore the possibility of using this material in a more cellular arrangement that could be applied to domestic, and possibly also multi-storey, structures.

The solution sought in this project solved the problem at 1:10 scale. At a full architectural scale, the solution and details would have to be different.

However, the general workflow and methods used in this scaled-down solution could be developed further in full-scale.

This experimental project served the purpose of demonstration and initiation of discussion.

Materials sourced

The material of choice for the experiment were birch Y-shaped branches which were collected in the forest. The material was cut to 40 cm lengths using a bandsaw. All ends of the branches were rounded with a tenon cutter (Figure 59). A typical tenon cutting blade set consists of 8, 10, 12, 15, 20, 25, 30, and 35 mm blades, so the branches were cut with the closest matching sizes. The collected material ranged from 12 to 30 mm in diameter. All branches and diameters were marked for identification after scanning (Figure 60).

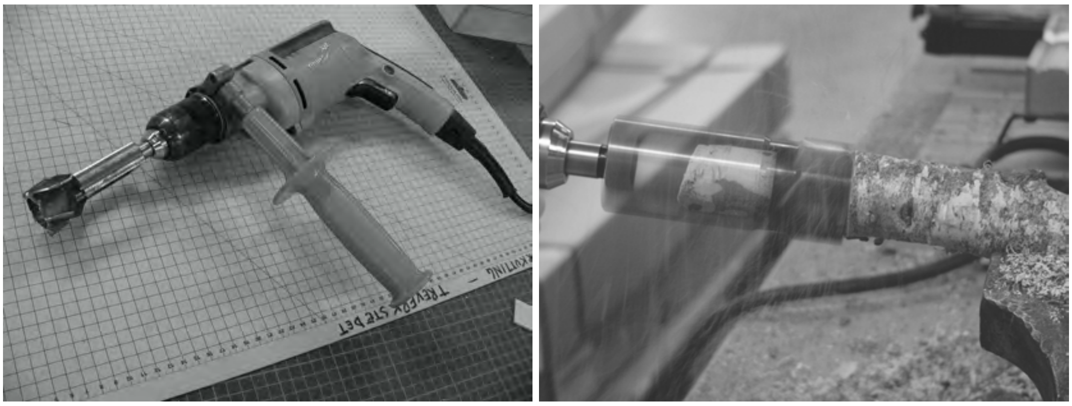

Figure 59

Tenon cutter. Left: the tool. Right: Cutting a tenon.

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 would not be appropriate to use 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[28].

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[28] As mentioned earlier, this project was conceived as hypothetical and would not directly translate to an architectural scale.

Figure 60
Y-timbers: marking the branches.

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 61).

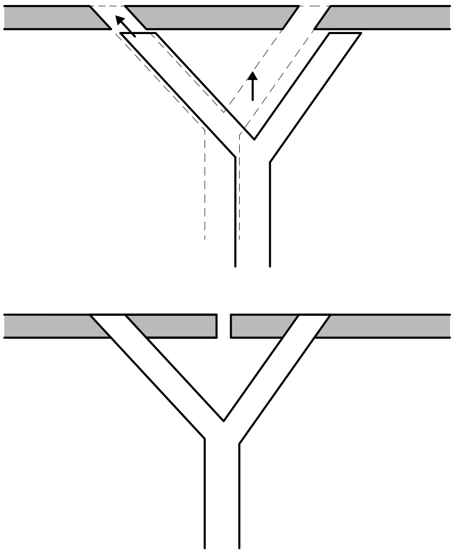

Figure 61
Y-timbers: the problem with inserting the branch's tops into oblique holes and its solution.

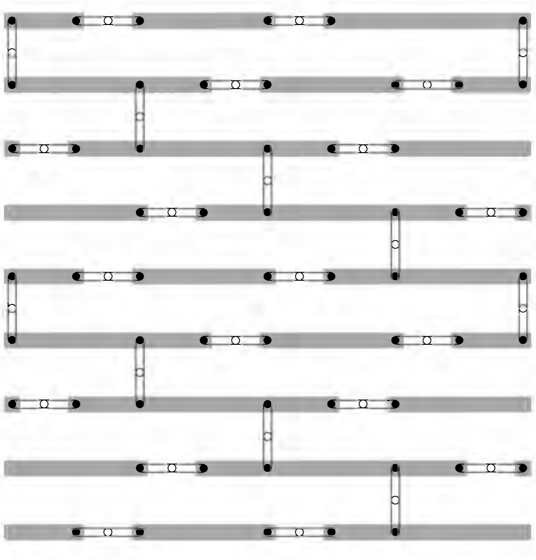

Figure 62
Y-timbers: layout of the endless pattern of columns.

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 digitisation 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. Initially, in order to digitise the branch geometries, a desktop size robotic arm AL5D (Figure 63) with an Arduino (Figure 66) microcontroller[29] was used. The arm was programmed with a custom made forward and inverse kinematics script written in Grasshopper (Figure 64). However, this digitisation method proved not precise enough to deliver useful and reliable information. Firstly, the arm only scanned external points on the branches which could not easily be converted into 3D models of the branches. Secondly, precision of the AL5D arm was not reliable.

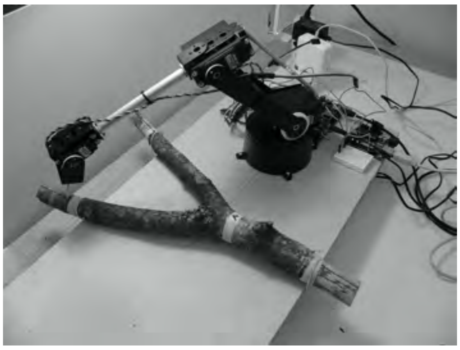

Figure 63

AL5D robotic arm digitising the branches.

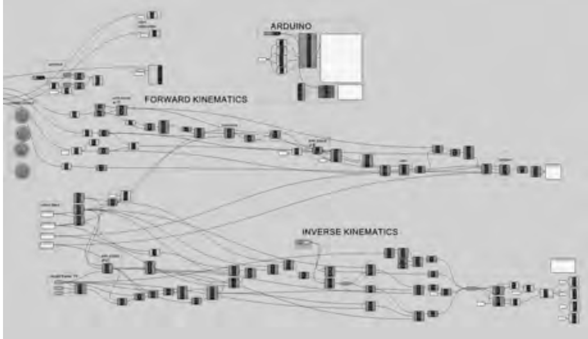

Figure 64

Grasshopper definition for forward and inverse kinematics for AL5D robotic arm.

Finally, for obtaining branch geometric information, a handheld Artec 3D scanner capable of producing a 3D mesh model from a physical object was used (Figure 65). 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 67).

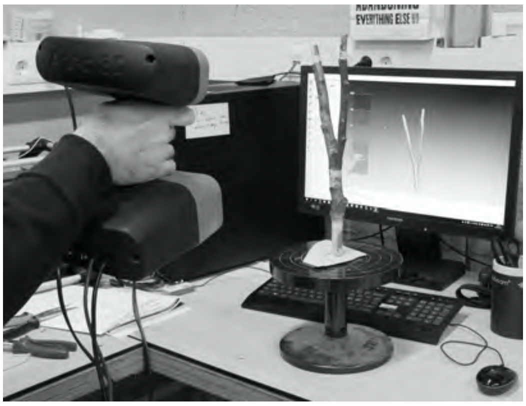

Figure 65

Y-timbers: 3D scanning.

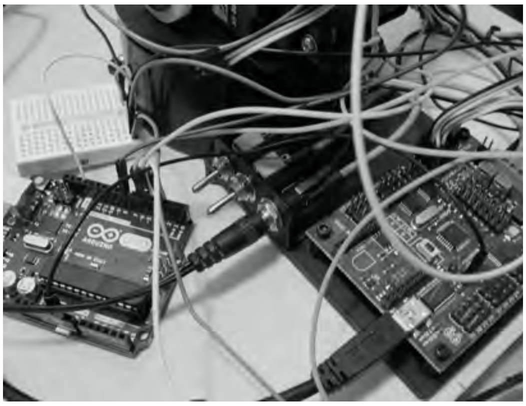

Figure 66

Arduino controller and AL5D wiring.

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

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[29] Arduino is a do-it-yourself microcontroller kit for prototyping digital devices (http://www.arduino.org).

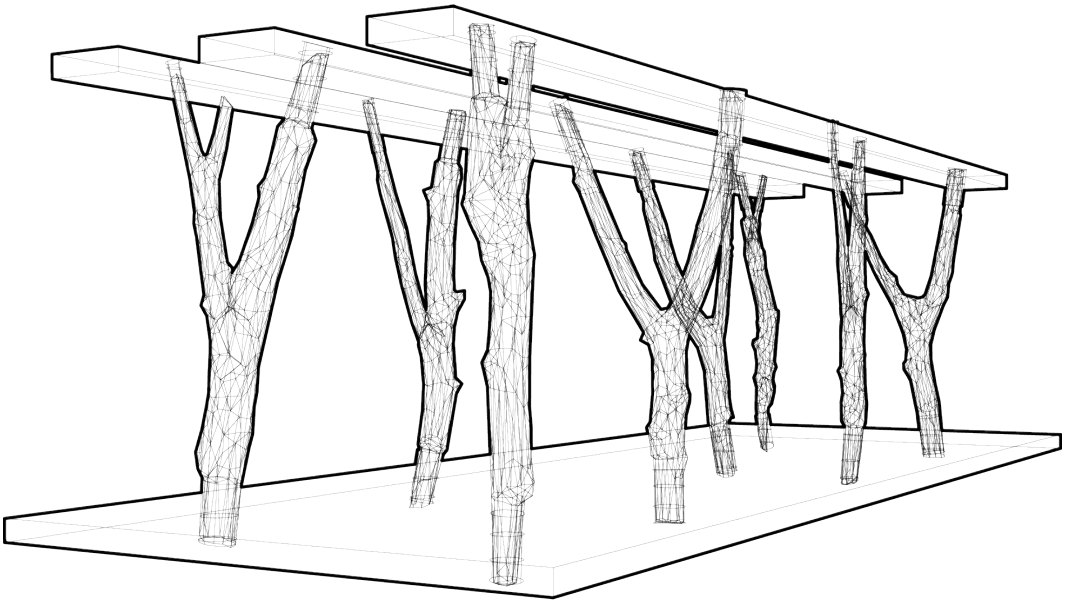

Figure 67
Y-timbers: Rhinoceros 3D drawing with the branches and slabs.

Finally, an industrial Motoman robotic arm was used to mill oblique holes in the polyurethane slabs[30] (Figure 68).

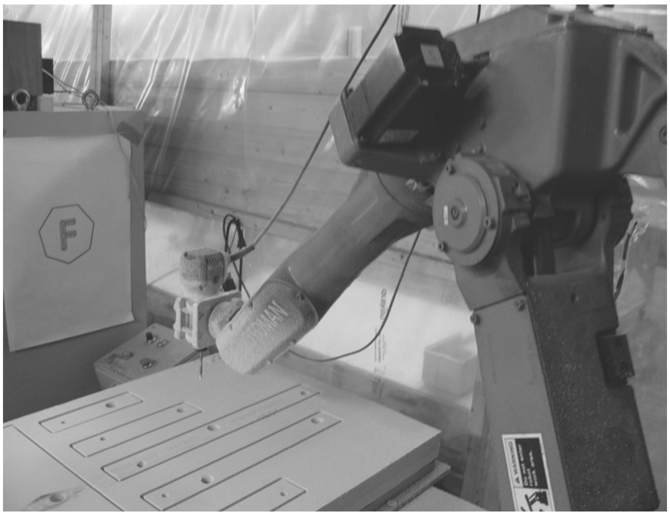

Figure 68
Y-timbers: robotic milling.

Figure 69
Y-timbers: the final model.

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[30] See https://vimeo.com/192430402

Results

The model was assembled without problems and all the mortises corresponded well to the tenons. The final form was stable, yet easily demountable (Figure 69, Figure 70).

Figure 70
Y-timbers: the final model.

The drawings in Figure 71 illustrate, how this system could be used to assemble multi-storey buildings.

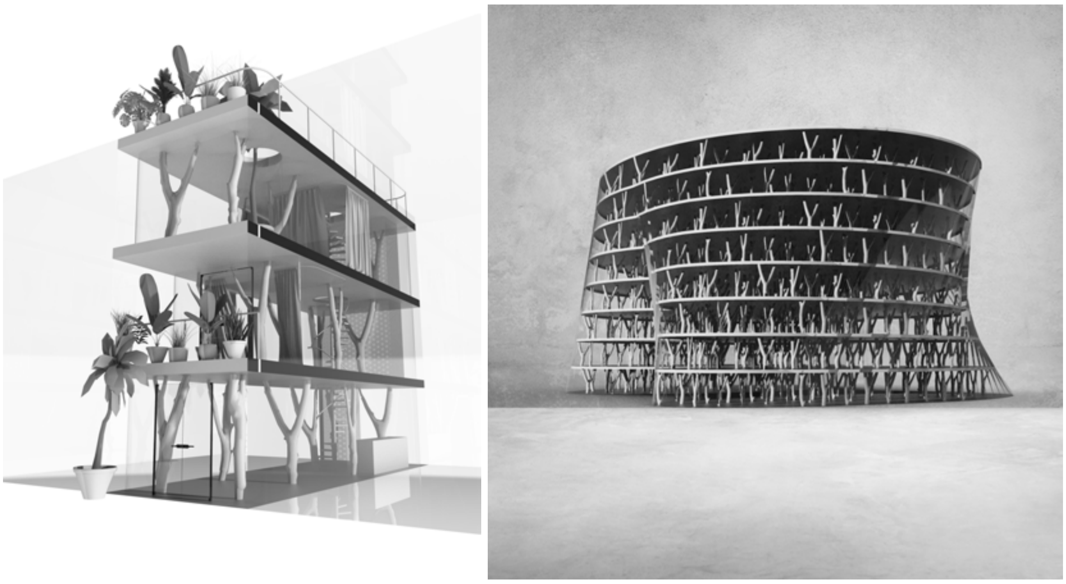

Figure 71
Y-timbers: multi-storey buildings.

Discussion

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.

Advantages of the Y-timbers system

The devised procedure minimized processing of the material. The forking timbers were not processed more than branches cut to the same length and ends rounded with a tenon cutter. As the precedents that were meant to be permanent buildings (Woodchip Barn in Hooke Park or Festival Foods Grocery Store in Madison) demonstrate, in a full-scale application the timbers should additionally be debarked. As is the case with these projects, the main environmental benefit of the presented solution lies in finding use for the innate strength of naturally grown forked timber shapes rather than producing these shapes by mechanical connections.

Applications

The *Y-timbers* project strove to expand the possible uses of this material. The designed "endless pattern of columns" (Figure 62) creates an opportunity for a cellular layout that could be used in domestic architecture. The system, based on irregular shapes of columns, allows for vertical stacking where the head of the column below does not coincide with the base of the column above due to this irregularity. It would have to be structurally tested whether the natural Y-shape would sufficiently cross-brace the structure.

Similar to the two earlier experiments, *BackToBack* and *Swelling Vault*, the *Y-timbers* experiment was only a sketch of a potential project that was devised to initialise discussion.

SUMMARY OF THE EXPERIMENTS

These experiments set off to make use of natural wood properties and behaviours in the design of building components. Considered were (a) anisotropy of wood (see p. 31), (b) heterogeneity of wood (see p. 34), (c) taxonomic variability of wood (see p. 36), and (d) naturally grown shapes of wood (see p. 66). In experiment (i) *BackToBack* anisotropic shrinkage on drying from green (a) was used. In experiment (ii) *Swelling Vault* anisotropic swelling after increasing moisture content (a) was used. Finally, in experiment (iii) *Y-timbers* naturally forking wood shapes (d) were used.

The table inFigure 72 outlines how these properties were used in relation to their possible applications. The experiment (i) *BackToBack* proposed a method of connecting wooden parts in components with avoidance of metal connectors or adhesives. The experiment (ii) *Swelling Vault* proposed a method for producing wooden curvilinear panels which avoid wasteful subtractive milling processes, energy intensive steam-bending, or toxic wood softeners. The experiment (iii) *Y-timbers* proposed a method for cross-bracing structural pillars while avoiding metal connectors.

	experiment	**properties of wood used**	**scale**	**use of IT**	**avoidance of**	**possible applications**
(i)	BackToBack	shrinkage on drying from green	1:1	CNC precision and repeatability	metal connectors adhesives	solid wood panels all-wood connectors
(ii)	Swelling Vault	anisotropic swelling on increased moisture content	1:1	digital simulation	wasteful milling steaming chemical softeners	curvilinear panels moulds formworks
(iii)	Y-timbers	strength of naturally grown forked shapes	1:10	3D scanning CNC versatility	metal connectors wood processign	structural pilars cross-bracings

Figure 72

Comparison of three experimental projects.

These experiments contributed to the existing material- and performance-oriented approaches to wood design in four areas:

- Focus on possible low-tech execution methods – the *Swelling Vault* project used only conventional carpentry techniques, and the digital manufacturing methods used were kept to the necessary minimum in all the experiments
- Focus on application of unprocessed material – the *BackToBack* and *Y-timbers* projects used unprocessed roundwood; the *Swelling Vault* project used standard solid wood parquet blocks
- Expansion of potential technique applications – the *BackToBack* and *Swelling Vault* projects sought ways of delivering generic building components, applicable in various configurations and situations; the *Y-timbers* project proposed a cellular construction system applicable in a domestic situation, as opposed to a generic, hall-type building
- Focus on environmental benefits of the devised techniques – all three projects offer reduction in the use of chemicals, energy, time, and

waste quantity; enable recycling of components; increase volume yield of timber; and provide healthy living environments

The role of computational design and digital manufacturing

The three experiments began as low-tech construction projects. However, it proved unpractical and unfeasible to avoid using computational design and digital manufacturing techniques. In all three experiments, information technologies were pivotal to the testing, ideation, and fabrication processes. Experiment (i) *BackToBack* was based on precision and repeatability offered by a CNC machine; experiment (ii) The *Swelling Vault* used digital simulation to predict wood shapes resultant from the swelling process; and experiment (iii) *Y-timbers* drew upon 3D scanning and versatility of robotic milling.

While the *Swelling Vault* (iii) 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 the Mexican-American philosopher and artist Manuel DeLanda's (b. 1952) observation:

> [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, p.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 discussed here, wood behaviour 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 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 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. This includes structural performance testing, development of software and manufacturing methods for industry-sized 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* (i) project. The geometry, sizes, and proportions of the incisions must factor into the structural behaviour 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* (ii), wood had a limited capacity to take on various shapes and hence limited possible outcomes; while in *Y-timbers* (iii), natural shapes dictated the aesthetics of the final form. This methodology suggests that material properties ***can guide the designed form***.

One key observation about the experiments is that many aspects of form can be dictated by the material's traits, behaviour, composition, and shape. Thus, many of our assumptions about design are challenged. The designer no longer imposes a form upon a material. This requires rethinking the approach to aesthetics, tolerances, and 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, this thesis argues to the contrary. This process can open new opportunities for architecture and at the same time address environmental problems. 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. The following Part II of the thesis provides perspectives on this observation about the experiments.

PART II: Perspectives

Chapter 3: Perspective 1 – Design methodology. Reframing as a trigger of material innovation in architecture

MATERIAL INNOVATION IN WOOD ARCHITECTURE

This chapter discusses motivations, processes, and methods of innovation in architecture. This part outlines the design theories that form the frame of reference for innovation. In the second part, it relates these concepts to the subject matter of this thesis, in order to establish a framework for a methodological approach for "reframing wood construction".

This chapter is particularly concerned with material innovation. The meaning of material innovation is not limited here to the development of new materials, but also to the way in which existing materials are used. As observed by Thomas Schröpfer, '[m]uch material innovation emerges not in the making of new materials but in transforming the way in which we handle them' (Schröpfer et al., 2011, p.23). This observation relates very well to wood, the material with a very long history in construction, and which can still be used in an innovative way. To this end, this chapter investigates the processes and methods of material innovation associated with finding new applications and new connections between already existing approaches, rather than devising completely new ones. This is usually done by way of changing the frames of references and forming new conceptualisations of materiality.

Motivations of material innovation in architecture

The very concept of innovation is not easy to define. The colloquial meaning of the term is often associated with creativity, taking risks, departing from convention: for instance David Neelman (b. 1959), the founder and CEO of the American airline JetBlue, defined innovation as "trying to figure out a way to do something better than it's ever been done before" (as quoted in May (2007)). "Doing something better" is associated with "doing it differently", thus innovation is innately linked to deviating from the obvious and to designing, understood as solving problems. It is the reverse of conservativeness, which focuses on upholding the existing or recreating the conventional order. The Canadian philosopher of communication theory Marshall McLuhan (1911-1980) warns us against this type of conservativeness: '[f]ailure to notice the new opportunities is also failure to understand the new powers [...]. This failure leaves us in the role of mere automata' (McLuhan, 1995, p.344). In this light, innovation is a necessary condition to responsibly face the future.

Material innovation has been part of the debate throughout the history of architecture (Kretzer, 2017, p.25-65). In architectural theory, innovation is entangled with aesthetic and moral values; and as such, it differs significantly from the seemingly same concept in engineering. The variety of factors that motivate innovation in architecture spans between economic, social, and environmental needs. As commented by the French historian of architecture and technology, Antoine Picon (b. 1957), it appears at the intersection of those factors, and the innovative designer's role is to "decode" the involved issues (Picon, 2010b, p.51).

How should the innovative designer "decode" the issues that concern architecture in the 21st century? Today the context of architectural innovation is framed by environmental concerns and technological developments. As of 2013, according to the European Commission and Energy Efficient Building[31] (EeB) initiative, the construction industry and buildings are responsible for 40% of total European energy consumption and 36% of CO_2 emissions (EeB, 2013, p.6). The discipline of architecture is, or aspires to be, the driver of the industry. If this is the case, it bears the responsibility, or at least a part thereof, for these figures. In parallel, digital technologies impose pressures on the profession by rapidly developing new methods of design (computational design), construction (digital manufacturing), and project management (Building Information Modelling, BIM). A question arises as to how these new methods can be used with a goal of orientating architecture towards a sustainable provision for industry and a more environmentally responsive practice. EeB identifies that the 'Information and Communication Technologies (ICT) are playing a pivotal role in Energy Efficient Buildings' (ECTP, 2017, p.18). Various efforts are being made towards that goal, and solutions are being sought through computerised environmental performance analysis, life cycle assessment, tools for energy efficiency design, production management, etc.

Orientating the innovation towards these issues corresponds with the current trend in design theory and practice; where the meaning of design is generated through addressing environmental challenges. Since the 2000s, a growing interest in the field of design has been the search for new and meaningful products that reduce their impact and integrate better with the natural environment (Utterback, 2006, p.2).

In line with the above, the role of design thinking is not merely to produce an aesthetic value, but also to provide for the sustainable environment. Design innovation then, should be geared towards finding solutions at the intersection of environmentally responsive technologies, economic viability, human and societal needs, and aesthetic values. In this context, environmentally responsible design achieves an important status, and becomes a key guiding principle for design innovation.

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[31] Energy Efficient Buildings is a committee of the European Construction Technology Platform (ECTP) for innovative built environments (http://e2b.ectp.org).

Processes of material innovation in architecture

Bearing resemblance to the motivations above, processes of material innovation in architecture are also compound. As mentioned at the beginning of the chapter, these processes are both technologically and theoretically driven. The material innovation in architecture can be induced by adapting new developments from other disciplines, or discovering new connections between existing elements. In both cases, this requires new theoretical frameworks and new conceptualisations of materiality. The key feature of design innovation is a change of perspective, and the resulting changes in value systems.

Technologically driven innovation

Examples of technologically driven innovation include adaptations of newly invented materials (e.g. steel), developments of new and more effective methods of manufacturing existing materials (e.g. float glass), and developments of new machines (e.g. steam engine). The list below includes some key inventions that profoundly affected architecture and other design disciplines since the 18th century:

- industrial production of cast iron (Coalbrookdale ironworks established in England by Abraham Darby in 1707) enabled its use in engineering and building structures;
- steam wood bending (fist patented in England in 1720) increased pliability of wood and allowed the achievement of curved shapes that were not possible earlier;
- buzz saw (invented in 1777) boosted the output of sawmills;
- steam engine (James Watt (1736-1819), England, 1782) enabled the industrial revolution;
- the assembly line (first used in food processing by Oliver Evans, Newport, Delaware, USA, 1783) opened the way for mechanic production and prefabrication;
- mechanic-cut nails (patented by Clifford Thomas in 1790) and mechanic-cut tacks (patented by Jesse Reed in 1804) enabled development of wood construction systems based on butt joints, e.g. balloon frame;
- milling machine (invented in 1792) boosted the output of sawmills;
- connection of steam engine with wood-processing machines (planer machine by Joseph Bramah (1748-1814) in the UK, and gate sawmill by Oliver Evans (1755–1819) in the USA, both in 1802) immediately doubled the output of sawmills, and in the USA the output increased by 100% from the 1830-40s, by 350% from the 1840-50s, and by 50% in each of the following decades;
- band saw (invented in 1808) boosted the output of sawmills;
- balloon frame construction system (invented in the early 19th century) introduced industrial processes and standardisation to wood construction;

- Portland cement (patented by Joseph Aspdin, Leeds, UK, 1824) improved the load bearing capacity of concrete;
- corrugated metal sheet (patented by Henry Palmer in London, UK, in 1829) allowed cladding and weatherproofing of buildings at a fraction of the price point of earlier cladding materials – the corrugated sheets achieve strength through shape so fewer structural members are necessary, which contributes to the economic viability of this solution;
- modern plywood (since the 1830s; patented by John Mayo in the USA in 1865; hot-plate press for plywood patented by Christian Luther in 1896) changed the shape of timber-based building components from longitudinal to planar, and opened the way for new applications of wood;
- coal-tar creosote – wood preservative (John Bethell in 1838) increased timber longevity and the scope of its applications;
- steam powered circular saw (since 1840) contributed to the development of wood construction systems based on standardisation, e.g. balloon frame;
- thermo-hydro-mechanical wood bending process (patented by Michael Thonet in Austria in 1842) allowed for mass production of repetitive curved wooden components;
- plate glass (patented by Henry Bessemer in the UK in 1848) changed the relationship, and our understanding, of walls and windows in buildings;
- reinforced concrete (patented by Joseph Monier in Paris, France in 1848 (for plant pots), and in 1867; testing by Thaddeus Hyatt and David Kirkaldy in the USA in 1877) radically changed the scope of possible architectural forms;
- steel making process of Henry Bessemer (Sheffield, 1850s, first presented in Cheltenham, UK in 1855) allowed for wide use of steel in construction, and popularised structural member slenderness unknown before this time;
- bending laminated wood in two directions (patented by John Henry Belter in the USA in 1858) increased the scope of possible geometries for wooden components;
- glued laminated timber – glulam (the oldest example – Southampton, UK, from 1860; patented by Otto Hetzer in Weimar, Germany in 1907) increased the structural length and capacity of timber beams and columns, reshaping the appearance of wood based structural systems;
- cheap production of aluminium (Charles Hall in Ohio, USA, and Paul Heroult in Paris, France, in 1886) introduced this lightweight and durable material to construction;
- Bakelite – the first plastic (Leo Baekeland in New York, USA, in 1907) paved the way for wide spread use of lightweight, durable, and infinitely mouldable plastics;
- monocoque aircraft fuselage (patented by Loughead Aircraft in the USA, in 1918) introduced a new structural system based on sheet-material, that brought new efficiencies to construction;

- polyethylene – PE, the most common plastic (Eric Fawcett and Reginald Gibson in Northwich, UK, in 1933) transformed design in the 20th century;
- chipboard (since the 1930s) introduced a cheaper alternative to plywood for interior applications;
- water-resistant phenol-formaldehyde and later formaldehyde resin glues (since the 1930s) widened the scope for applications of timber derived products (first water-resistant exterior-grade plywood: Washington State's Harbor Plywood Company in the USA in 1935);
- NC (numerically controlled) machine which used punch cards to control computer-operated servo motors connected with a milling tool (invented by John T. Parsons (1913-2007) in the USA in the1940s) introduced flexible manufacturing;
- particleboard (since the 1950s) waste fibres and sawdust mixed with urea-formaldehyde resins, compacted and compressed (chips, wood shavings)
- medium-density fibreboard -- MDF (since the 1960s) introduced a cost effective, isotropic, well-shaping, and easy to finish alternative to natural wood;
- oriented strand board -- OSB (since the 1970s) introduced an improved alternative to plywood;
- cross-laminated timber -- CLT (since the 1990s) increased the scope of timber use, and changed the appearance of wood-based construction systems.

The developments in the list above did not originate in the field of architecture or design, however they sparked the expansion of new developments and technologies beyond their original fields. In the 19th century this expansion, amplified by a new conceptualisation of materiality, i.e. calculable structure, resulted in a radical redefinition of the concept of form in architecture. New developments allowed the achievement of new shapes, built with effectiveness, slenderness and transparency, unknown before this time. Also, mechanized production enabled the development of repetitive prefabricated components, that in turn affected modernist aesthetics.

Theoretically driven innovation and disruptive technologies

The model of material innovation outlined in the previous section is based on new material developments that affect architecture and design by the processes of expansion beyond their original fields. This is not the case when we consider an old material, such as wood, for which an innovative use is found. For this case, I use the term "theoretically driven innovation", where a new conceptualisation of materiality plays a pivotal role.

The processes of theoretically driven innovation become more and more networked today, and involve an increasing number of actors (Utterback, 2006, p.20). For instance, as mentioned earlier, the framework of material innovation in architecture must include the environmental impact of materials used: the energy and release of toxic substances as they are extracted, processed, shaped, cut, formed, and finally disintegrated. These considerations were not at the fore a few decades ago. In this multi-actor, networked, and ever-changing environment, a possible way forward for material innovation can be found at the systems level; where new solutions appear by creating new assemblies of components, and new connections between them. This type of innovation can be based on an improvement of existing components rather than a radical new technology (Utterback, 2006, p.10-11).

In the 1990s, the Harvard Business School professor and technology theorist Clayton Christensen (b. 1952), coined the term “disruptive technology”, by which he described technologies or products that unexpectedly replace existing and well-established ones. As an example, Christensen discussed the hard disc drive industry, where in the span of two decades the number of megabits per square inch of a disc surface increased by 35% a year, and the physical size of the discs was also reduced at a similar pace (Christensen, 1997, p.23), which ‘toppled the industry's leaders’. Christensen observed that disruptive innovations were often technologically straightforward, where off-the-shelf components were put together in a new, usually simpler way than before (Christensen, 1997, p.28). In other words, disruptive innovations are often intellectual rather than technological developments.

The notion of disruptive technology, as presented by Christensen, aligns with the concept of theoretically driven innovation as discussed here. It points to the direction of innovation in wood architecture; where new intellectual achievement and new conceptualisation of the material can lead to a new way the material is used. I argue, that this new conceptualisation is possible thanks to new technologies, digital manufacturing, and computational design, rather than driven by it.

Disruptive technology in the history of architecture

This model of innovation has been present throughout the history of architecture, however not very explicitly. For instance, as noticed by architectural historians (Frankl, 1962, p.37-38, Addis, 2007, p.95), the development of Gothic structural systems was not triggered by technical development and inventions in other areas, as was the case for new materials appearing in the 19th century. Even the pointed arch, the element being almost synonymous with the Gothic style, was not Medieval: it appeared already in prehistoric ornament, the section of the Treasury of Atreus (c. 1250 BC) had this form, it was known by the Greek mathematicians and Roman architects, and finally the Islamic architects were the first to use it architecturally (Frankl, 1962, p.20). The pointed arch was a new combination of already known components that manifested itself in profound change of the built form. The British historian of engineering and construction materials, Bill Addis (b. 1949), echoes Christensen’s characteristic of disruptive technology in his description of the development of gothic cathedrals: ‘devising new ways of designing cathedrals during the twelfth and thirteenth centuries was due not only to technological developments in the conventional sense as no new materials or structural devices were invented; rather, old ones were used in new ways and new combinations' (Addis, 2007, p.92). The main development was intellectual rather than technological in origin. The array of used materials was well known and widely used by the Romans: stone, bricks, timber, wrought iron, glass. Relatively small material improvements; like cutting stone blocks to more manageable sizes, roof trusses made of timber using mortise-and-tenon joints, iron used to carry tension forces, e.g. as ties in arches (Addis, 2007, p.93, 95); contributed to the development of radical new built forms. In the same vein, the combination of iron frames with glass enabled the development of very large and ornate windows. The new building forms of medieval cathedrals were made possible by the combination of four principal structural innovations. In 1835 German architect Johannes Wetter (1806-1897) was the first to connect the lightness of the gothic walls with the combination of four elements: the cross-vault, the rib, the pointed arch, and the buttress (Frankl, 1962, p.37-38).

In the case of the Gothic style, new material developments played a secondary role; innovation took place at the systems level, where the network of interconnections was at the fore. The main driver of innovation was a new conceptualisation of materiality, i.e. the new combination of four, already known, principal elements. This combination enabled the old materials, stone and brick, to be used with more flexibility (Addis, 2007, p.95) and led to new forms in architecture.

Methods of material innovation in architecture

Innovating by finding new combinations in the network of interconnections eludes the positivist understanding of design methodology that can be reduced to a step-by-step linear model, based on "problem definition" and "problem solution". In the 1990s the American professor of design, Richard Buchanan, observed that innovative solutions were often sparked by "repositioning" a design problem from one place in a system to another, and he formulated this idea as "a doctrine of placements" (Buchanan, 1992).

Buchanan's formulation is based on the 1960s "wicked problem" approach of design thinking that he credits to German design theorist Horst Rittel[32] (1930-1990). According to Rittel, the wicked problems are "a class of social system problems which are ill-formulated, where the information is confusing, where there are many clients and decision makers with conflicting values, and where the ramifications in the whole system are thoroughly confusing" (Rittel as cited in Buchanan (1992, p.15)).

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[32] The term wicked problem was first introduced by the philosopher Karl Popper (1902-1994) and was reintroduced in the context of design by the design theorist Horst Rittel in the mid-1960s (Broadbent, 2003, p.6).

As humorously said by the design researcher Nigel Cross (b. 1942): “stating the problem is the problem” (Nigel Cross as cited in Broadbent (2003, p.6)). Solving wicked problems is not possible through a simple process of linear analysis and synthesis (Buchanan, 1992, p.15). In order to define a methodological framework for design thinking that leads to innovation, Buchanan introduced a “doctrine of placements”. “Placements are patterns of invention” with a capacity to cross through different specialised subject matters. Buchanan says that ‘[t]he boundary of a placement gives a context or orientation to thinking, but the application to a specific situation can generate a new perception of that situation and, hence, a new possibility to be tested. Therefore, placements are sources of new ideas and possibilities when applied to problems in concrete circumstances’ (Buchanan, 1992, p.13).

“Placements” can lead to understanding material objects in the context of larger systems – environments and cycles. They can open a range of new questions, such as issues of ‘conservation and recycling, alternative technologies, elaborate simulation environments, “smart” products, virtual reality, artificial life, and the ethical, political, and legal dimensions of design’ (Buchanan, 1992, p.11).

Buchanan evoked examples of this “innovative repositioning” of design problems within “larger systems, cycles, and environments”, that included “deconstructivist architecture”, and “graphic design and visual communication”. In deconstructivism, the repositioning took place ‘in the context of signs, symbols, and visual communication, and led to breaking old categories and shift[ed] general attention toward new questions’. In the latter example, graphic design refocused from ‘personal expression through image making [...] toward that of an interpreter of messages’. Buchanan illustrates this shift in graphic design and visual communication with the example of a strategy change for guiding clients through large stores. While traditional graphic design yielded larger signs but no apparent improvement in navigation – the larger the sign, the more likely people were to ignore it; studying the problem from the perspective of customer experience ‘led to a change in display strategy, placing those products that people are most likely to identify in prominent positions’ (Buchanan, 1992, p.11-12).

The method of innovative repositioning of design problems can serve as a benchmark and an analogy for the design strategy[33] of this study, as it offers an important insight into the mechanisms of innovation. In the methodological framework discussed by Buchanan, the innovation is not sought by a step-by-step linear model, but rather by placing the design problem in a wider context that ‘can generate a new perception of that situation’ (Buchanan, 1992, p.13).

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[33] I use the terms “method” and “strategy” interchangeably. In relation to architectural research Wang and Groat define “strategy” as the skilful management and planning of anything and the overall research plan or structure of the research study. They separate its meaning from “tactics”, which refers to a more detailed deployment of specific techniques, while both “strategies” and “tactics” belong to the range of “methods” (Wang and Groat, 2013, p.10).

This can lead to understanding material objects in the context of larger systems – environments and cycles, and open a range of new questions, such as issues of 'conservation and recycling, alternative technologies, elaborate simulation environments, "smart" products, virtual reality, artificial life, and the ethical, political, and legal dimensions of design' (Buchanan, 1992, p.11). These issues include the central problems of this thesis, which seeks solutions related to environmental and ethical dimensions of design, and therefore the method of repositioning is pursued further.

REFRAMING AS A TRIGGER OF MATERIAL INNOVATION IN ARCHITECTURE

The first part of this chapter outlined the motivations, processes, and methods of innovative design, as discussed in current design theory. It set out to introduce innovation as the necessary condition to face future challenges, and identified the environmental issues as central to these challenges. It argued that these concerns have the capacity to generate meaning in design and architecture. Further, it was observed that the processes of material innovation are not always driven by new material developments. At the methodological level, it was recognised that disruptive technologies are often sparked by placing problems within larger contexts, and by establishing new relationships between already existing elements, rather than by devising radically new technologies. Pivotal to the thesis is the method of innovation by repositioning, where the new perception of a problem situation is a result of the changing context of this situation.

In this section of the chapter, these concepts are related to the subject matter of this thesis. Striving to answer the central question of the study, i.e. ***are there more efficient and effective ways to use wood in construction****,* it is proposed to look at the problem of manufacturing timber components. Part I of the thesis gave an account of various experimental attempts at material innovation. These experiments responded to the presented methodological framework.

In line with the discussed methodological framework for material innovation, it is proposed to use the method of repositioning, as introduced by Buchanan (see p. 93). The examples of this design strategy evoked by Buchannan and Christensen, were based on new perceptions at the level of 'signs, symbols, and visual communication' which 'shift general attention toward new questions' (Buchanan, 1992, p.11-13), or on a new combination of already known components that led to a simpler, and more successful, 'product architecture' (Christensen, 1997, p.20-37). In the case of this thesis, the strategy is based on finding new relationships between form, material properties, manufacturing, and design strategies. In this thesis, in relation to wood construction, the term ***reframing*** is used rather than "repositioning"; which, by employing the evocative wordplay, denotes the particular material context of repositioning.

The concept of reframing is applied in order to shift the perception of the material, which will eventually lead to new strategies towards finding better alternatives for using wood in construction. The aim of this reframing is to reconceptualise the material, so that previously disadvantageous characteristics can be seen as resources that could be used in new design strategies. To this end, various wood material properties; such as moisture induced movement, shrinkage from green to dry, and naturally grown shapes; will be investigated as starting points for the design of timber construction components.

The investigation in the first section of the chapter led to the observation that a profound innovation can also be driven by intellectual realisation rather than technical development. The task of accessing material characteristics as resources is premised on the development of modern digital technologies. Their flexibility, precision, and repeatability allow for different interaction with the material in comparison to the dominant approach based on industrialised mass production. Thus, digital manufacturing and computational design methods are pivotal in planning the experimental projects presented in Part I. Nevertheless, this intellectual realisation – the reframing – or new conceptualisation of materiality, remains the most important feature of the proposed approach.

This new conceptualisation requires a detailed study of the existing concepts of materiality in design and architecture. To this end, the following chapter scrutinises the history of the role of material in architecture and design in relation to philosophy and technology.

Chapter 4: Perspective 2 – Design theory. The relationship of form and matter in architecture

Philosophy plays a key role in design theory and technology studies. The American philosopher and cognitive scientist Daniel C. Dennett (b. 1942) observed that '[t]here is no such thing as philosophy-free science; there is only science whose philosophical baggage is taken on board without examination' (Dennett, 1995, p.21). This observation can be extended to architecture and technology; and this chapter examines the "philosophical baggage" of the discussed approach to wood architecture and design. This "baggage" includes philosophical and technological positions that have potential to contribute to formulating a theoretical framework for the material innovation direction discussed. The key focus of the chapter is architecture and its theory; but, when necessary, philosophy and engineering are also discussed. These are only introduced in order to complement the argument, and provide the necessary background.

This chapter sets out to answer the question, ***What is the direction of innovation that results from the material experiments presented in Part I, Chapter 2?*** and further, to identify the features that characterise this approach. It outlines the metaphysical relationship of form and matter in relation to architecture; and discusses the proposed reconceptualization of this relationship, based on the analysis of these material experiments. The object of this study is the part of design theory that deals with metaphysics[34] of building materials and technology, and how different conceptualisations of this metaphysics affect design methods. This is presented against the background of architectural history (Figure 73).

The central assumption of this chapter is that the history of architecture can be reviewed vis-à-vis the relationship of form and matter and its conceptualisations. The German philosopher Martin Heidegger (1889–1976), in his influential essay *Der Ursprung des Kunstwerkes* (*The Origin of the Work of Art*)([1950] 2002), discussed the essence of art through the concepts of being and truth. He remarked that '[t]he distinction between matter and form is the conceptual scheme deployed in the greatest variety of ways by all art theory and aesthetics' (ibid., [1950] p.9). Heidegger saw the form-matter duality as a conceptual mechanism through which every being, not only a work of art, can be understood. In the same vein, the Swiss architect Jacques Herzog (b. 1950) commented that "the history of human culture could be written on the basis of the dialectics of material versus immaterial" (in interview with Toshiko Mori (2002, p.80)). This comment referred to the concept where "material" in the dialectics is related to matter and its physical conditions, and "immaterial" to formal and abstract values. In the words of Herzog, the work of his architectural practice Herzog & de Meuron "deals with the paradox of our physical world" (Mori, 2002, p.80) implicit in this relationship.

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[34] The word "metaphysics" is understood as '[t]he branch of philosophy that deals with the first principles of things, including abstract concepts such as being, knowing, identity, time, and space' (https://en.oxforddictionaries.com/definition/metaphysics).

Based on this dichotomous notion, one can assume there are two possible perspectives on design theory: one that prioritises the "formal", and the other that prioritises the "materialistic" approach to design. In this chapter I argue that the materialistic perspective, however existent, is rare in both theory and history writing on the subject. As a result of the long established hierarchy that has prioritised form over material, and idea over its manifestation; materials are mainly examined for their capacities to act as a servant to form (Lloyd Thomas, 2007, p.2). It reflects the conviction that permeates all art theory that the idea is superior over its manifestation. In this context, the materialistic perspective can be seen as countercultural, opposing well-established hierarchies and the accepted order.

The conceptualisation of materials in the profession and discipline of architecture started to change as a result of the need for more sustainable architecture. Within the framework of sustainable construction, materials must be considered in terms of their performance as well as their appearance[35]. While traditionally, materials were concerned either in technical or aesthetic terms, sustainability caused a shift in architectural theory in the 2000s. Some other perspectives began to emerge: emancipating material as the outright counterpart to form (Weston, 2003), "biographies" of materials, such as iron (Rinke and Schwartz, 2010), concrete (Forty, 2012), steel (Fry and Willis, 2015), or brick (Haynes, 2019), or contextualising materials vis-à-vis modern technologies (Fernandez, 2006, Addington and Schodek, 2005, Schröpfer et al., 2011, Kolarevic and Klinger, 2008). These new perspectives, though still countercultural, begin to gain momentum. The particular perspective of materiality in relation to design, proposed in this thesis, corresponds with the aforementioned perspectives. This chapter positions the proposed approach within the wide discussion surrounding materiality in design theory.

I argue that one reason for examining this countercultural perspective is that it offers a new repertoire of methods in design. The existing methods are not capable of embracing the materialistic perspective, e.g. material behaviour as a design potential eludes the means of design methods, from working drawings to building information models (BIM). In order to address this challenge, a change of the frame of reference is necessary. To this end, I try to identify various forerunners to that alternative perspective on materiality in the history of architecture. The end goal for this approach is to establish a new methodological framework for design: being ***material-centred***, making use of natural material features and traits, and activating material behaviour and self-forming capacities.

The philosophical foundation for this new methodological framework is based on the current New Materialism discourse, which acknowledges both

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[35] To illustrate how this entered the profession, Katie Lloyd Thomas brings the example of the changes in material specification in the UK since the 1960s, when materials had to conform to particular performance standards (fire-rating or acoustic separation) rather than be specified by kind (Lloyd Thomas, 2007, p.7).

human and nonhuman agency in the production of form. This discourse reconfigures and gets past well-established dichotomies, such as nature-culture, body-thought, concrete-abstract, subject-object, human-nonhuman, matter-mind, real-ideal, digital-manual, formal-material, etc. (Dolphijn and van der Tuin, 2012). New Materialism proponents, such as the Canadian philosopher Brian Massumi (b. 1956) or Manuel DeLanda, argue in favour of recognising the potential of matter and energy to self-organise; and see an opportunity there for the development of design (Massumi, 1992, DeLanda, 2001, DeLanda, 2004). DeLanda proposed to reconceptualise the origin of form in design:

> not as something imposed from the outside on an inert matter, not as a hierarchical command from above as in an assembly line, but as something that may come from within the materials, a form that we tease out of those materials as we allow them to have their say in the structures we create (DeLanda, 2004, p.21).

DeLanda proposed a form generation process where material would be seen as an active counterpart to the designer; thus, the form "may come from within the material" as opposed to being imposed "from the outside". This chapter outlines the scope of potential, in relation to wood construction, that stems from this proposal. The method to access this potential is based on the reframing method, as outlined in Chapter 3. Therefore, the central hypothesis of this chapter is that ***it is possible to innovate wood construction by reconceptualising the role of material in the design process***. This reconceptualization is based on New Materialism. Taking inspiration from there, various dichotomies are questioned that shape the existing design theory: form-matter, design-construction, digital-material, nature-culture, human-nonhuman, architecture-engineering, etc. The second hypothesis is that ***going past these dichotomies will result in a new frame of reference, which will allow new design methods to be devised, with a view to accessing latent and palpable material potentialities***. The end goal of these new processes is to establish a design methodology that would produce results with a lower environmental impact. This chapter's aim is to shed some light onto this new frame of reference, and to position the project of ***reframing wood architecture*** in architectural theory.

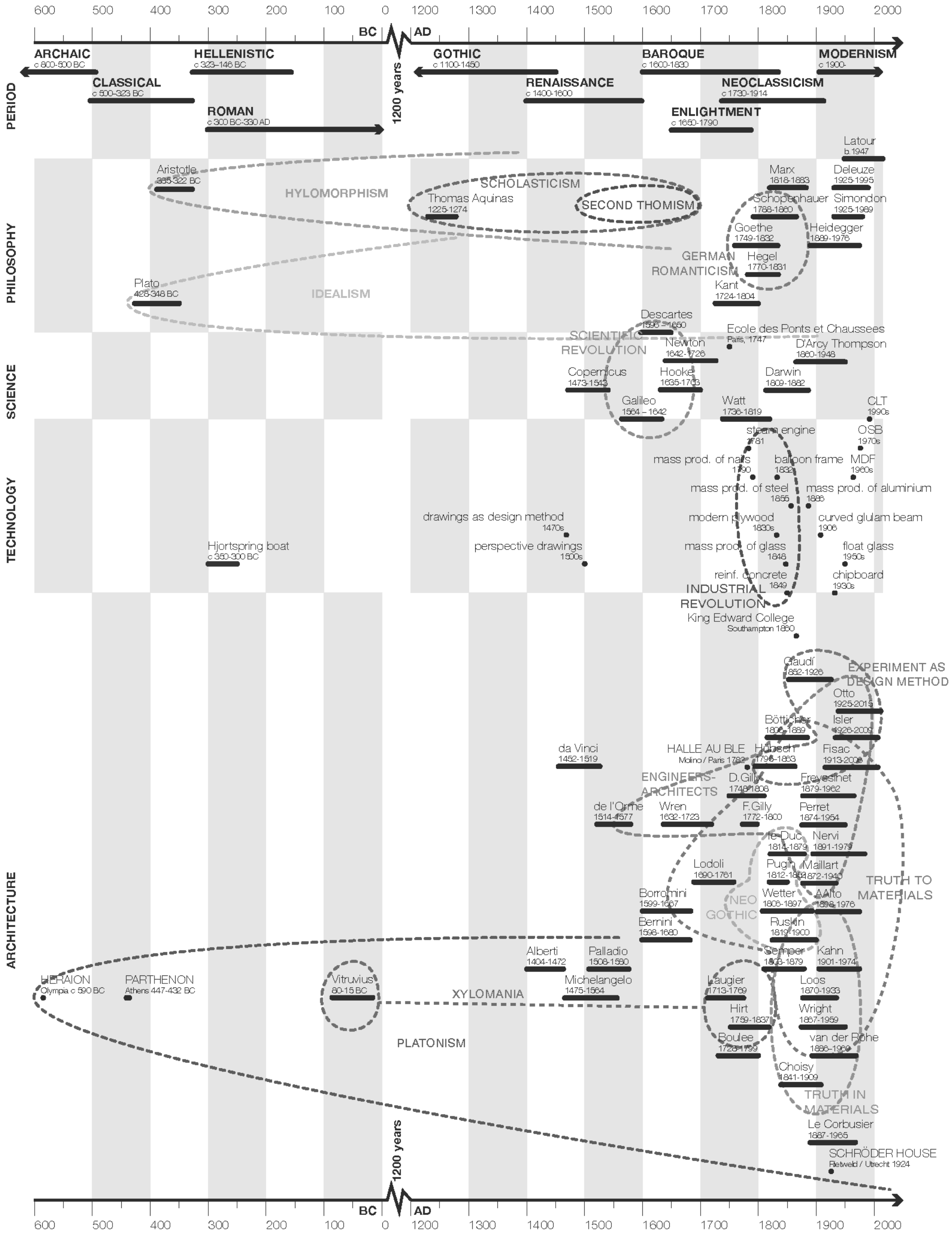

Figure 73
Chronologic diagram of the threads in Chapter 4.

HYLOMORPHISM – THE CLASSICAL FRAMEWORK FOR THE FORM-MATTER RELATIONSHIP IN ARCHITECTURE

The foundation of the hylomorphic form-matter relationship in Ancient Greek philosophy

The elemental philosophical stances regarding the form-matter relationship were defined, probably for the first time, in ancient Greece. For Plato (c. 428–348 BC), form was an idea[36] or *eidos*[37]. Thus, form achieved a higher, ontological status, while the material world was only an image of the real world. This notion emanates from his entire legacy, e.g. an illustration was evoked in *Book X* of his *Republic* (c. 380 BC) – the maker follows the ideal "form" rather than existing things, these being a mere resemblance of the real:

> Whenever a number of individuals have a common name, we assume them to have also a corresponding idea or form […]. Let us take any common instance; there are beds and tables in the world […]. But there are only two ideas or forms of them – one the idea of a bed, the other of a table. […] And the maker of either of them makes a bed or he makes a table for our use, in accordance with the idea […]. God […] desired to be the real maker of a real bed, not a particular maker of a particular bed, and therefore He created a bed which is essentially and by nature one only (*Republic* 596-597, trans. Jowett)[38].

Plato built a hierarchical relation, where he ascribed divine status to the ideas and forms of objects, such as beds or tables, while their earthly instances were just imperfect representations. When applied to architecture, this concept signifies the primacy of the ideal and the formal above material

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[36] As stated in the *Historical Dictionary of Ancient Greek Philosophy* '[t]he modern English word "idea" is not a good translation of the Greek word idea; "form" is probably best' (Preus, 2015, p.205).

[37] *Eidos* is Ancient Greek for form, shape, kind, or species. It is a noun from the verb *idein* meaning *to see* (Preus, 2015, p.139).

[38] I have chosen the 19th century Benjamin Jowett's translation of Plato's *Republic*, which more clearly refers to ideas and forms than later translations. Today's reader should make allowances for Jowett's particular Christian bias, thereby exemplified by referring to the personalised and capitalised God (Plato, [c.380 BC] 1888, p.308-309).

considerations, where the architect assumes the status of the sole creator. This concept is facilitated by architectural formal orders, proportioning systems, or preference for pure geometrical solids. Other concerns, such as material's natural geometrical features, idiosyncrasies, dimensional instabilities, ageing, weathering, etc., are secondary for the designer, who operates in the realm of the *eidos*. A designer's role is to bring order and meaning through representation of higher and pure ideas; material is seen as offering resistance that has to be overcome. This understanding permeated the entire history of western architecture, with the most evident manifestations in the Classical, Renaissance, Neoclassical, and Modern periods. For theorists promoting social construction of technology (SCOT), this way of thinking reflects and supports the hierarchical power relations in society, where the upper class deals with the ideal and the lower class with material aspects of technology. This relationship can be traced to the foundation of slave labour (see p. 120).

In a critique of his teacher, Plato's disciple Aristotle (384-322 BC) made a distinction between form and matter, laying a foundation for the fundamental metaphysical distinction in philosophy between idealist and materialist theories[39]. Aristotle, in his *Physics* and *Metaphysics* ([c.350 BC] 1928) introduced the concept of matter - *hylē*[40], the substrate out of which all physical things were made. Form was rendered the structure – *morphē*[41], which gave physical things their characteristics and attributes. This idea was further advanced in the Middle Ages by the Scholastic thinkers, such as Thomas Aquinas (1225–1274) or Bonaventure (1221–1274), and later termed "hylomorphism" in the 19th century. In the view of an Aristotelian, hylomorphism defines a thing as a unity or a combination of form and matter; medieval thinkers extended its meaning to body and soul, and consequently to all beings including angels[42].

Aristotle characterised every thing as consisting of two intrinsic principles, one potential, *hylē* (matter), and one actual, *morphē* (form): 'one element is matter and another is form, and one is potentially and the other actually' (*Metaphysics* VIII.6, 1045a23-24). These two principles could not exist independently, but only within this unity or composite:

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[39] This holds true despite the fact that, arguably, neither Plato could be unambiguously called an idealist, nor Aristotle a materialist, when applying contemporary definitions.

[40] *Hylē* translates to lumber in Ancient Greek. Aristotle appropriated the word, for *matter* had been an unknown concept before him. The same root of the word was followed by the Romans – Cicero (106 - 43 BC) used the word *materia* to translate *hylē*, which also translates to lumber in Latin (Preus, 2015, p.239).

[41] *Morphē,* in distinction to idea and eidos, refers to touchable shape, rather than visible form. In order to refer to form Aristotle often combines morphē with eidos (Preus, 2015, p.255).

[42] https://www.britannica.com/topic/hylomorphism

> And in one sense matter is said to be of the nature of substratum[43], in another, shape, and in a third, the compound of these. (By the matter I mean, for instance, the bronze, by the shape, the pattern of its form, and by the compound of these the statue, the concrete whole.) Therefore, if the form is prior to the matter and more real, it will be prior also to the compound of both, for the same reason (*Metaphysics* VII.3, 1029a2-6, trans. Ross).

In order to discuss the concept of potentiality as the characteristics of matter, Aristotle used the example of wood, which could "potentially" become a statue of Hermes:

> Actuality, then, is the existence of a thing not in the way which we express by potentially; we say that potentially, for instance, a statue of Hermes is in the block of wood and the half-line is in the whole, because it might be separated out, and we call even the man who is not studying a man of science, if he is capable of studying; the thing that stands in contrast to each of these exists actually (*Metaphysics* IX.3, 1048a30-35, trans. Ross).

Thus, matter had the capacity to become an object while remaining passive in the form-giving process. Aristotle extended Plato's hierarchy, between divine ideas and their earthly representations, into a further division within the earthly representations or physical substances. Between form and matter, form acquired a higher status than matter. Form was the structuring and dynamic principle. Matter was subjected to and adapted to a change of form. Matter was an undivided and singular substance capable of expressing multiple, differentiated and changing forms. As a consequence, materials became a subset of matter ('by matter I mean, for instance, the bronze'). A physical substance was form imposed on matter:

> When the matter is one, different things may be produced owing to difference in the moving cause; e.g. from wood may be made both a chest and a bed. But some different things must have their matter different; e.g. a saw could not be made of wood, nor is this in the power of the moving cause; for it could not make a saw of wool or of wood. But if, as a matter of fact, the same thing can be made of different material, clearly the art, i.e. the moving principle, is the same; for if both the matter and the moving cause were different, the product would be so too (*Metaphysics* VIII.4, 1044a25-30, trans. Ross).

What followed was that two objects of the same shape but made of different materials had the same eidos (species). Matter stood lower in the hierarchy, while materials were merely a subset of matter and so were interchangeable:

> Neither do a brazen and a wooden circle, then, differ in species; and if a brazen triangle and a wooden circle differ in species, it is not because of the matter, but because there is a contrariety in the definition (*Metaphysics* X.9, 1058b12-15, trans. Ross).

This understanding was critical for the formulation of a Classical theory of architecture, where material substitution did not entail change in built form. This phenomenon is discussed in the following section.

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[43] '[T]he substratum is that of which everything else is predicated, while it is itself not predicated of anything else' (Aristotle *Metaphysics* VII.3, 1028b35-36).

The position of an architect as the omnipotent form giver is supported by this theoretical formulation. Hylomorphism recognises matter as inert, where form can only be imposed on it: '[w]ood will surely not move itself—the carpenter's art must act on it' (*Metaphysics* XII.96, 1071b29, trans. Ross). In this hierarchical relationship between materials and the form giver, materials lack any potency:

> For at least the substratum itself does not make itself change; e.g. neither the wood nor the bronze causes the change of either of them, nor does the wood manufacture a bed and the bronze a statue, but something else is the cause of the change (*Metaphysics* I.3, 984a22-25, trans. Ross).

However, this elemental stance, reshaped by the various accretions accumulated during the passing centuries, remained the irreducible benchmark for architectural discourse. The very notions of form and matter have proliferated with meanings but their relationship structured this discourse. Therefore, in prevalent architectural theory and practice, matter has been inert and not capable to define form, and materials were only a subset of matter. An architect, in this hierarchical relationship, achieved the highest status of the omnipotent form giver. In the process, the resistance of matter to being formed was ignored and overcame. This formulation supported both slave labour and industrialisation (see p. 120).

Classical hylomorphism in Ancient Greek architecture

Little is known about the developmental path of the oldest architectural Classical orders, the Doric and the Ionic. Monumental stone temples appeared in Ancient Greece between the late 7th and the early 6th centuries BC. The first known stone temples were built to Apollo in Didyma, Artemis in Ephesus, and Hera in Samos. The latter, called *Dipteros I* and constructed between c. 575 and 560 BC, was the first monumental temple made completely of stone and built in the Ionic order. Archaeological evidence shows that earlier temples made out of wood, with columns of large trees and mud brick walls, were constructed on the same site. *Dipteros I* was more than three times the size of its wooden predecessor; it was widened more than it was elongated. This in turn increased the weight of the enlarged tiled roof, which forced the change of the structural material from wood to stone during this rebuilding, as the available timbers did not suffice to carry the weight (Hahn, 2001, p.65, 69, 70-73). The Doric order was established at the beginning of the 6th century BC, with the oldest known example being the *Heraion* temple in Olympia from c. 600-590 BC. Also, in this instance, wood was used extensively: both the sheathing of the wall-ends and the original columns were made of wood. There are mentions of oak supports in the rear porch (*opisthodomos*) as late as the 2nd century AD. As evidence suggests, the wooden columns were gradually replaced by stone ones over a long period of time (Barletta, 2001, p.126).

"Xylomania"[44] is a slightly derogative term describing the conclusion that the Classical orders originated in wooden construction (Figure 79). This opinion can be traced to the 1st century BC and the oldest theoretical treatise *De Architectura* (*Ten Books on Architecture*) ([c. 25 BC] 1914) written by the Roman author and architect Marcus Vitruvius Pollio (c. 80-15 BC). Vitruvius posited that the first dwelling was built in the forest, with branches and trees[45], and the forms resulting from wooden construction were trans positioned to stone construction to form the basis of the Classical orders. In the introduction to Book II of the treatises, dedicated to materials, Vitruvius described the origin of architecture. Chapter I of the Book, titled *The Origin of the Dwelling House*, advanced the concept of the primitive hut, which was presented as the wooden predecessor of the formal architectural stone orders. Vitruvius established the evolutionary view of development that has dominated architectural theory ever since:

> [The men of old] by observing the shelters of others and adding new details to their own inceptions, [...] constructed better and better kinds of huts as time went on [...].
>
> Then, taking courage and looking forward from the standpoint of higher ideas born of the multiplication of the arts, they gave up huts and began to build houses with foundations, having brick or stone walls, and roofs of timber and tiles; next, observation and application led them from fluctuating and indefinite conceptions to definite rules of symmetry[46] (ibid., [c. 25 BC] p.38-39, 40-41).

Book IV explained the origin of the three architectural orders: the Doric, the Ionic, and the Corinthian. In this Book Vitruvius linked the notion of the orders as based on 'the proportions, strength, and beauty of the body of a man' (ibid., [c. 25 BC] p.103) with the idea that their wooden origin was based on the concept of the primitive hut as introduced in Book II. He characterised

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[44] *Xylo* – from Ancient Greek *ksúlon* – wood. The term was used by Hübsch in his influential treatise *In what style should we build?* (Hübsch, [1828] 1992, p.71).

[45] This has been confirmed by archaeological evidence from the Neolithic period, e.g. the Çatalhöyük houses from 7000 BC built with mud bricks and timbers (Moore, 2012, p.94) or the Hug houses from the same period based on a twig-knitted construction technique (Tokay, 2005). Interestingly, the *primitive huts* in Çatalhöyük were built with a construction system known today as a frame structure or, in Semper's terms, tectonic. The structural principle of a Neolithic dwelling was based on timber columns supporting thatched roofs and wattle-and-daub walls, filled with a wickerwork of saplings and covered with a thick coat of clay (Moore, 2012, p.189). According to current archaeological evidence, in wood construction the tectonic approach predates the stereotomic – based on solids cut and assembled in compression – by a few thousand years. The oldest known remains of log huts, dated to c. 1200-800 BC, were found in excavations in the village of Buch near Berlin (Berge, 2009, p.217). The change from tectonic to stereotomic might have resulted from the scarcity of local long length wood, as log timber building could be constructed from shorter elements. This may be the oldest known case of wood material agency in design. The stereotomic technique had also developed independently in other parts of the world, like China and Japan.

[46] Symmetry was a key concept for Vitruvius, as it defined beauty and brought order and harmony to the arrangement of building parts. Book III discussed the ideas of symmetry and proportion in more detail, describing rules on ratios as derived from the proportions of the human body.

triglyphs, metopes, and mutules as resultant from earlier timber construction, and being its imitation:

> So it was that some ancient carpenters, engaged in building somewhere or other, after laying the tie-beams so that they projected from the inside to the outside of the walls, closed up the space between the beams, and above them ornamented the coronae and gables with carpentry work of beauty greater than usual; then they cut off the projecting ends of the beams, bringing them into line and flush with the face of the walls; next, as this had an ugly look to them, they fastened boards, shaped as triglyphs are now made, on the ends of the beams, where they had been cut off in front, and painted with blue wax so that the cutting off ends of the beams, being concealed, would not offend the eye. Hence it was in imitation of the arrangement of the tie-beams that men began to employ, in Doric buildings, the device of triglyphs and the metopes between the beams.
>
> Later, others in other buildings allowed the projecting principal rafters to run out till they were flush with the triglyphs, and then formed their projections into simae. From that practice, like the triglyphs from the arrangement of the tie-beams, the system of mutules under the coronae was devised from the projections of the principal rafters. Hence generally, in buildings of stone and marble, the mutules are carved with a downward slant, in imitation of the principal rafters. For these necessarily have a slanting and projecting position to let the water drip down. The scheme of triglyphs and mutules in Doric buildings was, therefore, the imitative device that I have described (ibid., [c. 25 BC] p.107-108).

Vitruvian theory can be described as anthropomorphic, as it derived the proportions of the Classical order from the proportions of the human body. Together with symmetry, proportioning systems achieved a higher status than material considerations. Construction became Architecture when men 'passed from a rude and barbarous mode of life to civilization and refinement' (ibid., [c. 25 BC] p.40). That coincided with the change of their primary construction material from wood to stone; but the change of material did not affect the built form. This notion drew upon the Platonic *eidos*, which stood hierarchically higher than its earthly representations, but even more so upon the Aristotelian hylomorphic model of the form and matter relationship. As outlined earlier, matter was passive and inert in this relationship, and form was imposed on it. Materials, being a subset of matter, were interchangeable; while the form was the primary and structuring principle[47].

In light of today's knowledge and archaeological evidence, it is not possible to reconstruct the exact developmental path of the first Classical orders. Despite the well documented existence of the wooden predecessors of the stone temples, which started to appear after the 7th century BC, finding archaeological evidence of the exact architectural forms and ornaments is

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[47] On the other hand, it can be argued that the Aristotelean hylomorphic idea leaves more margin for material agency. While the idea did not see material as active in the form-giving process, it laid foundations for materialist approaches. Often attributed to Michelangelo (1475–1564): "every block of stone has a statue inside it and it is the task of the sculptor to discover it" (in another version Michelangelo tells the pope how he knew what to cut away from the stone for his David sculpture (1501-1503): "It's simple. I just removed everything that did not look like David"), this proverb actually originated in *Metaphysics* where Aristotle remarks that we can speak of seeing Hermes in the uncarved stone (*Metaphysics* V.7, 1017b7). This stance can be regarded as formative for the recognition of material agency.

very difficult. Wood, as an organic substance, is perishable. Information can only be found by negative impressions left by timber on floors, walls, and in the ground; or by secondary sources such as pictorial representations, or literary and epigraphic references (Tucci, 2014, p.242-243, Wright, 2005, p.13-14). Vitruvian theory asserted that the architectural forms of the orders had been first developed in wood, and then were petrified and frozen after the material change to stone. A reconstruction of events from Vitruvius dates the origin of the Doric style to the 12th-11th century BC (Barletta, 2001, p.4). While today it is generally accepted that individual elements of the order appeared piecemeal between the late 7th and the early 6th centuries BC; the combination of components that characterise the Doric style appeared in the 2nd quarter of the 6th century BC. The orders were evolving and always capable of change (ibid., p.154, 156). The forms of the Classical orders did not directly represent construction techniques, or earlier ornaments, but rather elaborated on structural forms (ibid., p.125-137).

The petrification of timber construction plays a role in the founding myth for architectural theory. The Classical orders' primacy in architectural theory had not been challenged until the early 18th century[48], when the Gothic style became the touchstone for new theories based on a contemporary worldview, characterised by the architectural historian and theorist Alberto Pérez-Gómez (b. 1949) as "protopositivist" (Pérez-Gómez, 1983, p.50). This worldview resulted from epistemological developments of the 17th century Scientific Revolution. Most notable was the contribution of Italian polymath Galileo Galilei (1564–1642) who surmised that the laws of nature were mathematical, and formulated the foundations of material science and statics (ibid., p.166-168, 238-248).

Hylomorphism and separation of design and its product, design and construction, and design and engineering

This section elaborates on how hylomorphism has shaped architectural design since early modern times, i.e. the Renaissance. This account is used as a counterpoint for the definition of the proposed ***reframing*** wood construction. Outlined are historical facts, such as the introduction of drawing as a medium for the architectural profession in the 15th century, the Scientific Revolution and the advent of engineering in the 16th and 17th centuries, and the Industrial Revolution of the 18th and 19th centuries; all of which reinforced the hylomorphic model and established it as dominant in Modern architectural design. In addition to the earlier discussed theoretical

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[48] In 1702 the critic and *President du Bureau des Finances* in Paris, Michel de Fremin, stated that the knowledge of the orders is only a minimal part of architecture (Pérez-Gómez, 1983, p.50). Fremin based his critique of the orders on rational grounds, advocating the use of common sense: in the choice of building materials, in craftsmanship, and in the arrangement of building components (Angelil, 1987, p.302).

separation of form and material in Classical architecture, this formed a basis for further processes of separation and division. These were both theoretical, such as that of the separation of the act of design and its product, i.e. built material form; and in the design profession, such as that of dividing design and construction, or architecture and engineering. The proposed ***reframing*** of wood construction identifies these dichotomies as erroneous, and strives to look past them.

Separation of the acts of design and construction in the 15th century

In architecture, the process of separating the design and its product accelerated in the Renaissance with Neoplatonic thought, which brought a new awareness of Platonic philosophy. The Renaissance Neoplatonists identified beauty as independence of form from matter (Forty, 2000, p.151-153), which laid a foundation for the separation of the act of design and its product. Effectively, this separation led to the development of the design profession.

In the mid-15th century, the Italian architect and Renaissance man Leon Batista Alberti (1404–1472) wrote *De Re Aedificatoria* (*On the Art of Building*), the first book on architecture published since Classical antiquity. It made the distinction between "lineaments", which are the product of thought; and "matter", which is the product of nature[49] (Alberti, [1443-1452] 1988, p.5), and asserted that 'it is possible to project forms in the mind without recourse to the material' (Alberti, [1443-1452] 1988, p.7). Alberti thus advanced and amplified the Vitruvian notion that materials can be interchangeable without affecting the architectural form. This formulation led to the separation of the act of design, dealing with ideas and pure forms; and its product, i.e. the built material form.

This clear-cut distinction between design and its built form was instrumental in the development of the architectural design[50] profession, established on the separation of roles in the act of design and its subsequent construction. Since Alberti, architecture has been a separate field from construction; design could be conceived as abstracted from the act of building and also from building materials. This separation was facilitated by the introduction of drawing as a design method in the 1470s and perspective drawing in the 1500s. Drawing liaised design with the developing science of geometry and perspective, and thus moved design activity to the domain of abstract thought. Since then, design became a more intellectual rather than a manual enterprise; and its

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[49] Contrary to the German art historian Erwin Panofsky (1892–1968), the British architectural historian Adrian Forty (b. 1948) argues against reading this distinction as equivalent to the dualism of form and matter, as the concept of Alberti's lineaments is very distant from 'any notion of form' (Forty, 2000, p.153).

[50] The term *design* as used and understood today originated in the Renaissance.

central method became pictorial representation, distancing architects from the material world. As a consequence, it resulted in the reduction of materials to the white space between lines delineating forms in projective drawings; and it solidified the hierarchical relationship between form and material in design, which prioritised form and idea above its physical manifestation. This is evident, for instance, in the work of the Italian High Renaissance architect Andrea Palladio (1508-1580), whose buildings were frequently clad with unassuming and imitating stone stucco, and who stated that "buildings are esteemed more for their form than for their materials" (as cited in Forty (2000, p.153)).

A second consequence of this separation of design and construction, also facilitated by the means of projective drawings, was the appearance of the notion of authorship. The architectural historian Mario Carpo (b. 1958) discussed Alberti's pursuit of identical replication (Carpo, 2011); which, not coincidentally, was paralleled by the invention of moveable type by the German printer and publisher Johannes Guttenberg (c. 1400-1468) in the mid-15th century. When the design intent could be unambiguously transmitted from the architect to the builder, the building could be considered an exact copy of the design. The architect thus assumed the role of the sole design author, and by the same token reduced the role of the builder to a mere tool. The separation of the acts of design and construction further amplified the hierarchy descendent from the hylomorphic concept in antiquity, which prioritised conceptual work with ideas over manual work with materials.

Scientific Revolution and the conceptual abstraction of matter in the 16th and 17th centuries

Baroque coincided with the return of Scholasticism and the thoughts of Thomas Aquinas (compare p.106). This "second Thomism" began in the late 15th century and continued until the end of the 17th century. In Western art, it resulted in a turn towards naturalism, realism, and sensuality (Cullen, 2000, p.45); which was based on the hylomorphic separation of form and material and the conceptual "abstraction of matter". For instance, Encyclopaedia Britannica characterises the use of stone by the greatest sculptor of 17th century Italy, Gian Lorenzo Bernini (1598-1680), as being "completely emancipated from stoniness by open form and by an astonishing illusion of flesh, hair, cloth, and other textures, pictorial effects that had earlier been attempted only by painting" (as quoted in Cullen (2000, p.55)).

The return to Scholasticism and Aristotelian thought founded the beginning of modern science. The Scientific Revolution symbolically began with the publication of *De Revolutionibus Orbium Coelestium* (*On the Revolutions of the Heavenly Spheres)* by Nicolaus Copernicus (1473-1543) in 1543. That moment when the Earth was no longer the centre of the World, and more importantly the method of logical reasoning behind it, conventionally marks the start of modern science. Since then, the cause-and-effect explanation started to replace the mystical spirit and, as awareness of investigative power increased, new discoveries began to replace traditional beliefs. In 1628 William Harvey (1578-1657) discovered the circulation of blood in the body using a rigorous approach that laid the foundation for the scientific method. A new theory of cosmos, motion in physics, and proof of a vacuum's existence were all resultant from the rigorous scientific process advanced in the 17th century (Vignais and Vignais, 2010, p.49-137). Following the same pattern, the concept of matter went through the process of not only philosophical but also scientific scrutiny. In the first half of the 17th century René Descartes (1596-1650) in France brought matter under the domain of calculable physics by depriving it of indeterminacy and unpredictability. Descartes designated mind and matter (*res cogitans* and *res extensa*) as two independent categories that can only be combined in the human consciousness, thus breaking off with the Aristotelean-scholastic world view (Moravánszky, 2018, p.47-48). In 1638 Galileo Galilei in Italy was the first who clearly distinguished between the strength of a material and that of an object made from this material, i.e. the difference between the properties of a material and that of a structure (Addis, 2007, p.191). Towards the end of the 17th century in England, Isaac Newton (1642-1726) introduced the concept of mass that effectively replaced the concept of matter in physics. It is important to note that besides his historic contribution to the body of scientific knowledge in the 1687 *Mathematical Principles of Natural Philosophy*, Newton also formalised the methodical approach. By means of combining an inductive approach and a mathematical description of observations, Newton used experiment to form a basis for drawing binding conclusions. Thus, the Scientific Revolution of the 17th century brought new rationalism to science, based on the scientific method of inquiry. Rationalism was enabled by the theoretical "abstraction of matter", through which matter became a more operational and calculable concept.

In his seminal book *Architecture and the Crisis of Modern Science* (1983), Pérez-Gómez drew a parallel between modern science and Modern architecture. The operational principle of both is based on 'a distance between objects and mind, so that the latter could affirm its right of jurisdiction over the materiality of the former' (Pérez-Gómez, 1983, p.167). This dichotomy echoes the dualities between form and material, or ideas and their manifestations. The hierarchical relationship, where the mind acquires priority over material objects, appeared in the second half of the 16th century as one of the key features of the Scientific Revolution. In the realm of architecture and design, this formulation of the hierarchical relationship paved the way for construction innovations in the 17th century. The main difference between innovative approaches in the engineering of late Renaissance and Baroque was in the shift from using geometry to the method of statics (Kurrer, 2008, p.189). The "abstracted matter" became susceptible to calculation and, to a certain extent, more predictable.

Pérez-Gómez pointed to the design of fortifications at the turn of the 16th and 17th centuries as the turning point, where a more pragmatic understanding of engineering began to appear. It included taking into account both the irregularities of topography and that of building materials, which came from the realisation that ‘imposing an arbitrary geometrical figure upon a terrain was insufficient’ (Pérez-Gómez, 1983, p.208).

Separation of architecture and engineering in 18th century France

Moving questions concerning matter, and in the case of construction more specifically building materials, to the domain of calculable physics was a two-century long process that led to a clear-cut separation of architecture and engineering as two distinct professions. The need for innovation had fuelled the development of engineering since the Renaissance. While the earlier protoplast-engineers approached problems by observation and generalization, new methods began to appear towards the end of the 16th century. Some builders started to look for design procedures based on rational and systematic processes. One such example was Rodrigo Gil de Hontañón (1500-1577), a 16th century Spanish cathedral designer. In about 1565, having found with frustration that there was not a general rule in place for the design of vaults and abutments, de Hontañón tried to collect rational design rules. Collecting existing rules regarding construction was an important step forward towards the rationalisation of construction, but also a necessary condition for design innovation. It facilitated a new method of innovation based on systematic processes, not on incremental yet slow and non-directed improvements. This method of using rational and systematic design processes based on mathematics was used in 16th century shipbuilding. For instance, Matthew Baker (c. 1530–1613), a “mathematical practitioner” and English Tudor shipwright, realised that merely improving on the designs of earlier ships would not generate a different and superior vessel. Baker surmised that the means of drawing could allow a connection between mathematics and ships design, and became the first English shipwright who used drawing as a method to design ships in the 1580s. On paper, design problems could be seen in a new light, and various techniques could be adapted and transferred, reaching out to much wider expertise base than traditionally associated with shipbuilding. It was becoming clear that design disciplines of the time required new methods for innovation, and rational and systematic experimentation had the potential to lead to unforeseen benefits in construction as it did in other disciplines (Addis, 2007, p.150-153, 190-191, Johnston, 1994, p.107-110).

The interest in rational, systematic, and quantitative methods in architecture and construction started to increase towards the 18th century. In 1691, the French architect Pierre Bullet (1639-1716) was first to provide a concrete application of mathematics to determine volumes, quantities, and the cost of a building. These quantitative methods were largely based on the abovementioned conceptual “abstraction of matter”, where building materials were seen as homogeneous and uniform. Bullet thus failed to provide rules for determining dimensions for structural wooden beams, and concluded that these cannot be absolute as wood qualities vary among various types of wood. In 18th century France, this interest in the quantitative methods in architecture resulted in a number of treatises dealing with the quality of building materials, specifications, structural soundness, and efficiency. The first systematic tests of wooden beams which took into account all the important factors affecting the strength of wood, such as the way a tree has been felled or its moisture content, were carried out by the French naturalist and mathematician Comte de Buffon (1707-1788) in the first half of 18th century. In parallel to material science, statics also began to develop as a branch of mechanics, based both on empirical observation and algebraic calculation. In 1712, French mathematician Philippe de La Hire (1640–1718) was the first to apply a truly mechanical hypothesis to the problem of arch and vault stability. In 1773 the French physicist Charles-Augustin de Coulomb (1736–1806) proposed the first scientific method for solving structural problems, enabling the application of de la Hire's theory by utilising his values of friction and cohesion. Interestingly, Coulomb's equation for the design of retaining walls is still in use. The first truly analytic treatise on strength of materials as understood today, integrating experimental observation with mathematical theory, was written in 1798 by a French mathematician and engineer Pierre-Simon Girard (1765-1836) (Pérez-Gómez, 1983, p.223-226, 244, 265-266). The 18th century developments of Coulomb and Girard were direct successors of the 17th century science of materials and mechanics as initiated by Galileo. Later, the French engineer Claude-Louis Navier (1785-1836) brought theory closer to real behaviour by introducing the elastic limits of materials to his formulas in 1826. Navier was the first to systematically apply the mathematical theory of elasticity to engineering problems, and as a result, iron became progressively more calculable than traditional masonry (Picon, 2010b, p.61).

The conceptual "abstraction of matter" that triggered the unprecedented development of material science and statics in 18th century France also manifested itself in the relationship of architectural design and construction. The French Neoclassical architects of the 18th century, such as Étienne-Louis Boullée (1728-1799) or Claude Nicholas Ledoux (1736-1806) reinvigorated the distinction between design and building (Pérez-Gómez, 1983, p.133-134, 148). This distinction was facilitated by the method of reducing material objects to idealised three-dimensional solids. Boullée saw regular and symmetric Platonic solids as a source of beauty in architecture (Pérez-Gómez, 1983, p.136-137, Gelernter, 1995, p.171-172). He echoed the Renaissance architects, saying that architecture is the product of the mind, while construction is merely an auxiliary art: "[i]n order to execute, it is first necessary to conceive. Our earliest ancestors built their huts only when they had a picture of them in their minds" (Boullée as cited in Gelernter (1995, p.172)). Accordingly, drawings illustrating perspective treatises of this period reduced objects to their essential geometrical configurations without the fine detail, and for Ledoux even trees could be seen as spheres or pyramids (Pérez-Gómez, 1983, p.154).

Inevitably the gap between the disciplines of architecture and structural engineering resulted in their evolution into two distinct professions. While formal architectural education began in France with the founding of the

Académie Royale d'Architecture in 1671 (Keller, 2017, p.18), the first engineering school *École des Ponts et Chaussées* in Paris was founded in 1747, marking the split of the professions (Frampton, 1987, p.8, Pérez-Gómez, 1983, p.198-199).

Positivism, which underpinned the Industrial Revolution of the 19th century, was also the philosophical backbone of the development of structural engineering as a separate profession. The doctrine of Positivism could be traced to the English philosopher Francis Bacon (1561-1626); but it was fully formulated in France, most notably by the mathematician and philosopher Pierre Simon Laplace (1749–1827) at the turn of the 18th and 19th centuries, and the philosopher Auguste Comte (1798-1857) in the 1830s and 1840s. Laplace believed in mechanical determinism and, based on Newtonian mechanics, proved the mechanical stability of the solar system without a need for the intervention of God[51] (Flew, [1979] 1984, p.197). Comte studied the development of human thought and social structures, and traced their movement from "theological" stages to the "positive" stage. He notably phrased his programme in an aphorism: "science whence comes prediction; prediction whence comes action" (ibid., [1979] p.69, 283). Positivism rid science of traditional and mythical references, making the laws of nature knowable to reason by mathematical analysis. By doing so, it created the illusion of control and domination of the human mind over nature, and laid a foundation for rapid modernisation to follow in the next two centuries. In the light of Positivistic thought, any intellectual operations not verifiable by mathematical reason were invalid. It created a hierarchical relationship, where scientific thought gained primacy over the sphere of dreams, poetry, and imagination (Pérez-Gómez, 1983, p.273-274).

This intellectual context was reflected in the development of technical education. In the *École Polytechnique*, established in 1794 as 'a product of the French Revolution and the Age of Enlightenment'[52], the apprenticeship arrangement of the *École des Ponts et Chaussées* was replaced by lectures following a compulsory curriculum. In the *École Polytechnique* an architect or engineer could be considered qualified to practice based on examinations and theoretical tests, without any involvement in actual building practice (ibid., p.278, 289). This education system produced a new, very influential, and dominant figure in the industrial society: a "technical specialist", 'arrogant and self-sufficient [...], [w]ith an infinite faith in mathematical reason, [who] had little or no knowledge of society, its history and problems, and despised the humanities because their content was always ambiguous and practically impossible to formulate with mathematical certainty' (ibid., p.277).

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[51] Laplace made a famous, although potentially apocryphal, remark to Napoleon about God, "I had no need of that hypothesis" (Flew, [1979] 1984, p.197).

[52] History of École Polytechnique [Online]. Available: https://www.polytechnique.edu/en/history [Accessed 20.11.2015].

The central method for representing and conceptualising spatial relationships by the graduates of the *École Polytechnique* was descriptive geometry, invented by the French mathematician Gaspard Monge (1746–1818) in 1795. Comte called it “the only conception […] capable of providing a precise idea of the characteristic doctrines that constituted the essence of engineering” (as quoted in Pérez-Gómez (1983, p.282)). At the end of the 18th century, descriptive geometry became a “disruptive technology” (compare p. 92), providing a synthetic system that facilitated arts, crafts, and engineering; and being instrumental in the advancement of industry. By bringing representation to a new level of abstractness, not concerned with any specifics (“abstracted matter”), it became applicable to a wide range of disciplines. It echoed the role played by the introduction of drawing and perspective drawing at the end of the 15th century, which facilitated the separation of design and construction by bringing new tools of representation and a new level of abstraction (see p. 112).

With the advent of Positivistic civil engineering, the role of architecture could either be reduced to decoration, or else it had to adapt more rationalistic methods of exact sciences. In line with the latter, the French architect Jean-Baptiste Rondelet (1743-1829) published the first truly effective book on building science in 1802, providing step-by-step solutions to all sorts of practical problems. In a Positivistic manner, applying descriptive geometry to the problems of construction for the first time, Rondelet defined the art of building as “a happy application of the exact sciences to the properties of matter” (Rondelet as cited in Pérez-Gómez (1983, p.287)). His role in architectural history can be seen as a forerunner for architectural determinism; where the form of architectural elements is derived from the strength of materials, with solidity and stability of structure the primary objective. His formulation bridged the gap between theory, based on logical reasoning and exact sciences, and practice. Rondelet’s view of the history of architecture was akin to Comte’s account of social evolution: a linear process towards rational construction, through the progressing mathematisation of the profession. He disregarded Classical Greek architecture for the alleged transposition from wood to stone without changing the built forms; and Renaissance and Baroque architects for their “capricious, sumptuous, or gigantic projects” (Rondelet as cited in Pérez-Gómez (1983, p.289)) as these clashed with his rationality. Conversely, he praised the Roman and Gothic construction methods as determined by necessity and used appropriately. Rondelet advocated the use of methods of efficiency and economy in architecture; thus, for instance, his contribution to the establishment of a normalised decimal system (Pérez-Gómez, 1983, p.286-291). By the application of unambiguous descriptive geometry, he effectively eradicated any need for transcendent or symbolic knowledge in construction, and at the same time enabled the designer to dominate and direct the craftsman without any practical knowledge of building techniques. Rationalist methods based on the conceptual “abstraction of matter”, yet again, amplified the hierarchical relationship between the designer and the builder.

Industrial Revolution and solidification of the hylomorphic model in the 18th and 19th centuries

The scientific method, which had developed since the 16th century (see p. 113), resulted in a new way of developing technologies, not based on slow incremental accumulation of knowledge improved through experience, but in large leaps. The scientific method was transferred to technology as "the method of invention"[53], and resulted in the 18th and 19th century Industrial Revolution. The Industrial Revolution was the key turning point in the building material / construction relationship. The construction industry strove to follow the example of industrial production, where the new economy demanded machine tools to replace human force. This replacement effaced the relevance of human tacit knowledge in favour of scientific knowledge, and was facilitated by new, more calculable, and predictable materials. This section explains how the processes solidified and expanded the hylomorphic model. It outlines the concepts of division of labour and homogenisation of the materials, which facilitated these processes.

Division of labour is a concept where work is divided into separate tasks allocated to individuals and which require specialised equipment and skills. This concept was known already in Ancient Greece, and was discussed by Plato (*Republic* 369-371, trans. Jowett)[54]. An early proponent of this division of labour was Sir William Petty (1623-1687) the 17th century English economist, scientist, physician, and philosopher. Petty observed how, in Dutch shipyards, several teams specialised in doing particular tasks for consecutive ships in order to increase productivity. In the 1650s Petty applied this method to surveying Ireland (the *Down Survey*), so that about a thousand unskilled subordinates produced pieces of the work; which were then coordinated by a few dozen district surveyors and clerks. This innovative division of labour resulted in unprecedented efficiency and accuracy (Prendergast, 1997, p.46-48). In *An Inquiry Into the Nature and Causes of the Wealth of Nations*, the fundamental work in economics published in 1776, the Scottish economist and philosopher Adam Smith (1723-1790) argued that division of labour together with specialisation of skills and equipment substantially increased productivity.

In the second half of the 19th century, the German philosopher, economist, sociologist, and socialist Karl Marx (1818-1883) revealed the structure of the capitalist industrial mode of production in *Das Kapital. Kritik der politischen Ökonomie (Capital. Critique of Political Economy)* (Marx, [1867] 1906). Marx characterised manufacturing, which is the basis of industrial mechanised

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[53] As put by the English mathematician and philosopher Alfred North Whitehead (1861–1947): 'the greatest invention of the 19th century was the invention of the method of invention' (Whitehead, 1925, p.98).

[54] Plato: 'all things are produced more plentifully and easily and of a better quality when one man does one thing which is natural to him and does it at the right time, and leaves other things' (*Republic* 370, trans. Jowett).

production, as stemming from handicrafts. Marx described how manufacturing is based on both the union and split of handicrafts: a union of various and independent handicrafts reduced to partial processes necessary in the production of one commodity, and a split of one particular handicraft into detailed operations for individual labourers. Thus, manufacturing simultaneously unites formerly independent handicrafts and introduces divisions of labour into processes of production (ibid., [1867] p.371-372). In manufacturing, efficiency of the production process is achieved by the labourers performing repetitive tasks. Marx mentioned some efficiency gains from repeating one task by one labourer: the workflow is uninterrupted by changing place or tools by the labourer[55], his or her work methods are perfected, and it is easier to hand down skills that are confined (ibid., [1867] p.372-374). However, these gains are achieved at the expense of the labourers' intellect and health: Marx cited Smith as saying that "[t]he man whose whole life is spent in performing a few simple operations [...] has no occasion to exert his understanding [...]. He generally becomes as stupid and ignorant as it is possible for a human creature to become" (Adam Smith as cited in Marx ([1867] 1906, p.397-398)).

In Marxism, this division of labour supports the authority of a capitalist over labourers 'that are but parts of a mechanism that belongs to him' (ibid., [1867] p.391). Marx explained how 'the labourer is brought face to face with the intellectual potencies of the material process of production, as the property of another, and as a ruling power' (ibid., [1867] p.397). Further to that, and as a consequence of the substitution of machine tools for human force, 'the labourer becomes a mere appendage to an already existing material condition of production' (ibid., [1867] p.421). For the capitalist to maintain the hierarchical relationship, it is important that the labourer is blind to the complexity of the process in which he or she is taking part.

One hundred years after Marx, in the 1950-1960s, the French philosopher Gilbert Simondon (1924–1989) expanded this notion by linking labour and the hylomorphic model. Simondon likened the hierarchical order of slave labour and that of the form-matter relationship. While labour is "essentially the operation commanded by the human and executed by the slave", the hylomorphic model is based on "the active character of form and the passive character of matter", which "respond to conditions of transformation into a social order that assumes hierarchy" (Simondon as cited in Combes (2013, p.72)). In this formulation, form is related to power and to giving commands,

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[55] In 1980 Deleuze and Guattari in their *Mille plateaux (A Thousand Plateaus: Capitalism and Schizophrenia)* discuss how the very act of movement and following the 'matter-flow' defines the artisans and distinguishes them from workers: 'artisans are complete only if they are also prospectors; and the organization that separates prospectors, merchants, and artisans already mutilates artisans in order to make "workers" of them'. Deleuze and Guattari say, 'to follow the flow of matter is to itinerate, to ambulate', and bring the example of carpenters who in order 'to find the wood with the right kind of fibres' have to go to the forest (Deleuze and Guattari, [1980] 2005, p.409).

while matter to inertia and slavery. Thus, the Ancient hylomorphic concept of Aristotle (see p. 137) gained a new social and Marxist dimension.

Further to that, Marx went on to state that the replacement of human force for machine tools, pivotal to the Industrial Revolution, required 'the conscious application of science, instead of rule of thumb' (Marx, [1867] 1906, p.421). This statement acknowledged that by the mid-19th century it became clear that there were true and palpable benefits to the scientific approach; but also that this approach diminished the importance of the personal craftsman's expertise. The hierarchical relationship of the powerful form-giver and the inert labourer was facilitated by the scientific approach. In order to advance "the conscious application of science" in support of the industrial processes, the role of materials in the processes had to be reconceptualised. The industrialised manufacturing process, based on the division of labour, and on breaking down manufacturing to separate processes requiring minimum skill and expertise, depended upon uniform, predictable, and structurally homogeneous materials. More predictable materials, devoid of irregularities and inconsistencies, facilitated more mathematically orientated design in manufacturing and construction processes. When materials became more calculable, no more complex, tacit knowledge about the material behaviour was required from the labourer. Thus, the materials' and the labourers' roles intertwined in industrial processes.

The process that replaced the labourer for the craftsman bears resemblance to the process that separated the acts of design and construction (see p. 112). Both processes can be seen as a continuation and solidification of the lineage drawn from Antiquity's hylomorphic concept; which prioritised ideas over their physical manifestations and, subsequently, conceptual work over manual work. Both processes were based on a liaison with science: material science in the former case, and geometry and perspective in the latter. They also distanced the designer from the material world by the conceptual "abstraction of matter". Finally, both relied on docility of matter and workforce, and both resulted in the reduction of matter to inert and inactive materials, and of workers to mere tools.

The separation, between the folkloric frame of reference for traditional craftsmen and the scientific attitude, resulted in a mutual distrust among craftsmen and designers. This distrust was described already in the 17th century by André Félibien (1619 – 1695), a French historian at the court of Louis XIV. While working on his book, Félibien tried to learn about the techniques and tools of masonry, carpentry, plumbing, and other trades from the craftsmen themselves. Félibien, who approached the craftsmen with his scientific mentality, could not find "reasonable" interlocutors. Instead, he described meeting "ignorant and strange people, inventing ridiculous stories", pretending not to know what he wanted, and hiding the most common utensils from him (Pérez-Gómez, 1983, p.185-186). From the 18th century, a similarly dismissive tone towards craftsmen, whose expertise was based upon tacit knowledge of wood, can be found among ship builders. In 1755 Holland, the naval officer Cornelis Schrijver (1687-1768) attacked shipwrights for being backward and not applying geometric and scientific rules, calling them "nothing more than carpenters". In 1771 Spain, the ship builder Jorge Juan y Santacilia (1713-1773) complained that ship construction was left to 'mere carpenters'. This derogatory use of the carpenter's profession as an epithet was repeated in 1783 France by the professor of hydrography Pierre Lévêque, in 1851 England by the builder John Fincham (Ferreiro, 2007, p.23), and in 1855 France by the French Gothic Revival architect and theorist Eugène Emmanuel Viollet-le-Duc (1814–1879) (Bressani, 2014, p.427). In their opinion, the "mere carpenters" did not base their expertise on objective, exact, and mathematical knowledge; and in consequence were inferior to more scientifically-oriented engineers and designers. Contrary to this opinion, the ship builders were, in fact, highly trained professionals; however they lacked formal education, with skills based on practice and their own experience (Ferreiro, 2007, p.23-24).

Manuel DeLanda cited the 20th century British pioneer of material science, professor James Edward Gordon (1913-1998), saying that the success of steel in the modern world was caused not only by technical reasons, but also due to its ability to facilitate "the dilution of skills". Following Gordon, DeLanda stated that the implicit expertise of craftsmen, regarding complex material behaviour, is a "linguistically unarticulated knowledge" and can only be transmitted through experience. It cannot be codified in a suitable form for industrial mechanised production. Thus, steel was chosen as the default material for industrialisation, as it enabled routinisation of the processes, which then could be "looked up in handbooks" (DeLanda, 2001, p.132-134).

An array of 18th and 19th century material developments (see p. 89) facilitated the abovementioned mechanism, such as industrial production of cast iron (1707), modern plywood (the 1830s), reinforced concrete (the 1840s), cheaply mass-produced steel (the 1850s), aluminium (1886), and glulam timber (the 1860s). A common trait of these developments was the endeavour to achieve homogeneity and uniformity at the cost of material remanufacture, which affected the understanding of material's role in construction and design. Thanks to these scientific and technological leaps, as well as abundant and cheap fossil fuels, this approach was the most cost-effective.

In the 19th century industrial tradition, homogeneous materials achieved a higher status than heterogeneous ones. Marx explained the symbolic value of silver and gold by their uniformity and homogeneity. Marx argued that firstly, materials achieve abstract, idealised qualities by being devoid of irregularities and any signs of human labour, becoming thus capable of representing a monetary value; and secondly, uniform materials are divisible and capable of being reunited at will (Marx, [1867] 1906, p.102). A parallel between this symbolism and the role of material in the Classical tradition's hylomorphic model can be drawn: architects look for neutral materials for representing idealised and immaterial form. While the role of the hylomorphic model in Ancient Greek architecture was already described (see p. 108), the consequences of the industrial tradition on the role of material in design are discussed in a later section of this chapter.

Timber construction and industrialisation – the balloon frame system and manufactured wood products

Industrialisation affected wood construction at the beginning of the 19th century with the invention[56] of the balloon frame construction system (Figure 74). This system is based on a framework of standardised small softwood members which are nailed together. In the first half of the 20th century, Swiss art and architecture historian Sigfried Giedion (1888-1968), presented balloon framing as a technological rather than a "folk" development (Cavanagh, 1997, p.6). According to Giedion, balloon framing was enabled by late the 18th and early 19th century inventions of the steam powered circular saw and rapidly cut nails from sheets of iron[57] (Giedion, [1941] 1967, p.350). The system's novelty and competitive advantage lay in standardisation of timber members' sections to 2 by 4, or 2 by 6 inches, as well as in the avoidance of complicated joinery. The former allowed for fully interchangeable components, while the latter for division of labour and dilution of skills; thus, unskilled workers were able to erect the frames. Effectively, the system became a disruptive technology (compare p.92) in wood construction, changing the way the material has been used ever since. It complies with the earlier outlined definition of disruptive technology, as 'technologically straightforward, consisting of off-the-shelf components put together in a product architecture that was often simpler than prior approaches' (Christensen, 1997, p.28), and enabled by new technological developments, in this case the mechanical circular saw and rapidly cut nails.

In a typical balloon frame, the floor joists are attached to wall studs which run continuously through the full height of the building, from the foundation plate to the roof plate. The walls are built with light studs, rather than heavy posts, which allows them to be constructed on their side and then tilted up. Its main success and persistence have been a result of the considerable improvement in strength-to-weight ratio over log or traditional timber frame construction. Additional advantages would be the ease of transporting members to treeless regions, and the elimination of the need for highly-skilled carpenters to erect the structures.

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[56] The invention of the balloon frame system is much debated; it is frequently assigned to George Washington Snow (1797-1870) and the construction of a church in 1833 (Giedion, [1941] 1967, p.352-354), or a warehouse in 1832 (Sprague, 1981), both located in Chicago. Another line of research suggests an even earlier origin (1804), a more gradual development, and a collective authorship (Cavanagh, 1997).

[57] The mechanic-cut nails were patented by Thomas Clifford in 1790, the mechanic-cut tacks were patented by Jesse Reed in 1807, and the steam powered circular saw appeared in 1840.

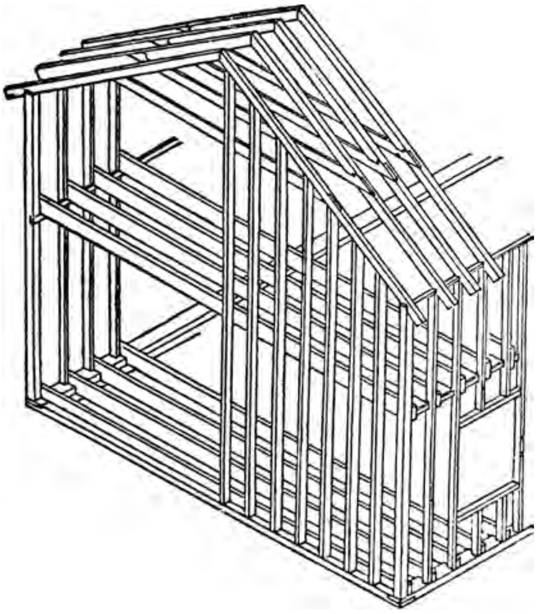

Figure 74
George E. Woodward, 1860, the Balloon Frame, axonometric view.

A simplification of joinery in balloon framing was achieved by replacing diagonal braces between the posts with the outer sheeting in order to make the building rigid. The frame, sheeting, and clapboards are nailed to each other in many places, where all the connections are equally important and equally contribute to the overall strength of the structure. The advantage of this approach lies in increased tolerance to human error or material failure: the connection between members relies on statistical probability of a good connection with sufficient redundancy in the system that allows for an odd weak piece of timber or a poor nailing job, while still maintaining the structure's integrity (Cavanagh, 1997, p.9).

This simplified joinery successfully applied the method of labour division (see p. 119). The new system not only replaced skilled carpenter with unskilled labourer, but demanded fewer people to erect the balloon frame structure. A 19th century American engineer, George E. Woodward (1829-1905), commented that "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 ([1941] 1967, p.349)). Solon Robinson (1803-1880) who claimed that he was using balloon framing as early as 1835 (Giedion, [1941] 1967, p.350), credited it for the quick development of some American cities, such as Chicago or San Francisco, which "have arisen from little villages to great cities in a single year" (Solon Robinson as cited in Giedion ([1941] 1967, p.351)).

The innovation of balloon framing can be considered in relation to the discussed earlier methodological framework of "repositioning" a problem within a larger system (see p. 93). Under this framework, the innovation is not sought by a step-by-step linear model, but rather by placing the design problem in a wider context that 'can generate a new perception of that situation' (Buchanan, 1992, p.13). In the case of balloon framing, the problem of efficiency of wood construction was placed in its wider socio-technological context, that resulted in a new and different method of using the material. This new method was not based on the incrementally built knowledge of joinery or structural systems, but instead on new technological developments and new methods of discovery. It was premised on the reductive and hylomorphic concept of materials in construction, where materials were conceptualised as homogenised, neutral, and passive. The efficiency and success of the balloon frame system relied on standardisation of wood and randomisation of its natural features. Only through these tactics could wood be submitted to industrialised mass-production.

The strategies of wood standardisation not only involved the unification of timber component sections, but also resulted in the development of an array of manufactured wood products since the first half of the 19th century: plywood, glulam, chipboard, MDF, OSB, CLT, etc. (see p. 33). The use of these products in construction is based on the same principles as the balloon frame system: efficient use of uniform and homogenous material, and minimisation of the need for skilled workers. These products enabled and facilitated the construction boom and the democratisation of construction in North America in the second half of the 20th century. One line of research suggests that an average small house built using traditional techniques required between 300 and 600 pieces of timber for sheeting and subflooring; while the same house, when substituting plywood, required only 70 sheets and half the number of nails. As in the case of balloon framing, unskilled workers could apply plywood panelling in a single and relatively easy operation. Consequently, between 1950 and 1992 in the USA, the amount of structural plywood used in an ordinary house increased by a factor of 5.7; and the use of particleboard by a factor of over 300 (Ore, 2011, p.270-272). Particleboard was introduced in the 1950s and started to replace plywood for certain applications.

Similar to the balloon frame system, manufactured wood products rely on randomisation in order to homogenise material behaviour. These products are manufactured from timber split into smaller parts or particles: scantlings, veneers, chips, or fibres, which are bonded together in order to achieve homogenisation of the material. Plywood consists of odd numbers of very thin sheets of wood glued together under pressure so that the grain of each two adjacent sheets is perpendicular. This holds the sheets in tension and prevents the plywood board from warping, twisting, and other movement. Most properties and behaviours of the original material are equalised and are dominated by the greater strength and dimensional stability of wood adhered parallel to the grain. Particleboards are the most extreme example of flaking among these products, where randomly distributed particles give the boards uniformity in all directions. Flat or elongated particles randomly run parallel to the board surface and give it a cross-ply effect with mutual stabilisation. Consequently, particleboards have uniformly reduced dimensional instability across the panel faces (Hoadley, 2000, p.229, 235-236).

However beneficial for the construction industry and for enabling cheap provision of housing and furniture, these products are based on energy intensive processes and use chemicals that are harmful to people and to the environment. Formaldehyde water-resistant resin glue has been used since the 1930s in plywood and since the 1950s in particleboard. Since the 1960s, various studies in the USA and northern Europe associated formaldehyde off-gassing from manufactured wood products with potential health risks. By the 1980s, the studies ultimately demonstrated that these materials emitted toxins harmful to humans. In 1987, formaldehyde was announced as a probable carcinogen to humans; and in 2005 the WHO International Agency for Research on Cancer confirmed that it causes nasopharyngeal cancer (Ore, 2011, p.277-282). More recently, legislation in the EU and North America limited the maximum allowed concentration of formaldehyde in finished products, and required warnings on the products. Even so, today some manufacturers use phenol-formaldehyde and melamine-formaldehyde adhesives (in which formaldehyde is still present but forms highly stable bonds during pressing and does not off-gas after curing). Also in use are formaldehyde-free resins in products such as polyurethane, polymeric methylene diphenyl diisocyanate, and polyvinyl acetate. It is recommended that appropriate air exchange rates are maintained in order to avoid VOC's concentration (Dangel, 2017, p.147-148).

The degree of processing in construction materials is a measure of energy expenditure in the manufacture of the materials, and the degree of its transformation and denaturation. Materials that are used in their natural state have a low degree of processing and transformed materials have high degree of processing. It is widely known that materials with a higher degree of processing, such as manufactured wood products, are harmful to human health. They also have a negative impact on the environment, both by the amount of energy expended in the manufacturing phase, and by the amount of pollution expended during their decomposition. Toxic substances used as preservatives, plasticisers, stabilisers, etc. are eventually being released into the ecosystem. A rule can be formulated that '[t]he higher the degree of processing, the lower the potential for quick and unproblematic decomposition' (König, 2011, p.19).

The history of wood industrialisation in construction, was initiated with the invention of the balloon framing system, and culminated with the development of manufactured wood products. This history is one of pursuing a uniform, neutral, and passive building material, which would submit to the hylomorphic model of imposing a form onto the matter. The model, when applied to wood design and construction, means that the tree shape no longer limits the shape of a building component; and that the material's structural inconsistency or dimensional instability no longer has to be accounted for during the design. This model gained momentum when it overlapped with the method of industrialised mass-production. Both the prevailing approach to design and the logic of industrial mass-production required uniform, neutral, and passive materials in the construction or manufacturing processes. The history demonstrates that following the hylomorphic concept of building materials and the logic of industrial mass-production can lead to environmental degradation and pose risk to human wellbeing.

Effects of hylomorphism on Modernist architecture

The Modernist architects and theorists of the late 19th and 20th centuries further compounded the form-matter relationship in regarding design and construction. In addition to various conceptualisations of matter that had driven a number of paradigm shifts in the history of Western architecture, as discussed earlier; the Modernist discourse made form problematic. Up until the end of the 19th century, form simply meant shape or mass; but since then it became entangled with a variety of often contradictory concepts vis-à-vis ornament, mass culture, social values, functionalism, meaning, reality, or technical and environmental considerations. The British architectural historian, Adrian Forty (b. 1948) defined form as the most important and the most difficult concept of Modern architecture (Forty, 2000, p.149-172).

The prevalent approach towards materiality in the Modern Movement stemmed from the Classical hylomorphic notion of form as independent of matter. The Finnish architect and theoretician, Juhani Pallasmaa (b. 1936), observed that ‘the main line of Modernist architecture has preferred materials and surfaces that seek the effect of flatness, immaterial abstractness and timelessness’ because ‘[t]he Modernist surface is treated as an abstracted boundary of volume, and has a conceptual rather than a sensory essence‘. For Pallasmaa in the expression of Modern architecture ‘form is vocal, whereas matter remains mute’ (Pallasmaa, 2000, p.79).

Figure 75

Le Corbusier, 1928-1931, Villa Savoye, Poissy. Left: Newly build villa. Right: during the period of decay.

This observation can be illustrated by iconic projects of Modern architecture built in the first half of the 20th century. The pre-1930s work of Swiss-French architect Le Corbusier (1887-1965) can be characterised using Pallasmaa’s words, as having “a conceptual rather than a sensory essence”. This was achieved with substantial effort to conceal the reality of materials and construction techniques. Villa Savoye in Poissy, built between 1928 and 1931, is a case in point. Photographs of the newly built villa and its later decay (Figure 75) reveal that the Platonic forms seemingly made of concrete – a material associated with modernity, purity, and formability – are actually of traditional brick construction, rendered to hide it. Strikingly Villa Savoye is still frequently regarded as an important figure of concrete architecture. For Le Corbusier, architecture was a plastic art; where any tectonic expression was naïve and obtrusive to the unity and consistency of the idea[58]. As a consequence, time and its effects on materiality were ignored. In a similar vein the British architect and author, Richard Weston (b. 1953), critiqued another icon of Modernist architecture. The 1924 Schröder House (Figure 76) designed by Dutch architect Gerrit Thomas Rietveld (1888-1964), was characterised as ‘a messy hybrid of timber, steel, masonry and reinforced concrete, but visually it appears to be composed entirely of coloured planes’ (Weston, 2003, p.53).

Figure 76

Gerrit Rietveld, 1924, Schröder House, Utrecht. Left: in the 2010s. Right: during restoration in 1979.

As Forty evoked, by the 1950s concrete became a neutral material for architects, devoid of materiality. For the Italian architect Giò Ponti (1891–1979), architecture should be judged for its “architectural essence”, and thus must be considered colourless and divorced from any material. Directly echoing Alberti (see p. 112) and Palladio (see p. 113), in 1957 Ponti wrote: “[a]rchitecture, after all, exists entirely in the design or in the model, being resolved before it is trans positioned to this or that material”. Ponti used concrete in order to make the buildings appear immaterial, as concrete, in his own words “had become normalised as a medium of modernity”. Forty makes a parallel to these approaches with the 1953 suggestion of French critic and philosopher Roland Barthes (1915-1980) that truly modern writing is without style (Forty, 2012, p.283-286). The swansong of Modernism, Peter Eisenman′s (b. 1932) notion of “cardboard architecture” as an “antimaterial statement” epitomises the negation of materiality by the late Modernist architects in the 1970s.

However, Modernist architecture also involved approaches focused on representational, symbolic, and sensual qualities of materials, which will be outlined in the following section. The mainstream Modernist architects of the “heroic” period sought immaterial abstractness and timelessness as the main quality of their design. The role of materials was either driven back in order to achieve the appearance of immateriality and abstractness, or ideologised in

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[58] Le Corbusier’s work is far from being unequivocal, but it holds true in the context of this chapter. However, in later work he was more interested in poetic and sensual qualities of materials; his perception in this regard could be seen as hylomorphic.

order to embody the spirit of industrialisation and mass production. The former approach is epitomised in the abovementioned iconic buildings of Modernist architecture. The latter is present, for instance, in the preference for tubular steel furniture among the Bauhaus-era designers; who saw design as based on innovations in industrialisation, where new production processes and new materials were used to yield new forms. Examples of tubular steel furniture of this period include the cantilever chair from 1926 by Mart Stam (1899-1986), the Wassily Chair (earlier known as B3) from 1926 and the Cesca Chair from 1928 by Marcel Breuer (1902-1981), the MR10 chair from 1927 by Ludwig Mies van der Rohe (1886-1969), the ME1002 work stool from 1930 by Hin Bredendieck (1904-1995) and Hermann Gautel (1905-1945), and the line of furniture numbered from LC1 to LC19 from 1928-1930 by Le Corbusier. Marcel Breuer's biographer, Magdalena Droste (b. 1948), noted that the success of his tubular steel furniture was grounded in 'the symbolic expression which it gave to the spirit of the avant-garde'; and as result, the tubular steel chair 'became the symbol of radical modernity and new living' (Droste, 1992, p.16). This ideological position was rationalised by designers using arguments based on practical grounds and the rationale behind industrialised production. Droste cited Breuer explaining his choice of tubular steel as dictated by its lightness, low cost, easy disassembly, and hygiene (ibid., p.16). Even more directly, in 1923 Le Corbusier called for replacing 'heterogeneous and doubtful [...] natural materials, which are infinitely variable in composition' by 'fixed ones' (Le Corbusier, [1923] 1986, p.232). Le Corbusier evoked the "laws of Economy", where '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' (ibid, [1923] p.232). Le Corbusier maintained an aversion to exposed wood grain and its "artistic veins" for his entire career, as it collided with 'the planar quality of his work' (Samuel, 2007, p.18); he stated in 1931 that "wood, being a traditional material, limited the scope of the designer's initiative" (Le Corbusier as cited in Ngo and Pfeiffer (2003, p.29)). However, it is possible to argue that for Modernist architects of this period, wood was not acceptable on ideological rather than rational grounds. When Le Corbusier or Rietveld used wood or plywood, the material was lacquered in bright colours to give it 'a machine-finished look' (Ngo and Pfeiffer, 2003, p.29). This strongly resembled the methods used in the construction of Villa Savoye or Schröder House; where the "fixed" material, concrete in this case, was emulated by the "traditional and doubtful" material, brick, that was then concealed.

Modernist architects of the "heroic" period in the 1920s can be seen as direct descendants of the over two-millennia old hylomorphic conceptualisation of the form-matter relationship, where matter was passive in the form-giving process. As outlined earlier, this concept permeates the entire history of architectural theory. It gave higher status to formal rather than to material considerations, and it resulted in separation of design and its product, which facilitated the development of the architectural profession and its separation from construction and engineering. Further, the hylomorphic concept was mutually amplified with the developments of division of labour and dilution of skills during the processes of industrialisation. In the 19th century, homogeneous materials, such as steel, achieved higher status than heterogeneous materials, such as wood; this became instrumental for the ideology of Modernism surrounding the use of materials in construction.

Skeuomorphism and ontological vs representational aspects of materials

The phenomenon of form remaining unaffected after changing material is defined in design theory as "skeuomorphism". Skeuomorphism is a concept where 'an object or feature which copies the design of a similar object made from another material but does not usually have the practical purpose that the original does'[59]. The term was coined[60] by British scholar Henry Colley March (c. 1838-1916) in the late 19th century (March, 1889, p.166); but more recently it has been used to denote 'an element of a graphic user interface which mimics a physical object'[61]. March argued that the development of skeuomorphism was rooted in psychology, and resulted in objects that did not have any structural function (ibid., p.166-168); this places it semantically close to the concept of ***representational*** material use, as outlined below.

Expressions of architectural skeuomorphism are frequent, with the most important example being the alleged petrification of wooden construction into the Doric order (Figure 76), dating from Vitruvius' time (see p. 108). The idea of skeuomorphism in architecture can be related to the opposing ***representational*** and ***ontological*** aspects of form, existing in architectural theory since the 15th century[62]. It is based on the distinction between ***representational***, i.e. ornamental, artistic, and symbolic, versus ***ontological***, i.e. structural, constructive, and rational, characteristics of form. Following on the notion of ***representational*** and ***ontological*** aspects of architectural form, it is possible to extend its meaning onto the understanding of the use and role of material in design, and so coin the notions of ***representational*** and ***ontological***

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[59] https://en.oxforddictionaries.com/definition/skeuomorph

[60] March derived the term from Greek *skéuos* meaning *tackle, tools, vessels, equipment, dress* (March, 1889, p.166).

[61] https://en.oxforddictionaries.com/definition/skeuomorph

[62] The Swiss architect and professor at ETH in Zurich Marc Angelil (b. 1954) credits Alberti for first articulating the idea of representational and ontological form, however not using these terms (Angelil, 1987, p.185-194). The idea was circulating between architectural historians in the late 1980s - early 1990s, e.g. the British architect and historian Kenneth Frampton (b. 1930) made it pivotal in his seminal *Studies in Tectonic Culture* (Frampton, 1995); it was also discussed by the American historian Mitchell Schwarzer (b. 1959). Frampton partly attributed this idea to Semper, however there are also some clear earlier analogies in Bötticher (Frampton, 1995, p.16, 71, 82). Also Schwarzer attributed the introduction of this concept in architectural thinking to Bötticher (Schwarzer, 1993, p.273).

use of material[63]. At its most basic, ***representational*** use of material in architecture relates to ornamental, visual applications; where the symbolic meaning and aesthetic characteristics of material come to the fore. Material properties, behaviour, and performance do not play a key role. The form is divorced from the material; it can be substituted by another material with the same appearance but different properties, behaviour, and performance without affecting the form. One such example is the Renaissance practice of applying stucco to imitate stone, or more recently, wood grain PVC or fibre cement panels (Figure 78). On the other hand, the ***ontological*** use of material is based on behaviour and performance characteristics of material, which play a key role in the form-giving process. Skeuomorphism, then, does not recognise the ***ontological*** essence of the material used, and is focused on its ***representational*** meaning.

Figure 77

Skeuomorphism: timbering is reproduced in stone in the ancient Greek rock tomb in Antiphellus.

Figure 78

Skeuomorphism: fibre-cement panel imitating wood grain.

In the context of material innovation and the ***representational*** and ***ontological*** use of material, skeuomorphism is an important case. It illustrates a working hypothesis that new materials do not contribute to innovation as long the new material is considered only in ***representational*** terms. This hypothesis can be extended into a further statement that the ***ontological*** use of material contributes not only to material innovation, but also to acquiring a new ***representational*** meaning for the material.

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[63] In today's parlance the term materiality usually refers to the former, while material logic to the latter, corresponding respectively to the soft and hard narratives of the use of material in construction.

Figure 79
Wooden origin of the Doric order, drawing from 1758 edition of *Ten Books on Architecture*.

Figure 80
Apple formats. Left: *Newstand* application for iOS5 (2011). Right: *News* application for iOS9 (2015).

Skeuomorphism is a design strategy that plays on the users' nostalgia and attachment to already known forms. One such recent example, from outside the realm of architecture, was the design for the applications on Apple devices (Figure 80). This design strategy had proved to be insufficient as a metaphor and was consequently forsaken by the company with iOS7 in 2013[64]. Contemporary Apple applications no longer use ***representational*** skeuomorphism, but adhere to the ***ontological*** determinants as being better related to their functionality. Looking closer into the realm of computer software, one can also observe an unconscious skeuomorphism. Such is the case of the presentation program PowerPoint. PowerPoint is a transposition of acetate overhead slides onto a new medium without consideration of the new medium's potentialities. While it is possible today to incorporate sound and animation in a PowerPoint presentation it is not possible to incorporate any meaningful interaction with the computer. It can be argued that the new medium did not synthesise its ***representational*** and ***ontological*** aspects.

A direct analogy can be drawn between the case of this graphic user interface and the use of materials in design. Skeuomorphism can be defined as the preservation of the ***representational*** features of a design conceived in one material and employed in a different material disregarding the new materials' ***ontology***: the material characteristics related to its behaviour and performance. Translation from one material to another while preserving the form intact is inherently ***representational***. Translation in this case is synonymous with representation rather than with innovation. The next section outlines how innovation can result from the synthesis of ***representational*** and ***ontological*** aspects of material in construction.

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[64] Interestingly, skeuomorphism came back with the advent of the Apple Watch in 2014. The watch had a clock-like interface. Yet again, the skeuomorphic metaphor proved to be the most appropriate to introduce a new product and its functionality in the most self-explanatory way possible.

Synthesis of the representational and ontological aspects of architectural form for material innovation

As it was observed by the French architect, theorist, and digital pioneer Bernard Cache (b. 1959): ‘architecture emerges in the move from one technology to another’ (Cache, [2000] 2007, p.387). This dictum can be paraphrased into a hypothesis that ***architectural innovation emerges in the move from one material to another***. If this is to hold true, the move should also synthesise the ***representational*** and ***ontological*** aspects of the new material. Therefore, a hypothesis is proposed that ***material innovation emerges in the synthesis of the representational and ontological aspects of the material***.

The English architectural critic and writer, Reyner Banham (1922-1988), argued that the idea of petrification of timber construction may be considered as a vehicle for innovation. In his opinion ‘[the] act of transposition served an important purpose in bringing a new material within the accepted body of formal procedures in building design [...] and in a very real sense, determined the appearance of the new architecture’ (Banham, 1960, p.30) For Banham, transposition of wood-framing techniques onto reinforced concrete construction (also see p. 151) resulted in integration of ‘a rectangular aesthetic of posts and lintels with the rectangular aesthetics of Abstract art that appeared after 1918’ with a profound effect on Modern-Movement’ (ibid, p.30). In Banham’s view, the inherent material properties of wood, i.e. its length and slenderness, affected the built form constructed in concrete, thus ‘determined the appearance of the new architecture’ in the 20th century. Yet again, inherent material properties had the capacity to determine the built form, in this case moved from one material to another.

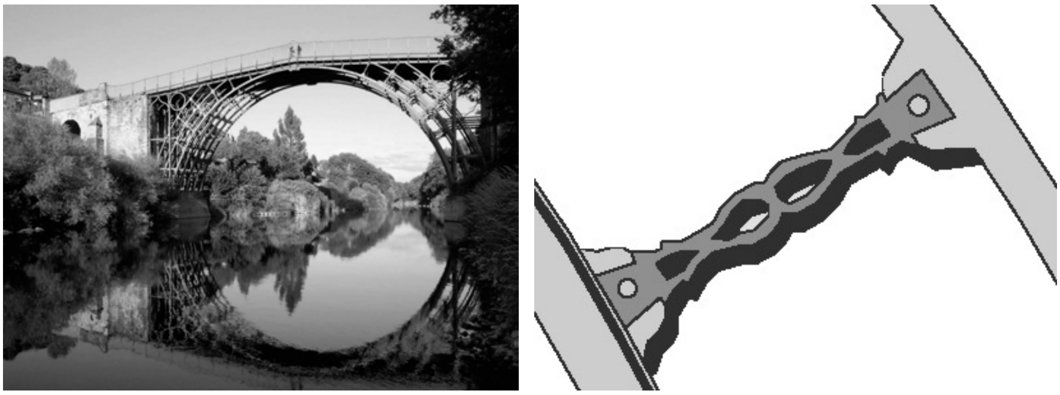

Figure 81

Abraham Darby III and Thomas Farnolls Pritchard, Cast Iron Bridge, 1778-1781, Shropshire. Left: View from River Severn. Right: Detailing of the bridge borrows blind dovetail and mortise joints from traditional timber construction techniques.

The introduction of a new material in construction usually begins with a skeuomorphic phase, after which a truly innovative phase begins, resulting in synthesis of the ***representational*** and ***ontological*** aspects of material in construction. One example of this process is demonstrated by structural cast iron in the late 18th century. The first engineering structure in the West[65] made from this material was the Ironbridge at Coalbrookdale in Shropshire, England, designed by Abraham Darby III (1750–1789) and Thomas Farnolls Pritchard (c. 1723-1777), and built between 1778 and 1781 (Figure 81). Detailing of the bridge borrows from traditional timber construction techniques: blind dovetail and mortise joints had been familiar to the workers (Silver and McLean, 2013, p.144). However, the true material innovation came when the forms of iron elements, components, and connections between them, were no longer a mere translation, or representation, of wooden forms, but corresponded to the ***ontological*** use of iron. This stage, apart from technological and economic problems, also brings a collision with commonplace structural intuition and aesthetics. New materials enable technical solutions that are not based on former solutions, and in many cases appear counterintuitive. Antoine Picon observed that 'the use of iron [...] leads to a disassociation of the architectural form from the techniques that enable its construction'. Picon illustrates his point with the Louvre's Colonnade built in 1667-1668, and designed by Claude Perrault (1613-1688), Louis Le Vau (1612–1670), and Charles Le Brun (1619–1690). In the Colonnade, iron reinforcements allow for replacing flat monolithic lintels, which would be typical for Greek or Roman colonnades, with flat arch stones reinforced with metal bars (Picon, 2010b, p.51). In other cases, such as the *Sainte-Geneviève* library in Paris from 1850 (Figure 82) designed by Henri Labrouste (1801-1875), or the Crystal Palace in London (Figure 83) from 1851 designed by Joseph Paxton (1803-1865,), the ***ontological*** use of iron demanded a slenderness that could not be assimilated into a classical system of form and proportion based on a solid body of stone, thus distancing architecture from the Vitruvian notion. A 19th century German theorist and architect, Adolf Göller, compared iron structure to stork's legs, which we perceive to be too thin because 'we imagine ourselves standing on such legs and feel ourselves in a very precarious equilibrium', and likewise we perceive iron columns to be flimsy (Weston, 2003, p.76). Reservation towards new materials were not only expressed by laymen. Director of the *École des Ponts et Chaussées*, French Enlightenment architect and engineer, Jean-Rodolphe Perronet (1708–1794), in his reports form 1779 and 1783, warned against iron as a bridge material, basing his arguments on its high cost and lack of competitiveness with masonry. Perronet stated that "one should not construct excessively large arches in iron because they could cost nearly as much as those built of hard stone and they would not be as solid" (Perronet as quoted in Picon (2010b, p.52)).

The subsequent development of iron construction has effaced that wariness. In 1827, the engineer Claude-Louis Navier wrote in defence of his failed

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[65] Chinese builders were constructing cast iron suspension bridges since the 6th century, already 1200 years earlier. The oldest extant example of an iron multi-storey structure is the 13-storey Yü Chhüan Ssu temple built in 1061 at Tang-yang in Hopei, China. The first iron-framed multi-storey building in the West was built in 1792-1793 at Shrewsbury Mill in England, more than 700 years later (Fry and Willis, 2015, p.151, Cowen, 1999).

suspension bridge project that “an iron built structure, just like a stone structure, may deserve to be called a monument, if grandeur and simplicity of form are to be found in it” (Navier as quoted in Picon (2010b, p.58)). In the 1830s the Saint Simonians, a French social and political movement focused on the effects of industrialisation on society, saw iron as the architectural material with a capacity to symbolise the new era of progress. These ideas were theoretically and architecturally developed into “structural rationalism” by Léonce Reynaud (1803-1880) and Eugène Emmanuel Viollet-le-Duc (1814–1879) in the second half of the 19th century. In opposition to Vitruvian doctrine, structural rationalism coupled structure and material, and linked these with moral values such as “honesty” or “truth” (Picon, 2010b, p.62-63)[66]. Iron acquired a symbolic value, synonymous with progress, that was paralleled and reinforced by developments in this material’s applications. The ***representational*** and ***ontological*** aspects of the material were synthesised.

Figure 82

Henri Labrouste, 1850, *Sainte-Geneviève* Library, Paris.

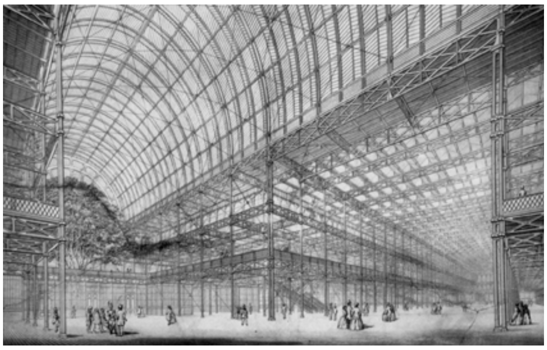

Figure 83

Joseph Paxton, 1851, Crystal Palace, London.

The process of turning iron into a widely accepted material was mirrored during the introduction of reinforced concrete. In Switzerland the material was introduced by the French foreman François Honnebique (1842-1921) in the 1890s. The Swiss historian, Hans-Ulrich Jost (b. 1940), outlined how initially its proponents were in minority; and the critique was based on aesthetic grounds (Jost, 2006, p.1743) ‘as an element of ugliness corrupting the “authenticity” of the landscape’ (ibid., p.1741). Reluctance towards this material was still present in 1921. In the words of the Swiss federal laboratory director of material tests, professor Mirko Roš (1879–1962): “[r]einforced concrete is an unfortunate misalliance: concrete breaks, iron rusts and theory

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[66] The case of Gothic style perception is another very similar example. In the Renaissance ‘the architects and theoreticians (...) hated the pointed arch, claiming that it was capable of carrying less weight than the round arch, and that it was ugly’ (Frankl, 1962, p.20). It is interesting to note that in support of the aesthetic and philosophical values, seemingly objective but false scientific arguments were used. As we know today, pointed arches, compared to Roman and Romanesque semi-circular arches, exert a lower outward thrust often forming quadripartite – intersecting pointed vaults. This enabled the old materials: stone and bricks, to be used with more flexibility (Addis, 2007, p.95).

is on strike" (Roš as quoted in Jost (2006, p.1742)). In winning acclaim for concrete, important roles were played by pioneering architect-engineers such as Robert Maillart (see p. 158). Also important was the expansion of technical knowledge at the Swiss Federal Institute of Technology (ETH) in Zurich; as a direct result of these technological advancements, the aesthetic quality of the material was also acknowledged. Reinforced concrete took the place of honour during the National Exhibition in 1939 (ibid., p.1748-1749). Hans-Ulrich Jost explains the success of the new material not only by its technical qualities, but also by its public recognition established through linking the new technology with cultural and political values. In Switzerland, reinforced concrete became associated with granite, and also during the Second World War it became a mythologised component of national defence.

Figure 84
Hugh Strange, 2014, Architecture Archive, Somerset, installation of exterior CLT walls.

Figure 85
Hugh Strange, 2014, Architecture Archive, Somerset, interior view.

These examples demonstrate how the introduction of a new material in construction follows a process of initial skeuomorphism, and later technological development resulting in synthesis of ***representational*** and ***ontological*** aspects of this material, which leads to its new ***representational*** meaning and full acceptance. Picon noted that 'in the case of architecture and construction, as in many other areas of material culture, innovation comes about at the intersection of technical and social issues' (Picon, 2010b, p.51). This observation is close to the notion of the so-called "social constructivists", or theorists who advocate for social construction of technology (SCOT), where human agency shapes technology, rather than technology determines human action. For an innovation to spread in a society, it is necessary to win acclaim for it in this society; and this is not possible without producing a meaning for this innovation that exceeds merely technological or economic considerations. As typically a newly developed or newly introduced material is devoid of meaning, any meaning is produced in the process of synthesising the ***representational*** and ***ontological*** aspects of this material.

In relation to the proposed ***reframing*** of wood construction, the above observation can be applied to the relatively recent introduction of cross-laminated timber (CLT). After its introduction in the 1990s (see p. 43), aesthetic reference was found in both precast and in-situ concrete. For instance, the contemporary British architect Hugh Strange, whose office used CLT in their projects (Figure 84 and Figure 85), reflected that '[i]ts material attributes are perhaps closest to those of precast concrete, being a panelised material that is produced off-site to high tolerances, yet at times its appearance can resemble in-situ cast concrete' (Strange, 2013, p.69). This reflection, which can be seen as an inverse of the petrification of wood, or a "lignification of concrete", demonstrates how the modern-day conceptualisation of wood as a building material is at the hylomorphic phase. This skeuomorphism acts as a catalyst for innovation in the same sense as proposed above by Banham. Banham saw the important role of such ***representational*** transpositions 'in bringing a new material within the accepted body of formal procedures in building design' (Banham, 1960, p.30). The acceptance of CLT among architects, builders, and clients may indeed be related to its resemblance to concrete. However, it does not produce a new meaning for the material, thus pushing wood into a very uncomfortable territory of competition: the economic, longevity, or fire-safety attributes of concrete can be hard to beat. This is not to say that wood, when certain measures are taken, can be cheaper, last longer, or withstand fire better than concrete. The proposed ***reframing*** of wood construction should be based on the synthesis of ***representational*** and ***ontological*** aspects of this material. It points towards a new meaning for wood as a building material; reconceptualised as an intelligent, eco-friendly, renewable, and health-beneficial material, which opens a range of new opportunities for designers, and may help to reform architecture.

MATERIAL-CENTRED CONCEPTS OF ARCHITECTURE AND CONSTRUCTION

Based on analysis of the Classical framework for the form-matter relationship in architecture, defined as hylomorphism in the previous section, it is possible to formulate the opposite framework that can be characterised as a non-hylomorphic concept of architecture and construction, and which can be called a ***material-centred*** concept of architecture and construction. ***Material-centred*** architecture can be defined as construction in which meaningful features do not adhere to the model in which forms are imposed onto the material, but which acknowledge material agency and the capacity of the material to take part in the form-giving process. It is a ***material-centred*** design method. It is intrinsically linked to particular material properties, traits, and behaviours. Its key characteristics are the material's performance, where the material used cannot be replaced by any other material, as only this material can achieve a particular thing. This process results in synthesis of ***representational*** and ***ontological*** aspects of the material. In the case of ***material-centred*** architecture the binary opposition of ***representational*** and ***ontological*** aspects of material, and of form, is irrelevant.

The experiments presented in Part I suggest that a possibility of ***material-centred*** wood architecture exists, where material agency becomes a valid and guiding design factor. The following section outlines forerunners of similar approaches in the history of theory in architecture, and formulates a basis for the case of ***material-centred*** wood architecture.

It is important to emphasise that these approaches were rare in the history of Western architecture, and that ***material-centred*** characteristics are graduated, i.e. there exist various degrees to which architecture can be characterised as ***material-centred***. Nevertheless, singling out the forerunners for the ***material-centred*** concept of architecture is the method through which the features and characteristics of the concept are determined.

Material agency

The abovementioned concept of material agency requires elaboration. In sociology the concept of agency is often paired with, and opposed to the concept of structure. In this opposition, either the actions of individuals are the prime movers with the capacity to structure societies, or the social structures supress individual freedom, actions, and their effects. While this concept of agency, understood as 'action or intervention producing a particular effect'[67] is, in general, not controversial; the idea of material, or nonhuman, agency often remains contested.

The concept of nonhuman agency is central to the actor-network theory (ANT) in sociology and science studies. ANT was developed in France in the 1980s by a group of scholars including Bruno Latour (b. 1947), Michael Callon (b. 1945), John Law (b. 1946) et al. ANT established science, technology, and society as a field of human and nonhuman agency in a symmetrical rather than hierarchical fashion. ANT is not anthropocentric, and it is based on a web of relations both material – between things, and immaterial – between concepts. In ANT these things and concepts are called "actants", which are defined as both human and nonhuman actors with equal ability to act. The notion of nonhuman agency is often contested because it assigns intentionality to inanimate objects. In relation to ANT's "actants", the concepts of agency and intentionality do not have to be coupled. The philosopher and sociologist Bruno Latour, one of the primary developers of ANT, characterised the quality of intentionality as being gradual: 'there might exist many metaphysical shades between full causality and sheer inexistence. ANT does not claim that objects do things 'instead' of human actors [...] [t]he project of ANT is simply to extend the list and modify the shapes and figures of those assembled as participants and to design a way to make them act as a durable whole' (Latour, 2005, p.72).

A similar approach to nonhuman agency, which is decoupled from the notions of intentionality or volition, can be found in the work of British philosopher and sociologist Andrew Pickering (b. 1948). For Pickering, 'the world is filled not, in the first instance, with facts and observations, but with *agency*'. He formulates a shift in science studies from epistemology to ontology, or more precisely from ***representational*** understanding based on accumulation of data and knowledge, towards performative condition characterised by "dance of agency", human and nonhuman (Pickering, 1995, p.5-20). Pickering draws upon a long tradition of using the concept of material agency without imputing intentionality. He quotes, for instance, the English polymath William Whewell (1794-1866), who wrote in 1841 that "in many cases the work to be done may be performed by various agencies; by men, by horses, by water, by wind, by steam" (Whewell as quoted in Pickering (1995, p.6)).

The concept that allows seeing both human and nonhuman actors in a symmetrical, rather than hierarchical, fashion bears a lot of potential for the concept of ***material-centred*** architecture. As elaborated in previous sections, matter is traditionally assigned a subordinate role in design. This positioning supports existing power relations, and limits the potential for innovation in

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[67] https://en.oxforddictionaries.com/definition/agency

architecture and design. In consonance with Latour, it is possible to acknowledge material agency without assigning intentionality and vitality to the nonhuman; to extend the list of participants of the process; and to access new effects, affects, and efficiencies. The approach that acknowledges material agency has the capacity to embrace unexpected outcomes or effects arising from the material side by the process of cooperation. Pickering says that 'disciplined human agency and captured material agency are [...] constitutively intertwined; they are interactively stabilized'. He credits this observation to Engels' coproduction, later recalled by Callon and Latour, and dubbed by Law "heterogeneous engineering" (Pickering, 1995, p.17). The following sections outline forerunners and examples of this process in architecture and its theory.

The presented examples of ***material-centred*** architecture do not seek to support a position where matter would intentionally produce forms. Instead, the examples depict a certain productive state of entanglement of human and nonhuman agents, where this dualism is blurred. As human and nonhuman actions are entangled, so are human intentionality and volition. Thus, the human subject is not central, as was the case in Classical and Modernist models; and as a result, the stance can be called post-human.

Material-centred concepts in vernacular and non-Western construction

It is possible to point to numerous examples of ***material-centred*** approaches in the history of Gothic, vernacular, and non-Western architecture; or beyond the field of architecture, for instance in shipbuilding. These examples are skimmed through in this argument, as this chapter's "mine" (see p. 21) is the development of design theory surrounding the relationship of form and matter in the history of architecture, and the small amount of primary theory developed around these areas of construction.

The Vikings' shipbuilding technique (c. 850-1050) was a vernacular construction method that did not rely on designing a form for which materials would have to be subservient. While it is not an architectural example, it is relevant in the context of this argument since it is centred around using wood features and properties as a guiding design principle. The design of a Viking ship was never drawn on paper, it existed solely in the builders' imagination. One of the most important skills of Viking builders was the ability to identify appropriate trees in the forest that would lend themselves to shaping various parts of the ship's structure; and, where possible, take advantage of a natural joint where a branch grew out of a trunk (see p. 140). Then, by riving the logs radially along the wood grain (an equivalent to the quarter sawn conversion), the wood grain and strength of the planks were not compromised, allowing for very thin shipboards – only about 2.6 cm (Durham and Noon, 2002, p.11-12). This thinness, combined with the clinker-building construction technique, resulted in the overall structure being flexible. One contemporary experiment indicated that the gunwale of a Viking ship replica in the sea was able to give and twist as much as 15 cm out of line while remaining watertight

(Wooding, 1998). This flexibility allowed the ship to withstand strong forces that push the hull and the sail in opposite directions while sailing the seas, despite using only light materials and keeping the overall ship weight low. Additionally, the ship's proportion of length to breadth of about 7:1 reduced the drag on it. The shape of the ship hull allowed for only about 0.5 m water depth when fully loaded, thus enabling close approach to the shores and entering into shallow rivers. Further, this shallow draft, together with curved stem and stern posts, aided the overall manoeuvrability. The Viking shipbuilders' approach managed to synthesise the material features of wood (i.e. naturally grown shapes), its properties (i.e. flexibility), and the design needs (i.e. seaworthiness and low draft); hence, it produced an ingenious wonder of the sailing world, a cultural icon, and an enabler for the entire Viking world. This was made possible thanks to the working method where design was not separable from construction; where material agency, manifested by its features, properties, and available tools and techniques, guided the decisions in a ***material-centred*** manner.

The scarcity of architectural theory surrounding these approaches is partly caused by the fact that various "earthly accounts" that affected the development of construction techniques are often not accounted for in architectural history. Architectural historians frequently fail to notice many important factors contributing to development of architectural form. For instance, the development of European roof structures can be rendered as being resultant from cultural and environmental factors, such as the growth of structural understanding, craft practices, social conditions, contact with other building cultures, the need for larger spans, climatic conditions, and available construction or covering materials (Yeomans, 1992). All of these factors affected the shape of roof structures, and contributed significantly to architecture in any given period, while architectural theory mostly problematized stylistic considerations. In some cases, the entire line of particular construction developments remains unrecognised. Such is the case of history and theory overlooking the entire progress of the trussed timber roof between the 17th and 19th centuries. This was caused by the fact that 'changes took place during a time when roof structures were no longer visible and so did not contribute to the interior architecture' (ibid., p.2).

However rarely acknowledged, tools, techniques, and technologies; combined with the available materials; play the key role in development of built form. For instance, the introduction of the old Germanic tool *Klingeisen* – a curved drawknife, known as *medrag* in Norway – had an influence on the appearance of log buildings in Scandinavia (Zwerger, 2012, p.129-130, Holan, 1990, p.147).

In the Japanese tradition, carpenters' tools are central to the ethos of the profession and also determine the shape of the built form. As noticed by the author's writing on the history of Japanese carpentry, we can not only 'follow the evolution of wood joints through the history of tools' (Graubner, 1992, p.1), but also'[t]he tools – the dōgu – link the men, the materials and the methods in building practice to create the structures and timber detailing of Japanese architecture' (Coaldrake, 1990, p.29).

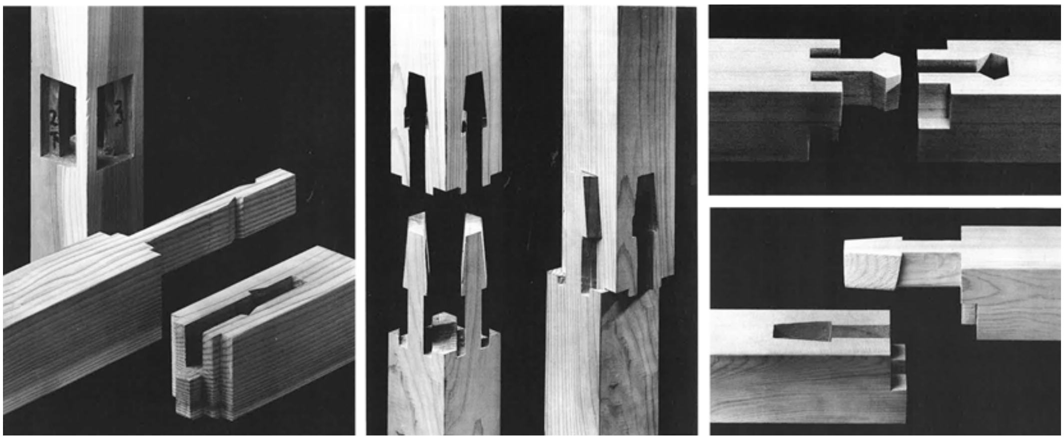

Figure 86
Tsugite – Japanese splicing joints.

The development of *tsugite,* splicing joints, in Japanese carpentry is a case in point how various material and unnoticed factors are at play during the development of construction. In the seismic condition of Japan, long timbers must be used for the necessary building rigidity, a fact that caused the depletion of tall trees as early as in the 11th-12th centuries. The richness and sophistication of the *tsugite* joinery technique (Figure 86) resulted from a combination of environmental factors[68], traditional building forms, aesthetic canons[69], and the resistant yet easy to work with *hinoki* wood (Japanese cypress). At its peak, Japanese joinery-carpentry distinguished 200 different wood joints, both *tsugite* (splicing) and *shiguchi* (perpendicular), with more than 100 joints needed for construction of a single shrine or temple in the 17th-19th centuries (Graubner, 1992, p.1, 20-23).

The development of Japanese joinery exemplifies how the ***material-centred*** concept leads to a synthesis of ***representational*** and ***ontological*** aspects of the material. Japanese joinery synthesised ***representational*** aspects (building traditions and aesthetic taste, such as the dislike for *koguchi*) with ***ontological*** aspects (properties of *hinoki* wood, and the lack of and the necessity of using long timbers). This synthesis resulted in unprecedented richness and cultural performance of Japanese carpentry-joinery, but little architectural theory was proposed around this kind of process.

Philibert de l'Orme and material innovation in 16th century France

The earliest trace of the ***material-centred*** concept in Western architectural theory can be found in the work of Philibert de l'Orme (1510 or 1514-1577), the French Renaissance architect, scholar, and writer. De l'Orme was one of the first French architects to catch up with the masters of the Italian Renaissance,

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[68] That is the depletion of tall trees in the 11th-12th centuries.

[69] For instance: dislike for exposed end-grain (*koguchi*).

and he also became the first French author to propose a complete architectural theory. Mindful that Italian realities differ from French, he contributed several inventions to architecture based on his interest in technology, engineering, and materials, rather than on imitation of Italian developments[70].

Figure 87

Philibert de l'Orme, 1567, *Colomne Françoise.*

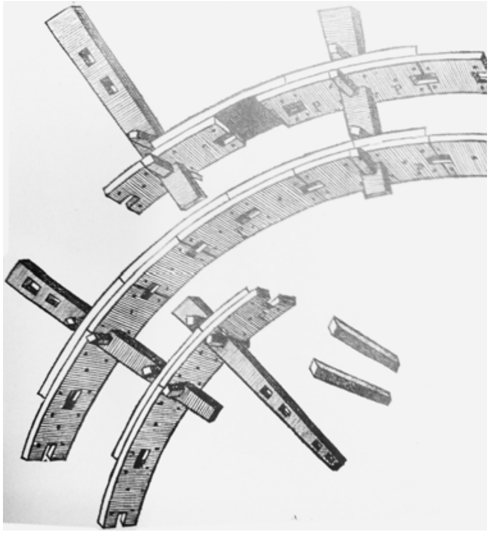

Figure 88

Philibert de l'Orme, 1561, a method for constructing roofs, vaults and floors out of small pieces of wood.

Figure 89

A primitive hut, drawing from 1775 edition of *An Essay on Architecture.*

In 1567 de l'Orme published his main theoretical work *Premier Tome de l'Architecture*. In it he invoked the idea of petrification of timber construction proposing a column for a French order – *Colomne Françoise* (Figure 87). De l'Orme used an analogy of how, in his opinion, the ancient architects wrapped metal bands around timber columns to prevent them from cracking. He believed that after the forms of the timber columns were allegedly petrified, the plants that had grown between the bands and the timber columns became inspiration for the ornamentation of stone columns. De l'Orme used this analogy in his own proposal for *Colomne Françoise* in order to overcome the size limitations of French stone: as this stone could only be used in drum form, the column had to be made from four or five stacked stone pieces with ornaments hiding the joints. In other words, the solution was found in responding with a material transposition of the nature of wood – bands preventing cracking – to French stone and its size limitations. The Canadian architect and researcher Myriam Blais observed that 'his stone columns are true to wood while they celebrate stone' (Blais, 1994, p.17-19). De l'Orme managed to synthesise the ***ontological*** aspect of material agency – the small French stones – with the ***representational*** concept of wooden architecture petrification from the ancient Classic legacy. An earlier de l'Orme invention, published in 1561, is also based on a transposition between materials. In this

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[70] https://www.britannica.com/biography/Philibert-Delorme#ref175887.

invention – a method for constructing roofs, vaults, and floors out small pieces of wood (Figure 88) – the transfer of manner goes from stone to wood, by application of the method of stereotomy to timber construction. De l'Orme managed to transcend the merely skeuomorphic approach by stressing the ***ontological*** aspect of his proposal: "one can use this invention as one does with stonework. There is no work or figure that this invention cannot do as long as one understands the traits. Because wood, according to its nature, has to behave in a different manner than stone" (De l'Orme as quoted in Blais (1994, p.16)).

In the context of this thesis, especially interesting are de l'Orme's motivations in relation to his new method of wood construction. He claimed that the method not only allowed materials of lower value to be used, i.e. shorter pieces of timber; but also reduced the use of raw materials, waste, wall thicknesses and reinforcements. He declared that the cost and time of construction was also reduced by eliminating the need for big lifting equipment. He claimed that the invention 'can be of great advantage structurally, financially and aesthetically' (Campa, 2006, p.530). This suggests that there can be real benefits when the predominant concept of imposing forms onto matter is forsaken.

Philibert de l'Orme can be seen as the first architectural theorist to move beyond the hylomorphic concept, and towards the acknowledgement of material agency, with a view to find noticeable and real advantages. He built upon the century's old idea of skeuomorphism, but managed to synthesise ***representational*** and ***ontological*** aspects of material use. In his *Colomne Françoise* he managed to synthesise the ancient architectural concept of petrification of timber construction with necessity of using a particular material. In his method for wooden structure to span more than the length of the material, he synthesised the method of constructing in stone with the traits of wood. Moreover, de l'Orme managed to embody this synthesis in architectural theory. His legacy and the continuators of his timber construction ideas are discussed later in this chapter (see p. 171).

Marc-Antoine Laugier and Carlo Lodoli – conceptualisations of material agency in architectural theory of 18th century Italy and France

The 17th and 18th centuries in continental Europe were dominated by Baroque architecture. In the mid-18th century, as a reaction to this style, two architectural theorists formulated independent stances based on their particular viewpoints on the form-material relationship in architecture. The theorists were the French Jesuit priest Marc-Antoine Laugier (1713–1769) and the Venetian Franciscan friar Carlo Lodoli (1690-1761).

The idea of the Doric order as a petrified timber construction derived from a primitive hut was adopted and popularised by Marc-Antoine Laugier in his influential book *Essai sur l'Architecture (An Essay on Architecture)* in 1753. Laugier's argument reacted against the Baroque and Rococo ornamentation of his day and more generally against 'Gothic, Arabesque and Moorish Orders, showing little inventiveness, taste and accuracy' (Laugier, [1753] 1977, p.40) which he saw as barbaric and not related to the Classical model of architecture.

Laugier echoed Renaissance authors such as Alberti or Palladio in saying that the quality of architecture lies in its proportioning systems rather than in the richness of its materials or ornaments. In order to support his argument, and to elevate the main elements of the Classical orders, Laugier stated that the columns and the pediment are inherited from the primitive hut of a savage, constructed from timbers and branches (Figure 89):

> [The savage] chooses four of the strongest [branches], raises them upright and arranges them in a square; across their top he lays four other branches; on these he hoists from two sides yet another row of branches which, inclining towards each other, meet at their highest point. [...]. All the splendors of architecture ever conceived have been modelled on the little rustic hut [...]. The pieces of wood set upright have given us the idea of the column, the pieces placed horizontally on top of them the idea of the entablature, the inclining pieces forming the roof the idea of the pediment (Laugier, [1753] 1977, p.11-12).

Laugier tried to establish the indisputable source of architectural form, by recourse to rationality and quasi-scientific enquiry, in order to provide designers with "fixed" and "evident" principles to base and justify decisions (Pérez-Gómez, 1983, p.61-62, Gelernter, 1995, p.173-174). Yet when examined through the lens of the discussion surrounding skeuomorphism (see p. 130), Laugier failed to contribute to material innovation by providing argumentation based on solely ***representational*** grounds. Laugier's theory did not lead to innovative use of materials, but instead reverted to the long existing concepts of Classical architecture; and in their support equipped architects with a clear and conspicuous frame of reference.

At the same time and in reaction to the same Baroque excess, an entirely different and new concept of "truth to materials" surfaced in Venice, Italy. Carlo Lodoli, known as "the Socrates of architecture", argued that the form of ornaments must be consistent with the materials in which they are made (Forty, 2000, p.294, 296). Lodoli saw imitation of materials as morally flawed: "giving marble the appearance of wood was the same as putting money to deplorable use" (Lodoli as cited in Forty (2000, p.296)). But even more importantly, for Lodoli, using the same forms for wood and stone was a serious mistake of the Greeks, whom he accused of lacking reason (Neveu, 2012, p.57-58), and said that "this was sheer masquerade or, to put it bluntly, a lie" (Lodoli as cited by Algarotti in Angelil (1987, p.337)) [71].

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[71] This notion appeared in the 1753 Francesco Algarotti's (1712-1764) *Saggio sull'Architettura* (*An Essay on Architecture*), where he stated that architecture should be consistent with the nature of the materials used in construction, and a certain material representing another is a great abuse. Material qualities and properties; such as their rigidity, flexibility, or strength; should be consistent with architectural forms. In this light the alleged transposition of wooden forms into stone in classical architecture was its original mistake (Pérez-Gómez, 1983, p.254).

Lodoli used the word *indole* to denote the inherent nature, properties, and characteristics in relation to materials. By saying that 'the function of the material used in the construction of buildings depends on the nature of the material itself' (Memmo citing Lodoli, as translated by Neveu (2012, p.56)) Lodoli linked functionality with the *indole* of the material. Materials are functional when employed in line with their characteristics; and function is synonymous with truth, which is closely related to performance. While the unity of truth and utility can be traced to the English philosopher Francis Bacon (1561-1626), Lodoli derived the concept of performance of material and structure directly from Galileo. It was Galileo who discovered that structural sizes cannot be increased by enlarging all dimensions proportionally – at a certain threshold, size is inevitably changed to a stronger material so that the structure will not collapse under its own weight (Angelil, 1987, p.338, Neveu, 2012, p.56-57).

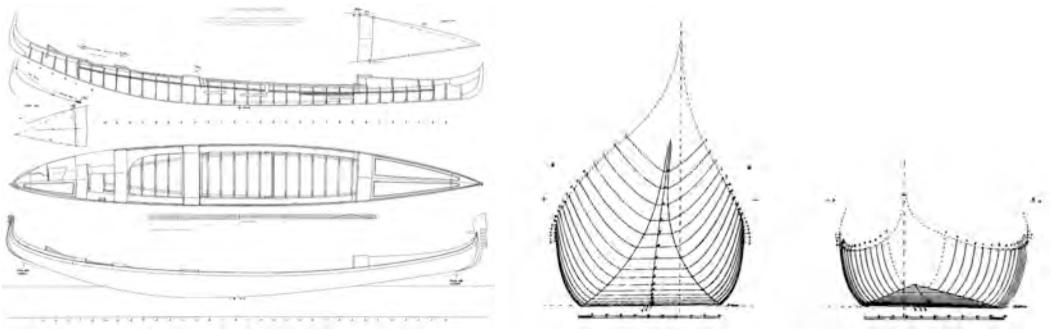

Figure 90
Gondola drawings showing its asymmetry.

Lodoli promoted designs where, just like in the case of musical instruments, the form results both from the performance of the instrument and from the materials. For Lodoli, one example of beauty, as understood through performance, was the Venetian gondola (Figure 90). Being one of the few boats that are asymmetrical both in plan and section, it is only functional while it is used and weighted by the gondolier. That makes it well suited to its performance in the lagoon: the large craft is easily manoeuvrable and the gondolier does not have to shift the oar from side to side. When pushed without the gondolier acting as ballast, it would turn to one side. Regarding material use, Lodoli points to the fact that every part of the boat is made with a different type of wood. One good example here is the *fòrcola* – the wooden oar post. It is highly customised: it relates to the height, weight and technique of the gondolier. Because it allows for up to 12 rowing positions, it requires a complex shape with various curves and facets (Figure 91). The *fòrcola* could not be made of any other material than wood; and the preferred wood is walnut for its hardness, durability, and tight grain (Neveu, 2012, p.59-60). The forms of the gondola and the *fòrcola* are subordinate to function and material rather than to any pre-given, imposed order. These forms developed in the context of particular conditions, such as the local environment of the lagoon or the gondolier's rowing techniques, not as an aesthetic style or taste. Variations and idiosyncrasies, if present in the work, are never a result of the craftsmen's personal preferences; but rather of the abovementioned conditions combined with material traits. Lodoli, however by no means a prolific builder, applied his ideas in practice. One example is his design for a chair, unfortunately known only from written sources. Rather than following any particular style, Lodoli used the shapes of his own shoulders and buttocks to form the back and seat of the chair. Lodoli was the first to call this way of designing "organic" (Neveu, 2005, p.33, 112). Similarly, in the design for window frame renovations in the hallway of the hospice San Francesco della Vigna in Venice (c. 1743, Figure 92), Lodoli replaced existing sills with new stone pieces formed after catenary curves, as an optimal form to prevent them from cracking (Neveu, 2012, p.61-62). In Lodoli's approach, form should not be understood as simply subordinate to technology: his interest was in the synthesis of ***representational*** and ***ontological*** aspects of building materials and discovering their essence. Alberto Pérez-Gómez sees it as a 'rejection of rational reductionism and an early form of hermeneutic criticism', which for him is 'the most appropriate method for architectural theory' (Pérez-Gómez, 1983, p.255).

Figure 91
Fórcole. Left: The complex shape. Right: In use with an oar.

Figure 92
Carlo Lodoli, ca. 1743, renovation of hallway window frames in the hospice San Francesco della Vigna in Venice.

These examples demonstrate how, for Lodoli, form and beauty resulted from the symmetrical relationship of material and function, but also from human and material agency. Both the required material and the intended use, on equal rights, dictate the form to the designer. For the first time in architectural theory, performance was seen as beauty. The designer consciously ceded some of the decisions concerning form to the agency of the material and function: the shapes of the chair followed the features of the human body, the window sills followed the optimal shape of the force flow.

Lodoli referred to a new notion of truth, not understood as synonymous with beauty in the Classical sense, but associated with consistency and performance. Initially intended as a countermeasure to the Baroque and the influence of the Classics; Lodoli's truth, related to the way materials are used, became an early forerunner to the current shift of interest in architecture: 'from what the building is to what it does' (Leatherbarrow, 2009, p.43). Lodoli was not only the first to see material and function as equal partners in the form-giving process, but also the first who defined function as situated performance, e.g. the gondola only works when it is used in a certain way, or the stone in the window sill is shaped by specific loads.

It is important to note that Laugier's and Lodoli's formulations coincided with the beginning of decoupling architecture and engineering as professions in the mid-18th century. In this situation, when another profession took over some responsibility regarding the physical aspects of construction, architecture needed to rethink its position towards materiality. Both stances became protoplasts for the main architectural positions vis-à-vis the use of material as known in Modernism. Laugier's remedy in proportioning systems epitomised the primacy of idealism, effectively leading to the denial of materiality. While on the one hand, Lodoli's "truth to materials" stance motivated the rational discourse of Viollet-le-Duc; on the other hand, it inspired Ruskin to assign moral values to materiality.

Tectonics and the development of the concept of form in the 19th century

This thesis seeks to identify relationships among the developments in the understanding of architectural form and innovation. As mentioned earlier (see p. 127), the concept of form evolved substantially in 19th century architectural theory; and this evolution is consequential to the present conceptualisation of form in architecture. Taking a position on material agency and engaging in the ancient form-matter discussion was determinative for the 19th century discussion surrounding tectonics, and in turn for Modernism and our current understanding of the role of materials in design. The phenomenon of material transposition was elevated to the role of a formative myth, and the subscription to it was an act of faith.

The present predominant conceptualisation of form is indebted to idealist philosophy, as well as to the concept of architectural tectonics which was formulated in 19th century Germany. In 1790 the German philosopher Immanuel Kant (1724–1804), in his *Kritik der Urteilskraft (Critique of Judgement)*, established form as the basic category of the perception of art, rather than a property of a thing. For Kant, in accord with idealism, form was superior over its material manifestation. Further to that, form lay in the beholding, not in the thing beholden. The source of beauty was not in objects themselves but in the process by which they were perceived. "Purposiveness" became a new principle of aesthetic judgement. Decoupling beauty with truth established aesthetics as a branch of knowledge independent, and separate from morals or ethics. This philosophically developed and expanded the concepts established some 40 years earlier by Lodoli in the context of architecture (see p. 144). German Romantics at the turn of the 18th and 19th centuries, most notably Johann Wolfgang von Goethe (1749–1832) and August Wilhelm Schlegel (1767–1845), pushed the concept further; seeing "organic form" as a sign of an inner life force or a "genetic principle". For 19th century idealist philosophers, such as Georg Wilhelm Friedrich Hegel (1770–1831) or Robert Vischer (1847–1933), form – in the Platonic vein – was a property above and before things, knowable only to the mind, "the surrogate of Idea". The first architectural writer for whom form was an important concept, Gottfried Semper (1803–1879), was indebted both to Hegel and Goethe in his understanding of this concept (Forty, 2000, p.154-157).

While the watershed line in architectural discourse of the time followed the opposition of Greek versus Gothic (which could roughly translate to idealist versus materialist, neoclassic versus romantic, artistic versus utilitarian, or ***representational*** vs ***ontological***) positions, the Romantic philosophers refused to follow this clearly drawn opposition in their architectural preferences. Hegel opted for a synthesis of the Greek and Gothic positions under the label of "Classical Romanticism", while Goethe vacillated between these two all his life. Goethe initially preferred Gothic; after moving to Weimar in 1775, he advocated Palladianism as the counterpart to the contemporary progressive culture. In later life, after appreciation for Neogothic, Goethe finally opted for a reconciliatory "third style" in 1823 (Frampton, 1995, p.62, 63, 67) with an idea that bears resemblance to the Hegelian approach.

At the beginning of the 19th century, the abovementioned opposition manifested itself in architectural discourse with discussion about the wooden origin of the Doric order. A heated debate in Germany between the architect Heinrich Hübsch (1795–1863) and the art historian and archaeologist Alois Hirt (1759-1837) revolved around this difference. In his 1822 book *Über griechische Architectur* Hübsch challenged[72] the Vitruvian theory that the Doric order originated in wooden construction. Hübsch could possibly have been inspired by the German philosopher Arthur Schopenhauer (1788–1860), who in 1818 called the idea of Greek architecture's wooden origin "absurd". Schopenhauer alleged this origin derived from rational load distribution:

> all the laws of columnar arrangement, and consequently the form and proportion of the column in all its parts and dimensions down to the smallest detail, follow from the conception of the adequately appropriate support to a given load, a conception well understood and consistently followed out; therefore to this extent they are determined a priori. It is then clear how absurd is the idea, so often repeated, that the trunks of trees or even the human form (as unfortunately stated even by Vitruvius, iv, 1) were the prototype of the column (Schopenhauer, [1818] 1958, p.413-414).

A few years later in 1828, in his influential treatise *In welchem Style sollen wir bauen? (In What Style Should We Build?)* Hübsch sustained his position. He strived to find an architectural style for the then emerging German state; and in doing so, challenged the Vitruvian theory in support of the proposed

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[72] French architect Claude Perrault (1613-1688) can be considered the first who questioned the concept of the wooden origin of the Greek temple in 1683, when in his *Ordonnance des Cinq Espèces de Colonnes selon la Méthode des Anciens* (*Ordonnance for the Five Kinds of Columns after the Method of the Ancients*) he argued that there was no connection between the proportions of the column and the human body or a tree, and thus no objective rules had been based on thereof.

Rundbogenstil based on the Romanesque arch (Frampton, 1995, p.67). Hübsch's argument can be seen as related to the ***ontological*** aspects of construction, as also conveyed by his experiments with catenary curves (see p. 166). In 1838 Leo von Klenze (1784-1864), a German Neo-classicist architect and writer, concluded in his *Aphoristische Bemerkungen gesammelt auf seiner Reise nach Griechenland* that the origin of the Doric order cannot be traced more readily to wood than to stone construction. This opinion is generally accepted by most historians today. In the mid-19th century Karl Bötticher, in *Die tektonik der Hellenen (Greek Tectonics)* supported Hübsch's materialist arguments. Bötticher did not see the Doric order as either a derivative from earlier developments in wood construction or from other cultures, but as a reflection of the character and rites of a particular Greek tribe (Gutschow, 2000). In the same vein the French Gothic Revival architect and theorist, Eugène Emmanuel Viollet-le-Duc, opposed the petrification theory and attacked it in his *Entretiens sur l'architecture (Discourses on Architecture)* in 1858. In 1899 the French engineer and architectural historian François Auguste Choisy (1841–1909), in a similarly reconciliatory tone, stated that the Doric order derived both from the tradition of timber construction and the technical demands of masonry (Frampton, 1995, p.5-6, 49, 58, 87, 125). Choisy, who stated that "a whole body of forms [...] arise naturally from the material employed" (Choisy as quoted in Banham (1960, p.29)), valued Greek and Gothic architecture equally high. This reconciliation demanded inventions of yet undiscovered prehistoric modes of stone construction. This prehistoric construction allegedly had affected a "masonry of wood" that in turn was a base for the Doric order. Interestingly, Choisy found this prehistoric transposition – a "carpentry of stone" – in Indian architecture where "the stone is put to work in the manner of wood, with all the joining techniques that suit wood" (Choisy as cited in Banham (1960, p.29)).

Developed around the same time, concepts of architectural tectonics were determined by material agency. The term "tectonics" is inseparable from materiality; e.g. Antoine Picon saw it as 'based on prescriptions regarding the proper use of materials' (Picon, 2010a, p.161). These prescriptions are culturally conditioned and vary in any given historical period. Tectonic discourse was initiated by Prussian architects Friedrich Gilly (1772–1800) in the 1790s and Karl Friedrich Schinkel (1781–1841) in the 1820s and 1830s, and coincided with a current interest in Gothic architecture. While describing the Mainz cathedral in 1835, the German architect Johannes Wetter (1806-1897) was the first to state that Gothic architecture and its artistic forms were wholly consequential of their construction system (Frankl, 1962, p.20, 37-38). In 1841 the Anglo-French architect and theorist, a proponent of the Gothic revival, Augustus Welby Northmore Pugin (1812–1852) was the first to link Gothic architecture with "structural truth", and introduced this concept to the English language. Pugin created a unifying theory that associated the consistent relationship of form and structure with moral virtues. He contrasted the Vitruvian concept of architecture with the medieval use of materials in vaulted structures. Pugin argued that tectonic form should be determined 'by the nature of the material' (Frampton, 1995, p.37).

In the 1840s, the German architect and archaeologist Karl Bötticher (1806–1889), a disciple and colleague of Schinkel, defined architectural tectonics as "the activity of forming a building". In contrast to earlier theories that focused on the imitation of objects, Bötticher's tectonics were concerned with the processes behind making a building. Tectonics integrated the studies of function, structure, and symbolism in architecture (Schwarzer, 1993, p.267-268, 274). Besides redirecting interest towards rational principles, tectonic discourse also introduced the idea of dynamic relationships as informing design. The root of the term "tectonics" was the Ancient Greek noun *tektōn* – related to the Sanskrit *taksan* – referring to carpentry and to using an axe. It denoted a carpenter, which signified the important role of wood construction and its constructor in the development of architecture. Before Bötticher, the German scholar and historian of ancient Greece, Karl Otfried Müller (1797–1840), used the term in the context of art and architecture in 1830 (Frampton, 1995, p.4-5). Even earlier, in 1781, Immanuel Kant had coined a philosophical term *Architektonik* in a more metaphorical sense in his *Kritik der reinen Vernunft* (*Critique of Pure Reason*). In the 1844 introduction to volume one of *Die Tektonik der Hellenen (Greek Tectonics)*, Bötticher distinguished *Kernform* (core form) from *Kunstform* (art form), and designated the ***ontological*** to Gothic and the ***representational*** to Greek architecture (Frampton, 1995, p.71, 82). Bötticher, in opposition to his contemporaries Hegel and Kant, considered architectural form as subordinate to need, material and technical innovation' (Schwarzer, 1993, p.273). In Bötticher, *Kernform* achieved intrinsic, or ***ontological*** status; while *Kunstform* achieved extrinsic, corresponding to ***representation***. For Bötticher the relationship of *Kernform* to *Kunstform*, two categories which could further be reduced to structure and ornament, became a criterion for appraisal of architectural invention. Any new structural principle could be analysed in relation to whether it received an adequate form based on this relationship (Hvattum, 2004, p.61).

Bötticher's motivation was to prepare the ground for radical technological innovation: introduction of iron as a material representing the dynamic character of industrial society. In 1846 Bötticher argued that iron would provide a structural principle for a new style, superior to both Gothic and Greek systems (Frampton, 1995, p.83-84). An analogy, if not continuation, can be found in the work of both Viollet-le-Duc and the French architect Auguste Perret (1874-1954) who saw concrete as a material capable of reconciliation between Platonic form and structural expression. Perret admitted to having transposed wood-framing techniques into concrete techniques in his buildings constructed before 1914, pointing to the half-timbering of northern France as the source of inspiration (Banham, 1960, p.38-39). In a later period, Perret went as far as reversing the alleged petrification of timber into stone. In 1952 he stated that "[i]n the beginning architecture is only wooden framework [...] [a]nd the prestige of the wooden frame is such that one reproduces all the traits, including the heads of the nails" (Perret as quoted in Frampton (1995, p.125-127)).

The German architect Gottfried Semper (1803–1879) was possibly the most ambiguous architectural theorist of the 19th century. His theories were interpreted either as idealist or materialist, proto-functionalist or eclectic, Marxist or liberal capitalist (Hvattum, 2004, p.8-9, Moravánszky, 2018, p.196-197). In his seminal 1851 book *Die Vier Elemente der Baukunst* (*The Four Elements of Architecture)* Semper proposed an ethnographically infused theory of the four primal elements: the “earthwork”, the “hearth”, the “framework–roof”, and the “membrane”. The four elements formed a base for two fundamental procedures: the “tectonics” of the frame and the “stereotomics” of the earthwork. Semper’s distinction between the lightweight and tensional tectonics and heavy and compressional stereotomics was reinforced by the German language differentiation between two classes of walls: *die Wand* – screenlike wall, and *die Mauer* – massive wall (Frampton, 1995, p.4-5). This observation brings an unexpected agency of the language[73] to the development of architecture, in this case being instrumental in formulating the Modern style as characterised by separation of post-and-beam structure and lightweight infill walls. Semper’s contribution to architectural theory, in making the distinction between tectonics and stereotomics, is in proposing a consistent theory not based on imitation (***representational*** principles) but on constructive standards (***ontological*** principles).

In the 1860s Semper proposed his *Stoffwechseltheorie,* a theory of material transposition, where he referred to the aforementioned discussion about the wooden origin of the Doric order and skeuomorphism. Semper challenged the tradition of the wooden hut; he traced the origin of triglyph and metope ornamentation used in the Doric order to textile origin, rather than timber. In the *Stoffwechsel* theory, when the motifs of art or architecture are translated from one material to another; it is their original significance, purpose, and meaning that are being translated (Hvattum, 2004, p.11). Form in this process is not fixed, but rather a continuously changing configuration.

Truth to materials in Modernist architecture

As mentioned in the section on the effects of hylomorphism on Modernist architects of the “heroic” period, Modernist architecture also involved approaches focused on various qualities of materials. A group of architects active in the late 19th and first half of the 20th centuries; including Adolf Loos (1870-1933), Frank Lloyd Wright (1867-1959), Ludwig Mies van der Rohe (1886-1969), and Louis Kahn (1901-1974); opposed extensive ornamentation and advanced a notion of architectural form as resultant from materials and

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[73] The observation of the agency of language in relation to tectonics is validated by numerous examples of different readings assigned to inherently like elements, e.g. the American and French readings of beams and trusses are conditioned by their respective names in both languages. The English language separates them, where in French one word is used to describe both (Picon, 2010a, p.146).

technological processes, often declaring affinity to Eugène Emmanuel Viollet-le-Duc.

In the second half of the 19th century Viollet-le-Duc, in opposition to Classicism, formulated[74] the principles of structural rationalism: a doctrine of architectural composition based on "truth to materials". In his own words, this '[c]omposition should have reference to two elements – the material made use of and the processes that can be applied to it'. The composition that suits one material, will not suit another. Materials should be used in accordance with their physical properties, the overall building structure, and its structural expression. Skeuomorphism and imitation were not considered honest. While iron is the material with which Viollet-le-Duc is mostly associated, he also discussed his doctrine in relation to wood. Its properties 'absolutely demand certain use', such as the rule to 'leave the wood to a certain extent free in a transversal direction'. Viollet-le-Duc lamented that 'authors recommend wood to be used in ways contrary to its nature; that they think that their extravagances are the triumphs of art', while 'on account of its fibres, which are parallel to each other, wood permits the use of only flat or straight forms' (Viollet-le-Duc and Hearn, 1990, p.170-172). This formulation by Viollet-le-Duc goes beyond the hylomorphic model of architectural design; where, as discussed earlier, materials could be interchangeable, material considerations were below the formal ones, and materials' natural behaviours should not inform design decisions. On the other hand, this formulation cannot be fully regarded as ***material-centred***, as it did not consider materials as form-givers. For Viollet-le-Duc, 'wood permits the use of only flat or straight forms', and wood movement should be factored-in but then obliterated. This formulation has been predominant in the discussion surrounding the use of material among the Modernist architects, and it does not provide any theoretical framework for the experiments presented in Part I.

At the end of the 19th century the Austrian-Czech architect Adolf Loos formulated the notion of *Formensprache* that, on its surface, stood in strong contrast with the idealist and ***representational*** positions. Loos derived the origin of forms from materials that supposedly had their own "language": '[e]very material possesses its own language of forms, and none may lay claim for itself to the forms of another material. For forms have been constituted out of the applicability and methods of production of materials. They have

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[74] Viollet-le-Duc can be linked with Carlo Lodoli (see p. 26), and to some degree with Philibert de l'Orme (see p. 138). Viollet-le-Duc discussed handling materials in the second volume of his most important work on the theory of architecture *Entretiens sur l'architecture (Discourses on Architecture)* published in 1872, as well as in *Histoire de l'habitation humaine depuis les temps prehistoriques (The Habitations of Man in all Ages)* in 1875, and in his last work *Histoire d'un dessinateur, comment on apprend a dessiner (Learning to Draw, or the Story of a Young Designer)* in 1879. In assigning moral values to the use of materials, he was possibly also inspired by the book *Seven Lamps of Architecture* by the English art critic and thinker John Ruskin (1819–1900) in 1848, published more than two decades before his own formulation of the doctrine (Viollet-le-Duc and Hearn, 1990, p.169-179).

come into being with and through materials' (Loos, [1898] 1982, p.66). This formulation refers to Viollet-le-Duc's notion of form as resultant from materials and technological processes; it also echoes Semper, who wrote in a similar vein that '[e]very material conditions its own particular manner of formation by the properties that distinguish it from other materials and that demand a technical treatment appropriate to it' (Semper, [1860] 1989, p.258)[75]. However, while Loos' work brought an important contribution to the discussion surrounding the ornament in architecture; it did not contribute in a similar way to formulating any operational methodology regarding the use or understanding of material's role in design, and thus material innovation. His interest in material went only as far as its applicability in cladding, and the relationship between cladding and structure was not important for his theory.

Frank Lloyd Wright was, similarly to Loos, a follower of Viollet-le-Duc. Unlike Loos, Wright advocated for ornament as a consequence of the fabrication process. Contrary to Semper, who was concerned that mechanical production allows imitation of rich material with cheaper material, Wright saw the machine's potential to deliver a democratic product of high quality (Frampton, 1995, p.101). In relation to woodworking and machine production, Wright wrote at the beginning of the 20th century that woodcarving is 'an insult to its finer possibilities as a material having in itself intrinsically artistic properties, of which its beautiful markings is one, its texture another, its color a third', and continued that '[t]he machine has emancipated [the] beauties of nature in wood; made it possible to wipe out the mass of meaningless torture to which wood has been subjected since the world began, for it has been universally abused and maltreated by all peoples but the Japanese' (Wright, [1901] 1974, p.66). Wright saw the appropriate treatment of wood in the simple post-and-beam systems of Japanese joinery-carpentry, which exposed its 'intrinsically artistic properties'. This simplicity could then be replicated by the modern machine, which 'by its wonderful cutting, shaping, smoothing, and repetitive capacity, has made it possible to so use it without waste that the poor as well as the rich may enjoy today beautiful surface treatments of clean, strong forms' (ibid., [1901] p.66). Despite coining the notion of "the meaning of materials", and statements such as 'What shape? Well, the answer lay, in what material?'[76] (Wright, 1974, p.76); Wright's approach to wood was clearly hylomorphic. The "meaning" was reduced to ***representational*** (e.g. grain, texture, colour) rather than ***ontological*** (e.g. properties, behaviours) aspects of the material, and any synthesis of these aspects was not seriously considered as informing the architectural form.

Ludwig Mies van der Rohe's work and writing embody the opposing vacillation between the capacity of the material and "endless space". In 1938

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[75] Despite the similarity between the Semper's and Loos' statements, their fundamental stances were different: Semper had not seen form as determined solely by material, but saw material as modifying the particular idea.

[76] Wright in relation to his Unity Temple in 1932.

in his inaugural address at the Armour Institute of Technology, he distanced himself from the opposition of materialistic against formal principles of order. Mies proposed a third way: “the organic principle of order as a means of achieving the successful relationship of the parts to each other and to the whole” (van der Rohe as quoted in Johnson (1978, p.199)). In the speech, he praised historical wooden construction as exemplifying the synthesis of ***ontological*** and ***representational*** aspects of materials and form:

> ‘Where can we find greater clarity in structural connections than in wooden buildings of old? Where else can we find such unity of material, construction and form. [...] [E]ach material has its specific characteristics that one must get to know in order to work with it. [...] Each material is only what we make it’ (ibid., p.197-198).

Here, suggesting the unity of “material, construction and form” van der Rohe took one step further than Loos or Wright, opening a possibility for material agency becoming an equal consideration to form and idea. This was also evident in some of his work. In the German Pavilion in Barcelona from 1929, van der Rohe provided evidence for his respect for material qualities that could take place before and above form. Van der Rohe redesigned the entire pavilion in order to accommodate a block of onyx of particular size (Figure 93), as he described later: “I looked around in huge marble depots, and in one I found an onyx block. That block had a certain size and since I only had the possibility of taking this block, I made the pavilion twice that height” (Mies van der Rohe (as quoted in Carter (1961, p.100)).

Figure 93

Mies van der Rohe, 1929 (reconstructed 1983-1986), German Pavilion, Barcelona.

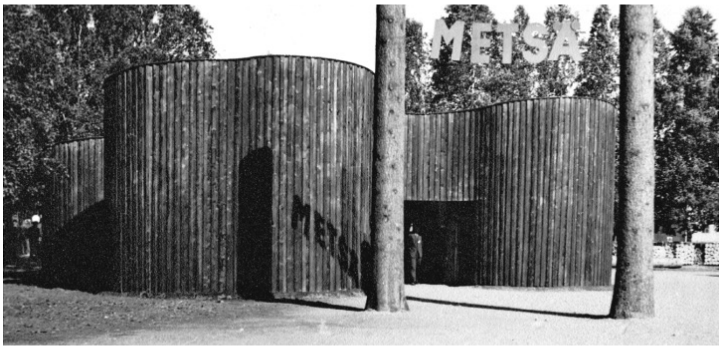

Figure 94

Alvar Aalto, 1938, Lapua pavilion.

As Frampton put it, ‘the sublime for Mies resided in the quality of the material itself and in the revelation of its essence through careful detailing’. But the resulting tectonic of his work was ‘partly ontological and partly representational’ (Frampton, 1995, p.171, 190). That accounts for the ambivalence in both the classification and the reception of van der Rohe’s work. He is often regarded as a Platonist, interested in geometry and its universal meaning; however, his words often stated the opposite. For instance, he declared in 1923 that “We refuse to recognise the problems of form, but only problems of building. Form is not the aim of our work, but only the result. Form by itself, does not exist” (van der Rohe as quoted in Johnson

(1978, p.189)). In this quote, Mies implied that form could possibly follow function or material, but could not be imposed upon it.

Louis Kahn, another modernist architect influenced by Viollet-le-Duc, is also regarded as a Platonist (Johnson, 1994, p.81); even despite his famous personification of brick. In this personification, the brick when asked "what do you want", answered "I like an arch", and when reminded that "arches are expensive", still insisted "I like an arch" [77]. This slightly frivolous dialogue was intended to convey the notion of truth to materials to Kahn's students. However, in actual fact, it did not express the desire of the brick but that of the designer, following the Platonic ideal of an arch. Form definitely took priority over matter in this dialogue. In like manner, the architects of the iconic AT&T building in New York from 1984, Philip Johnson (1906-2005) and John Burgee (b. 1935), explained the circular carving in its open pediment. Very similar to the aforementioned Kahn argument, Burgee explained: "We deliberately used carved stone at AT&T. Why not exploit the very nature of the material? Its intrinsic quality is such that it can be carved" (Burgee as cited in Johnson (1994, p.87)). What Burgee calls "intrinsic quality" of the material should rather be called its susceptibility to being carved. This reference to "the very nature of material" exactly mirrors the attitudes invoking truth to materials, where the moralistic position can be seen as hypocrisy.

The notion of truth to materials, as outlined above, can be criticised for three reasons, characterised as: (i) flawed methodology, (ii) exclusiveness, and (iii) thermal problems. (i) The abovementioned Modernist architects were using vague, ***representational***, and moralistic notions of culturally conditioned material agency. These were recently described by some theorists as 'metaphors [...] very difficult to use [...] as a basis for a more operational understanding of the form-material relationship' (Sandaker, 2008, p.24), and as 'not generally robust to the point of promoting an inventive interaction with materials' (Fernandez, 2006, p.9). As a result, the idea of truth to materials could not be incrementally developed, and formalised as a working method. For this reason, it did not lead to material innovation as envisioned by de l'Orme, Lodoli and Viollet-le-Duc. (ii) The notion of truth to materials excluded, based on moralistic grounds, the whole market of hybrid and composite building materials, thus hindering material innovation in architecture. For instance the Swiss architect, Christian Sumi (b. 1950) tries to demount the notion of truth to materials in his buildings by intentionally using hybrid products, such as concrete panels with wood fibres or wood panels with a concrete component, (Moravánszky, 2000, p.39, Moravánszky, 2018, p.156-158). (iii) Using solid, exposed structural materials often leads to thermal bridging or insufficient insulation of buildings. The multilayer wall structures, enforced as the result of the first oil crisis in 1973, and even more so by the current environmental concerns, are incongruent with the notion of

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[77] This "dialogue" was transcribed from the Master Class at Penn run by Kahn in 1971 as featured in the 2003 documentary film (Kahn, 2003).

truth to materials. The internal layers of the external wall, which play the morally important role of insulation, are not “honestly” expressed, and thus the moralistic argument is called into question.

Despite these criticisms, the notion of truth to materials played an important role in the 19th and 20th centuries forging national and local identities. One interesting example related to wood can be found in the furniture design of the Finnish architect Alvar Aalto (1898-1976). Aalto’s identity was inextricably tied with his home country, and Finland’s landscape is inseparable from forests and wood. Aalto believed that wood is viable both for “psychological” and for “biological” reasons. In 1949, Sigfried Giedion published the second edition of his seminal book *Space, Time and Architecture: The Growth of a New Tradition* (first published in 1941 then revised, extended and republished in 1949, 1959, 1962, and in 1967). In it he characterised the work of Aalto as based on a number of creative tensions between: irrationality and standardisation, East and West, primeval culture and modern civilisation, etc.; which could all translate as the opposition of nature versus culture (Figure 94). As put by the American art historian Martin Eidelberg (b. 1941): “Aalto took technology as his means and nature as his model, and the interplay between the two found not only an artistic expression but also a new form of modernism” (Eidelberg as quoted in Ngo and Pfeiffer (p.33)). This tension is evident in the choice of plywood as his material for furniture, since 1929. Plywood represented a set of characteristics that were important for Aalto: the natural world, the regional specificity, and the modernity. Being made of organic material – wood – plywood embodied the natural or the “irrational” element. In the case of birch plywood, it referenced the national tree of Finland. Finally, plywood, as based on mechanical production processes, symbolised the modern culture and standardisation. The first batch of the Paimio furniture designed for his Paimio Sanitarium, most notably chairs Model 31 and Model 41 from 1931-1932, was made with beech, more flexible and easier to work with than Finland’s native birch. Yet the goal of Aalto and his technical collaborator Otto Korhonen was to find a way to utilise more locally abundant wood. As well as to tap into the economic affordability of using a local material, the idea was to produce furniture that would be identified with the newly independent country. Finally, after many trials and broken frames, they were able to use birch in the same manner as the imported beech (Ngo and Pfeiffer, 2003, p.33). This process allowed the agency of the local wood to be taken into account for its symbolic value, and successfully deliver a viable product. Aalto described this process as “laboratory experiments”, during which testing pieces were built to determine the characteristics and limits of the material. Aalto alluded to the scientific method; however, judging by the dates of the experimental pieces, as pointed out by some authors, these should rather be called “semi-scientific” as they were made post-factum ‘to artistically express the beauty of laminated wood’ (ibid., p.33-34). Regardless of to what extent the process was truly scientific, in his furniture design Aalto achieved a synthesis of material properties and cultural ideas.

In its totality Aalto's approach to material in design was ambivalent, in the same manner as the other Modernist architects outlined before. One interesting example of this inconsistency is his use of non-standard bricks in *Kulturitalo* in Helsinki built between 1955 and 1958. The wedge-shaped bricks were Aalto's solution for building curved walls; but this had been earlier criticised on moralistic grounds by Frank Lloyd Wright, whom Aalto admired and called "his old friend". However, Wright referenced the use of special custom-made bricks as unnatural in the Monadnock Building in Chicago from the 1890s, not in the *Kulturitalo* project (Moravánszky, 2000, p.44).

The presented examples, focused on the synthesis of material properties with cultural ideas, illustrate how their approach is incapable of being formalised as a working method. These examples, where the ***representational*** aspects of designed form were prioritised, effectively inhibited material innovation in architecture. The following sections discuss the work of outliers in the profession, who refused to follow the clearly determined roles of architects, engineers, technologists, and builders; and by doing so were able to bring a meaningful contribution to material innovation in architecture.

The case of concrete's material agency

The previous section outlined the theory and work of Modernist architects who declared interest in the role of building materials in design. It concluded that these architects were using a moralistic and aesthetically-driven concept of materiality, which could not be developed into an operational method. This section discusses the work of designers whose work points in the direction of how such methods could be developed. In order to break away from the hylomorphic model of understanding material's role in design and to move towards acknowledging material agency in design, these designers had to cross disciplinary boundaries, thus could not be clearly described as architects, engineers, builders, or fabricators.

Concrete[78] is a material that does not have any form on its own. At first glance this characteristic deprives it of any potential for agency in design. But surprisingly its shapelessness, when understood as an unlimited ability to take shapes, brings about the most palpable examples of a more operational method for ***material-centred*** design. A line of development can be drawn from structural rationalism and its influence on the aforementioned Perret (see p. 151), through the pioneers of pre-stressed concrete: the French engineer Eugène Freyssinet (1879-1962), the Swiss engineer Robert Maillart (1872-1940), and the Italian engineer Pierre Luigi Nervi (1891-1979). The

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[78] Concrete as a building material is not the primary focus of this thesis; however, this section was very important to theoretically develop and explain the concept of material agency. The case of concrete is useful to flesh out the concept before proceeding to discussion of the case of curved wood.

primary connecting characteristic is the investigation of 'the organic potential of the material' (Frampton, 1995, p.212). One of the key examples of harnessing this organic potential is Robert Maillart's storage shed near Chiasso from 1924. Here the cross-section of the structural concrete components was modified to reflect the stresses – an endeavour not possible without a material having the unlimited ability to take shapes (Figure 95). The same holds true for the work of Nervi, who saw both structural and expressive creative potential in the fluid state of concrete. Nervi distinguished between rigid and fluid material's capacity to follow the stress: '[r]einforced concrete beams lose the rigidity of wooden beams or of metal shapes and ask to be molded according to the line of the bending moments and the shearing stress' (Nervi, 1965, p.22).

The examples of these architect-engineers adhere to a different concept of form than the one characterised as the hylomorphic model; it presents a new model that can be described as more organic. The agency of forces, as the form-giving factor, is more closely related to that described by Scottish biologist and mathematician D'Arcy Wentworth Thompson (1860–1948), than to that of Vitruvius or Alberti. In 1917 D'Arcy Thompson characterised the process of morphogenesis in nature and its resultant form as a "diagram of forces". He asserted that '[t]he form [...] of any portion of matter, whether it be living or dead, and the changes of form, which are apparent in its movements and in its growth, may in all cases alike be described as due to the action of force' (Thompson and Bonner, [1917] 1961). Thus, D'Arcy Thompson saw the agency of forces as the decisive factor in the morphogenetic, or form-giving, process in nature. This process then is based on the bottom-up, as opposed to the top-down principle. The bottom-up and top-down principles can be likened to, respectively, the ***material-centred*** (non-hylomorphic) and hylomorphic concepts of form in architecture, and further to the ***ontological*** and ***representational*** roles of material in design. In the top-down process the a priori form is imposed onto matter; as is the case of the architecture based on Classical design, or other ordering and proportional systems. In this process the margin for other agencies is very narrow, if any. Contrary to that, the bottom-up process allows for various other agencies contributing to the morphogenetic, or form-giving process. This process does not imply intentionality of the actors (see p. 138); and it includes agencies that cannot be derived by reason alone, such as material heterogenic traits or any other unexpected factors. The bottom-up process has some capacity to integrate the unknown, as opposed to the top-down approach prevailing in design.

In relation to the integration of the unknown in the design process, the Spanish architect Miguel Fisac (1913-2006) produced very interesting work with flexible formwork for concrete. Fisac claimed that 'the root of the constructive solution lies in the aesthetic and practical association of the material' (Soler and Fisac, 1996, p.65), and devised a concrete pouring method into formwork lined with flexible plastic sheets. Based on the self-organisation process, Fisac's method resembles, in its concept, the experiments with catenary curves. However, the important difference is that it was not only concerned with technical abstraction of forces and materials, but it was directly applied in the fabrication process of the final product. This work turns towards the notion of architecture where design is not understood as planned by the media of drawings and projective geometry. It is also an example of reversing the dominating perspective where materials play a serving role to the form. In Fisac's work material agency comes to the fore, playing out the material's indeterminacy and unpredictability (Figure 96).

Figure 95

Robert Maillart, 1924, storage shed near Chiasso.

Figure 96

Miguel Fisac, 1973, house in La Moraleja, Madrid.

This method of using flexible formwork was not new and could be traced back to Vitruvius, who explained a method of constructing retaining walls filled with clay in woven reed baskets. However, in the context of concrete, it was first patented in Germany in 1898 and then in the UK and the USA in 1899 by the German architect and inventor Gustav Lilienthal (1849–1933). Lilienthal patented a method of making fireproof floors, later marketed as *Terrast Decke*. It was based on casting concrete on top of paper, cardboard, or fabric, supported by wire-netting sagging between floor joists so that the concrete hung down in catenary curves (Figure 97). In section profile, the solution strikingly resembles Lodoli's design for the window frame renovations in the hallway of the hospice San Francesco della Vigna in Venice from c. 1743 (see p. 147). Lilienthal claimed that this shape increases the strength of the floor as the stress is uniformly distributed. At the end of the 20th century, its loadbearing capacity was confirmed during a structural survey carried out on the Königin-Elisabeth-Hospital in Berlin, also constructed in this system, where it was determined to be 10 kN/m^2 (West, 2017, Chapter 2, Section 1).

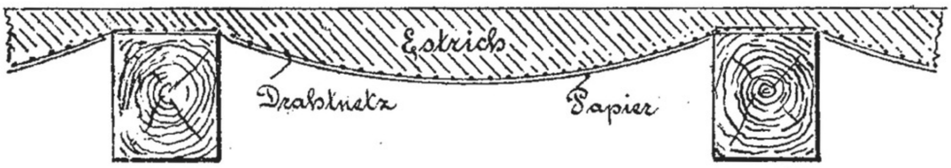

Figure 97

Gustav Lilienthal, 1898, *Terrast Decke*, a fireproof ceiling made with wire netting, paper or fabric, and screed.

Fabric formwork was further developed by the Tasmanian-Irish engineer James Hardress de Warenne Waller (1884–1968), most notably in his

Ctesiphon concrete shell system that could span up to 150 metres (Figure 98). The first prototypes, built in 1943, spanned 12 m and 32 m with only 25 mm thickness of unreinforced concrete. Between the 1940s and 1970s the system was deployed in over 500 structures built in Ireland, the UK, Spain, Greece, South Africa, Zaire, Nigeria, Zimbabwe, Kenya, Tanganyika (today's Tanzania), the Belgian Congo, Egypt, India, Australia, and Cyprus. It was also employed in the first Felix Candela's (1910–1997) thin shell structure in San Bartolo, and then again in a rural school near Ciudad Victoria in 1951. Patented in 1955, the *Ctesiphon* system was based on a series of parallel structural arches, between which concrete was cast on suspended sagging fabric, which doubled as reinforcement. The sagging fabric naturally formed corrugations that additionally stiffened the shells (West, 2017, Chapter 2, Sections 2-3, Veenendaal et al., 2011, p.165-167, Williams, 1996). Expanding the idea of the *Terrast Decke* system, the *Ctesiphon* system demonstrates how material efficiency can be achieved through synthesising material self-organisational properties: the tendency of fluid concrete weighted fabric to form a catenary shape, the catenary shape's structural stress distribution, and the global form, i.e. the resultant corrugation that additionally stiffens the shell.

Figure 98

James Hardress de Warenne Waller, 1948, *Ctesiphon* shell construction for an experimental building for H.M. Ministry of Works, Barnet, UK.

In 1969 with the *Centro de Rehabilitación para la MUPAG* project in Madrid, Fisac was the first to use flexible concrete formwork for architectural expression rather than utility. Fisac, who applied the method in several buildings until the 2000s, was interested in how the behaviour of the material engages with and influences the process of building. Despite that, his main focus at the time was surface treatment; he referred to these projects as "Textures" (Soler and Fisac, 1996, p.249-250). In his earlier work he experimented with a concept that he named "Bones" – hollow, pre-stressed and post-tensioned beams, taking inspiration from vertebrate animals. It had an objective to unify the concepts of structure, construction, material properties, and economics. The "Bones" concept was applied on the roofs of several buildings in the 1960s (ibid., p.132-165). Fisac did not manage to take the next logical step to unify both approaches: the "Textures" with the "Bones", that would respectively synthesize the ***representational*** and ***ontological*** aspects of concrete. Other architects took over the reins in this regard.

In the late 1980s through the 1990s, both Canadian architect Mark West (b. 1953) and Japanese architect Kenzo Unno (b. 1949) independently used fabric formwork for concrete, while searching for an alternative cheap and sculptural method to produce loadbearing elements (West, 2017). West's Oxbow Park pieces of this period are characterised by limited control over the results, and therefore were described as 'mannered, sloppy, free form [and] artistic' (Hay, 2007, p.56). In the 1990s, West founded the Center for Architectural and Structural Technology (CAST) at the University of Manitoba in Winnipeg, dedicated to the architectural exploration of fabric formwork. With access to industrial facilities and the ability to cast large objects, West started exploring the potential of the technology by casting beams and floor slabs shaped according to natural force paths, as well as optimised concrete trusses and thin shells, blurring the distinction between structural and architectural qualities (Veenendaal et al., 2011, p.168, 171-172). West refers to his process as natural form-finding: self-assembling "[the] final geometric form by finding the precise geometries demanded of it by gravity and the laws of nature" (West as cited in Hay (2007, p.56)). The CAST approach gained popularity in the late 2000s, which has been reflected in student experiments and industrial design prototypes. The most notable of these are at the Architectural Association School of Architecture (AA) in London – the Grompies project resulted in models of long-span roofs; at the University of Michigan – the FattyShell project used rubber as a formwork; and at the University of Edinburgh (UE) and the University of East London (UEL), led by Remo Pedreschi (UE) and Alan Chandler (UEL) in association with Mark West (CAST) – collaboration resulted in a series of test pieces and the Wall One and Wall Two projects (Chandler and Pedreschi, 2007). The rationale of all these projects is based on finding expressive forms, structural beauty and effectiveness, as well as material savings. These projects generate important questions about the designer's degree of control on the results.

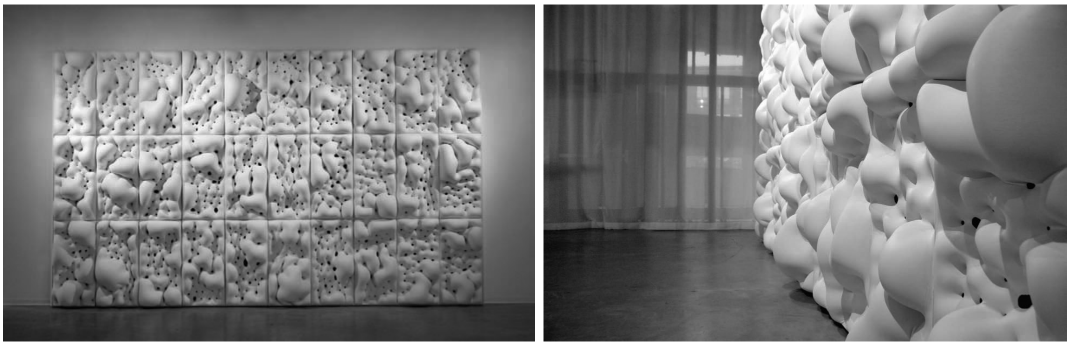

Figure 99
MATSYS, 2006, P_Wall.

Had it been possible to use digital technologies to curb the process, how would it have affected the design? To what degree could the process be predictable, and how could computers deal with the incalculable? Research into the numerical analysis of fabric formwork has been undertaken on a limited scale. The main problem is that numeric methods are deterministic. Computational design tools have the capacity to facilitate complex processes and to deal with large amounts of data and information, but their methods do not leave much room for the unpredictable.

Particularly interesting in this context is the series of P_Wall projects (2006, 2009, and 2013) by MATSYS, 'a design studio that explores the emergent relationships between architecture, engineering, biology, and computation'[79] (Figure 99). Andrew Kudless (b. 1975), the founder of MATSYS, devised a "brute force algorithm" that controls the "densities of constraints" for flexible formworks and predicts 'the larger pattern [...] within tolerances that would not completely endanger the casting process' (Kudless, 2012, p.480).. In relation to the form-giving process and control over the result, Kudless referred to both D'Arcy Thompson and to British wood-turner and theorist David Pye (1914-1993). While D'Arcy Thompson described the morphogenesis of the organic form in nature as the result of the forces acting on it; Pye, on the other hand, discussed the relationships among the making process: design, material, techniques, and tools. Pye coined the phrase "the workmanship of risk", which characterised material practices that accept 'risk as an essential by-product of innovation and life' (ibid., p.475-477). To build his argument, Pye contrasted the workmanship of risk with the workmanship of certainty; he likened the former to writing with a pen, and the latter to the process of printing. Handwriting, or the workmanship of risk, 'is not predetermined, but depends on the judgment , dexterity and care which the maker exercises as he works'; while in printing, or in the workmanship of certainty, 'the quality of the result is exactly predetermined before a single salable thing is made' (Pye, 1968, p.20). The workmanship of certainty is focused on delivering large quantities of products; and, just as the printing technology, is inseparable from Modernism. This dualism between the workmanships of risk and certainty frames the question regarding control of the process. The process, by which material agency and its self-organisational capabilities turn into valid design factors, becomes the workmanship of risk. For a computationally-centred designer such as Kudless, this risk lies in the incalculability of qualitative or too complex data.

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[79] http://matsysdesign.com/category/information/profile/

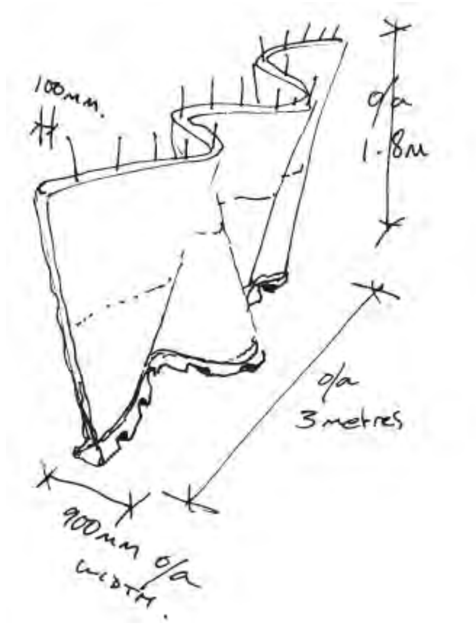

Figure 100
Alan Chandler, 2003, *Wall One*, drawing with “o/a” dimensions.

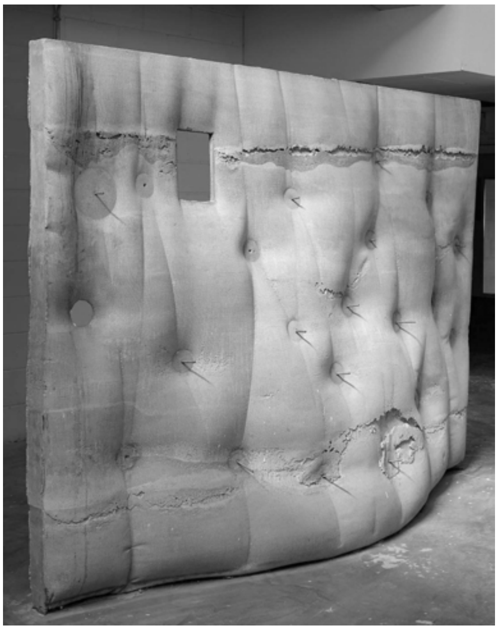

Figure 101
Alan Chandler, 2003, *Wall One*.

The problem of process control is central to the flexible formwork endeavours of all the above-mentioned designers. Alan Chandler referred to the installation of formwork for the *Wall One* project from 2003 (Figure 100) as a “jig”: “a device for holding a piece to be worked, rather than a means of predetermining the piece exactly” (as quoted in Lloyd Thomas (2007, p.47)). Similarly, the dimensions on his drawing for the project were marked as “o/a” – “on or about”, leaving margin of error or adding tolerances for the unpredictable process (Figure 99). It is possible to think about the position of the designer in the entire process – from the limited amount of possible concrete shapes flexible formwork can assume, to the inability to predict exact dimensions – as being a loss of control. However, this loss of control also brings palpable gains; as, for instance, in the example of the loadbearing capacity of the *Terrast Decke* system demonstrated. Today, companies such as Fab-Form in Delta, Canada offer fabric-based formwork for tubular columns and footings, which they advertise as more sustainable and cost effective than traditional methods[80]. The cost of formwork has always been the deciding factor for whether to execute elaborate concrete shapes. In the case of Erich Mendelsohn’s (1887-1953) Einstein Tower in Potsdam, Germany, built between 1919 and 1922, the material had to be changed from concrete to brick, as it was not possible to find builders capable of constructing the complicated formwork (Moravánszky, 2018, p.278). In this light, the loss of control over form can be seen as compensated by the gain of strength, reduction of cost and effort, and potential environmental benefits.

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[80] https://www.fab-form.com/about/overview.php

The case of curved wood in construction and form-finding

Form-finding

Some of the experiments with flexible formwork for concrete, outlined above, can be characterised as direct form-finding; or as Mark West refers to it, as a process of "natural form-finding by self-assembling" (see p. 162). Form-finding in architecture is understood as a design method where the form is not known in advance, but it is dictated by the distribution of forces, such as material's self-weight and other loads. In the most extreme cases, no bending is present in form-found structures under load, only compression or tension stresses. Examples of such structures include shells or gridshells, cable-net or tensioned membrane roofs, and tensegrity structures. A more technical definition describes form-finding as 'a forward process in which parameters are explicitly/directly controlled to find an *optimal* geometry of a structure which is in static equilibrium with a design loading' (Adriaenssens et al., 2014, p.2). While usually in the process the geometry is initially unknown and is generated by the loads coming from the structure's self-weight and cladding; the process may also begin with a pre-defined geometry, or can be controlled by changing the boundary conditions, supports, external loads, topology of the model, internal forces, and their relationship to the geometry.

Where wood construction is concerned, examples of direct form-finding, as in the flexible formwork method, are scarcer. In most cases, where the form-giving process of a shell or gridshell structure is based on the form-finding method, another translation between the found form and the final product is needed. This is achieved by means of building models that represent the distribution of forces. The concept of using a catenary arch in the design process is an example of transposition of the scientific method into the realm of architecture. This method is based on hanging models, made from flexible materials or chains, upside-down; so that when weighted, or under self-load, they form catenary shapes. The method is premised on the fact that the catenary shape works in pure tension; when it is inverted it works in pure compression, free of bending, thus producing a structurally optimised form. The resultant form, then, has to be translated from the model to the actual structure. This translation process does not occur in the direct form-finding method, as represented by the flexible formwork method, where the construction material within the given constraints finds its form in which it remains as a fixed component of the final structure.

The Archway of Ctesiphon in Iraq from 531–579 is often regarded as the oldest known example of an inverted catenary arch used in construction. It became the inspiration and the name for the *Ctesiphon* concrete shell system of James Waller (see p. 161). However, there is no direct proof that this shape is catenary (Kurrer, 2008, p.194). The first documented non-circular masonry arch, *Ponte Santa Trinita* designed by Bartolomeo Ammannati (1511 - 1592) was built in Florence in 1569 (Figure 103). As revealed by the investigation following its 1944 destruction and preceding its reconstruction – the shape of the arch was verified as catenary, but it was turned by 90 degrees. It is not sure how the shape was established, but it is clear that the catenary curve was not used appropriately in structural terms, as it should be turned by 180 rather than 90 degrees to act in pure compression (ibid., p.189-191).

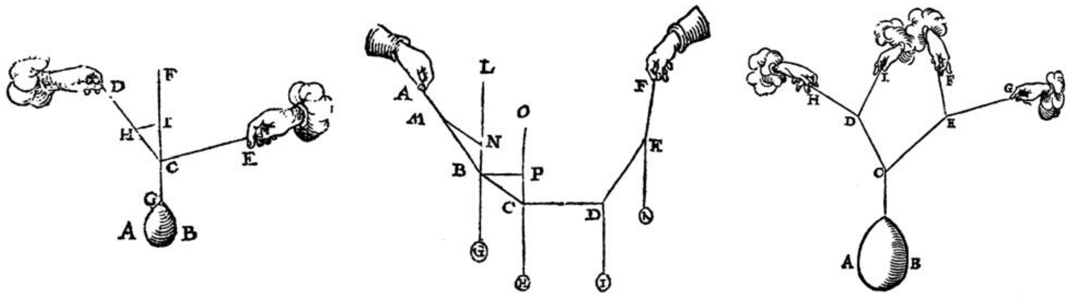

Figure 102
Simon Stevin, 1586, first known drawing of catenary arch.

The first known drawing of a catenary arch with weights attached (Figure 102) was made by Flemish mathematician and physician Simon Stevin (1548–1620) in 1586, 17 years after the construction of *Ponte Santa Trinita* (ibid., p.193). In 1676 the English polymath, philosopher, and architect Robert Hooke (1635-1703), formulated the idea of an arch following the catenary: “as hangs the flexible line, so but inverted will stand the rigid arch” (as quoted in Ochsendorf and Block (2014, p.8)). Hooke’s idea was to use this method in order to establish optimised shape for load bearing structures; his first attempt was made during work with Christopher Wren (1632–1723) on the dome of St Paul’s Cathedral in London, built between 1675 and 1720. In 1748 the Italian physicist and mathematician, Giovanni Poleni (1683-1761), demonstrated that the catenary line of thrust lies within the masonry of the dome of St Peter’s Cathedral in Rome, thus the then 100 year old structure was stable and safe. In 1837 Kassel, the hanging chain technique was used to determine the shape for a 16 m diameter dome of a *Giesshauss* (foundry), reducing the thickness in its upper two-thirds to 175 mm. The method was developed and introduced in Germany by the aforementioned (see p. 150) architect and proponent of the *Rundbogenstil*, Heinrich Hübsch. In the 1890s the German architect Friedrich Gösling (1837–1899) used 2D and 3D chain models to determine catenary shapes for arches and vaults (Addis, 2014, p.35-37).

At the beginning of the 20th century, the Catalan architect Antoni Gaudi (1852–1926) used models consisting of hanging and weighted strings to establish the forms of inclined columns and vaults in the crypt of *Colònia Güell* in Barcelona, constructed between 1908 and 1917, and still unfinished (Figure 103). Gaudi was inspired by the work of Viollet-le-Duc, and similarly to him saw the natural and organic forms as models for a national architecture; however, his own work was much more “organic” in its formal character. In the method that Gaudi developed, the experiment became the form-giving factor; however, its result was not treated as the final project as the process allowed for architectural subjectivity (Moravánszky, 2018, p.73-75).

Figure 103
Antoni Gaudi's hanging model.

Figure 104
Bartolomeo Ammannati, 1569, *Ponte Santa Trinita* in Florence.

While the above methods were based on a single or a series of 2D hanging arches to determine the 3D shapes; the Swiss engineer Heinz Isler (1926–2009) brought the technique into three dimensions. Isler used funicular and pneumatic models; most famously sheets of cloth, either left hanging wet in the freezing temperatures of a winter's night (Figure 105), or soaked in liquid plaster or resin. When hardened, the shapes were inverted and their geometry recorded for use in the final concrete shells, which achieved unprecedented slenderness and elegance. The shells spanned between 30 and 60 metres, at a thickness of between 80 and 100 millimetres – achieving a slenderness ratio of approx. 1:500[81]. This method was used in numerous realised projects, with almost 1400 shell structures constructed in Switzerland alone, including Wyss Garden Centre in Solothurn (1962), supermarket in Bellinzona (1964), factory for F. Kilcher at Racherswil near Solothurn (1965), Garden Centre Florélite in Plaisir (1966), Deitlingen Süd Service Station in Flumenthal (1968), Sicli SA factory in Geneva (1969), and the Aichtal *Naturtheater* (outdoor theatre) near Grötzingen (in collaboration with architect Michael Balz, 1977). The method was used in a number of tennis halls and swimming pools as well, e.g. Heimberg tennis courts (1977), and Health & Racquets Club in Norwich, Norfolk (in collaboration with Copeland Associates and Haus + Herd, 1987 and 1991). In addition, Isler's system was used in hundreds of industrial "bubble" shells spanning up to 55 m (Garlock and Billington, 2014, Chilton, 2000, Chilton, 2010). For Isler, the purity of the natural form-finding process stood above other considerations, such as the irregularities of site and its context; and for this reason, he

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[81] Calculations based on information from Adriaenssens et al. (2014, p.311-315).

believed that shell structures harmonise better with the natural environment than with other constructed forms (Kotnik and Schwartz, 2011, p.189-190).

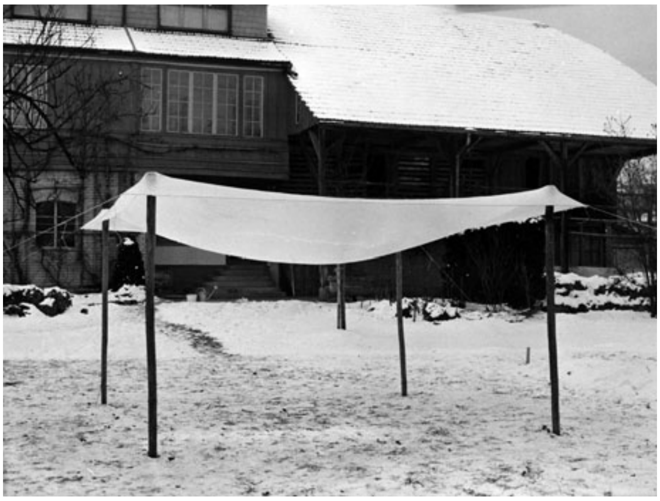

Figure 105
Heinz Isler's 3D hanging model.

Figure 106
Heinz Isler, 1959, 39 possible shell forms and "etc".

This limitation was identified by the German architect Frei Otto (1925-2015). For him "[t]he experiment does indeed lead directly to the form, which in itself has already passed through an optimization model, but a design work can only be seen with reference to the complexity of a building project and to the way the building integrates into its surroundings and into society" (Otto as quoted in Kotnik and Schwartz (2011, p.190)). In 1957, Otto founded the Institute for Lightweight Structures (IL) in Berlin, which moved to Stuttgart in 1964. In the second half of the 20th century, together with his team at IL, Otto developed several form-finding techniques using membrane models, suspended nets, soap films and bubbles, glue, paper, sand, and wool thread machines. The models were measured and surveyed after the equilibrium geometry was established; then analytical calculation methods were applied to the structures (Addis, 2014, p.36-39, Glaeser, 1972, p.7-10). In contrast to Isler, Otto manipulated the boundary conditions of his tensile structures in an attempt to make them more contextual. Otto designed and constructed numerous structures based on his method, which achieved impressive lightness. His most notable projects were the German Pavilion for the Montreal Expo (1967), the Olympic Games Tent in Munich (in collaboration with Günter Behnisch, 1972), *Multihalle* in Mannheim (1975), the Aviary at Munich Zoo (1980), a Palace in Saudi Arabia (in collaboration with Buro Happold, 1985), and the roof structure of the Japanese Pavilion at Expo 2000 in Hanover (in collaboration with Buro Happold and Shigeru Ban, 2000).

The problem of incongruity between structurally optimised form and architectural qualities was addressed by Japanese engineer Mutsuro Sasaki (b. 1946), who specialises in reinforced concrete shells and is known for his collaborations with Toyo Ito (b. 1941), SANAA, and Arata Isozaki (b. 1931). Sasaki built upon and extended the form-finding method of Gaudi, Isler, and Otto; where his main contribution is an integration of predefined "architectural" form and structural optimisation. Sasaki's method, called "sensitivity analysis", is based on an approximation of an initially designed free-curved shape, with rational and structurally optimal shapes. Sensitivity analysis is fully based on numerical algorithms; it avoids analogue form-finding techniques, as these would not be efficient in seeking "local optimum solutions" within a very limited search space, defined by the initially designed free-curved shape. The idea originated in the early 2000s, and as of 2011 five reinforced concrete shells had been realised by Sasaki: Kitagata Community Centre in Gifu, Japan in 2001-2005, with Arata Isozaki; both the Island City Park *Gringrin* in Fukuoka, Japan in 2003-2005, and Kakamigahara Crematorium in Gifu, Japan in 2004-2006, with Toyo Ito; the Rolex Learning Centre in Lausanne, Switzerland in 2005-2009, with SANAA; and Teshima Art Museum in Kagawa, Japan in 2008-2010, with Ryue Nishizawa (Sasaki, 2014). Sensitivity analysis allows the architect much more agency in the design process than the aforementioned form-finding method – the architect-designed free-curved shape is the starting point. However, from the structural optimisation perspective, the pool of possible solutions is much more limited.

In the built examples of Gaudi, Isler, and Otto; where the form was found using the inverted catenary arch method; the designers attempted to apply scientific methodology in the design process. In light of the discussion surrounding hylomorphism, it can be seen as an attempt to propose a ***material-centred*** model for architecture; it introduces and gives priority to the nonhuman agency of the self-organising material system; and it illustrates the possible productive state of entanglement of human and nonhuman actors. One key difference to the hylomorphic model is that the human is not central in the design process anymore. As a result, the distinction between the human and nonhuman actors is blurred, and their relation is symmetrical rather than hierarchical (see p. 138).

This design method, despite being able to produce forms of unrivalled structural efficiency, has not became widely accepted and used in architecture. This was caused by twofold limitations: (i) the method, being based on the inverted catenary arch, produces only curvilinear structural shapes, and is not applicable in all situations; and (ii) due to its reductionist character, the experimental scientific working methodology does not have the capacity to address the complexity of architectural form, and cannot define a kind of general design technique, which considerably limits the design potential (Kotnik, 2011, p.27-29).

Until now, the form-finding method was seldom used to integrate more criteria than structural, i.e. the inverted catenary generating a line of thrust in pure compression. It remains unknown whether and how more criteria, including qualitative factors, could be integrated into this method. Therefore, the abovementioned Otto's postulate to see design work "with reference to the complexity of a building project and to the way the building integrates into its surroundings and into society" has not yet been met by the method.

More specific criticism of the form-finding method claims that it seems to enforce a singular and non-negotiable optimised solution to a given problem, in other words, that this process is deterministic. If this claim holds true, the method would always produce a singular solution to any structural problem in any given situation, and the designer would become obsolete in the process. This criticism was defended by Heinz Isler in 1959 with the presentation of his paper at the first congress of the International Association for Shell Structures (IASS) in Madrid. Isler illustrated his presentation with a sketch of 39 possible shell forms, to which he added an "etc" (Figure 108), in order to give "a hint as to the tremendous variety of possible shell forms" (Isler as quoted in Chilton (2010, p.67)). This formulation coincides with the notion that there exist an infinite number of good enough, as opposed to optimised, solutions to a given problem. The formulation is used in solving multi-objective optimisation problems, and can point towards a potential possibility for integrating more criteria than only structural efficiency into the form-finding method, as postulated by Otto. American scientist Herbert Simon (1916-2001) observed that in ill-structured problems, like design, which cannot be solved by linear reasoning; optimised subsystems should be avoided. Instead, designers should look for solutions "satisficing" each subsystem. The solution then is not a singular solution but a multiplicity of solutions (Simon, [1969] 1996, p.119-121). In the case of form-finding, the designer operates in the design space of these multiplicity of solutions, or Isler's "tremendous variety of possible [..] forms". The objectives that are usually used for structural optimisation are also included in such a design space, and respond to a variety of factors; such as minimisation of material and weight, deflections or dynamic vibrations, and maximisation of stiffness; the designer selects the best trade-off between these factors (Adriaenssens et al., 2014, p.3). The designer can filter the design noise in either a direct or non-direct way, a process that bears resemblance to the multi-objective optimisation known as Pareto front[82]. Felix Candela expressed this working method, and related it to the notation of beauty in explicit terms, by saying in 1973 that "an efficient and economical structure has not necessarily to be ugly. Beauty has no price tag and there is never one single solution to an engineering problem. Therefore, it is always possible to modify the whole or the parts until the ugliness disappears" (as quoted in Garlock and Billington (2014, p.257)). Yet, to what extent qualitative criteria could be integrated into the process still remains to be investigated.

Curved wood in construction

Historically, using curved wood in building construction has been mostly motivated by maximising the structural span. Other factors include cultural and aesthetic reasons, as well as acoustic and light-related performance of

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[82] The Italian academic Vilfredo Pareto (1848-1923) introduced the concept of economic efficiency with two or more objectives in 1906. The concept that introduced a frontier of "Pareto efficient" or "Pareto optimal" solutions in place of a singular solution can be more generally applied in design, for instance, in structural design for the trade-off between the displacement under load and the amount of used material (Benjamin, 2012, p.14)

wooden surfaces. The case of curved wood in construction is a lens that can flesh out the form-material relationship in architecture.

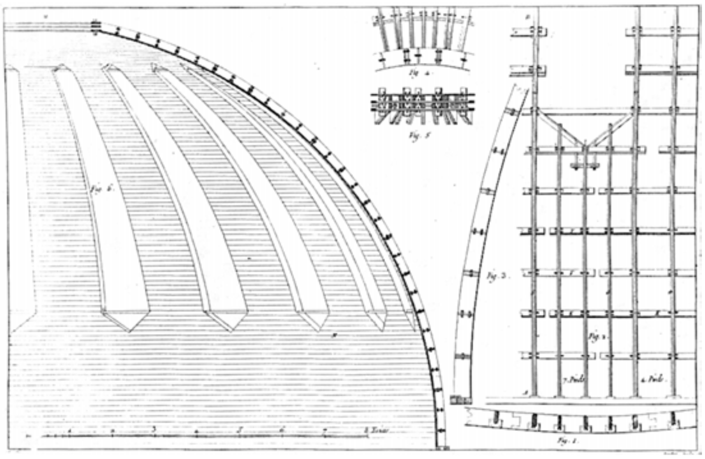

Figure 107

Jacques-Guillame Legrand and Jacques Molino, 1782, *Halle au blé*, Paris.

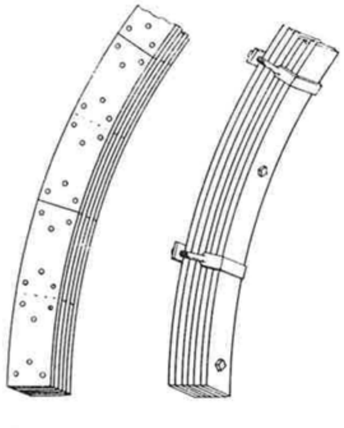

Figure 108

Curved plank structures. Left: de l'Orme's system, 16th century. Right: Emy's system, 19th century.

Using curved timber planks has been of interest to builders, and systematically investigated, since the time of Loenardo da Vinci (1452-1519) and Sebastiano Serlio (1475-1554). It was seen as an economical way of using the material. The main goal was to span more space than was allowed by the limit of the tree size. The first curved plank structures were made of two or more layers of thin timber planks and nailed together in a curved shape. The aforementioned 16th century French architect Philibert de l'Orme, was first to construct curved plank structures spanning up to 19.5 metres. De l'Orme's method was based on stone and masonry principles, using short connected segments, and favouring semi-circular profiles that he believed lent the structures their loadbearing capacity. De l'Orme placed the planks, sawn into arched shapes from wide boards, edgewise in layers (Figure 88, Figure 108 left).

These experiments had been neglected for nearly 200 years, when the French architects Jacques-Guillame Legrand (1743-1808) and Jacques Molino (1743-1831) picked up de l'Orme's ideas and erected a 38 metre wide wooden cupola as part of the *Halle au blé* in Paris in 1782 (Figure 107). In Germany, David Gilly (1748-1808), the father of Friedrich Gilly – one of the initiators of the tectonic discourse (see p. 150), published the first comprehensive German work on curved-plank structures in 1797 (Hahmann, 2006, p.1502-1506). In 1800, David Gilly used a French timber roofing method, stemming from de l'Orme's method, for a military gymnasium in Berlin (Frampton, 1995, p.64). The same year, and using the same method, hydraulic engineer Franz Ernst Theodor Funk constructed six spans of the 96-metre-long Weser bridge (*Bunte Brücke*) near Minden. In 1805, lecturer at the Rostock Academy, Jacob Christian Gustav Karsten declared the parabolic shape as the strongest for roofs. This work was further developed by Royal building surveyor of Bavaria, Johann Michael Voit (1771-1846) and architect Johann Andreas Romberg

(1806-1868), who recommended an inverted catenary shape for curved plank rafters in 1850 (Hahmann, 2006, p.1506-1509).

In 1809, German architect and engineer, Friedrich Wiebeking constructed a 42-metre span bridge over the Alz River in Altenmarkt using a laminated timber cross section for the first time. Made with boards bonded together on site, the structure was extraordinarily slender, achieving a 1:155 ratio between the beam height and span. Unfortunately, inadequate bracing and lack of weather protection for the timber did not allow the bridge to stand for long. In 1823, French engineer and colonel in the engineering corps, Armand Rose Emy (1771-1851) made fundamental improvements to de l'Orme's method. By laying the boards on top of each other flat and bolting them together (Figure 108), he achieved extraordinarily long spans, e.g. 21 metres in the Libourne barracks hall. Emy even designed a wooden arched structure of tremendous slenderness, spanning 100 metres (Steurer, 2006, p.94-95).

Figure 109

Assembly hall of King Edward College, Southampton, 1860.

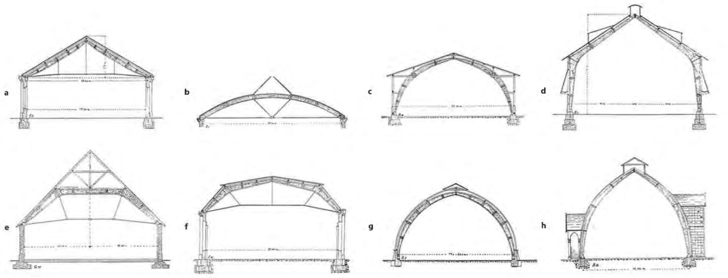

Figure 110

Hetzer AG catalogue of glulam structurs, early 20th century.

French engineer and art of building and construction professor at the Engineering and Military School in Metz, Paul Joseph Ardant (1800-1858) strictly distinguished the behaviour of masonry from that of iron and timber, and also was first to use the theory of elasticity in the analysis of curved plank arches. His 1847 publication initiated the decline of this type of structure by stating that the assembled curved plank structures had less than half of the ultimate strength of solid curved timber elements; and that timber structures, in the long term, can be safely loaded only to 1/8 of their ultimate strength (Hahmann, 2006, p.1510-1514).

Ardant's work coincided with the development of a new technology – glued laminated timber (glulam). The oldest extant example of glulam timber used in construction is the assembly hall of King Edward College in Southampton from 1860 (Figure 109). Otto Hetzer (1846-1911), following a 20-year experiment and testing period, patented a curved glulam beam (Figure 110, Figure 111, Figure 112) in 1906 (Steurer, 2006, p.100-103, Müller, 2000, p.21-26). In 1942, after the introduction of water-resistant phenol-resorcinol adhesive that allowed for external use, glulam beams prefabricated to specification became the industry standard. They were utilised everywhere that long spans – longer than available material – and/or curved wood, were concerned. This solution is not without its downside, as it utilises toxic chemicals, adhesives, and a substantial amount of energy.

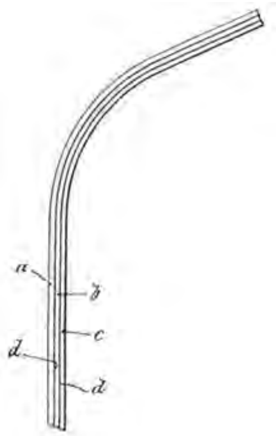

Figure 111

Otto Hetzer, 1906, patent No.197773, curved glue-laminated timber.

Figure 112

Hetzer AG, 1910, crematorium curved glulam timber roof structure, Baden-Baden.

An interesting alternative was shown by Frei Otto. Built in 1975, *Multihalle* Mannheim (Figure 113), the significant gridshell project designed in collaboration with Carlfried Mutschler and Partners, was constructed out of two profile layers of 50 x 50 mm hemlock laths in each grid direction (Figure 114), spanning 60 metres laterally and 85 metres longitudinally. The idea to split the structural section into two laths allowed for tighter bending radii, as these are dependent on material thickness. Effectively, the final structure achieves a 6-metre radius in some places. The laths were first laid flat and then deformed to the desired shape (Figure 115). The final form-finding method was based on preliminary wire models and suspended net models at 1:100 scale, which were subsequently used for close-range photogrammetry. The details were further tediously drafted by hand[83] (Bächer et al., 1978). The architectural programme of the building was specified as an exhibition hall in which other events could also be organised. The design team responded to the brief by proposing a gridshell; which at low cost covered a 7400 m^2 area without internal supports, and provided flexible floorplans with good lighting conditions through the translucent covering. The building proved to be very successful and has survived to this day, beyond its intended lifespan. Originally intended only as a temporary structure for the exhibition, since 1998 it has achieved a protected monument status. The roof membrane had to be replaced in 1981, and in the 2010s some local deformations were reported, leading the municipal authorities to consider potential repairs in 2016 (Chilton and Tang, 2016, p.Chapter 2).

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[83] This closer investigation of the early form-finding method shows how it can be characterised as analogue computing, where the resultant form was computed during the experiment by the interactions within the material system of the physical model. Both Otto and Isler belonged to the generation that trusted more in the suspended chain than in the computer model, as stated by the former, while the latter only ever had one computer in his office, and only used it for word processing (Chilton, 2010, p.67).

Figure 113

Frei Otto, Carlfried Mutschler and Partners, 1975, *Multihalle* Mannheim.

Figure 114

Frei Otto, Carlfried Mutschler and Partners, 1975, *Multihalle* Mannheim. The laths are laid flat.

This alternative approach is based on prioritising the agency of the material system over the human designer in the form-finding process. By this prioritisation, wood achieves strength from the double-curved roof shape; its grain is not compromised, but follows the flow of structural forces. As a result, the slenderness ratio of the loadbearing element, or the amount of material used per square metre of structure, is still difficult to beat. However, this indirect form-finding method can be characterised as based on material (adjective) agency, where the actual building material does not play a primary role; as in the case of the direct form-finding method, based on the material's (noun) agency.

Figure 115

Frei Otto, Carlfried Mutschler and Partners, 1975, *Multihalle* Mannheim. The laths being deformed to the desired shape.

When the material's agency is given priority, the quantifiable results are often bewildering and long-reaching. For instance, there are advantages of bending green wood, e.g. it has weaker strength properties so it is easier to bend; it can be bent beyond its proportional limit; and allowing for elastic spring back, it can be dried in the bent position. The disadvantages are shrinkage and drying defects resulting from the drying process (Hoadley, 2000, p.177).

In 2002, Buro Happold and Edward Cullinan designed the Weald and Downland Museum in Sussex, using 4 layers of 50 x 35 mm laths of green oak to span 16 metres. The structure strengthened during the natural drying process. Using oak, about twice as strong as other common timbers, allowed smaller cross-sections of the laths. Therefore, because the bending radius is dependent on material thickness, smaller bending radii limits were possible.

And further, using the material in its green condition allowed the advantage of a lower modulus of elasticity, and bending beyond its proportional limits (Slavid, 2005, p.30, Davey, 2009, p.74-77). Even more radical is the 1988 Richard Burton, Frei Otto, and Buro Happold workshop building in Hooke Park, Dorset, achieving a 15-metre span (Figure 116). The workshop was proposed as an experimentally constructed shell, using round green Norway spruce thinnings – tapering from 180 to 65 mm in diameter – garnered from a local forest. The shell is formed from bent poles connected at the top through lapping bolted joints (Davey, 2009, p.20-21, Cook, 2001, p.168-169). The added value of the project is in finding a use for thinnings, a by-product of silviculture (forest management).

Thinnings are the young trees removed from a forest in order to accelerate the growth rate and improve the wood quality of other trees. The practical closeness of trees planted in a cultivated forest is dependent on planting costs, response to thinning, markets for material removed in the thinning process, the future impact of quality considerations on the logs, and forest health implications (Shmulsky and Jones, 2011, p.265). One research (Kellog and Kennedy as cited in Shmulsky and Jones (2011, p.264)) proves that the initial narrow spacing and later thinning strategy made the remaining trees twice as expensive as planting to a wider spacing, unless there was a commercial market for the thinned material. The product of thinning, juvenile wood, is considered inferior in quality to normal wood. Its strength is up to 50% lower due to low density resulting from thin cell wall layers, shorter cells, and a high microfibril angle. That angle affects directional shrinkage as well; the longitudinal shrinkage in thinnings from green to oven dry amounts to 2%, while the average value for longitudinal shrinkage for other wood is negligible and does not exceed 0.2%. This may cause radial cracking, as juvenile and other wood are usually present alongside each other and are not sharply delineated in the cross-section of a tree, but gradually vary from ring to ring. Juvenile wood is unsuitable for wood composite panels as it increases thickness swelling and linear expansion. Its low cellulose and high lignin content also makes it undesirable for high-grade paper (ibid., p.107-115). Due to these reasons, thinnings are usually used for firewood or left in the forest as waste. Finding use for this abundant and obsolete material has the potential to revolutionise softwood forestry[84].

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[84] For a discussion on the advantages of using unprocessed roundwood in construction see p. 97.

Figure 116

Richard Burton, Frei Otto, and Buro Happold, 1988, workshop building in Hooke Park, Dorset. Left: Aerial view. Right: Interior.

The Canadian architect, Richard Kroeker designed a series of buildings made of small diameter roundwood thinnings based on Native American architecture and boatbuilding. The Mi’kmaq builders traditionally used green, round, unsawn wood that was bent to take structural advantage from curvature. The indigenous assembly was a spring-loaded, stressed skin structure composed of lightweight and locally sourced parts. While none of the components had sufficient strength on their own, together in the tensioned assembly they became structurally sound. Kroeker’s design process, in projects such as the Pictou Landing Health Centre, took place in real time with reference to the behavioural limits of the material, the anticipated use, and material performance. Local, small-diameter red and black spruce tree thinnings were used (Figure 117). To achieve curvilinear, efficient forms, wood was worked when it was green and flexible (Kroeker, 2013, p.475-476, Cavanagh and Kroeker, 2005, p.139).

Figure 117

Richard Kroeker, 2007, Pictou Landing Health Centre, Trenton, Nova Scotia, Canada. Left: Components. Right: Erected structure.

The design processes applied in the above projects by Otto, Buro Happold, or Kroeker do not comply with the definition of hylomorphic architecture. The main difference with this definition lies in the elevated role of material and material's agency in the form-giving process. As mentioned before, the case of the *Multihalle* can be characterised as guided by material (adjective) agency; where the form was determined by a process resembling the scientific method, by means of inverting hanging models, and the designer could only indirectly manipulate the form by changing its boundary conditions. The cases of the Weald and Downland Museum, the Hooke Park workshop, and the Pictou Landing Health Centre can be characterised as guided by material's (noun) agency. Wood properties (such as the modulus of elasticity in the particular green condition) and forest management technology (producing thinnings as its by-product) directly influenced the built form. Besides some cultural accomplishments, such as the continuity between indigenous and modern techniques in the case of the Pictou Landing Health Centre, the projects all achieved unrivalled material efficiency and substantial savings in used energy.

Definition of material in architecture in relation to wood

As discussed in previous sections, "material" (noun – material's agency) and "material system" (adjective – material agency) play a key role, and take an important position in the non-hylomorphic ***material-centred*** design process. The words "matter", "material", "mother", "measure", "making", and "manufacturing" share the same Vedic Sanskrit root *mā-*; where *mātrā* meant material and also dimension, *mātr* – mother, and *māna* – to build (Moravánszky, 2018, p.32). Interestingly, both the Ancient Greek word used by Aristotle for matter – *hylē*, and the Latin word *materia* that Cicero (106 - 43 BC) used to translate *hylē,* also meant "wood" or "lumber" (Preus, 2015, p.239).

Also discussed earlier, the hylomorphic model defines "matter" as a potentiality rather than an actuality; the implication of this is that it passively submits to the "form" or the "idea" (see p. 105). In the English language the noun "material" is defined as the matter from which a thing is or can be made[85]; or the elements, constituents, or substances of which it is or can be composed[86]. This definition of material assumes its passive role. Things can be made "from" or "of" it; which directly follows the hylomorphic definition and the hierarchy it suggests. This definition does not directly apply to: the role of wood in the discussed projects by Buro Happold (p. 174) or Kroeker (p. 176), the role of concrete when the flexible formwork was used, or the material systems in the work of Gaudi (p. 166) and Otto (pp. 168 and 173). Similarly, it does not apply to the role of wood in the experiments presented in Part I. Can a material that produces a bond or a shape by itself, or includes a structural connection as its feature, submit to this definition? Are the things –

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[85] https://en.oxforddictionaries.com/definition/material

[86] https://www.merriam-webster.com/dictionary/material

connections, shapes, structures – “made from” or “composed of” wood, or “made by” wood? This thesis suggests the latter alternative.

Architectural theory in the early 21st century started to shift focus towards a redefinition of material and its role in architecture and construction. In the previous century, from the 1970s until the 1990s, architectural discourse had problematized history and philosophy rather than materiality. In the 2000s the focus of this discourse was shifted towards “the real”. This was caused on the one hand by rising ecological concerns, and on the other by the post-postmodern need for realism, amplified by the post-digital need for quantifiable techniques and evaluation. Under the banner of “digital materiality”, substantial effort has been put towards integration of digital or robotic fabrication into the design process. It is arguable whether is it fully legitimate to say 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, p.14). However, there has been good progress in this synthesis during the last decade. As of today, the impact of the digital on the material realm cannot be ignored. As noticed by Picon, the concept of information shapes our ideas about materiality in the same fashion as concepts of energy shaped it during the Industrial Revolution, and concepts of movement shaped it during the Scientific Revolution (Picon, 2010a, p.143-144).

Emerging fields of material science, such as nanotechnology, change the form-matter relationship. Material became the object of design – this process in itself is not new, but it gains a new momentum today. The main goal is to design and manufacture materials with exceptional properties. Engineering problems that were, in the past, solved by means of structure, are currently sorted out at the material level. That turns around the traditional role of materials in design: rather than playing a passive structural role, they are responding and becoming more active. The boundary between material and structure, or matter and form, is blurred. Picon brings the car bumper example, which evolved from a structural protector to an energy absorber that was enabled by the development of energy absorbing composite materials (Picon, 2010a, p.159).

Using these ***ontological*** aspects of materials as design resources requires a process of ***reframing*** the metaphysical understanding of materials’ role in design. Philosophy in the 20th century provides a possible way of reformulating the form-matter relationship for design disciplines. This reformulation has potential to define a new ontology of wood in architecture.

Mid-20th century philosophy started to question the concept of hylomorphism. In the 1950s Martin Heidegger, in his aforementioned (see p. 101) essay *Der Ursprung des Kunstwerkes (The Origins of the Work of Art)*, criticized hylomorphism as being insufficient – the fusion of form and matter is additionally controlled by the purposes served by the thing: ‘[the] serviceability is never assigned and added on afterwards to beings’ (Heidegger, [1950] 2002, p.10). The material choice in design is informed by this serviceability: ‘[for] the jug, the ax, the shoes, [...] form determines the arrangement of matter and prescribes [...] the kind and the selection of the matter rather than merely is the result of a distribution of matter' (ibid., [1950] p.10). In 1964 Gilbert Simondon, in *L'individu et sa genèse physico-biologique*, criticised hylomorphism as based on a hierarchical relationship where form is superior to matter and is not concerned with the transformative processes. In his doctoral thesis (1958), Simondon defined 'the technicality of an object' as 'an intermediary between form and matter' (Simondon, 1958, p.84).

This intermediary condition is explained with an example of the composition of an adze; where Simondon points to 'the progressive heterogeneity of tempering at certain points', a result of the transformative process that distributes the properties across the tool. He reflected that, '[t]his tool is not merely a block of homogeneous metal shaped according to a particular form', but it is 'made of a metal whose make-up varies at different points', which is instrumental in the functioning of the tool (ibid., p.84). A heterogeneous material is diverse in character or content[87]; or more specifically, in this case, possesses a gradual change of material properties. The state of being heterogeneous is the quality of an object that does not allow characterization of it as a material in the strict sense, as it also bears some characteristics of a structure. Consequently, '[t]he tool is not made of matter and form only'. The dualism of matter and form is transcended by the manufacturing process: '[t]he tool retains within it the result of the functioning of a technical ensemble. The production of a good adze requires a technical ensemble of foundry, forge, and tempering' (ibid., p.83-84). This formulation, based on observation of the gradual change of material properties and its consequences for the functioning of an object, eludes the dichotomies of form-matter or form-structure. Moreover, it couples "the technicality of an object", understood as "an intermediary between form and matter", with "a technical ensemble". This coupling is a starting point for Chapter 6.

In 1980, the thread of the meaning of heterogeneity of materials was picked up by French philosophers Gilles Deleuze (1925-1995) and Felix Guattari (1930-1992) in their seminal *Mille plateaux: Capitalisme et Schizophrénie (A Thousand Plateaus: Capitalism and Schizophrenia)* (Deleuze and Guattari, [1980] 2005). Deleuze and Guattari evoked the examples of two building materials: concrete and wood. In the former example they found similar gradual changes of properties, as Simondon did in the composition of an adze. Concrete is a "heterogeneous matter", and the distribution of reinforcement bars corresponds to the distribution of the structural loads:

> Not only is concrete a heterogeneous matter whose degree of consistency varies according to the elements in the mix, but iron is intercalated following a rhythm; moreover, its self-supporting surfaces form a complex rhythmic personage whose "stems" have different sections and variable intervals depending on the intensity and direction of the force to be tapped (armature instead of structure). [...] It is no longer a question of imposing a form upon

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[87] https://en.oxforddictionaries.com/definition/heterogeneity

a matter but of elaborating an increasingly rich and consistent material, the better to tap increasingly intense forces (ibid., [1980] p.329).

Is reinforced concrete a structural system or a material? The concept of “armature instead of structure” refers to the abovementioned tendency to blur the boundary between form and matter, or to solve engineering problems at the material rather than structural level. Embracing and harnessing material heterogeneity turns around the traditional role of materials in design – from passive form-takers to more active structural systems.

When discussing Simondon, Deleuze and Guattari adopted his notion of ‘the technological insufficiency of the matter-form model, in that it assumes a fixed form and a matter deemed homogeneous’. They concluded, ‘Simondon demonstrates that the hylomorphic model leaves many things, active and affective, by the wayside’ (ibid., [1980] p.408). In order to visualise an alternative approach, they brought the example of ‘the variable undulations and torsions of the fibres guiding the operation of splitting wood’, which is ‘a question of surrendering to the wood, then following where it leads by connecting operations to a materiality instead of imposing a form upon a matter’ (ibid., [1980] p.408). While this operation of splitting wood should not be literally understood as a prescription for a design method, it points to a new direction, where a spectrum of potential in “following the material” becomes available after transcending the hylomorphic model.

Is wood a material?

By extension of the analogy of reinforced concrete, wood may be perceived as a structural system[88] rather than as a material. Moreover, a piece of wood eludes the current definition of material: it has a heterogeneous and anisotropic structure, and also a naturally grown shape. It is a thing on its own, and so it is ***more than*** “the matter from which a thing is or can be made”. This insight has potential to profoundly change our design approach. This realisation means that we can no longer conceive wood traits and natural behaviour as defects or problems to overcome; on the contrary, they can become internalised by design, whose job is then to harness their potential.

This philosophical conceptualisation of wood coincides with the scientific notion that wood is not a material but can be characterised as a lignocellulosic biomass composed of cellulose, hemicellulose, and lignin. In this scientific notion, a material is defined as ‘a substance with consistent, uniform, continuous, predictable, and reproducible properties’ (Rowell, 1990, p.3); which does not apply to wood. For this reason, wood is often omitted in university courses in material science (ibid., p.3). One paper, authored by Roger M. Rowell from the Forest Products Laboratory at the USA Department of Agriculture, Forest Service, characterised sheet wood

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[88] Structural system can be defined as an arrangement of interconnected elements that resists and transfers loads. Both the micro- and macro-structure of wood can be seen as such.

products; such as flakeboards, particleboards, or chipboards; as composites. Level of uniformity of these composites depends on the degree of decomposition and flaking of wood – the smaller the chips or particles, the closer to being "a true material":

> The perception that wood is not a material as defined is easy to understand. Wood is anisotropic (different properties in all three growing directions of a tree), may contain sapwood, heartwood, latewood, earlywood, juvenile wood, reaction wood, knots, cracks, splits, checks, and may be bent, twisted, or bowed. These defects occur in solid wood but need not exist in wood composites. The smaller the size of the components in the composite furnish, the more uniform become the properties. For example, chipboard is less uniform than flakeboard, which is less uniform than particleboard, which is less uniform than fiberboard. Fiberboard made from lignocellulosic fiber can be very uniform, reproducible, consistent, etc., and is very close to being a true material as defined above (ibid., p.3).

Material science in the 20th century recognised the existence of materials as belonging to a larger continuum, spanning from subatomic to macroscopic levels. In 1968 the British metallurgist and theorist of science, a participant of the Manhattan Project, Cyril Stanley Smith (1903-1992) noted, 'I predict the development of some new principles of hierarchy that will enable the effective resonance between molecule and organism to be explored: possibly the way to this may be pointed by the emerging science of materials, [...] complex enough to demonstrate a kind of symbiosis between scales, the interwoven importance of both atoms and aggregates' (Smith, 1968, p.644). In order to "explore the resonance between molecule and organism" Smith postulated a liaison between scientists and craftsmen, where 'each must supply something lacking in the other' (ibid., p.644), proposing a reconciliation, as it were, between the two groups in question (see p. 120). This postulate also involves reversing the process of "abstraction of matter" (see p. 113); when material engineers, in order to design new materials with specifications needed for a given service, have to look at the relationship of a material's composition and properties.

This formulation was extended into the field of architecture, with the particular example of wood as construction material, by the architect and researcher Michael Hensel (b. 1965). Hensel identified four domains of active agency within his proposed notion of performance-centred design, where material organisation is one of them; however, it forms a complex together with another domain – spatial organisation (Hensel, 2010). This complex was defined as 'a synthesis of the various scales and their complex interactions' (Hensel, 2011, p.4). Under this framework, wood's internal structure must be understood in relation to environmental conditions affecting tree growth. Higher in the hierarchical organisation system, material behaviour is determined by material properties and environmental conditions. This in turn has to be harnessed by architectural design, which is the basis of the 'instrumentalisation of material behaviour as performative capacity' (ibid., p.8).

The understanding of "performative capacity" in the complex of the "material and spatial organisation" is closely related to Lodoli's 18th century concepts of material *indole* and situated performance (see p. 144); or musical instruments where the form results both from the desired performance of the instrument and the characteristics of the materials. In these approaches, material properties, structure, form, and function are not treated separately, but are convergent. They replace the traditional form vs function, and structure vs material dichotomies with a synergetic relationship. Hensel illustrated this synergy with the example of a traditional Islamic screen-wall *mashrabiyya*[89] (Figure 118), which achieves multifunctionality[90] by addressing various requirements at different levels of the organisational hierarchy of the “material and spatial organisation complex”. Wood releases moisture during the day as temperatures rise, thus cooling the interior; the latticework provides privacy and shadow, and allows air to enter into the room. The ratio of balusters to interstices, as well as of the baluster’s surface area to its volume, are optimised to control the rate of air exchange, cooling and humidification. The layout and size of interstices lend themselves to create different patterns, driven not only by aesthetics but also to prevent glare at eye level while compensating the air exchange rate by providing wider openings above (Hensel, 2011, p.14-15). And further, the entire spatial organisation of projecting oriel windows enclosed by *mashrabiyyas* cater to catch winds from three sides and provide shadow underneath. Thus, various scales within the inseparable “spatial and material organisational complex”, from the cellular level, to the level of the building component, are employed to address various design tasks, mitigated by local environmental conditions.

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[89] *Mashrabiyya* – wooden grille or grate used to cover windows or balconies (Petersen, 2002, p.177).

[90] In this context, multifunctionality is opposed to specialisation when a component or a building part is designed to address a singular requirement.

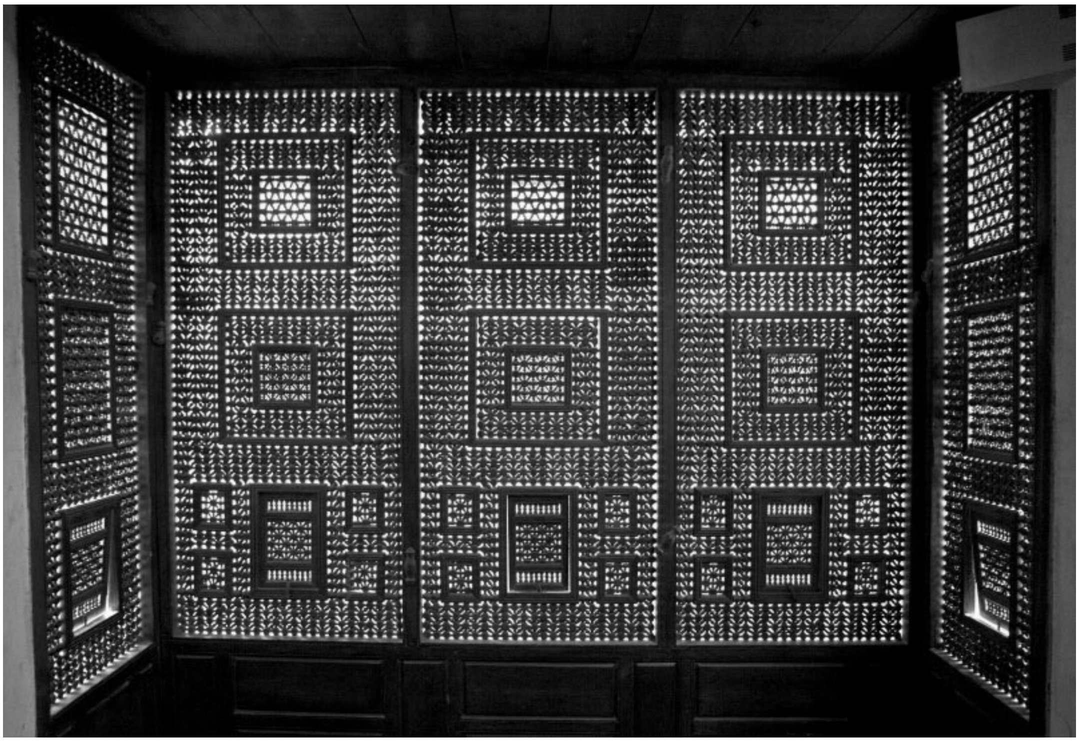

Figure 118
Mashrabiyya, al-Suhaymi House, Cairo, Egypt.

Hensel's concept, of seeing the "spatial and material organisation complex" as working at nested levels corresponding to various scales, fits in with earlier concepts that saw structures, both natural and manmade, as based on hierarchical scale-levels and their interactions. For instance Roderic Lakes (b. 1948), an engineer and material scientist, observed that structure may be present at many size scales in various man-made and natural materials; and that this characteristic determines, in large part, these materials' properties. Lakes likened this make-up to that of the Eiffel Tower in Paris. The Eiffel Tower can be described as a third-order hierarchical structure, composed of small girders forming larger components. This strategy was predicated on the ease of construction, as well as on a perceived structural advantage. Lakes claimed that wood, being a cellular solid, is one example of material with an internal structural hierarchy. Understanding this hierarchy is not only useful for the description of materials, but can also bring benefits to newly-designed materials because this organisation of the internal structure, in some cases, can result in new possibilities, such as simultaneous high strength and high toughness, which are usually mutually exclusive (Lakes, 1993). In the realm of architectural and structural design, Bjørn Sandaker (b. 1954), who specialises in the relationship of structural and architectural design, observed and theoretically described the difference between global and local structural form. The former can be characterised as a structural system, while the latter is a structural component (Sandaker, 2008, p.33-37). Sandaker divided materials into two categories: bi-directional – working well both in compression and in tension (steel, reinforced concrete, or wood), and mono-directional – working well only either in compression or in tension (masonry, cast iron, or textiles). He observed that materials belonging to these categories, play different roles at two different scales of form (ibid., p.37-53).

These concepts bear some potential for constructing a theoretical framework for ***material-centred*** architecture. Acknowledging that materials have structure on their own and this structure is inseparable from the larger “material and spatial organisation complex”, as postulated by Hensel, can widen the spectrum of the “structural form” in the extension of the model proposed by Sandaker. This can open new possibilities for the materials to address design problems on various levels of this spectrum, as the example of *mashrabiyya* demonstrated.

The projects presented in Part I hint at this direction. The *BackToBack* project demonstrates how the swelling of wood from green, which depends on the cellular level structure of the material, can be harnessed to produce a bond. The *Swelling Vault* project demonstrates how the isotropic dimensional instability of wood, also dependant on the cellular level structure, can be harnessed at the level of organisation of the parts (wood blocks), in order to produce three-dimensional shapes. The *Y-timbers* project demonstrates how the naturally grown shapes of wood can be used as components of larger structures, where advantage is taken from the innate strength of natural forking. All three examples can be characterised as ***material-centred*** objects, predicated on the concept that wood is “more than material”, and that its structure can be seen in relation to the design task. Through this approach, it was possible to use the undesired characteristics as design strategies. These undesired characteristics of wood are shrinkage on drying, movement related to changing moisture levels, and naturally grown forking shapes; and they do not allow wood to comply with the material science definition of material as ‘a substance with consistent, uniform, continuous, predictable, and reproducible properties’.

SUMMARY AND DISCUSSION

This chapter set out to reveal patterns of attitudes towards materiality in design through a study of the history and theory of architecture. The objective was to position the approach to wood in design as presented in the Part I experiments.

It was identified that the principal dominating attitude towards materiality in design can be described as hylomorphic, based on the Classical formulation of the relationship of form and matter by Aristotle. It was outlined how this formulation resulted in gradual processes of separation: of design and its product, design and the act of construction, and the professions of design and engineering. Two aspects of material use of in design were distinguished, and labelled as ***ontological*** and ***representational***. These followed the distinction of two different aspects of architectural form that was originated by Alberti. Material innovation in architecture and the proposed ***reframing of wood construction*** was characterised as a synthesis of the ***ontological*** and ***representational*** aspects of construction materials.

Based on the thorough analysis of the predominant hylomorphic model of the form-matter relationship in architecture, a new ***material-centred*** model was discussed. Key to this model is the concept of material agency. Various historical material innovators; as well at the cases of fabric formwork, form-finding, and using curved wood in the history of construction; were discussed in relation to this model. The conclusion was that, in the ***material-centred*** model, wood should not be perceived as a material in relation to wood construction; but rather as a structural system in itself, with a capacity to actively engage with the process of construction.

Positioning material-centred design in the history and theory of architecture

Using attitudes towards material agency as an indicator, it is possible to categorise periods in the history of architecture with respect to primacy of form and primacy of matter.

The “primacy of form” category gathers the periods characterised by idealism and supressed material agency. As outlined in this chapter, in the light of Plato’s philosophy, “form” is synonymous with “idea” (see p. 105), and in particular Classical, Renaissance, and Modern architecture prioritise form over material agency. This chapter also demonstrated how later historical events, such as the Industrial Revolution, reinforced and stabilised this idealistic approach.

Despite this dominating status of the idealistic approach, there are period examples in the history of architecture when material agency gained more importance. These examples can be allocated closer to the “primacy of matter” category. The examples are related to material innovators, such as Gothic cathedral builders, or Baroque engineers in the Age of Enlightenment and Scientific Revolution. These approaches would not submit to the definition of ***material-centred*** design as presented in this thesis. However, taking the attitude towards material agency as the key indicator, it is possible to find affinity between these approaches and ***material-centred*** design.

A speculative diagram (Figure 119) illustrates how the proposed notion of ***material-centred*** design can be positioned in the theory of architecture:

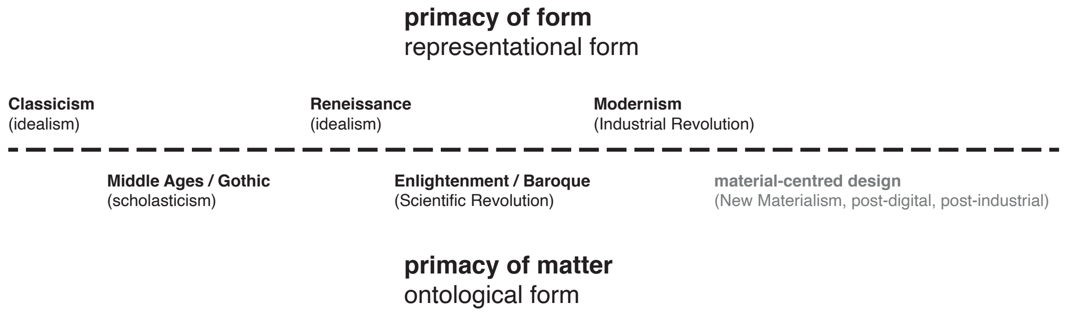

Figure 119

Speculative diagram showing positioning of the notion of *material-centred* design in architectural history and theory.

Wood as a structural system

In the proposed ***reframing*** of wood construction, the acknowledgement of wood as structural system rather than as a material may lead to design innovation where certain concrete gains can be achieved. Seeing wood as having a structure on its own, and that can be used as a design potential, opens design opportunities where material defects and weaknesses could become its strengths. Wood variability, dimensional instability, anisotropy, heterogeneity, etc., could be seen as these design potentials. The method of this ***reframing*** is based on utilising these material properties that can be characterised as performative, or in other words, as serving to affect an (i) action, (ii) change, or (iii) actuality. The three experiments presented in Part I present a spectrum of this performative potential: (i) from producing an inseparable joint by way of action, i.e. shrinkage from green in the

BackToBack project; (ii) through a change of form by way of moisture induced anisotropic movement in the *Swelling Vault* project; and (iii) to the application of the naturally grown shapes that results in the actuality of the constructed object in the *Y-timbers* project.

These performative materials can be seen in the continuum of the “spatial and material organisation complex” as outlined in the previous section. In this “complex”, as presented by Hensel (see p. 181), various design problems, such as internal air quality, are addressed at different size scales. By extension, within the proposed ***reframing*** model, it is possible to address the problem of form at the material change (ii), or actuality (iii) level, or the problem of structural joints at the level of material action (i).

At present, building materials are not classified as performative and non-performative. In the current handbooks on materials for architects and designers, materials are either presented as uncategorised (Lyons, 2014), or divided as grown, oil-based, and mined (Lefteri, 2014), or as stone, limes and aggregates, fired, unfired, organic, and metals (Slocombe, 2012), etc[91]. In general, wood is regarded an organic material, which reflects 19th century scientific thinking. In the age of depleting resources, Holger König, a member of the United Nations Environment Programme, proposed to revise the system by which materials are distinguished and divided the construction materials according to their origin: mineral, vegetable and animal. That reflects the discussion about the origins of energy initiated by the anti-nuclear movement, which led to the distinction between two types of energy: renewable and non-renewable (König, 2011, p.18). By analogy, classifying wood as a performative material would be the first step towards ***reframing wood construction***.

Wood, if understood as a performative material, could also be perceived as sharing some characteristics of “smart materials”; however, it does not fully comply with the strict scientific definition.

In 1988, a precise and narrow definition of smart materials was proposed by Iqbal Ahmad, director of the Materials Science Division of the United States Army Research Office. In acknowledgement of growing confusion in the scientific circles regarding the looseness of terms (“smart”, “adaptive”, and “intelligent”); Ahmad postulated a definition of “smart materials” as:

> A system or a material which has built-in or intrinsic sensor/s, actuator/s and control mechanism/s whereby it is capable of sensing a stimulus, responding to it in a predetermined manner and extent, in a short/appropriate time and reverting to its original state as soon as the stimulus is removed (Ahmad, 1988, unpaginated).

Wood does not fully comply with this definition. While it could be seen as having built-in sensing, actuation, and control mechanisms; it does not always

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[91] Architects, in general, take great freedom in classifying building materials, e.g. authors of one paper suggested a classification based on levels of familiarity rather than physical characteristics, and divided material as unfamiliar, familiar, contemptible, unknown, and knowable (Cardwell et al., 1997).

respond in a short or appropriate time, nor does it revert to its original state when the stimulus is removed.

Further definitions of smart materials were provided by NASA as “materials that *remember* configurations and can conform to them when given a specific stimulus”; or by the *Encyclopedia of Chemical Technology* as “objects that sense environmental events, process that sensory information, and then act on the environment” (as quoted in Addington and Schodek (2005, p.8-9)). In 2005, the American researchers Michelle Addington and Daniel Schodek (1941-2013) extended these definitions and proposed five characteristics of smart materials in the context of design and architecture: (1) immediacy – real-time response, (2) transiency – response to more than one environmental state, (3) self-actuation – intelligence is internal to rather than external to the material, (4) selectivity – response is discrete and predictable, and (5) directness – the response is local to the activating event (ibid., p.10). For this broader formulation, wood could be seen as fulfilling most of the criteria set up for smart materials; however, e.g. the immediacy of response (1) is difficult to achieve at the scale of a building component. In my own experiments presented in Part I, it took months (*BackToBack*) or days (*Swelling Vault*) for the material to expand its dimensions.

Chapter 5: Perspective 3 – Design and technology. Technological framework for material innovation in wood architecture

The previous chapter outlined the relationship of form and matter in architectural theory. It identified this relationship as critical for the formation of the discipline, and at the same time limiting for material innovation. This current chapter, discusses a different relationship, seeking a new framework for material innovation in wood construction, where construction technology plays the key role. The departure point is the observation made by Simondon that an adze "is not made of matter and form only", but its make-up is also a result of the "technical ensemble of foundry, forge, and tempering"; thus, elevating the role of technology in the production of form (see p. 179). This formulation is remote from standard architectural theory, which is concerned with the formal taxonomy of buildings more than with the technological processes behind them.

The previous chapter concluded that the hylomorphic model (see pp. 105, 108, 178), which originated in Ancient Greek philosophy and permeated the theory of Vitruvius, was formative for the field of architecture. It provided the founding myth based on the alleged petrification of timber construction into the Doric order; which, in the form of skeuomorphism, became the central metaphor for the role and use of materials in design. This chapter proposes a different alternative, the bio-cybernetic metaphor, which has the potential to be more operational for material innovation.

The chapter sets out to discuss a new periodisation model for wood construction, which integrated more criteria than building types taxonomy, or the form-matter relationship. Instead, these new criteria are based on the cybernetic models that describe systems in terms of their energy-matter-information relationships. This model is then superimposed over a periodisation model of design methodologies. Through this, a new perspective of wood construction is formulated. This shift of focus from form-matter to energy-matter-information opens new ways of thinking about material innovation in architecture.

In the cybernetic model, information is identified as the key component of the systems. To this end, the role of information technologies in architecture is outlined and discussed.

PERIODISATION OF WOOD CONSTRUCTION AND DESIGN METHODOLOGIES

In 2009, Christoph Schindler (b. 1973) proposed a new periodisation model for wood construction in his doctoral thesis *Ein architektonisches Periodisierungsmodell anhand fertigungstechnischer Kriterien, dargestellt am Beispiel des Holzbaus* (2009) at the ETH in Zurich. Schindler used the case of timber construction development to discuss the interactions of processing and fabrication technologies with architecture through the history of construction. His periodisation model was not based on formal, typological, or taxonomic analogies; but rather it took a systemic view, based on interactions among the components of a system. Schindler referred to the Austrian biologist Ludwig von Bertalanffy (1901–1972), one of the founders of the general systems theory (GST), and the American mathematician Norbert Wiener (1894-1964), one of the founders of cybernetics, as the main influences of his conceptual framework.

In the 1920s, von Bertalanffy introduced the concept of "system"[92] in biology, by which life phenomena were explained through the examination of interactions at all levels of an organism's organisation. These systems, based on constant exchanges of matter and energy between the organism and its surroundings, were called "open systems". At the end of the 1940s, he extended his approach to a universal model applicable in all sciences, today known as GST. For von Bertalanffy the most general principles of systems were the same for inanimate natural objects, organisms, mental or social processes, etc. Von Bertalanffy broke away from the reductionist view in science, where the properties and behaviours of components of systems were considered in isolation, disregarding the relations between them. In GST the relationships between individual phenomena at the microscopic level are studied as a system in order to investigate laws for macroscopic emergent

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[92] System as understood in GST was defined by Hall and Fagen as "a set of objects together with relationships between the objects and between their attributes" (Hall and Fagen cited in Schindler (2009, p.32)).

phenomena such as complexity, equilibrium, feedback, and self-organization (Schindler, 2009, p.31-32).

Norbert Wiener approached machines with the same method that von Bertalanffy used to describe biological systems. While von Bertalanffy described “open systems” based on exchanges of matter and energy of living organisms, Wiener developed the concept of “closed systems” in the context of automated warfare in the Second World War. In his seminal 1948 book *Cybernetics: Or Control and Communication in the Animal and the Machine*, Wiener coined the term “cybernetics”, in relation to self-regulating mechanisms in the new scientific discipline of a general theory of machines and their interactions with humans. At the core of cybernetics lay the feedback mechanism; which, for instance, could be used to predict the trajectories of the USA Air Force defence missiles and the opponents’ aircraft. The cybernetic “system” was modelled on the human brain which was understood as a system of switches, control loops, feedback loops, and communication nodes; whose inputs and outputs were predictable and controllable. Central to this was the new concept of “information”; which, Wiener defined as a third category, next to matter and energy. Wiener’s cybernetics together with von Bertalanffy’s biological open systems were consolidated into GST; which today has become the generally accepted theoretical framework of technological systems in scientific literature, with the three categories of matter, energy, and information (ibid., p.33-34).

Schindler’s periodisation model explained the integration of wood fabrication with manual, industrial, and information technologies. In a cybernetic fashion, it was based on the relation between the three categories of matter, energy, and information; in each respective period. Schindler identified three waves of technology in the history of wood construction: (1) *hand-tool technology*, (2) *machine-tool technology*, and (3) *information-tool technology*. While Schindler’s model did not relate to design methods, it can be juxtaposed with the model of generations in design methodology, as presented by John Broadbent (2003) from the University of Technology Sydney (UTS). Broadbent distinguished four phases in the development of design methodologies: (a) *craft methods*, (b) *design-by-drawing methods*, (c) *hard system methods* (HSMs), and (d) *soft system methods* (SSMs).

Hand-tool-technology and craft methods

In the first wave of Schindler’s model, *hand-tool technology* (1) dominant in the preindustrial era, the main operator of energy-matter-information was man’s hand and the main intellectual achievement was the design of tools. Tools operated by hand followed the growth direction of the tree and the fibre direction of the wood. Natural shapes of wood were incorporated into the design. Parts playing the same role in the building structure, even when sharing the same dimensions, were not interchangeable. For instance, every component in a half-timbered building had to be individually adapted to fit other components (ibid., p.91-125). Broadbent’s *craft methods* (a), which were based on trial-and-error modifications over centuries, and where the 'product information was stored in the form of the product itself' (Broadbent, 2003, p.3), were the appropriate design methodological response for this phase.

Machine-tool technology and design-by-drawing methods

The second wave in Schindler's model, *machine-tool technology* (2), was connected with the Industrial Revolution of the 19th century. Machines were substituted to perform repetitive physical operations, while a human operator processed information. The design of the interconnection of power source and machine tool was the crucial intellectual achievement. This interconnection probably happened already in the 13th century. Around 1230, French architect Villard de Honnecourt depicted a water-powered reciprocating saw in his sketchbook. It has not been confirmed that this sawmill existed, as the first documented sawmills date from the 14th century. Water- and wind-powered sawmills were improved over the following five centuries. The first truly standardised timber was produced in the 18th century, after the invention of parallel saw blades. Also, when a more cost-effective iron production method was devised by Abraham Darby (1667–1717) in 1707, the replacement of wooden sawmill machinery parts with iron ones allowed the production of timber components with unprecedented speed and precision. Furthermore, James Watt's (1736-1819) improved Thomas Newcomen's (1664-1729) steam engine in 1782. The connection of the steam engine with wood-processing machines appeared in 1802, simultaneously in the UK, where the planer machine was introduced by Joseph Bramah (1748-1814), and in the US, where the gate sawmill was introduced by Oliver Evans (1755–1819).

These inventions and developments immediately doubled the output of sawmills; in the USA output increased by 100% in the 1830-40s, by 350% in the 1840-50s, and by 50% in each of the following decades. The working process was adjusted not to the potential of the hand, but to the potential of the machine. As the machines produced parts with precision and repeatability, the parts became interchangeable (Schindler, 2009, p.127-181). As discussed earlier (see p. 123), mechanisation resulted in homogenisation of wood, mass production of wood-based products, and standardised building components. The *machine-tool technology* (2) was well facilitated by the hylomorphic design process, with its central method of representation by drawing. This corresponds to Broadbent's second phase, *design-by-drawing methods* (b). Interestingly, Broadbent added that '[d]rawing has limited capacity to represent dynamic physical relationships' (Broadbent, 2003, p.3); which is for instance exemplified by the *Swelling Vault* project, that clearly does not belong to this phase.

Information-tool technology, and hard and soft systems methods

The third wave of Schindler's model, *information-tool technology* (3), began when machines started to replace both physical and intellectual operations. The highest achievement was the interconnection of the power source, the machine tool, and the computer. At present, the wood construction industry is at this stage of development. Critical to this conceptualisation of the third wave is the distinction made between mechanisation and automation. While mechanisation allowed the production of parts with speed, precision, and repeatability; automation allowed for flexible manufacturing. This mode of manufacturing was first introduced already in 1804, with French weaver Joseph-Marie Jacquard's (1752-1834) invention of the Jacquard loom, that used punched cards to control a sequence of operations. By changing the cards, the pattern of the loom's weave was also changed. The Jacquard loom met the criteria of *information-tool technology*, where a machine processed energy (steam or electric power), matter (woollen thread), and information (stored in the punched cards). Man was removed from the creation of the product, and instead became the creator of the process. This automated process was limited to weaving machines until developments in electronic data processing in the first half of the 20th century.

In the second half of the 1940s, American inventor John T. Parsons (1913-2007) developed the first numerically controlled (NC) machine, which used punch cards to control computer-operated servo motors connected with a milling tool. The machine was used for production of helicopter rotor blades. The production of NC woodworking machines accelerated in the mid-1970s, and by the mid-1980s it structurally changed the woodworking industry. Today a variety of computerized systems are offered, including band saws, drills, lathes, nailing machines, and machining centres.

Especially interesting in the context of *information-tool technology* are the so-called machine centres, with automatic tool changers, operating on sheet timber products (milling machines), and on timber profiles (automated joinery machines). Their main characteristic is the ability to produce "one of a kind" parts with the speed and precision of mechanised production. The machining centres are universal machines that can perform multiple tasks, and can be fitted with a variety of tools, such as milling bits, drills, saw blades, etc.; this characteristic opened the way for new potential in industrial production. Schindler points to the fact that in the late 2000s, timber construction started moving away from wood profiles to sheet and plate timber products, such as CLT. It also allowed designers to dispense with grids to locate openings, as doors or windows can be cut anywhere in plate products (ibid., p.183-217).

Broadbent's HSMs (c) and SSMs (d) phases correspond to Schindler's *information-tool technology* (3) wave. HSMs are highly procedural, are rooted in natural science methods, and conform to well-structured problems; so 'they proved largely unable to address the "unbound complexity" of the real world' (Broadbent, 2003, p.4). SSMs, in contrast, are well-suited to ill-defined, or “wicked” problems – the class of problems that most people encounter in everyday life, and are the concern of architectural design (see p. 93). These problems are ‘thoroughly confusing’, and are ‘without solution, only the opportunity to do better’ (ibid., p.6). SSMs are ‘inclusive of all stakeholders’ and introduce ‘the social and psychological domains’ in a problem situation (ibid., p.8).

This formulation bears some potential for the material innovation in architecture in relation to the conceptual framework for ***reframing wood construction***. For instance, the wicked problem: “how a three-dimensional shape can be more efficiently produced from wood”, was addressed in the *Swelling Vault* project by innovative ***reframing***. Rather than improving existing techniques such as laminated bending or milling, this ***reframing*** method employed several stakeholders of the problem situation: the human need to produce a three-dimensional shape, wood and its properties and behaviour, and technology including available tools and computational simulation techniques. Through this widening of the scope of stakeholders, or ***reframing*** the problem, it was possible to devise an innovative technique of bending wood. The computer simulation allowed for predicting three-dimensional outcomes of two-dimensional block patterns. The emergence of the form was dictated by material behaviour; i.e. moisture induced swelling where its main property, the curvature, was not reducible to the properties of its constituent parts. The process, based on dynamic relations rather than individual behaviour, was not linear; and as such it did not submit to design methods other than to those based on computation.

The ***reframing*** of the problem, together with the design methods used, allowed for accessing material properties and behaviours as design resources. These properties and behaviours, when seen through the lenses of Schindler’s *hand-tool* (1) and *machine-tool* (2) technologies, would commonly be considered setbacks. The ***reframing*** of the problem allowed for not only accepting these setbacks, but also turning them into advantages. The *Swelling Vault* project harnesses the material characteristic usually seen as disadvantageous, i.e. moisture related dimensional instability. The innovative reframing, allowed not only to “even up” or “compensate” for it, but also to turn it into a design strategy. And even more, this strategy resulted in palpable and quantifiable gains – the shape is achieved with minimal environmental impact.

This example, of using SSMs to solve a wicked architectural problem by including technology in the scope of the problem stakeholders, suggests that the third wave of timber construction technological development in Schindler’s model still bears some potential for material innovation. The model can be expanded vis-à-vis the formulation of hylomorphic vs ***material-centred*** design; or in other words, the problem of application of material characteristics in design. From this perspective, *hand-tool technology* (1) has the capacity to integrate material characteristics into the design; while *machine-tool technology* (2) has not. The evidence of this is that, under the framework of *hand-tool technology*, it was possible to use hand tools in connection with material traits (e.g. grain direction), or to incorporate the naturally grown shapes of wood in design. Contrary to that, for *machine-tool technology* (2) there are demands for standardisation and homogenisation of material (e.g. wood-based panels), as discussed already. On closer inspection, some characteristics of *information-tool technology* (3) take after *hand-tool technology* (1), i.e. it enables the use of non-standardised and non-interchangeable components. What follows is the reliance on logistical systems of labelling, and the allowance for all-wood joints, as opposed to the metal connectors introduced during the *machine-tool technology* wave. By extension, the role of material properties and behaviours in design also bear resemblance in these two periods (1 and 3). In other words, while *machine-tool technology* (2) tended to minimise the effects of material properties and behaviours, a new potential has been opened by *information-tool technology* (3) in this regard.

LEARNING FROM BIOLOGICAL SYSTEMS: EVOLUTIONARY MANAGEMENT IN WOOD CONSTRUCTION

The periodisation model of wood construction presented by Schindler resonates with the approaches that strive to model the fields of design and technology on biological systems. This is not surprising given that the conceptual framework of the periodisation model is based on the General Systems Theory (GST), which originated in the field of biology. The approaches that strive to model the fields of design and technology on biological systems are called “biomimetics”, “bionics”, or “biomimicry”. The term “biomimetics”, to describe the process of transferring ideas from biology to technology, was coined by the American inventor, engineer, and biophysicist Otto Herbert Schmitt (1913–1998) in the 1950s and 1960s. He defined biomimetics as “biology + technology” and applied it in the field of engineering. In the English language, it is defined as ‘relating to or denoting synthetic methods which mimic biochemical processes’[93]. In 1960 the term “bionics”, to denote the science of systems which have some function or characteristic copied from natural systems, was coined by an American medical doctor and USA Air Force colonel Jack E. Steele (1924–2009). In 1997 an American author and innovation consultant Janine M. Benyus (b. 1958) coined the term “biomimicry”, widening the scope of biomimetics to the field of design. Since then biomimicry has been limited to imitating the morphological aspects of the biological world (Vincent et al., 2006, p.471, Mazzoleni and Price, 2013, p.xix). While it is typically concerned with the exploration of the animal and the plant kingdoms in a search for models that could be translated to design; its dictionary meaning suggests it could be used in a wider sense: ‘the design and production of materials, structures, and systems that are modelled on biological entities and processes’[94]. Following this definition, this section outlines the implications of the biological metaphor in the field of design at the epistemological level, as related to the “production of systems that are modelled on biological processes”. It is at this more general level, that the relationship between biology and technology is

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[93] https://en.oxforddictionaries.com/definition/biomimetic

[94] https://en.oxforddictionaries.com/definition/biomimicry

being sought, rather than in any direct formal or structural mimesis. The metaphor is discussed as a base for the proposed ***reframing wood construction,*** and as a potential alternative to the dominating hylomorphic model, based on the metaphor of skeuomorphism (see p. 130).

Biological vs technological systems

While biology and technology, or nature and engineering, are very different in their organisation, modes of operation, etc., they both are driven by the resolution of technical problems. British biologist and pioneer of biomimetics, Julian Vincent (b. 1943), compared biological and technological systems based on how they solve technical problems at different size scales with respect to their use of information, energy, time, space, structure, and substance (Figure 120). Conversely to the technological systems, the biological systems use information and structure rather than energy to solve technical problems. In living organisms, information stored in the genetic code is used to drive specific reactions at the cellular level and self-assemble structures (Vincent et al., 2006, p.474-478).

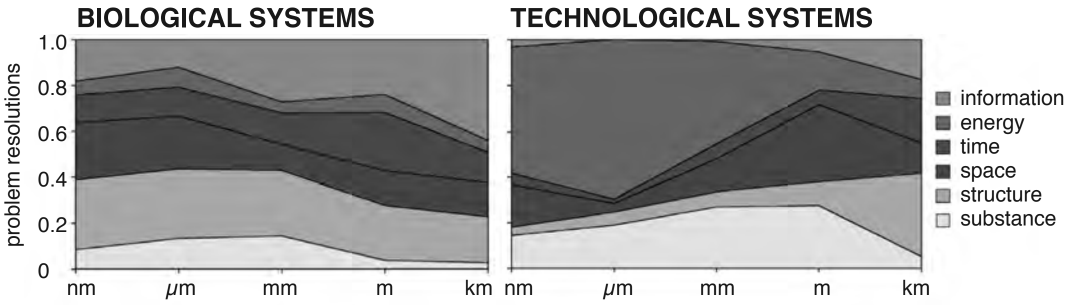

Figure 120

Comparison of biological effects and engineering TRIZ[95] solutions arranged according to size / hierarchy. Technology uses energy as the primary driver for solving engineering problems across the nanometre to metre scales, with information playing a smaller role. In contrast, biological systems use energy sparingly (about 5% of the cases), relying instead on information and structure. The similarity in solving problems between these two systems is only 12%.

Vincent argued that technological systems “kill [...] the information” of raw materials, with a substantial expense of energy to make this material “random with no intrinsic information” and “ordered with imposed shape and structure” for the final product. Conversely to nature, where “shape is cheap but material is expensive”; evidence showed that in engineering “material is cheap and shape, resulting from energy-intensive processing, is expensive”. Vincent pointed to our ability to tap abundant and cheap fossil fuels,

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[95] TRIZ is a theory of inventive problem solving developed in the Soviet Union in the1950s.

beginning in the Industrial Revolution, as a key turning point in our relationship with nature. The scarcity of material in nature leads to several rational solutions, such as blurring the distinction between structure and material, multifunctional use of material, hierarchical structural organisation, or elimination of waste. There is definitely something momentous we could learn about resource management from nature[96].

This insight is a meaningful epistemological contribution to technology; as it strives to introduce criteria and principles in order to regularise the science of biomimetics, and thus make it more accessible to technologists (ibid., p.481). The comparison of biological and technological management systems is based on systems thinking. It uses cybernetic categories (information, energy, time, space, structure, and substance) that can be roughly mapped to the categories used in Schindler's periodisation model (energy, matter, information). Therefore, following this system of inquiry, it would be possible to set goals for wood construction technologies based on the observation of biological systems.

In the German speaking world, the concept of systems thinking was originated by German biochemist, ecologist, and a member of the Club of Rome, Frederic Vester (1925-2003). Based on systemic and cybernetic approaches, Vester contrasted 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, p.160). This formulation transcends the framework of resilience. While resilience is the ability to absorb and release stresses, no gains are sought after being exposed to the stress; the main goal is to "bounce back" and to remain unaffected. Quite the contrary, Vester's 4th rule, reflecting the bio-cybernetic stance, takes inspiration from the martial arts strategy of exploiting the opponent's force. This insight, as a metaphor, opens a new perspective when applied to our understanding of materials in construction.

Applying principles of evolutionary type management to wood construction means finding solutions based on material behaviour and self-organisational capacities, rather than enforcing form over material. This approach promotes manufacturing and construction techniques that are non-wasteful, less energy consuming and toxic, and provides vital alternatives to manufactured wood products in order to overcome the scarcity of good quality and large-dimension timbers. By replacing energy-expensive industrial processes with naturally occurring changes in the material and putting this potential to use; such solutions, when scaled up, would constitute a significant move towards sustainability.

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[96] Julian Vincent in video interview with Susana Soares (Jackman, 2007).

The experiments presented in Part I can be directly related to the evolutionary type of management, which "exploits existing forces in accordance with the ju-jitsu principle, rather than fight against them with the boxing method". Quite literally the forces induced in the *BackToBack* (i) project by shrinkage during drying from green, and in the *Y-timbers* (ii) project by the anisotropic swelling after increased moisture content, were harnessed according to the 4th rule of Vester's bio-cybernetics. The force, which can amount to over a tonne per square centimetre (see p. 34), was harnessed and used to advantage rather than simply attenuated or obliterated. By doing so, the resilient model of interaction with material was transcended. This was made possible due to processing information, rather than applying external energy: information about wood shrinkage (i) and swelling (ii) was used to produce the effects by means of component orientation within the overall system (i, ii), digital simulation (ii), and manufacturing (i). From this perspective, the bio-cybernetic metaphor is relevant to these projects at the operational level.

CYBERNETICS AND THE USE OF INFORMATION TECHNOLOGY IN ARCHITECTURE

The concept of information is critical: in Wiener's cybernetics, in the 3rd wave of *information-tool technology* from Schindler's periodisation model, in Vincent's concept of biomimetics, and in Vester's systems thinking. This section takes a closer look at information technology's application in architecture in relation to cybernetics and systems thinking as outlined in previous sections.

Cybernetics and computational design in the 1960s and 1970s

The use of computer aided techniques in architecture dates back to the 1960s. The earliest experiments used computer power to enable systemic and cybernetic approaches in planning. Greek architect and urban planner Konstantinos Doxiadis (1914-1975) had been interested in computers since the late 1950s, and began developing mathematical models of settlements in 1962. The outcome consisted of "electromagnetic maps" and "cartographatons", which aimed to reveal the "invisible forces" of urban networks. Brothers, Wolfgang (1930-2005) and Eberhard (1921-1997) Schnelle, established themselves as organisational consultants in the late 1950s. Together with a team of engineers, mathematicians, and information scientists; the brothers developed a scientific planning method based on cybernetic premises that they called *Organisationskybernetik* (*organisational cybernetics*). In 1961, using the *Organisationskybernetik* approach, they designed the *Buch und Ton* office space in Gütersloh. This approach to office design became very influential, especially in the UK and USA where it reached its apogee in the 1970s. While originally it promised to create a decentralised, target-orientated office society, as well as a more humane office environment; it is criticized today for two reasons. Firstly, it did not actually establish the employees as equal partners in the work process – the system was focused on company profits (Rumpfhuber, 2011). Secondly, it contributed to the promotion of artificially homogenised interior environments based on statistical averages of comfort and safety, eventually leading to a strict dichotomy between the inside and the outside (Hensel, 2013, p.71-72).

In the 1960s, Russian-British architect and designer Serge Chermayeff (1900-1996), and British architect and theorist Christopher Alexander (b. 1936), criticized the role of architecture for being based on preconceived truths and intuitions, producing obsolete design products. Instead they argued for an analytical and systemic approach towards planning, where the objects of study are "links", "interactions", and "patterns". In their 1963 book, *Community and Privacy: Toward a New Architecture of Humanism*, Chermayeff and Alexander proposed that the electronic computer is capable of managing all the possible combinations; and, although unable to invent, is certainly able to identify patterns. In 1962 Alexander, together with American engineer Marvin L. Manheim (1937-2000) at MIT, developed a computer program called HIDECS (Hierarchical Decomposition of Systems); where the ideas about using a computer to calculate relationships between design elements were to be implemented. Alexander methodically identified many parameters related to highway design projects. The computer program then sorted out interactions between various requirements and clustered them into a logical graph representing compatibilities between these requirements. The translation process into a space diagram, though, was still done by hand. Alexander claimed that HIDECS could be used to solve any design problem because the program computed relationships between "any collection of things whatever" (Alexander as quoted in Steenson (2017, p.31)) and not their actual content. However, towards the end of the 1960s he stopped using a computer to calculate these relationships because design problems, which he likened to a "network" or a "language", were too complex (Steenson, 2017, p.30-31).

The experiments of this early period aimed towards changing architecture into a self-correcting and developing science; but were limited in terms of possible input, processing, and output. In 1965, American architect and systems theorist, Buckminster Fuller (1895-1983), and British artist and sociologist, John McHale (1922-1978), conceived *World Games* as a computer model that monitored the current state of the world. It contained compiled statistical material, maps and diagrams, and considered everything from natural resources to manufactured goods and services. The model was accessible to everyone and handled enormous amounts of information. Some thirty years before the appearance of the internet, it was clearly doomed to remain a mere speculation.

A similar spirit dominated the 1960s research by Nicholas Negroponte (b. 1943) at MIT. He looked into environmental management with a computer programmed to see the physical environment as an evolving organism rather than as a designed artefact. This effort resulted in the development of URBAn5, a CAD program able to produce 3D model drawings. Likewise Hungarian-French architect, urban planner, and designer; Yona Friedman (b. 1923); proposed monitoring urban phenomena and visualising these via "effort maps" – which would be changing all the time. Further, they would allow the user to design and position a house (selected from a systemised repertoire) showing all the possible alternatives, benefits, inconveniences, and costs.

In the 1960s and 1970s, the first computerised environmental analysis programs started to appear. The most notable was the Package for Architectural Computer Evaluation (PACE), written in Fortran, and developed by Thomas Maver in 1970 at Architecture and Building Aids Computer Unit Strathclyde (ABACUS) in the Department of Architecture and Building Science, University of Strathclyde. PACE was focused "not on optimization of a single parameter but on production of a comprehensive and integrated set of appraisal measures". The program interacted with designers, who could submit modified designs for "re-appraisal"; and, through the "repetitive man/machine interaction", arrive at the "optimum" design solution. At this time, digital building performance analysis tools were the main interest of research into using computational design techniques in architecture; for instance: the first use of computer graphics building appraisal was in 1966, the first integrated package for building performance appraisal appeared in 1972, and the first computer-generated perspective drawings appeared in 1973 (Kolarevic, 2005, p.196).

In the 1970s, Frei Otto and the Institute for Lightweight Structures (IL), in cooperation with the Institute for the Application of Geodesics in Building (IAGB) at the University of Stuttgart, used a "large computer CDC6600" and a program written in Fortran to determine cable forces, cable lengths, and the spatial coordinates of joints in the form finding method. The computed coordinates were used to check the data previously empirically determined in hanging chain experiments. The first application of this method was in 1972, for the structural analysis computation of Olympic Stadium roofs in Munich (Hennicke and Schaur, 1974). The details were further tediously drawn by hand.

Second wave of computational design in the 1990s

In the 1970s and 1980s, another family of techniques was developed – computer-aided design (CAD) systems – geared towards the acceleration of drafting and modelling techniques, which became mainstream in architectural computer use. This was accompanied by a weakening of interest in cybernetics and computational design.

In the early 1990s, New Zealand architect Mark Burry (b. 1957) laid the foundation for parametric design while working on the continuation of Gaudi's project for the Sagrada Familia church (1882-ongoing) in Barcelona. Burry realised that the CAD software, existing at the time for architects, was not sufficient for the extremely geometrically complex Gaudi project; and, similarly to Gehry Partners, turned towards the software used in the car and airplane industry, as well as "scripting" (Burry, 2011, p.28-32).

Also, in the early 1990s, Japanese architect Makoto Sei Watanabe started developing software programs to simulate ecological systems, applying their logic to design. By 1994, Watanabe completed the first of his programs: the so-called "induction cities", capable of generating models of city blocks in a computer. In the *Sun-God City* and *Wind-God City* projects (1995), conceptual cities were generated; where natural forces – sunlight and wind – participated in the design process. However interesting it was to give natural forces the agency in the design process, the projects remained reductionist; for they dealt with only one phenomenon to generate entire cities. Later in the 2000s, Watanabe transferred these ideas into an architectural scale as the "induction design" program. This resulted in built projects like *Shin Minamata Mon* (2005), which integrated form generation with structural optimisation; but, as the structure was a monument rather than a building, no other architectural criteria were added in the process (Watanabe, 2002).

In 1995 British architect, researcher, and educator John Frazer, who started experimenting with computers in the late 1960s, published *An Evolutionary Architecture* (Frazer, 1995). Frazer postulated architecture is a form of artificial life; where design is a process of an evolutionary development responding to the user and the environment with the use of computer processing power. In the 1990s and 2000s, exponentially growing computational power combined with new developments in computer programming – like object-oriented programming, stochastic methods, and genetic algorithms; and new engineering tools – like finite element modelling (FEM) and computational fluid dynamics (CFD). These allowed the implementation of tools for optimising thermal or lighting performance of buildings on the one hand, or generating prediction scenarios for whole regions on the other. An early example of the former category can be illustrated by the 1995 *Project ZED* in London by Future System architects and Arup engineers, where the aerodynamic envelope was computationally optimised. The latter category includes projects such as the *REGIONMAKER* (2002) or *KaisersRot* (2001). *REGIONMAKER* was a sophisticated software devised by Dutch architecture and urbanism practice MVRDV. It was capable of analysing enormous amounts of data from many sources in order to generate scenarios for whole regions, based upon optimising algorithms (Maas et al., 2002). *KaisersRot*, developed by the researchers at ETH in Zürich and KCAP Architects and Planners, optimised land use and evolved sustainable patterns of plot layouts from a "collection of intelligent objects with changeable parameters". Similar to the experiments of Negroponte or Friedman, the computer became an enabler for the bottom-up approach.

Computation, digital fabrication, and digital materiality in the 2000s-2010s

Computers in the 2000s acquired the capacity for generating geometries for construction components. The result is coding used to command the NC or CNC (computer numerically controlled) machines. A method called "the digital chain" was devised; where digital tools, at all process stages, are linked together in order to ensure the uninterrupted flow of information (see for instance Rudenauer (2005)). This method was based on dividing structures into smaller parts that then became interconnected and acted together. A change in the overall geometry resulted in a change in the whole system, where all components had to change to adapt to the new geometry. The "parametric" models were based on building components that were identical from the point of view of construction and structure, but differentiated in the final form according to the defined parameters. This allowed the principles of "mass customisation" to be implemented in architecture; that is to produce a series of individualised products at the price point of mass production (compare "one of a kind components" in Schindler's 3rd wave *information-tool technology*, p. 195). That method, using the strategy known in the industry as "file-to-factory", became a generally accepted mainstream approach for high-profile projects by the end of the decade, where it is used to construct free-form geometry.

Shigeru Ban's Centre Pompidou in Metz (2010) belongs to the large-scale structures in wood that could not be constructed without computational design. Complex form generation and production became the main aspiration of the "file-to-factory" method in construction. In parallel, Computer Aided Design (CAD) programs evolved into Building Information Modelling (BIM) programs, "a shared knowledge resource for information about a facility forming a reliable basis for decisions" (BSA, 2012). Industry Foundation Classes (IFC), an object-based file format, has been introduced in order to provide a standard for data exchange between stakeholders in the design process, but the overall framework for cooperation still requires further development.

The results of "parametric design" in architecture are often accused of being reductionist, as they belong to the realm of an abstracted computational model, and mainly deal with quantifiable problems. A challenge for computational design is how to handle complex and conflicting information; the interplay of external forces belonging to incompatible disciplines do not always provide quantifiable information.

By mid-decade of the 2000s, another group of research-oriented architects started to appear. They strove to converge the digital and analogue domains in architectural design, promising to efface the reductionist image of computational design. Fabio Gramazio and Matthias Kohler, both architects and professors at the Chair for Architecture and Digital Fabrication at the ETH Zürich, proposed the term "digital materiality" as a synthesis of the digital and the material, where the material operational constraints and characteristics become incorporated in the design and manufacturing processes leading to "unforeseen ventures in conceiving architectural designs" (Gramazio et al., 2008, Gramzio and Kohler, 2012). Gramazio and Kohler pioneered using industrial robotic arms for construction of buildings and components. In experimental projects such as *The Sequential Wall* (2008, Figure 121), the manufacturing techniques used, by the purpose-programmed robot, bear similarities to pre-industrial artisanship which integrated the characteristics of the material together with the production process.

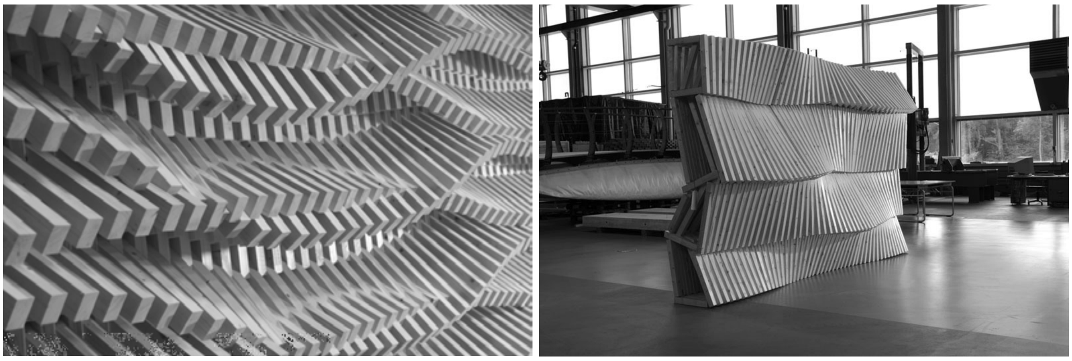

Figure 121
Gramazio Kohler Research, 2008, The Sequential Wall.

The architect and researcher, Achim Menges, together with the teams from the Institute for Computational Design and Construction at the University of Stuttgart and Harvard University's Graduate School of Design, researched the converging of material and assembly knowledge in design. The investigation was carried out through designing and building several experimental structures and pavilions. Wood is one of the materials under this investigation (see also p. 53). In his own words, Menges presents "an alternative design approach and associated computational design tools that aim at understanding wood's differentiated material make-up as its major capacity rather than a deficiency" (Menges, 2009, p.66). Menges distinguished the following three threads in his computational design research with wood (Menges, 2012, p.40-42).

(1) "Activating anisotropy" – where a number of projects investigated the utilisation of differential stiffness of wood used in compressive surface systems. Computational models were developed that aligned the microfibril angle – at microscopic level, with the geometry of digitally fabricated parts – at macro level, in order to accommodate the mean force vectors.

(2) "Employing elasticity" – where various projects were investigated to explore the computability of wood bending. **(a)** Wooden gridshells were constructed by utilising robotically fabricated members of varying cross sections together with laser-cut cladding elements; assembled flat, they rose to a predefined double-curved shape using computer-controlled actuators. **(b)** The gradual kerf depth, length and frequency were investigated in order to control curvature. As a result, a 5-metre tall hyperboloid prototype was assembled. **(c)** The *ICD/ITKE Research Pavilion 2010*, at the University of Stuttgart (Figure 122), sought innovation in regard to integrating skin and structure into one mono-material and then employing elastic behaviour. **(d)** Other projects investigated differentiated vacuum lamination and even biochemical manipulations.

(3) "Instrumentalising irregularity" – *Microstructural Manipulation* research, at Harvard University Graduate School of Design, looked at the microscopic level of the material itself. The system used a laser cutter to precisely remove earlywood that reduced the self-weight of timber without substantially reducing the load-bearing capacity. As a result, an undulated, lightweight compressive surface structure was constructed.

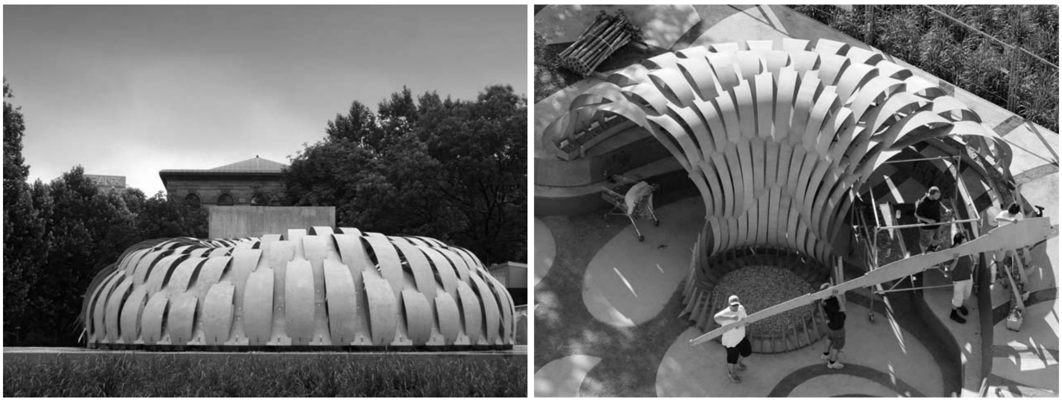

Figure 122
ICD/ITKE Research Pavilion, 2010, University of Stuttgart. Left: Finished structure. Right: Under construction.

The abovementioned work was an important inspiration for this thesis. The use of material properties of wood such as anisotropy, elasticity, or irregularity, as well as the application of computational design methods to activate these properties in the form-giving process, aligned the work very closely with the objectives of this thesis. However, the similarity ends there, as most of the projects use very thin wooden components. While this thinness reinforces the material's responsiveness to external stimuli, such as moisture, these components could not be easily applied structurally in "real scale" construction, and the techniques could not be directly scaled up. It is important to add that, more recently, the team in their Urbach Tower project employed overlapped double layers of 90 mm CLT in alignment with the characterised above "activating anisotropy" (1) strand (see p. 54); thus used construction material of more standard structural thickness. Also contrary to the project of ***material-centred*** design, this work can be seen as prioritising formal over pragmatic solutions.

Yves Weinand (b. 1963), architect and structural engineer, and a professor at the IBOIS Laboratory for Timber Construction at the EPFL in Lausanne, operates in "real scale" construction. Weinand himself positions his work in Schindler's 3rd wave *information-tool technology*, where computational design and digital manufacturing play the pivotal role for tectonic quality. IBOIS carries out research into timber structures by applying bending, weaving and folding techniques (Buri and Weinand, 2011, p.56, 60-62). Bending and weaving uses the elastic qualities of wood, integrating the mechanical and structural principles of textiles applied at full building scale. This approach derives from an observation of existing textile techniques and fabrication methods, and combines with the study of timber rib shells, woven wood fabrics, structural analysis, and optimisation processes (Weinand, 2009). Folding increases the stiffness of a thin plywood panel, hence extends its use from cladding to a load-bearing element. The chapel for the deaconesses of Saint-Loup in Pompaples by Localarchitecture (Danilo Mondada and Antoine Robert-Grandpierre) and EPFL IBOIS (Yves Weinand and Hani Buri) built in 2008 (Figure 123) was the first building designed and constructed using this method (Buri and Weinand, 2011, p.61-62).

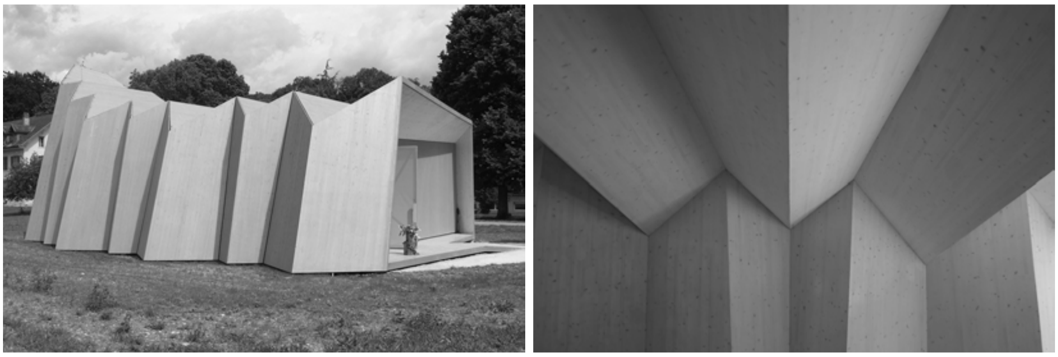

Figure 123
Localarchitecture (Danilo Mondada, Antoine Robert-Grandpierre) and EPFL IBOIS (Yves Weinand, Hani Buri), 2008, Chapel of St.-Loup, Pompaples. Left: Exterior view. Right: Interior.

Future directions

Integration of computational design and digital fabrication techniques with the material's information – its properties and behaviours – is a step on route to ***reframing wood construction*** following the ***material-centred*** model and the metaphor of bio-cybernetics. Two small scale experimental projects with wood embody this integration: (1) Hironori Yoshida's *Digitized Grain* and (2) Ryan Luke Johns and Nicholas Foley's *Bandsawn Bands*.

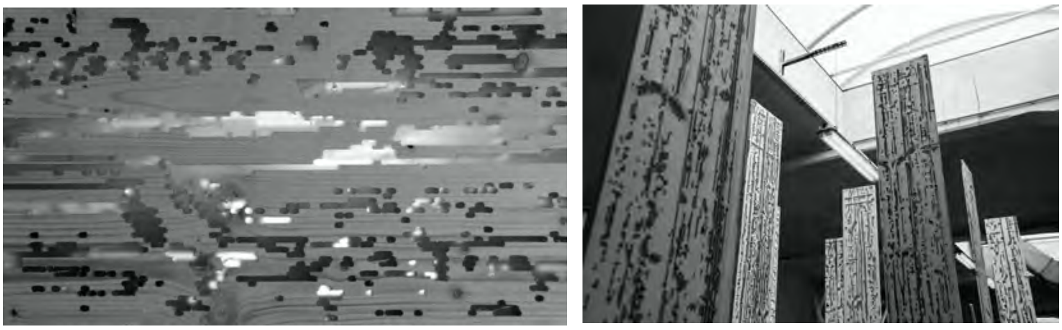

Figure 124
Hironori Yoshida, 2013, Scan-To-Production. Left: Close up. Right: 2013 Milano Design Week exhibition.

Yoshida's *Digitized Grain* (1) project sought to translate the craftsman's interaction with natural materials into a fully automated and interactive *Scan-To-Production* process (Figure 124). In 2010 and 2012 this process was employed in two art installations, where wood grain directly informed CNC toolpaths. The result was exhibited at Milano Design Week in April 2013. While the pieces displayed were characterised as art, according to the author the process could be used in product design, furniture, and interior applications. In the process the wood grain was digitally scanned, image-processed, and transferred into motion paths for a CNC machine. As a result, the grain pattern of wood was replaced by polyester resin based on pixel-colour analysis. The Scan-To-Production process, employing digital scanning and robotic fabrication, took material irregularities as design input and produced "hybrid material" (Yoshida and In, 2013).

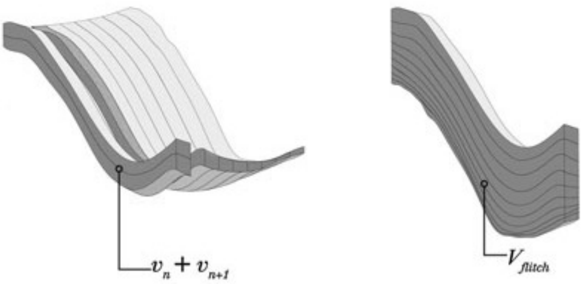

Figure 125
Ryan Luke Johns and Nicholas Foley, 2014, *Bandsawn Bands*, concept.

Figure 126
Ryan Luke Johns and Nicholas Foley, 2014, *Bandsawn Bands*, robotic fabrication.

For the *Bandsawn Bands* (2) project, Johns and Foley devised a technique for efficient fabrication of free-form surfaces based on grain features of wood flitches, and employed it in a chair design (Figure 127). Their project reverses the commonplace logic of digital manufacture: 'rather than transferring material [...] from a curved tree into dimensional lumber which is then re-machined into curvilinear digitally designed geometry', the authors 'take the tree as the starting point for design and move directly to digital fabrication. This leap in the production sequence enables more sustainable material efficiency while simultaneously conferring the natural aesthetic advantage of *beauty's found geometries*'. The devised technique uses a robotically operated bandsaw (Figure 126) to cut series of strips following the curvatures which are rotated and laminated; and approximate the doubly-curved, digitally defined geometry (Figure 125). As a result of the 'close relationship between available material and designed geometry', the process yields 'practically zero-waste' (Johns and Foley, 2014, p.18). Interestingly, some tool operations are closely connected to material features, e.g. the robot cut speed is programmed as a value proportionate to the curvature of the cut, ensuing from the grain pattern. As a result the method is 'one of few woodworking techniques which are explicitly not subtractive, but transformative' (ibid., p.25).

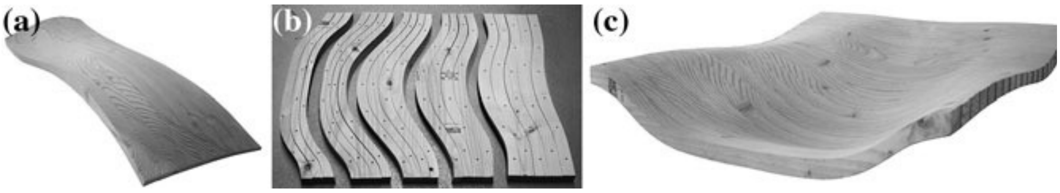

Figure 127
Ryan Luke Johns and Nicholas Foley, 2014, *Bandsawn Bands*.

Both projects (1) and (2) used advanced computational design and digital manufacturing techniques which are guided by material information – wood grain features. When scaled up, these techniques could have profound impact on methods of wood manufacturing. For instance, (1) the gradual replacement of certain portions of wood with resins, or other materials, could change wood properties, such as strength or stiffness, to perform a given structural task. This operation resembles Simondon’s “progressive heterogeneity” of the material composition of an adze (see p. 179), and Deleuze and Guattari’s “heterogeneous matter” and “armature instead of structure” (see p. 179). Another advantage of the direction, presented in the *Bandsawn Bands* (2) project, is the potential for minimising waste in digital manufacture. This time, it is an exemplification of “connecting operations to a materiality” as proposed by Deleuze and Guattari (see p. 180).

Chapter 6: Conclusion

The thesis set out to investigate whether there are more effective ways of using wood in construction. At the outset of the project, it was proposed that seeing material characteristics as design resources may lead to different architectural tectonics. These tectonics were understood as prescriptions regarding the proper use of materials, and more sustainable practices. This approach was named ***material-centred*** design.

In the development of the thesis, the first step was to carry out three experiments in wood construction focused on the relationship among ***material-centred*** design, digital technologies, and environmentally-responsible construction (Chapter 2). A study of material characteristics of wood helped decide to centre the experiments around anisotropic shrinkage and swelling, and naturally grown shapes of wood.

These experiments helped identify that some aspects of architectural form can be dictated by material traits, behaviours, composition, or shape. Further, they also challenged current approaches to architectural aesthetics, construction tolerances, sequences, and the role of kinetics and time in design. The experiments became a basis for theoretical perspectives, the main part of the thesis.

The first perspective looked at motivations, processes, and methods of material innovation in architecture (Chapter 3). It identified a method of innovation, proposed by Buchanan (1992), based on “repositioning” a problem in question, as relevant in relation to the methods used in the experiments. In this thesis, the repositioning is called ***reframing***. This ***reframing*** is based on a shift of perspective that allows design problems to be solved by using inherent material properties. The design problems solved were: connections of wood pieces in components, shaping double-curved surfaces, and bracing post and beam structures. These problems then were resolved by finding appropriate wood properties and behaviours, and using them as design resources. This method resulted in solutions that minimised use of external energy and toxicants. However, application of this method also produced solutions that could not easily be characterised in terms of architectural design theory. The resultant forms were negotiated between design intent and the wood system’s capability to take shapes (this was most evident in the *Swelling Vault* experiment).

This realisation served as a perspective to scrutinise architectural history and theory (Chapter 4). Patterns and attitudes towards materiality in design theory were studied in order to position the approach to wood in design as presented in the experiments. It was identified that much architectural theory is based on the hylomorphic concept that originated in Aristotle’s philosophy, and became a founding metaphor for architectural theory. This concept hinges on the duality of form and matter, where form is prioritised. The forms resulting from the experiments do not comply with the hylomorphic model’s frame of reference. The forms resulting from the *Swelling Vault* project can only be designed within the material constraints of the wood-system, and the designer using Y-shaped timbers must accept the natural variations of the Y-shapes. In all three experiments the designer was required to partially cede some of the control onto the material system.

The study revealed that the hylomorphic model led to separation of design and its product, and also of the acts of design and construction, resulting in two distinct professions of design and engineering. In contrast, the new proposed ***material-centred*** model strives to go past various dichotomies: form-matter, design-construction, digital-material, nature-culture, human-nonhuman, and architecture-engineering. Its result is a new frame of reference for architectural theory, one that allows new design methods to be devised, with a goal of accessing latent and palpable material potentialities.

The study of architectural theory revealed another pattern of material innovation: it emerges in the move from one material to another, and through the synthesis of ***representational*** and ***ontological*** aspects of materials; and it effectively produces a new meaning for a new material. While wood, by no means, can be considered a new material, there is still yet undiscovered potential that could be accessed through this synthesis, one that will result in a new conceptualisation of wood.

This new conceptualisation is based on considering wood as performative material, i.e. one that can (i) produce effect or action, (ii) produce change, or (iii) produce actuality. The three modalities of wood's performativity correspond to the three experiments presented in Part I of the thesis, respectively: (i) anisotropic wood shrinkage from green in the *BackToBack* project, (ii) anisotropic movement related to changed moisture content in the *Swelling Vault* project, and (iii) application of naturally grown wood shapes in the *Y-timbers* project. Going a step further, wood may not even be considered a material at all, instead it may be semantically positioned closer to a building system. This conceptualisation allows problems at the material level to be addressed in line with the concept of ***reframing***.

All three experiments used digital technologies in their processes, and this use of digital technologies was identified as pivotal in the provision for a sustainable environment. To this end, the role of technology in architecture was discussed as the last theoretical perspective on ***reframing wood construction*** (Chapter 5). The historical development of wood construction was discussed through the cybernetic model of Schindler (2009). This model shifted the focus of architectural theory from form-material to material-energy-information categories; and as such, it can be considered ***material-centred***. This new cybernetic metaphor is identified as more operational for material innovation. At this operational level, the thesis advocates techniques that "connect operations" to materiality and by doing so, seek solutions that minimise use of external energy, toxicants, and waste quantity.

The proposed frame of reference change redefines the meaning of wood as a construction material and its cultural performance. The limited predictability of the processes relying on material behaviour and its idiosyncrasy can be seen as design opportunity. Sharing the authorship with, to some degree, unpredictable and uncontrollable material, may seem counterproductive towards achieving design goals. This consideration bears resemblance with the "digital turn" in architecture, that has already questioned the Modernist idea of the standard and the Renaissance idea of the author[97] (Carpo, 2009, p.53). In addition to the aforementioned energy and material savings, the ***material-centred*** process offers a return to the pre-industrial and pre-modern models: the relation between the subject and object of design in the digital chain mirrors the Medieval master builder approach, or the distributed authorship of Wikipedia echoes the Medieval manuscript read-and-write mode. While *Encyclopaedia Brittanica* is much more stable and reliable, it cannot match *Wikipedia* in speed of reaction or availability. Analogically, the available *Swelling Vault* shapes are limited by the system's capacity to take shapes, and the dimensional tolerances must be increased in design, but the form is achieved with negligible environmental impact. This may be seen as a necessary trade-off that has to be made in order to access the benefits that come with this approach.

Design that follows material properties and behaviour yields objects that cannot be reproduced, thus resulting in cultural performance not seen since pre-industrial times. Just like the subject-object relation in the design process or the question of authorship, the cultural role of material in ***material-centred*** design takes after the pre-Modern and pre-industrial models.

Possible applications

The aim of this new proposed approach of ***material-centred*** design is to widen the scope of wood design, rather than replace the existing approaches. The ambition is to add to the repertoire of existing design methods. It is very possible for one construction project to combine design methods rooted in both approaches.

The various precedent projects presented in Chapters 4 and 5 indicated the possible areas of application. This area is unlimited, as ***material-centred*** design principles can be applied to any building programme, budget, complexity, size, location, etc. Another indication of possible applications is provided by the material experiments in Part I: *BackToBack* connection method can be used to prefabricate panels for assembly, *Swelling Vault* forming method yields shell-like 3D shapes that could become building components or formworks for casting components, while *Y-timbers* is a construction system. In principle, ***material-centred*** design operates at the

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[97] Mario Carpo evoked the example of the authorship of Wikipedia, comparing it to the medieval practice of scribes, and announced "the death of the author"; 'the digital turn is already threatening two foundational tenets of contemporary architectural theory: the modern idea of the standard, which rose with the Industrial Revolution and has defined modern architecture in the 20th century; and the early modern idea of the author, which rose with the humanists in the Renaissance, and has defined early modern and then modern art and architecture ever since' (Carpo, 2009, p.53).

level of building detail, and as such, it is not limited to any building type or scale.

If the approach of ***material-centred*** design in wood was widely accepted, it could become an important extension to existing design and construction methods. New methods would have to be developed, embraced, and entered into the repository of the timber industry's standard procedures. These new methods would entail changes in forestry, supply chains, and material remanufacture; as more varied, raw, and nonstandard material would be required. Diversification of the market demand (more species, naturally-shaped timbers, juvenile wood, etc.) would additionally have positive effects on the forestry. It would also be possible to seek synergies between the forestry and construction industry (see for instance p. 174).

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APPENDICES

Appendix 1: WÓJCIK, M. 2013 Wood unscripted potentials. How can material deficiencies become strengths? In: Transmaterial Aesthetics. Experiments with Timber in Architecture and Technology, 1-2 October 2013. ANCB Metropolitan Laboratory, Aedes Network Campus Berlin.

Marcin Wójcik, AHO Arkitektur- og designhøgskolen i Oslo (The Oslo School of Architecture and Design)

Wood unscripted potentials. How can material deficiencies become strengths?

Keywords: computational design, material agency in construction, form-finding, material self-organisation, wood in construction, wood properties

Timber as a material can be defined as a low-density, cellular polymeric composite (…). In terms of its high strength performance and low cost, timber remains the world's most successful fibre composite (Dinwoodie, 2000).

If someone invented wood today it would never be approved as a building material (Lstiburek, 2009).

1. Introduction

1.1. Approaches to wood in construction.

There exists a dichotomy in our approach to wood as building material as indicated by the two quotations above. On the one hand hardly any manmade material can rival wood in terms of its properties, on the other its use causes problems. 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. Reaction wood, spiral grain and juvenile wood – present in almost all timbers -- are seen as deficiencies, lowering the material value. This paper sets out to investigate how the wood traits that are commonly seen as shortcomings for construction could be used to bring value to the otherwise inferior material, and what kind of design methods and techniques that entails.

1.2. Wood properties and behaviour.

Wood is an extremely varied material – the physical properties are specie-specific while there exist approximately 30,000 species of trees, its anisotropic behaviour, porosity and heterogeneity reflect the material's complex internal structure (Bodig and Jayne, 1993). The modelling of the mechanical behaviour of timber is further complicated by the fluctuations in material characteristics being dependant on moisture, temperature and time (Wagenführ, 2008). No two pieces of timber are alike, all pieces vary at all structural levels and contain various imperfections that are seen as natural, conversion and seasoning defects (Lyons, 2010).

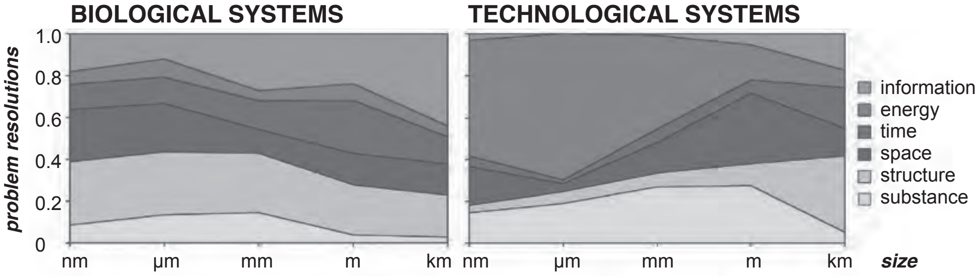
Variation and heterogeneity of timber is seen as a disadvantage in construction: *In the past some of the difficulties could be overcome by selective utilization of certain species and reliance on the larger and older age classes of trees possessing more uniformity. It is now clear, however, that we are no longer able to enjoy such luxuries. More and more trees are characterised by small sizes and greater variability* (Bodig and Jayne, 1993). In order to deal with the heterogeneous characteristics at the scale of mass production two main strategies have been developed. Firstly, manufactured wood products were developed with a goal to offset the problematic effects: *Modern structural composites have minimized and randomized the influences of these naturally occurring defects, but the dimensional* *instability of wood in service remains a definite problem* (Zink-Sharp, 2003). Secondly, understanding wood in engineering is based on simplification, idealisation and statistical average rather than individualised actual characteristics. In continuum mechanics structural analysis timber is considered a homogenous material (Wagenführ, 2008). It is also considered an orthotropic material, that is symmetric about three mutually perpendicular planes (Bodig and Jayne, 1993). These planes are related to the longitudinal, radial and tangential directions in the tree. That assumption implies that the tangential faces are straight and not curved and that the radial faces are parallel and not diverging (Dinwoodie, 2000).

2. Key concepts

The proposed approach to wood architecture is to be based on a set of concepts that form a conceptual framework of the research.

2.1. Systemic and biomimetic stance – the Ju-Jitsu principle.

Frederic Vester (1925-1983), a German biochemist, 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 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, casted, 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. Information is used to self-assemble structures, that unlike the engineered solutions are hierarchical. Vincent 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[1].



Comparison of biological effects and engineering TRIZ[2] solutions arranged according to size / hierarchy. Technology uses energy as the primary driver for solving engineering problems across the nanometre to metre scales, with information playing a smaller role. In contrast, biological systems use energy sparingly (about 5% of the cases), relying instead on information and structure. The similarity in solving problems between those two systems is only 12% (Vincent et al., 2006).

---

[1] Julian Vincent in video interview with Susana Soares JACKMAN, S. 2007. Susana Soares meets Julian Vincent .

[2] a theory of inventive problem solving developed in 1950s Soviet Union

Applying these principles to wood construction means to find solutions based on material self-organisational capacities rather than enforcing form over material. This approach would promote manufacturing and construction techniques that are non-wasteful, less energy consuming and toxic and provide vital alternatives to manufactured wood products in order to overcome the scarcity of good quality and large-dimensional timbers.

Processing a material means energy expenditure and may have an impact on health risks posed by this material, and also on this material's recycling: *The higher the degree of processing, the lower the potential for quick and unproblematic decomposition* (König, 2011).

2.2. Material-orientated design.

The problem of material agency of wood in construction can be tracked back to the 19th century and the rapid development of structural design induced by the introduction of homogenic and isotropic materials – namely iron and later steel. *Iron provided the physical basis for a mathematically oriented formulation of design, thoroughly justified by science* what resulted in a shift of focus to *a more rational, abstract and analytically driven understanding* of construction in structural design (Rinke, 2010). The process of standardisation affected wood construction as well -- the Balloon Frame System based on the 2 x 4 inches module has been introduced in 1830s. Manuel de Landa, Mexican-American artist and philosopher, argues that with the invention of homogenised building materials design has been reduced to a routine and consequently *the linguistically unarticulated knowledge* of craftsmen about complex material behaviour has been disregarded (de Landa, 2001).

Michael Hensel, architect and professor of architecture at the Oslo School of Architecture and Design (AHO), identifies architecture as a domain of *active agency*, where the spatial and material organisation complex is defined as a synthesis of the various scales and their interactions. While in the industrial tradition architects prefer materials that do not exhibit explicit behaviour and are *passive* or in a *stabile equilibrium,* as exemplified by the case of steel and iron, Hensel postulates dynamic condition required by the spatial and material organisation characterised by *active agency.* Wood structure must be understood in relation to environmental conditions affecting its growth. Higher in the organisation system, material behaviour is determined by the material properties and environmental conditions. This in turn has to be harnessed by architectural design, what is the basis of the *instrumentalisation of material behaviour as performative capacity* (Hensel, 2011).

In order to open a new space for design enquiry Achim Menges, professor at the Institute for Computational Design at the University of Stuttgart, envisions the micro scale of the material make-up as a continuum of reciprocal relations with the macro scale of the material systems. Following this approach necessary is understanding and interacting with wood at all scale levels of the material organisation in a holistic manner. Menges identifies computation as a prerequisite to search this space: *computation allows navigating and discovering unknown points within the search space, and thus enables an explanatory design process of unfolding material-specific gestalt and related performative capacity* (Menges and Ahlquist, 2011).

In the abovementioned approaches the process is informed by the capacity of the material systems. That reflects a wider tendency of shifting the interest from structure to material in design and engineering and blurring the distinction between them. Antoine Picon, professor of the History of Architecture and Technology at Harvard Graduate School of Design (GSD) brings an example of the evolution of car bumpers from structural protectors to energy absorbers, that was enabled by the development of energy absorbing composite materials (Picon, 2010). This in turn reflects the biological paradigm where there is no distinction between material and structure.

3. Case studies

3.1. Spiral grain.

First case presents a potential of material self-organisation taking advantage of spiral grain in wood seen by some wood scientists as the most serious single defect in softwoods.

Material deficiencies.

While wood with spiral grain has no abnormal shrinkage, spiral patterns in sawn timber affect the entire length of a piece. Spiral grain in sawn timber combined with change in moisture content causes a warp type called twist. Spiral grain induced twisting in transmission poles can amount to 50° and break the transmission lines. Additionally the strength in tension, and to a lesser degree in compression, decreases as the slope of the grain in timber increases. Machining and bending of such wood is difficult. For all these reasons spiral grain reduces log value. The actual cost of wood wastage due to spiral grain is difficult to assess, but at times the rejection rate of the crop may amount to 50% (Harris, 1989).

Biological outlook.

Wood structure is highly heterogeneous, with phenomena like reaction wood and spiral growth resulting from the environmental conditions of the tree growth (gravity, wind, sloping site and competition). Spiral growth is a persistent feature for many millions of years, thus unlikely a defect as such would have been eliminated by the evolution. This phenomenon can be observed for most tree species. Studies confirm that spirally grained trees are better suited to meet extreme wind and snow loads (Harris, 1989) as the spiral growth increases stiffness, stability and minimises the use of material in trees (Wagenführ, 2008).

Usage in design and construction.

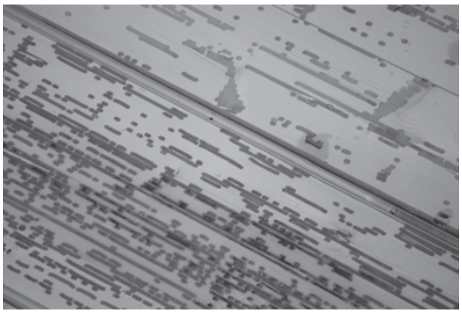
Japanese traditional woodworkers treated the irregularities in grain as an asset to resist certain loads (Brown, 1989). In the Scandinavian boatbuilding tradition *to ensure that the planking in the prow of a boat swept, sloped, in the right direction, it was suitable to choose a clockwise twisted log for the starboard planking, and an anticlockwise twisted log for the port planking* (Säll, 2002). In the 18th and 19th centuries trees with left-hand spiral grain were sought out for the curved moldboard section of the wooden plough. A large hardwood trees with pronounced left-hand spiral grain were greatly prized for the strength of the curved surface. Spirally grained poles also give warning of failure, as they fail progressively by splitting, what makes them favourable for pit-props and mining timbers (Harris, 1989). Andre Wagenführ, professor at the Institute of Wood and Paper Technology (*Institut für Holz- und Papiertechnik*) at the TU Dresden experiments with wood with spiral grain, taking advantage of the interdependence of the fibril angle, stiffness and toughness -- the shallower the slope of the fibrils, the smaller the force required for the deformation of the material (Wagenführ, 2008).

Potential developments.

Image based on a photo by J.A. Kininmost from HARRIS, J. M. 1989. Spiral grain and wave phenomena in wood formation, Berlin, Springer-Verlag.

The photograph depicting a twisted stack of timber as a result of the twist in the same direction in all the individual boards due to spiral grain shows how double-curved shapes can be achieved using minimum energy. Undulation of walls performs acoustically -- causing scattering and attenuation of sound waves, or structurally – providing for self-support. It is proposed to devise design and construction techniques that benefit from the twist phenomenon. Twist is caused by three main factors: (1) annual ring curvature – the closer a stud is sawn to the pith the more prone it is to twist, (2) spiral grain angle – the higher the spiral grain angle the larger the twist, (3) change in moisture content – the drier the studs are the more severe the twist is (Bäckström et al., 2004). That implies that the twist in a piece of timber can be predicted by controlling the way wood is sorted, converted and dried combined with measuring the grain angle. Wood with left-handed spiral grain – particularly prone to twist -- should be sorted out early in the supply chain. Spiral grain angle should be measured using non-invasive technique. There exist several techniques for providing internal cartography of a tree: tracheid effect using a laser beam to map the grain curvature (Grönlund et al., 2007), computed tomography (Sarigul et al., 2003), automated scanner systems, electromagnetic wave scattering (Gjerdrum and Bernabei, 2009), X-ray density measurement, ultrasonic *Sylvatest*, vibration measurement (Ranta-Maunus, 1999). All the methods are already in use or may find industrial application in the near future. Information acquired this way can be used to predict twist during drying (Säll, 2002) and employed in a digital form-finding simulation process to spontaneously achieve forms otherwise difficult and expensive to achieve.

The new *trait-to-form* method would be based on *form-finding* techniques combined with identification of advantages in material characteristics (*trait-finding*). Necessary is development of digital design tools that are orientated towards relationships – between material properties, behaviour, design intents, form and performance, rather than geometry, using simulation as a tool. A prerequisite is feedback from the material. That requires developments in two areas: non-invasive, quick and reliable gradation methods of wood and digital tools capable of simulating behaviour of material systems and allowing for real-time reaction at the manufacturing stage. That would result in reformulation of the linear design-execution process in order to allow for feedback in the workflow. The new integrated workflow should blur the distinction between simulation, design and manufacturing. Interfacing between these stages becomes the biggest challenge in the integrated process.



Digitized Grain*, Hironori Yoshida, 2013 -- a research project based on *an integrated process, being a modern translation of how craftsman reads characteristics of natural materials and dynamically reflects on fabrication processes. (…) For the automated production process, the material features are digitally scanned, image-processed and translated into motion paths for a seven-axis industrial robotic arm. This sequence of operations are executed by an algorithm and then transmitted to any kind of cnc machine that operates following the inputs generated by the program. The program can flexibly change the amount of tooling and resolutions of image processing. Text and photograph: http://www.caad.arch.ethz.ch/blog/scan-to-production/

3.2. Juvenile wood.

Second case investigates the potential of using juvenile wood, commonly present in the product of forest thinning that represents substantial part of the annual crop of timber, reportedly 50% in the case of the UK (Ross et al., 2009).

Material deficiencies.

Juvenile wood is considered inferior in quality to normal wood, unsuitable for construction, composite panels, high-grade paper, and not competitive as a source of energy (Ranta-Maunus, 1999, Shmulsky and Jones, 2011). Roundwood is not commonly used in the developed countries as a structural material due to the lack of design guidelines and readily available and reliable connectors, unavailability of the material through normal commercial channels, the difficulty when attaching cladding to irregular and round structure (Ranta-Maunus, 1999, Dickson et al., 2011).

Biological outlook.

Juvenile wood strength is up to 50% lower due to low density resulting from thin cell wall layers, shorter cells and high microfibril angle. That angle affects directional shrinkage as well. The longitudinal shrinkage from green to oven dry amounts to 2%, while the average value for other wood is negligible and does not exceed 0.2%. This may cause radial cracking as the juvenile and other wood is usually present alongside and is not sharply delineated but gradually vary from ring to ring (Shmulsky and Jones, 2011).

Advantages of roundwood thinnings.

Embodied energy of roundwood thinning material is 40% lower than of sawn lumber (Dickson et al., 2011). Further, the material self-replenishes over a much shorter period of time than that needed for sawn timber. The cost of debarked round timber is roughly a half of sawn timber while the characteristic bending strength of unsorted material may be even double the value of sawn timber (Ranta-Maunus, 1999).

Usage in design and construction.

Small diameter roundwood, a counterpart of thinnings, has been widely used for centuries -- mostly for their convenience in size and where quality was of secondary importance -- in such structures as sheds, barns or fencing. Recently 50 m span domes of small diameter roundwood have been shown to be fully feasible. 27 m high Observation Tower at Apeldoorn (architect Pieter Huybers; 1995) has been built of 2.5 and 3.6 m long and 12,15 and 20 cm in diameter debarked larch poles. The projects employ a design strategy based on three-dimensional space frames where short length and small cross-section of the poles are not a disadvantage, and using the whole cross-section additionally offsets the problem of weakness (Ranta-Maunus, 1999).

The Hooke Park Workshop, design Richard Burton of ABK and Frei Otto, engineers Buro Happold, 1989. Photographs http://www.aaschool.ac.uk/.

The workshop building Hooke Park in Dorset (Richard Burton, Frei Otto and Buro Happold, 1988) was an experimentally constructed gridshell using round (65-180 mm diameter) green Norwegian spruce thinnings achieving a 15 metres span (Davey, 2009, Romer, 2011). Richard Kroeker, a Canadian architect pursuing ecological sustainability, designed a series of buildings made of small diameter roundwood thinnings based on Native American architecture and boatbuilding. The indigenous assembly is a spring-loaded, stressed skin structure composed of lightweight and locally sourced parts. While none of the components has sufficient strength, together in a tensioned assembly they become structurally sound. The design process takes place in real time with reference to the behavioural limits of the material, the anticipated use and performance. To achieve curvilinear, efficient forms, wood is worked when it is green and flexible (Kroeker, 2013).

Pictou Landing Health Centre in Nova Scotia, architects Brian Lilley, Richard Kroeker, Peter Henry. Photograph R. Kroeker, from KROEKER, R. 2013. Lernen vor der Architektur der indigenen Volke Amerkas. Learning from Native American Architecture. *Detail,* 5.

Potential developments.

In silviculture the initial narrow spacing and later thinning strategy – necessary for improving the growth rate and wood quality -- makes the remaining trees twice as expensive as planting to a wider spacing, unless there was a commercial market for the thinned material (Shmulsky and Jones, 2011). A market study by the Technical Research Centre of Finland indicates the potential markets for thinnings in the development of small buildings as well as large engineered structures, which could be attractive when combined with unique architecture, especially in the leisure industry (Ranta-Maunus, 1999). A departure point for developing new techniques is research into material systems based on inferior in quality, short and small section components, where structural strength is derived from the combination of material behaviour and geometry.

While juvenile wood strength achieves about half the value of normal wood, its lower modulus of elasticity allows for bending it beyond the proportional limit, and even more so in green condition. Bending strength of round timber is higher than that of sawn timber of similar cross-section size, and small cross-sections are known to have relatively higher strength than large ones based on the Weibull theory (Ranta-Maunus, 1999). Processing thinnings into sawn timber causes problems, due to imbalance of stresses leading to deformities and cracks and low yield due to the conical geometry of the logs (Dickson et al., 2011). Even though high temperature drying can minimise cracking during drying, the bending strength of high-temperature dried logs is about 10% lower than of seasoned logs (Ranta-Maunus, 1999) and there are difficulties with effective kiln-drying roundwood timber above 75 mm diameter (Ross et al., 2009). The logical consequence then is to develop material and construction systems using roundwood logs in the green condition, harnessing the properties and behaviour of this particular material. As the presented examples demonstrate, it is possible to synergise various phenomena thus achieving wide spans, quick construction times, structures effective in terms of form compactness and weight to strength ratio at low cost and using obsolete materials.

The key aspect becomes than the identification of synergies within the organisation of material and construction systems. Architectural design has the potential to bridge the gaps between different levels of the hierarchical organization -- from the *nano* scale of wood internal structure affecting its behaviour to the *mega* scale of the world forestry. That is only possible through trans-disciplinary cooperation and systemic outlook.

4. Conclusions

The volume of wood commonly seen as defective is difficult to estimate, but it may be in the extent of 50% of the crop. It is proposed that architectural design plays a key role in finding applications for such wood by informing its methods by bio-cybernetics and biomimetics. In order to handle the challenge a new properties-led, integrated and continuous design and production process is proposed. The *trait-to-form* process is to be based on bottom-up emergence and self-organisation developed by feedback from the material in relation to the top-down constraints: particular design intent and environment. Key aspects of the *trait-to-form* process are: (1) identification of synergies within the systems of forestry, material characteristics and architectural tectonics, (2) focus in design on relationships between material properties, behaviour, design intents, form, tectonics and performance, (3) inclusion of real-time material feedback in the continuous design and production process, (4) incorporation of material system behaviour simulation in the digital design toolkit, (4) development of tectonic systems deriving strength from combination of material characteristics and geometry.

The proposed framework has a potential to address the environmental and economical problems at the same time contributing to the field of architectural design, and therefore it is intended to develop that methodology further.

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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-cyberntic 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 de-*

composition (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 partying-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 Santicilia, took advantage from the existing shapes of trees or irregularities of grain in order to achieve superior 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, *by1930 (...) 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 Violet-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 *Formenschprache* (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 menagement. 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 biochemist, 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 required 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 snuggly 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.

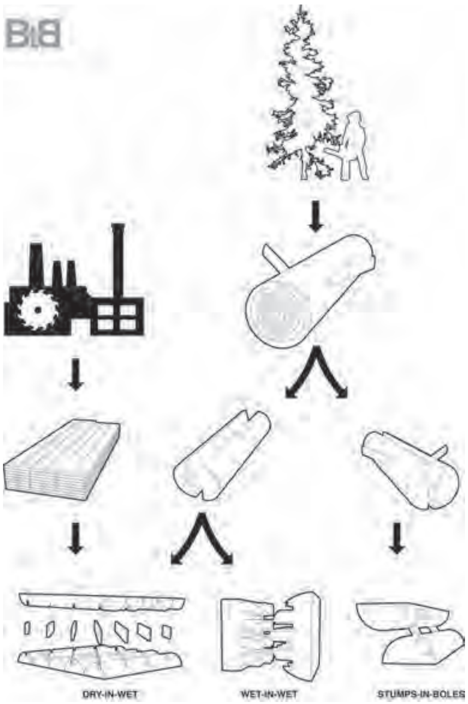

Figure 1
Three BackToBack design paths

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.

Figure 2
The BackToBack
dry-in-wet concept

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).

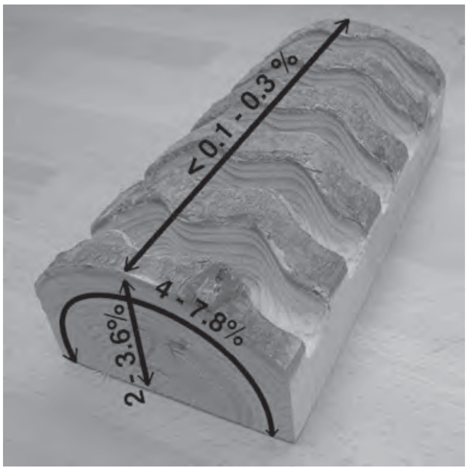

Figure 3
Orthotropic
shrinkage in
Norway spruce

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 loos-

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

ened 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.

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?

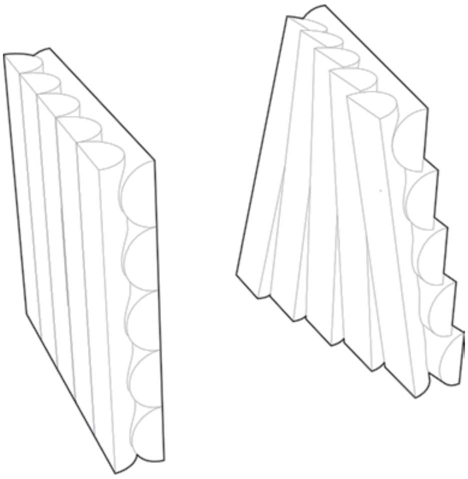

Figure 6
Using the BackToBack method production of both panels would require the same amount of time, material and energy

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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Appendix 3: WÓJCIK, M. & STRUMIŁŁO, J. 2014 Behaviour-based wood connection as a base for new tectonics. In: KEITSCH, M., ed. Resilience - 20th Annual International Sustainable Development Research Conference 2014, 2014 Trondheim. Norwegian University of Science and Technology, Department of Product Design.

BEHAVIOUR-BASED WOOD CONNECTION AS A BASE FOR NEW TECTONICS

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ABSTRACT
This paper joins into the debate on sustainable architecture and construction and the resilience of the architectural practice. It takes up the case of solid wood construction where heterogeneity of timber is considered a disadvantage in construction. Wood industry utilises expensive processes in order to overcome rather than exploit natural wood properties. We suggest a different approach that could lead to the reduction of environmental pollution and more economic use of resources, that is discussed with a proposed wood connection method based on harnessing material behaviour induced by a change of moisture relationships -- i.e. shrinkage. Two design paths are presented: (i) involving clinging of green component on dry insert and (ii) utilising anisotropy in green wood shrinkage. The main contribution of this paper is a new view on tectonics -- understood as proper use of materials -- that bridges the gap between wood material science and design disciplines. Both theoretical and methodological frameworks are presented and, supported by the demonstrated concept, showcase the potential of inducing far-reaching changes in the timber industry. By reducing waste and by reducing the need for chemistry and supplementary materials in wood joining and improving economic performance we can get closer to a sustainable practice.

Keywords: wood tectonics, material-oriented design, wood properties, digital manufacturing

1 INTRODUCTION

The project presented in this paper belongs to the intersection of the fields of (i) architectural tectonics, (ii) sustainable construction and (iii) construction technologies. Its main goal is the resilience of architectural practice. It is framed by the problem of solid wood construction, where it is argued for an alternative joining technique, based on material behaviour. The central research question being asked is how the inherent material properties can be used in the design and construction processes, with a working hypothesis that applying these may lead to a more sustainable and more feasible construction. Outlines of both theoretical and methodological frameworks together with designed and manufactured prototypes are presented in order to induce discussion.

1.1 The tectonic approach

The tectonic quality of architecture emerges from the interplay between material, construction technology, environmental and cultural factors, as evident in the development of splicing joints in the Japanese carpentry. In the seismic condition of Japan long timbers must be used for the necessary building rigidity, a fact that caused the depletion of tall trees as early as 11th-12th centuries. That environmental influence combined with the traditionally developed building forms, aesthetical canons -- such as the dislike for an exposed endgrain (*koguchi*) – and the resistant yet easy to work with *hinoki* wood (Japanese cypress), had effectively led to the richness and sophistication of the *tsugite* joinery technique (Figure 1). At its peak, Japanese carpentry distinguished 200 different wood joints, both *tsugite* (splicing) and *shiguchi* (perpendicular), with more than 100 joints needed for construction of a single shrine or temple in the 17th-19th centuries [1].

Figure 1. Tsugite – Japanese splicing joints (image source: [1])

The tools used affect the tectonic expression in a similar manner, as demonstrated by the example of the introduction of the old Germanic tool *klingeisen* – a curved drawknife, known as *medrag* in Norway (Figure 2) – and its influence on the appearance of log buildings in Scandinavia [2, 3].

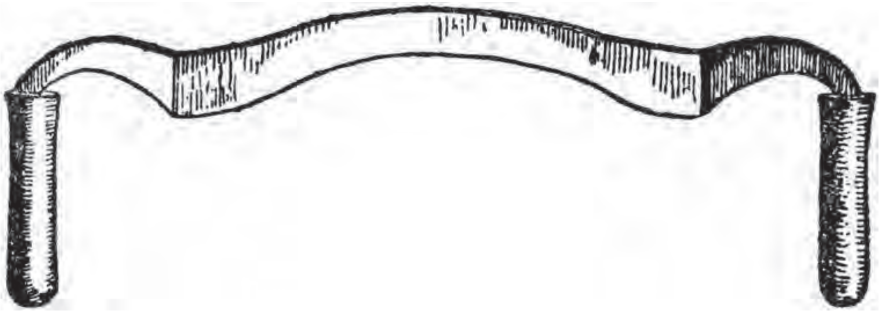

Figure 2. Drawknife

In the same vein Christoph Schindler, architect, designer and researcher, sees wood construction as the interaction of matter, energy and information, on which he based his periodization model that integrates fabrication with manual, industrial and information technology. Through the production technology we can see the wood construction and acknowledge that the technology not only radically reshaped the production of buildings, but equally their construction and appearance [4].

In our project the term *tectonics* is understood as the *prescriptions regarding the proper use of materials* [5]. Its root -- the Ancient Greek term *tektōn* (τέκτων) -- denotes a carpenter, a fact that signifies the important role of wood construction in the development of architecture. It is intended to take part in the historical discussion of the relation between form and matter in architecture, where it is proposed to see the form as emergent from the material and its capacities, as opposed to imposed onto the materials, like in the design based on proportioning systems and architectural orders. In the proposed tectonic approach two aspects are critical: (i) integration of material properties and behaviour with manufacturing and assembly logic and logistic and (ii) integration of the heritage of wood construction with state of the art technology.

1.2 The material

Wood is an extremely variable and stochastic material, involving a degree of randomness, where the physical properties are specie-specific while there exist approximately 30,000 species of trees. Its anisotropic behaviour, porosity and heterogeneity reflect the material's complex internal structure [6]. The modelling of the mechanical behaviour of timber is further complicated by the fluctuations in material characteristics being dependent on environmental conditions: moisture, temperature and time. The very specific characteristics and behaviour of wood are a result of reciprocal hierarchies: heterogeneous structure of the cellular network dependant on the fibre arrangement and anisotropy dependant on the fibre direction, tree specie, piece shape and thickness.

Today we face a similar problem to the aforementioned depletion of large trees in old time Japan. Small dimensional sizes, variation and heterogeneity of timber are seen as a disadvantage: *In the past some of the difficulties could be overcome by selective utilization of certain species and reliance on* *the larger and older age classes of trees possessing more uniformity. It is now clear, however, that we are no longer able to enjoy such luxuries. More and more trees are characterised by small sizes and greater variability* [6]. Thus remanufacture of timber is a way to meet the needs of modern economy. Remanufacture is a process not without impact on the environment. Approaching the problem from a different perspective our project utilises roundwood – a low-processed forest product.

2 THEORETICAL FRAMEWORK

The theoretical framework of the project is constituted by three concepts: (i) bio-cybernetics, (ii) biomimetic and (iii) material-oriented design. Sustainable solutions require transdisciplinary integration of multiple knowledge bases.

(i) Frederic Vester (1925-2003), a German biochemist, ecologist and the 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* [7]. (ii) That in turn resonates with the comparison of biological and technological systems as presented by Julian Vincent (Figure 3), professor of biomimetics at the University of Bath. 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, stored in the genetic code, rather than energy to solve technical problems. Information is used to self-assemble structures, that unlike the engineered solutions are hierarchical. Vincent 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 [8].

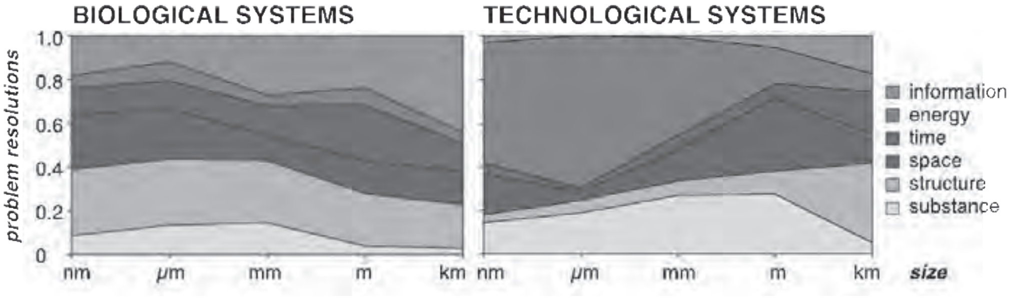

Figure 3. Comparison of biological effects and engineering TRIZ[1] solutions arranged according to size / hierarchy. Technology uses energy as the primary driver for solving engineering problems across the nanometre to metre scales, with information playing a smaller role. In contrast, biological systems use energy sparingly (about 5% of the cases), relying instead on information and structure. The similarity in solving problems between those two systems is only 12% [9].

Applying these principles to wood construction means to find solutions based on material behaviour and self-organisational capacities rather than enforcing form over material. This approach would promote manufacturing and construction techniques that are non-wasteful, less energy consuming and toxic and provide vital alternatives to manufactured wood products in order to overcome the scarcity of good quality and large-dimensional timbers. By replacing energy-expensive industrial processes with the naturally occurring changes in the material and using its potential, such solutions, when scaled up, would constitute a significant move towards sustainability.

(iii) The problem of material agency of wood in construction can be tracked back to the 19th century and the rapid development of structural design induced by the introduction of homogeneous and isotropic materials – namely iron and later steel. *Iron provided the physical basis for a mathematically*

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[1] a theory of inventive problem solving developed in 1950s Soviet Union

oriented formulation of design, thoroughly justified by science what resulted in a shift of focus to *a more rational, abstract and analytically driven understanding* of construction in structural design [10]. The process of standardisation affected wood construction as well -- the balloon frame system based on the 2 x 4 inches module has been introduced in 1830s. Manuel de Landa, Mexican-American artist and philosopher, argues that with the invention of standardised and homogenised building materials design has been reduced to a routine and consequently *the linguistically unarticulated knowledge* of craftsmen about complex material behaviour has been disregarded [11].

Michael Hensel, architect and professor of architecture at the Oslo School of Architecture and Design (AHO), identifies architecture as a domain of *active agency*, where the spatial and material organisation complex is defined as a synthesis of the various scales and their interactions. While in the industrial tradition architects and engineers prefer materials that can be considered homogeneous and predictable -- as exemplified by the case of steel and iron -- Hensel postulates dynamic condition required by the spatial and material organisation characterised by *active agency.* Wood structure must be understood in relation to environmental conditions affecting its growth. Higher in the hierarchical organisation system, material behaviour is determined by the material properties and environmental conditions. This in turn has to be harnessed by architectural design, what is the basis of the *instrumentalisation of material behaviour as performative capacity* [12].

3 EXISTING EXAMPLES

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. However when compared to the abovementioned balloon frame, post-and-beam or log constructions (pre-historic inventions) this must be considered young. CLT has become an industry-standard but its development is not over. CLT's production started in European alpine countries and it involves laminating planks by means of polyurethane glue (Figure 4). Polyurethane is a synthetic polymer and as such it is non-biodegradable. This is problematic when the entire lifecycle of the composite element is considered. Solid-wood panel building systems rely on metal connectors for assembly e.g. self-tapping screws. CLT manufacture overcomes the anisotropic nature of wood. Dried wood is used to yield a product that is as homogenous and standardised as possible. CLT production and assembly leaves room for improvement and innovation, which has been recognised by researchers and entrepreneurs. The following examples challenge the established standard CLT solution. They have to be considered parallel tracks within the same line of development as this research. One objective of innovation is to achieve panels free from volatile organic compounds. A number of research projects and available products tackle this issue.

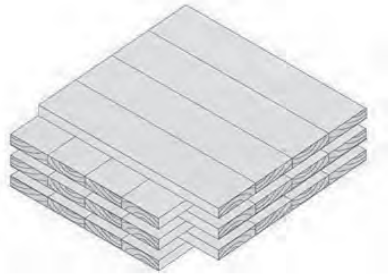

Figure 4. CLT cross-laminated timber (image source: [13])

Starting in the 1970s Julius Natterer, German engineer and professor of wood construction at the École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland, has worked with stacked-plank panels. Initially the softwood planks obtained from low-quality raw material were joined by steel nails, in later versions they were connected by means of dry beech dowels that swell by drawing moisture from the elements that they connect. This system, called Brettstapel, avoids using toxic adhesives in construction and allows all-wood element production. It employs the natural swelling phenomenon for the creation of a durable joint between the panel layers. Natterer chose not to patent the system and to make it available to everyone. Subsequently many firms have taken up the production based on his research. E.g. Austrian firm Thoma is marketing the system under the name Holz100 (Figure 5) and has been producing it since 2000 [15].

Figure 5. Thoma Holz100 system (image source: [14])

A similar principle is employed in the production of NUR-HOLZ (timber-only) elements (Figure 6), produced by the firm Rombach in Austria since 2009 [15]. They have the form of panels that can be used as walls and floors. Instead of glue (or dowels, as in the case of Holz100 system) the layers of timber slats are connected by means of hardwood screws. The system does not exploit the behavioural potential of the material (e.g. swelling) but it achieves an adhesive-free bond to yield a commercially viable product.

Figure 6. Rombach NUR-HOLZ system (image source: [16])

Interlocking Cross Laminated Timber (ICLT) system is being developed at the University of Utah (Figure 7). ICLT avoids the use of adhesives or mechanical (metal) connectors in the manufacture of panels by using dovetail-joint connection. The panels are designed to make use of wastewood – they use beetle-kill 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 number of layers and corresponding element thickness for different structural and physical parameters. As of 2013 two experimental buildings have been constructed in Utah using the technology [17, 18].

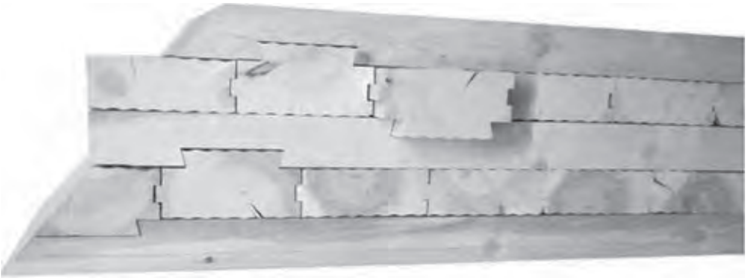

Figure 7. ICLT – Interlocking Cross Laminated Timber (image source: [17])

A different approach characterises the Swiss TopWall system invented by the engineer Hermann Blumer. It uses the natural properties of wood for constructing walls (Figure 8). The low shrinkage and high compressive strength of timber along the grain is exploited by positioning the wall elements vertically. The system has been used with success to erect a six-storey apartment complex in Zurich (Pool Architekten, Badenerstrasse, completed 2010). The 10 x 20 cm softwood studs are positioned next to one another and held in place by means of dowels that fix them to horizontal elements forming the top and bottom of each storey-high wall. They are also connected by dowels between themselves. The vertical elements are put in individually, allowing for a construction without using a crane. The resulting wall has a compressive strength comparable to concrete and many times that of a masonry wall of similar thickness [19].

Figure 8. TopWall (image source: [20])

Composite timber-concrete floor slab system developed by Julius Natterer of the EPFL in Lausanne is an example of low-treated wood use (Figure 9). One of the tested versions of the timber-concrete composite makes use of halved logs. An example of the use of this system is a house constructed in Clarens, Switzerland (1992). The composite action between timber members and the poured slab is provided by means of notches and complimentary steel anchors. Use of halved logs allowed the achievement of favourable economic results [21].

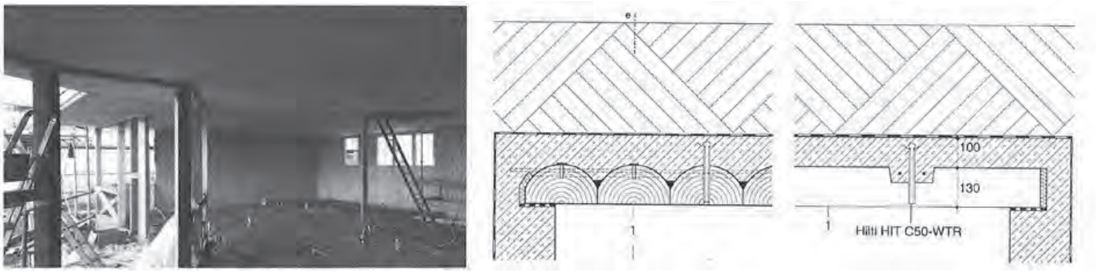

Figure 9. Composite timber-concrete floor slab (image source: [21])

The AV3 system developed in Norway [22] features a composite panel for the erection of walls in single-family houses (Figure 10). Panels are composed as a three-layer sandwich: between two layers of tongue-and-groove connected heartwood elements of sitka spruce an insulating core of pressed wood shavings is placed. The machined elements make use of the natural, conical shape of logs. Their long edges are tapered and only by alternating their directions an overall regularity of the panel is maintained.

Figure 10. AV3 system (image source: [22])

Friction welding of wood, explored by the IBOIS team at the EPFL in Lausanne employs the material properties of wood at its molecular level to create a permanent adhesive-free joint (Figure 11). Described in a number of papers (see for instance [23]) the technology of friction welding is used to bond metals and thermoplastics. It was shown that the same process can be used for bonding flat elements of wood. At present stage of development the technology can be used for creating joints that can be used inside of buildings/elements i.e. to create furniture or composite structural elements (*weldlam*). The limiting factor for large-scale elements is the costly machinery needed to produce sufficient pressure and high-speed friction required to achieve the bond. It is however imaginable, that large-scale solid-wood panels could be produced in the future using friction-welding.

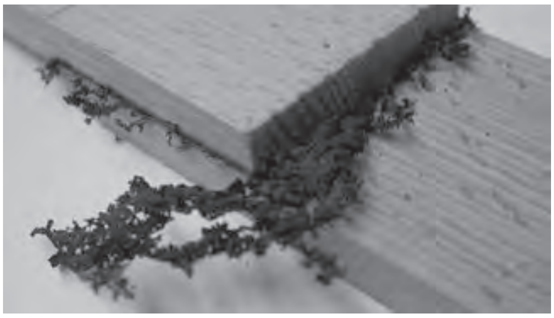

Figure 11. Friction welding (image source: [24])

4 DESIGN POTENTIAL IN MATERIAL DEFICIENCIES

In line with the established theoretical framework it is proposed to harness the anisotropic shrinkage in timber as it dries, use roundwood -- a low-processed raw material, and avoid additional fasteners and bonding agents. Various deficiencies – dimensional instability, anisotropic behaviour, round and irregular shape -- are worked with and used to minimise the energy expenditure in production.

4.1 Orthotropic shrinkage and movement in timber

Anisotropy may be utilised as a design strategy leading away from digital form-finding to trait-finding [25].

Anisotropy present in timber is a result of the alignment in the vertical axis of a tree of 90 to 95% of the cells as well as the orientation of the microfibrils in the middle layer of the secondary cell wall. Longitudinal and transverse degree of anisotropy of timber shrinkage due to water relationships amounts to approximately 40:1, in regard to thermal movement to 10:1 and for thermal conductivity to 2.5:1 [26].

Dimensional instability of timber is often seen as a serious problem to overcome. As far as water relationships in wood are concerned it can be divided into two separate phenomena: (1) shrinkage -- activated on drying and (2) movement -- present in service throughout the component life-span due to seasonal or daily changes in relative humidity or a fluctuating environment. The dimensional instability in timber is anisotropic, dependant on the fibre direction, the degrees of anisotropy are further dependant on the tree specie and the way the log was converted.

1. On drying wood begins to shrink as its moisture content drops below 30%. For green wood it is equal to 60-200% and below ca. 30% the moisture is no more in the cell cavity but in the cell wall. That stage, called fibre saturation point (FSP), marks dramatic change in wood properties, for instance compression strength increases three-fold between there and an oven-dry state. As timber is orthotropic in its water relationships shrinkage is different on the three principal axes, dependent on the tree specie: longitudinal 0.1-0.3%, radial 2-6% and tangential 5-10%, however -- as wood is not used in the oven-dry state but in-service moisture content amounts to 8-15% -- we should consider 50-75% of the aforementioned values [26], [27].
2. The anisotropy of movement can be accounted for by the same set of values as for shrinkage, yet its magnitude amounts to approximately one third [26], [27].

4.2 Green wood in construction

Strength and stiffness of timber decreases with the increase of moisture content, and above 20% of moisture content timber is susceptible to attack by fungi. For these reasons moisture is removed from commercial timbers by air-seasoning or in the drying kilns [26].

Using green timber has a long history in vernacular architecture. European, Russian and Japanese carpenters developed various techniques in order to factor-in different rates of longitudinal, radial and tangential shrinkage in timber components. Some vernacular methods, like the fabrication of hay and crop forks or using dry dowels in green wood exploit the inherent properties and behaviour of the material. It is generally not known when the practice of drying wood prior to working it has been introduced, but up until late gothic times wood was worked green [2]. An interesting feature can be found in traditional Scandinavian log house construction: horizontal orientation of logs -- the most common building method for hundreds of years -- took advantage of the radial shrinkage of the logs when drying, making the building tight. Interestingly, changing the orientation of the logs to vertical in the 18th century in order to achieve more freedom in shaping the building plan, resulted in the lack of tightness varying with the moisture content in the air. This effectively led to the increased use of dried timber boards in construction from the 19th century [28].

4.3 Small diameter roundwood in construction

Small diameter roundwood has been widely used for centuries -- mostly for their convenience in size and where quality was of secondary importance -- in such structures as sheds, barns or fencing. Today it is not commonly used in the developed countries as a structural material due to the lack of design guidelines and readily available and reliable connectors, unavailability of the material through normal commercial channels, the difficulty when attaching cladding to irregular and round structure [29, 30].

Embodied energy of roundwood material is 40% lower than of sawn lumber [30]. Further, small diameter roundwood self-replenishes over a much shorter period of time than that needed for sawn timber. The cost of debarked round timber is roughly a half of sawn timber while the characteristic bending strength of unsorted material may be even double the value of sawn timber [29].

Furthermore, processing a material means energy expenditure and may have an impact on health risks posed by this material, and also on this material's recycling: *The higher the degree of processing, the lower the potential for quick and unproblematic decomposition* [31].

4.4 All-wood connections

Todays wood construction systems use metal fasteners -- brackets, plates, screws and bolts for connections, which is problematic for the three reasons mentioned below:

1. Metal fasteners impede recycling of wooden components due to the difficulty with partying-out in a demolition process. Only about 0.03% of industrial wood comes from recycling -- some 0.5 million cubic metres of wood is reclaimed yearly (242,000 tones in 2000 [32], while it is estimated that about a third of the 3,400 million of cubic metres of annual worldwide timber harvest [33] is used in construction [34]).
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 [1].
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* [1].

A timber building system eliminating the need for metal connectors would substantially lower the environmental impact of structures erected using it by reducing the amount of energy used in the process and improving recyclability of timber components.

5 METHODOLOGICAL FRAMEWORK -- RESEARCH BY DESIGN

The chosen *research by design* method is based on experimental design projects. This method is not only best suited to address the research question but also the only possible to look at the topic of study from the chosen analytical perspective. There are three main reasons for carrying out research through physical experiments at full architectural scale:

1. Firstly, it provides for the interaction between construction, manufacturing and material

behaviour. It would not be possible to merely speculate about or simulate that interaction, as the number and character of involved parameters exceeds beyond computability. That interaction can only be captured by a physical process combining the digital and material domains. The sought solutions emerge from this synthesis of the digital and the material [35, 36].

2. Secondly, some phenomena are not scalable. It has been known since Galileo Galilei (1564 – 1642) that structural sizes cannot be increased by increasing all dimensions proportionally [37]. When scaled linearly by the same factor areas increase by a squared ratio while volumes increase by a cubed ratio. By the same token material behaviour is size-dependent too.
3. Thirdly, the mock-ups built at full scale allow for taking quantitative (using sensors and measuring equipment) measurements and qualitative (sensory) surveys that could be used in the evaluation and feedback thus enhancing the interactivity of the process.

This approach, contrary to speculative or simulation studies has a potential to shed some light onto the possible strategies of integration in architectural form of various criteria belonging to different domains.

Application of scientific working methodology, as formulated in natural science in the 17th century due to its reductionist character considerably limits design potential [38]. That becomes evident in the working method of Antonio Gaudi (1883-1926) -- hanging chain models serving to establish catenaries, Heinz Isler (1926-2009) -- funicular and pneumatic models used to determine geometry of freeform shell structures or Frei Otto (b.1925) -- form-finding method using membrane models, suspended nets, soap films and bubbles, glue, paper, sand or the wool thread machines. This experimental working methodology *and the resulting logical reasoning in the development and description of form does not (...) define any kind of design technique that can be generally applied in architecture* [38].

Figure 12 depicts our proposed framework for the *research by design* process with integration of the intuitive and scientific working methods. Out of the synthesis of multiple input factors a problem is formulated, for which qualitative design questions are posed, addressed by a series of design solutions proposed and evaluated in a heuristic process. This approach builds upon the work of Herbert Simon (1916-2001), American scientist who defined design solutions as based on ill-structured problems, that cannot be solved by linear reasoning, and advised avoidance of optimised subsystems in favour of solutions *satisficing* (a portmanteau of *satisfy* and *suffice*) each subsystem. The *satisficing solution* in Simon's definition is not a singular solution but a multiplicity of solutions [39]. Further, for the satisficing solutions scientific problems and more specific, quantitative questions may be formalised and addressed by logical reasoning, as a basis for evaluation feedback and refinement, and finally a selection and development of a chosen path.

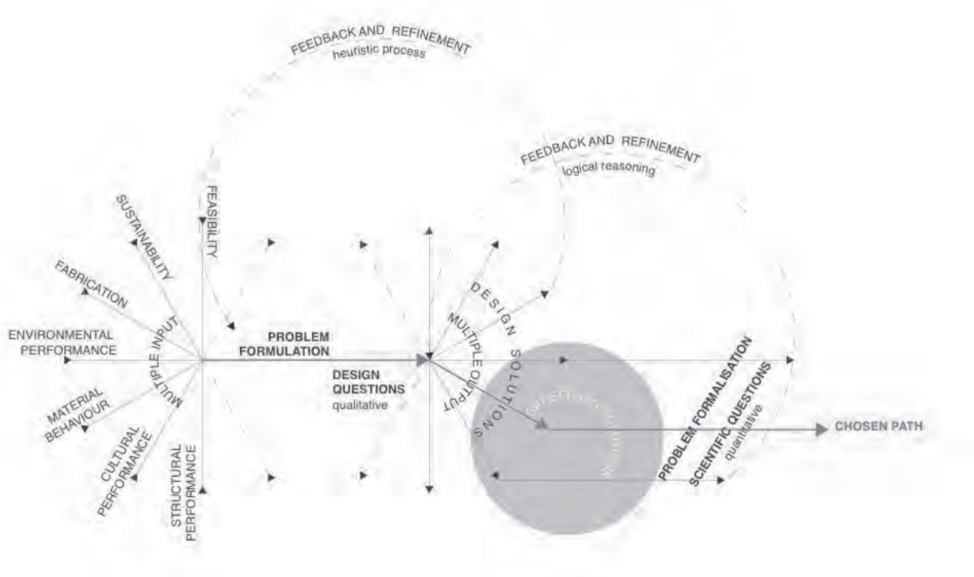

Figure 12. Research by design method framework

6 BACK-TO-BACK – A TEST BED

As a test bed for the proposed theoretical and methodological frameworks a design and production of a solid timber wood panel has been selected. The chosen design solution – in line with the minimum energy expenditure and minimum intervention principles -- is the *BackToBack* method, based on (i) harnessing the material behaviour – i.e. shrinkage, for a connecting mechanism, and (ii) using halved wood logs with the cut faces as the finish, while the raw round backs directed to the inside are used for connection.

Two Norway spruce trees aged ca. 15-20 years had been felled in a forest east of Oslo. The acquired 100-140 mm roundwood was converted to two panels within 10 days while still green. Two design paths were followed (Figure 13):

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. Special incisions were CNC-cut to harness the tangential shrinkage on the active side of the panel and tighten on the passive side.

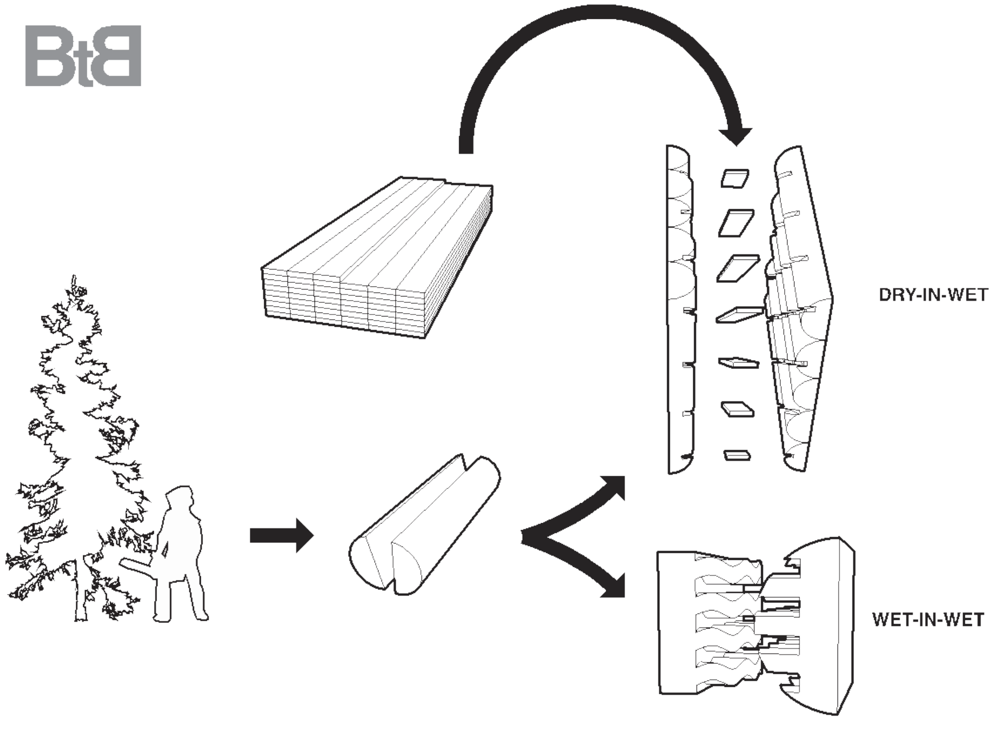

Figure 13. Two BackToBack design paths

6.1 Dry-in-wet

This project demonstrates and tests how material behaviour, i.e. green wood shrinkage activated on drying could be used for tightening on dry wood elements.

A series of incisions -- 20 mm wide and 150 mm apart -- was cut at 45° angle to the halved-log axis on the bark side. As the inserts dry pine boards 20 x 120 mm were used (Figure 14). 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. The further research questions involve the distribution, geometry and dimensions of these incisions and inserts.

Figure 14. The BackToBack dry-in-wet concept

6.2 Wet-in-wet

This project demonstrates and tests how material behaviour, i.e. 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% [26] - 7.8% [40], radial to 2% [26] – 3.6% [40] and longitudinal to <0.1% [26] – 0.3% [40] (Figure 15). Our test pieces indicated 5% tangential shrinkage after 2 weeks of keeping the wood at room temperature.

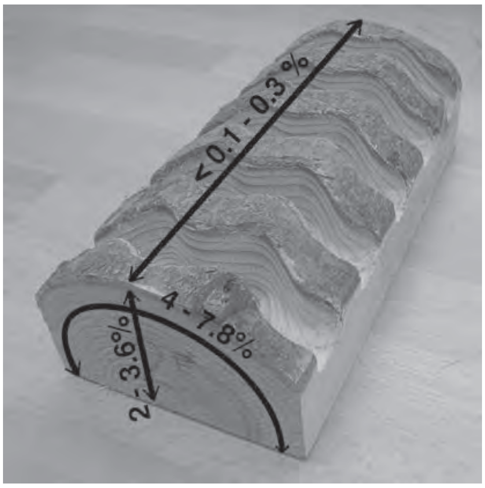

Figure 15. Orthotropic shrinkage in Norway spruce

A series of waving incisions -- 20 mm wide and 20 mm apart -- were CNC-cut perpendicular to the halved-log axis on the bark side, in order to produce the active elements of the panel. According to the abovementioned figures their width after drying should shrink to 18.5-19 mm 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 16).

Figure 16. BackToBack wet-in-wet concept

The waving pattern of the incisions and resulting ribs has been proposed in order to harness the tangential shrinkage, however its precise geometry, size and proportions remain subject to further research and development.

7 DISCUSSION

The main task of the presented prototypes is to illustrate the approach that makes use of material properties and behaviour instead of attempting to overcome them at the same time using material that is otherwise wasted. The minimisation of processing is achieved by halving (and/or debarking) only instead of full sawing on four sides prior to cutting the incisions. The connecting mechanism utilises only the phenomena already present in the material, without any external bonding agents at zero-energy expense. In this perspective the tests performed demonstrate that it is indeed possible to construct a behaviour-based connection and open way for further study.

If this path of development succeeded one could foresee large savings in chemicals, energy and time. The prototyped joint proposals exploit just two out of the many possible implementations of wood behaviour. Both proposed prototypes make use of wood shrinkage. The phenomenon of warp could potentially serve as a basis for the development of different types of joint. The presented prototypes must be further tested. More detailed and precise larger versions should be produced to allow accurate testing. Market viability of new products based on these principles requires further inquiry. And so does the exact environmental impact improvement and the resulting contribution of this technology to the sustainability of building practice.

7.1 The incisions pattern

The waving pattern of the incisions and resulting ribs in the wet-in-wet scenario has been proposed in order to harness the tangential shrinkage, however it remains subject to further research and development. The pattern: its geometry, sizes and proportions must factor in the structural behaviour of the panel as a building component, that is except of not being easily pulled apart it should transfer shear stress. Providing a shear force resistant connection between the pieces would dramatically increase the stiffness and hence the panel load-bearing capacity. The heterogeneous wood grain structure must be taken into account during sizing of the incisions regarding the shear force, a manifested reference to the material-oriented design. The material-informed design should include other variables affecting the shrinkage such as moisture content, tree specie and wood structural features.

A software model that would take into account the complex interplay of the abovementioned factors could help find a solution for the geometry of the incisions.

7.2 The tools

In the process both hand tools and a CNC milling machine were used.

The use of hand tools in the process was a potentially limiting factor due to two main reasons:

1. It did not permit to achieve sufficient precision to be able to accurately assess the results.
2. Additional work time was required to readjust the machines to the varying thickness through which they cut -- result of the conical, half-round cross-section and irregularity of the individual boles.

Both of the abovementioned problems applied to the CNC machining process as well, though these could be more easily overcome by different software and hardware setup. It has been noted during the experiment that CNC machining of green timber requires higher spindle speeds that offered by the milling machine available to us. At 6000 rpm the quality of the cut required a great deal of post-processing. In case of straight incisions a much quicker and producing better cut quality option would be to use a CNC machine with a circular saw rather than milling bits for cutting. Also, another CAM software, not based on STL solids as input but simply accepting CAD lines would highly speed up the process.

To this end -- besides the aforementioned development of software – an important line of progress of the project includes the development of hardware setup allowing for spending less energy and time on production.

7.3 The material

The aforementioned is highly affected by the wood material properties. This in turn, besides the moisture content, geometrical and structural traits heavily depends on the wood specie. Finding wood species making the most of the desired features is of paramount importance to the development of our project.

This approach draws inspiration from the *Spruce Goose* or Hughes-Kaiser HK-1 aircraft story: *Teams were dispatched into the woods of the United States and Canada to find specific trees for specific parts of the plane. The HK-1 was designed not with the invariant code of aluminium but with the variant performance of specific and unique traits in actual material* [41]. Originally, birch was chosen as a building material, but due to shortage in supplies fir, cottonwood, maple and balsa were used in different parts of the airplane accordingly to the specie-specific properties. In building construction, before the introduction of structural steel, builders often applied hardwood dowels in softwood structural elements, for their greater strength, connecting elements with more ease and saving time [42].

One recent example that illustrates that approach in architecture includes sports hall in Sargans, Switzerland where spruce and ash wood were used accordingly to their specific characteristics and role in the building (Blue Architects, completed in 2008).

As explained earlier, shrinkage for various popular woods may vary by as much as 200% (see 4.1). Further -- following the line of minimum intervention – as some species are more resistant to fungi, insect and rot attack than others, they could be used without any additional treatment. This feature is often combined with toxicity of the wood: yew (*taxus baccata*) and black locust (*robinia pseudoacacia*) are well known examples. There are rare cases of architectural application of yew for its properties (as the wood is scarce and currently under protection). Some 16th-18th century churches in Slovakia: in Hervartov (Figure 17), mainly, and in Točany and Kežmarok, partly, were made from yew [2]. More recently the Albisgüetli forestry operations centre in Zurich (Fahrländer Scherrer Architekten, completed 2013) features cladding with three layers of yew shingles [43] (Figure 17).

Figure 17. 16th century church in Hervartov (Slovakia) made from yew (photo M. Wójcik) and 2013 Albisgüetli forestry operations centre in Zurich clad with yew shingles (photo H.Henz, source [43])

7.4 The supply chains

Another question concerns forestry and wood supply: as roundwood and green wood are not available through normal commercial channels, working with this kind of material is not possible in standard practice. Implementing this solution would require a general remodelling of the current supply chains. On the other hand finding use for the product of forest thinning can have long-reaching advantages. In silviculture the initial narrow spacing and later thinning strategy – necessary for improving the growth rate and wood quality -- makes the remaining trees twice as expensive as planting to a wider spacing, unless there was a commercial market for the thinned material [44].

The product of forest thinning contains juvenile wood affecting the longitudinal shrinkage that, from green to oven dry, amounts to 2%, result of shorter cells and high microfibril angle [44]. That feature, providing for an interesting synergy, could also potentially be investigated in the development of the shrinkage-based connection.

7.5 Implications for architecture

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. As discussed above (see 7.3) some species may even offer high resistance of untreated exposed surface. 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, as mentioned earlier, 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.

Both 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.

8 ACKNOWLEDGEMENTS

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Appendix 4: WÓJCIK, M. & KŁACZYŃSKA, S. 2014 Continuing the 'Continua' I. Application of thin plywood in construction through biologically inspired approach. In: GU, N., WATANABE, S.-I., ERHAN, H., HAEUSLER, M. H., HUANG, W. & SOSA, R. (eds.) Rethinking Comprehensive Design: Speculative Counterculture. Proceedings of the 19th International Conference on Computer-Aided Design Research in Asia (CAADRIA 2014). Kyoto: The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

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CONTINUING THE 'CONTINUA' I

Application of thin plywood in construction through biologically inspired approach

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1. Introduction

This paper investigates a possibility of application of thin (ca. 5 mm) plywood as structural material. It takes departure from the Erwin Hauer's 'Continua' series (Figure 1), and proposes how it could be developed with the contemporary digital tools and by following the biological paradigm. The objective is to develop a new system that minimises wastage as well as to test how the resulting structure performance.

2. Biological paradigm

The re-design of the 'Continua' series takes inspiration from the biomimetic approach. Biological systems utilise information rather than energy in order to solve technical problems and to self-assemble structures that unlike the engineered solutions are hierarchical. Energy is used sparingly, single material often serves both structural and protective purposes, the distinction between material and structure is blurred (Vincent et al., 2006). Today's environmental concerns invoke interest in the efficient and rational biological systems.

3. 'Continua' worth continuing

Erwin Hauer (b.1926) is an Austrian-American sculptor, known for repetitive screen-wall systems based on modular elements cast in concrete, gypsum or acrylic resin or later CNC-milled in MDF and limestone (Hauer, 2004). These methods are time and energy consuming and produce waste. Our previous research indicates that ‘Design 3’ (1952) from the ‘Continua’ series would be applicable for external light-breaking building envelopes due to its light diffusing, wind and sound breaking capabilities.

Figure 1 - Erwin Hauer’s ‘Design 3’. Figure 2 and 3 - proposed solution.

4. Proposed approach

The proposed solution (Figure 2) is based on thin plywood bent to form and thus achieving strength. Elastic bending is induced with threaded rods with nuts (Figure 3). By doing so much less material and time are used to produce a final piece. This solution required reconfiguration of the modules, but the geometrical features of the original are sustained. Thin plywood is lightweight, durable, flexible and based on a renewable resource. CNC laser cutter enables variation without extra production time, allowing for changing the geometry in response to the environmental factors. Hierarchically, global form is controlled locally at a level of a single unit, that being dependent on the material properties. The proposed system uses the method of parametric design, where the local geometry is variable within the modular framework.

5. Further development

It is proposed to develop the system further, especially to provide for self-support through the overall geometry, e.g. shells. Another path of development includes adding material criteria as the elastic bending parameter.

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CONTINUING THE 'CONTINUA' II

Application of thin plywood in construction through biologically inspired approach

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1. Introduction

This paper investigates a possibility of application of thin (ca. 5 mm) plywood as structural material. It takes departure from the Erwin Hauer's 'Continua' series (figure 1), and proposes how it could be developed with the contemporary digital tools and by following the biological paradigm. The objective is to minimise wastage as well as to test how the resulting structure would perform structurally and as a light-controlling device.

2. Biological paradigm

The re-design of the 'Continua' series takes inspiration from the biomimetic approach. Biological systems utilise information -- stored in the genetic code -- rather than energy in order to solve technical problems (Vincent et al., 2006) and self-assemble structures that unlike the engineered solutions are hierarchical. Energy is used sparingly, single material often serves both structural and protective purposes, the distinction between material and structure is blurred. Today's environmental concerns and depleting resources invoke interest in the efficient and rational biological systems.

3. 'Continua' worth continuing

Erwin Hauer (b.1926) is an Austrian-American sculptor, known for repetitive screen-wall systems based on modular elements cast from moulds in concrete, gypsum or acrylic resin or later CNC-milled in MDF and limestone (Hauer, 2004). These are time and energy consuming and produce waste. ‘Design 3’ (1952) from the ‘Continua’ series would be applicable for external light-breaking building envelopes (Kłaczyńska, 2013).

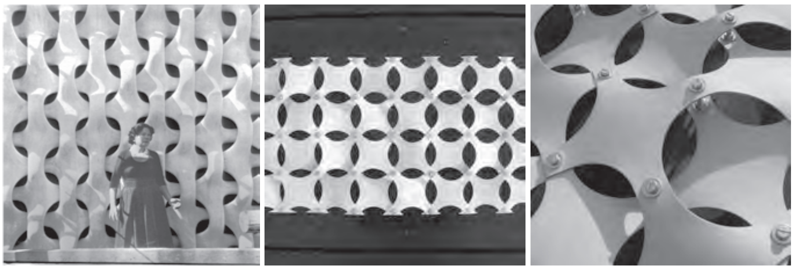

Figure 1 - Erwin Hauer’s ‘Design 3’. Figure 2 and 3 - proposed solution.

4. Proposed approach

The proposed solution (figure 2 and 3) is based on sheet material bent to form and thus achieving strength. Thin plywood is lightweight, durable, flexible and based on a renewable resource. Tension in bending is induced by threaded bars. The cross shape of the panels provides for achieving double curvature. The distribution of convex vs. concave panels regulates the overall stiffness. CNC laser cutter enables variation without extra production time. The system uses the method of parametric design, where sizes of the openings and amplitudes of the wave are variable. That allows for changing the geometry in response to the geometrical, structural and environmental factors. Hierarchically, global form is controlled locally at a level of a single unit, that being dependent on the combination of material properties and geometry. By doing so much less material, energy and time are used to produce a final piece. This solution required reconfiguration of the modules, but the geometrical features of the original ‘Design 3‘ are sustained. Further development of the system includes providing for self-support through the overall geometry, e.g. shells, as well as adding material criteria as a variable parameter by varying the number of plies in response to the curvature.

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Appendix 6: WÓJCIK, M. 2015 Counterculture, Ju-jitsu and Emancipation of Wood. In: ANNE LOUISE BANG, J. B., IRENE ALMA LØNNE, NITHIKUL NIMKULRAT (ed.) Tangible Means. Experiential Knowledge Through Materials. EKSIG 2015. Design School Kolding, University of Southern Denmark: Design School Kolding, Denmark.

Counterculture, Ju-jitsu and Emancipation of Wood

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Abstract

This paper sets out to formulate the notion of material-oriented design in wood. In this respect I propose an alternative ontology, where the material is seen as an equal rights partner to the designer. Further, I contrast the constructivist and evolutionary types of management, where in the latter systems are produced with minimal waste and energy expense. I discuss the implications of the approach on an example of five experimental projects, including my own in more detail. I advance that material-oriented design challenges the established form-matter relationship, design process, our understanding of authorship and bears an environmentally friendly potential.

Keywords

wood; material-oriented design; experimental design; New Materialism; material agency

Our approach to wood in architecture has been affected by the spirits of the Scientific Revolution, Enlightenment, and Industrial Revolution. Considering the material's high strength, low weight, low cost and abundance, "timber remains the world's most successful fibre composite" (Dinwoodie, 2000, p. 2), nevertheless it has lost market shares as raw material. It is not an optimal material for mass-production processes, due to its variability, inconsistent makeup and difficult to predict behaviour. The methods of wood remanufacture, focused on homogenising and standardising the material, are not without impact on the environment, effect of energy- and chemicals-intensive processes.

Is the raw material really used to its full potential following this model? In the context of arising ecological concerns, are there new efficiencies and effectiveness yet to be discovered? Could the *disadvantageous* traits be used to benefit? If so, what kind of reference frame that would entail?

The countercultural project

Striving to address these questions I propose to formulate a notion of material-oriented design. The material perspective, however not non-existent, is rare in the design disciplines[1]. As a result of the long established hierarchy that has prioritised form over material and idea over its manifestation "material is rarely examined beyond its aesthetic or technological capacities to act as a servant to form" (Lloyd Thomas, 2007). In this context material-oriented design appears as a countercultural project -- it opposes the well-established hierarchies and the accepted order.

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[1] In architectural theory the perspective started to shift in the mid-2000s. While traditionally materials were concerned either in technical or aesthetical terms, some other perspectives began to come forth: emancipating material as the outright counterpart to form (Weston, 2003), *biographies* of materials, such as iron (Rinke, 2010), concrete (Forty, 2012), or steel (Fry & Willis, 2015), or contextualising materials vis-à-vis modern technologies (Addington & Schodek, 2005; Fernandez, 2006; Kolarevic & Klinger, 2008; Schröpfer, Carpenter, & Viray, 2011).

I propose to base the project on the metaphysical foundation of New Materialism. The New Materialism discourse acknowledges both human and non-human agency in the production of form and strives to reconfigure and to think past the well-established dichotomies: nature-culture, body-thought, concrete-abstract, subject-object, human-nonhuman, matter-mind, real-ideal, digital-manual, formal-material etc. (Dolphijn & van der Tuin, 2012). The New Materialism proponents, such as Canadian philosopher Brian Massumi (b. 1956) or Mexican-American philosopher and artist Manuel DeLanda (b. 1952), argue in favour of recognition of the potential of matter to self-organise, and see it as a potential path of development for design (DeLanda, 2001; Massumi, 1992).

This, however, cannot be achieved by the existing design methods, not capable of embracing that perspective, e.g. material behaviour as a design potential eludes the means of design, from drawings to building information models (BIM). In order to address the challenge, a change of the frame of reference is necessary. To this end, I try to establish theoretical and methodological frameworks for material-oriented design.

The emancipation of wood

Architectural design is a complex entanglement highly affected by a variety of factors belonging to a wide range of disciplines. The tectonic quality of architecture emerges from the interplay between material, economical, technological, environmental or cultural factors. I propose to look at material agency in this complex interplay.

Material agency

British philosopher and sociologist Andrew Pickering (b. 1948) had formulated a shift in science studies from epistemology to ontology. More specifically, he indicates a shift from representational understanding – being an accumulation of data and knowledge -- towards performative condition characterised by “dance of agency” (Pickering, 1995, p. 21). This *dance* occurs between both human and nonhuman actors. Pickering sees material agency as undefined, constantly changing in time:

The contours of material agency are never decisively known in advance, scientists continually have to explore them in their work, problems always arise and have to be solved in the development of, say, new machines (Pickering, 1995, p. 14).

Architecture, not unlike science or engineering, encounters resistance and unpredictability of matter. From the designer’s perspective these are seen as inconvenient problems to overcome. In this light heterogeneous material and its behaviour cannot become design potentials. In my view this situation is a result of the long established hierarchy, where material manifestation is below the form and idea, additionally amplified by the19th century industrial standards where material is passive in the production processes.

An alternative ontology is offered by the actor-network theory (ANT)[2]. In the view of ANT *actants* are both human and nonhuman actors with equal ability to act. In ANT the concepts of agency and intentionality do not have to be bound together. At the same time, this is neither an anthropocentric nor a hierarchical concept. Central to the theory is a web of relations, being both material -- between things, and immaterial -- between concepts. In order to see architecture through this lens, emancipation of material is prerequisite. Latour describes a *nature-culture hybrid* that in the context of materiality and architecture may be understood as a synthesis of materials and cultural ideas. I argue that this concept is central to the material-oriented design.

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[2] ANT was developed in 1980s in France by science and technology scholars: Bruno Latour (b. 1947), Michael Callon (b. 1945), John Law (b. 1946) et al.

In 1990s French philosopher Michel Serres (b. 1930) proposed that objects -- inanimate matter and nature -- become legal subjects. For Serres, this subjectivity of objects is a necessary condition for bringing back the equilibrium to the world facing ecological disaster. As a remedy, Serres proposes *natural contract* – between human and nonhuman actors, not unlike our *social contract* – between humans (Serres, 1995). Serres thus linked material agency and ecology.

ANT established science, technology and society as a field of human and nonhuman agency in a symmetrical rather than hierarchical fashion. This approach has the capacity to embrace the unknown arising from the material side by the process of cooperation. Pickering says that "disciplined human agency and captured material agency are (…) constitutively intertwined; they are interactively stabilized" [3] (Pickering, 1995, p. 17).

That approach provided a theoretical framework for material performativity. Michael Hensel extended that formulation into the realm of architecture. In this view architecture is identified as a domain of active agency (Hensel, 2010), where the "spatial and material organisation complex" is defined as a "synthesis of the various scales and their complex interactions" (Hensel, 2011, p. 4). While in the industrial tradition architects and engineers prefer materials that can be considered homogeneous and predictable -- as exemplified by the case of steel and iron -- Hensel postulates dynamic condition required by the spatial and material organisation characterised by active agency. E.g. wood structure must be understood in relation to environmental conditions affecting its growth. Higher in the hierarchical organisation system, material behaviour is determined by the material properties and environmental conditions. This in turn has to be harnessed by architectural design, what is the basis of the "instrumentalisation of material behaviour as performative capacity" (Hensel, 2011, p. 8).

Beyond hylomorphism

Hylomorphism, a concept introduced by Aristotle (ca. 385-322 BC) in his *Metaphysics*, distinguished between form and matter. Matter -- *hyle* -- became the substrate out of which all physical things were made, while form was the structure – *morphe* – that gave them their characteristics and attributes. In the view of Aristotelian hylomorphism a thing is a unity of form and matter. This stance, however not seeing material as active in the form-giving process, laid a foundation for materialist approaches and was prerequisite for the recognition of material agency. The often attributed to Michelangelo (1475–1564) proverb: *every block of stone has a statue inside it and it is the task of the sculptor to discover it* – actually originated in *Metaphysics* where Aristotle remarks that we can speak of seeing Hermes in the uncarved stone. The mid-20th century philosophy started to question the concept of hylomorphism as being insufficient. In 1950s Martin Heidegger (1889–1976) posited that the fusion of form and matter is additionally controlled by the purposes served by the thing: "[the] serviceability is never assigned and added on afterwards to beings" (Heidegger, 2002, p. 10). The material choice in design is informed by this serviceability. French philosopher Gilbert Simondon (1924–1989) criticised hylomorphism as being based on a hierarchical relation where form is superior to matter and is not concerned with the transformative processes. Reflecting on a make-up of an adze, he points to "the progressive heterogeneity of tempering at certain points". The gradual change of material properties -- being instrumental in the functioning of the tool – eludes the dichotomies of form-matter or form-structure, and further:

The tool is not made of matter and form only. It is made up of technical elements arranged for a certain system of usage and assembled into a stable structure by the manufacturing process. The tool retains within it the result of the functioning of a technical ensemble. The

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[3] Pickering credits this observation to Engels' *coproduction*, later recalled by Callon and Latour, and dubbed by Law *heterogeneous engineering* (Pickering, 1995, p. 17).

production of a good adze requires a technical ensemble of foundry, forge, and tempering (Simondon, 1958, p. 84).

The thread of the heterogeneity of materials was picked up by Gilles Deleuze (1925-1995) and Felix Guattari (1930-1992) in their seminal *A Thousand Plateaus: Capitalism and Schizophrenia* in 1980. When discussing Simondon, Deleuze and Guattari reflect on “the variable undulations and torsions of the fibers guiding the operation of splitting” wood:

(…) it is a question of surrendering to the wood, then following where it leads by connecting operations to a materiality instead of imposing a form upon a matter (Deleuze & Guattari, 2005, p. 408).

In such formulation matter can only be *followed*, what obviously transgresses the hylomorphic conception. Deleuze and Guattari credit Simondon in this respect:

Simondon demonstrates that the hylomorphic model leaves many things, active and affective, by the wayside (Deleuze & Guattari, 2005, p. 408).

In this light, there is a spectre of potential in *following the material*, available after transcending the hylomorphic model. These *many things, active and affective* could be accessed, to our advantage, by entering into the Serres’ *natural contract* and making the Latour’s *nature-culture hybrids*.

Tectonics and time

The material focus engenders the problem of time in architecture. Materials change and perform in time. Shifting perspective to the material agency also requires refocusing from static to dynamic aspects of materials. This in turn triggers both change of the method of design and the way in which materials are used.

To this end I look into the discussion of architectural tectonics. The notion of tectonics brings about two important implications. Firstly, the term tectonics is inseparable from materiality, e.g. Antoine Picon sees it as “based on prescriptions regarding the proper use of materials” (Picon, 2010, p. 161). Secondly, the tectonic discussion -- in contrast to earlier theories that focused on the imitation of objects -- concerned the processes behind making a building[4]. The tectonic discourse, besides redirecting the interest towards the rational principles, introduced the idea of dynamic relations as informing design.

In the case of wood, the undesired by the current industry phenomena -- when seen through the lens of tectonics, agency and performativity -- could become generators for new tectonic systems. I argue that these systems would have a capacity to reduce the environmental footprint of construction: e.g. in my previous work it has been demonstrated that wood shrinkage from green to dry can replace metal connectors or adhesives in wood construction (Wójcik & Strumiłło, 2014a, 2014b).

I propose to see the discourse of tectonics as a move towards rational principles in architecture. Central to tectonics is the division made between the ornamental, artistic and symbolic versus structural, constructive and rational attitudes. A parallel could be drawn between these notions and the opposition of *representational* and *ontological* aspects of architecture, as presented by architectural historian Kenneth Frampton (1995)[5]. Following on

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[4] In 1840s Karl Bötticher (1806–1889) defined architectural tectonics as the activity of forming a building.

[5] Frampton partly attributed this idea to Semper, however he also points to (1995, pp. 71, 82) some earlier analogies in Bötticher, who in a similar vein to the ontological and representational aspects of architecture, opposed *Kernform* (core form) against *Kunstform* (art form), and designated the representational to the Greek and the ontological to the Gothic already in the first half of the 19th century (Frampton, 1995, pp. 71, 82). In Bötticher, Kernform achieves an intrinsic, or ontological

the notion of representational and ontological material-form relationship I propose to extend its meaning onto the understanding of the use of material. Under this framework I use the notions of *representational* and *ontological use of material*. In today's parlance the term *materiality* usually refers to the former, while *material logic* to the latter, corresponding respectively to the *soft* and *hard* narratives of the use of material in construction.

Ju-jitsu of matter and energy

The discussion about form – matter relationship in architecture could be enriched by some observations of biological systems. Julian Vincent, British pioneer of biomimetics, argues, that our technology *kills the information* of raw materials, with a substantial expense of energy to make the material ordered with imposed shape and structure for the final product. Quite the opposite, the biological systems use information and structure 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 (Vincent, Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006, pp. 474-478). Vincent argues that 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”. Vincent 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. The scarcity of material in nature leads to several rational solutions, such as blurring the distinction between structure and material, multifunctional use of material, hierarchical structural organisation or oblivion of waste. There is definitely something momentous we could learn about resources management from nature.[6]

To relate the discussion back to architecture I advance to use the concept of periodization of wood construction introduced by Christoph Schindler (2009). The model integrates fabrication with manual, industrial and information technology and is based, in a cybernetic fashion, on the relation between three categories: matter, energy, and information in each respective period. Schindler identifies three waves of technology in the history of wood construction: (1) *hand-tool*, (2) *machine-tool* and (3) *information-tool* technology. (1) In the first wave, dominant in the preindustrial era, the main operator of energy-matter-information was the man's hand, and the main intellectual achievement was the design of the tool. The tool operated by hand followed the growth direction of the tree and the fibre direction of the wood. Natural shapes of wood were incorporated in the design. Parts playing the same role in the building structure, even when sharing the same dimensions were not interchangeable. (2) The *machine-tool* technology is connected with the Industrial Revolution of the 19th century when machines substituted repetitive physical operations, while a human operator processed information. The design of the interconnection of power machine and machine tool was the crucial intellectual achievement. The working process was adjusted not to the potential of the hand, but to the potential of the machine what resulted in homogenisation of

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status, while Kunstform extrinsic, corresponding to representation, what prepared the ground for radical technological innovation: introduction of iron as a material representing dynamic character of the industrial society. Also Schwarzer (1993, p. 273) attributes the introduction of this concept to architectural thinking to Bötticher.

[6] This is especially important in the context of arising environmental concerns. Various efforts are geared towards providing a reference frame for material use in this regard. The concept of Life Cycle Assessment seeks to quantify the environmental impact of products over their entire lifecycle. Accordingly to the 2006 EU Eco-Innovation Panel material innovation should satisfy human needs and bring quality to life “with a life-cycle-wide minimal use of natural resources (material including energy, and surface area) per unit output, and a minimal release of toxic substances”. This notion is largely based on the concept of the *ecological rucksack* of materials and its measure – MIPS (material intensity, or material input, computed as mass per unit service), as introduced in early 1990s. The goal of MIPS is to maximise the amount of units of service with minimised use of material and material-intensive energy (Hinterberger & Schmidt-Bleek, 1999, p. 53).

wood and mass production of wood-based products and standardised building components. (3) The third wave in the Schindler's model began when machines started to replace both physical and intellectual operations. The highest achievement was the interconnection of power machine, machine tool and information machine.

I pose that this formulation can be expanded vis-à-vis the problem of material agency in design. From this perspective, the *hand-tool* technology (1) has the capacity to integrate material agency into the design, while the *machine-tool* technology (2) has not. The evidence of that are: (1) for the *hand-tool* technology – use of hand tools in connection with material traits (e.g. grain direction) and incorporation of naturally grown shapes in designs, and (2) for the *machine-tool* technology the efforts towards standardisation and homogenisation of material (e.g. wood-based panels).

While some characteristics of the *information-tool* technology (3) take after the *hand-tool* technology (1), e.g. non-standardised and non-interchangeable components, I pose that the role of material agency could also bear resemblance in the two respective periods. In other words, while the *machine-tool* technology (2) supressed material agency, a new potential has been opened for it by the *information-tool* technology (3). Such potential though requires a management strategy.

One possible management strategy is the concept of networked thinking, as originated by a German biochemist and ecologist Frederic Vester (1925-2003). Based on systemic and cybernetic approaches, in unison with the Vincent's theory, Vester 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, p. 160). This formulation transcends the framework of resilience. While resilience is the ability to absorb and release stresses, no gains are sought after in being exposed to the stress. The main goal is to *bounce back* and remain unaffected. Quite the contrary, Vester's 4th rule, reflecting the bio-cybernetic stance, takes inspiration from the martial arts strategy of exploiting the opponent's force. This insight opens a new perspective when applied to our understanding of material in construction.

The New Materialism of wood

While the possibility of application of the concepts of New Materialism and bio-cybernetics in architecture may sound vague, recently a series of researches attempted to take heterogeneous material properties into the production of form. I would like to discuss the ones dealing with wood (Figure 1, left to right): (i) Helen & Hard *Ratatosk Pavilion* at the V&A Museum in London, (ii) Hironori Yoshida *Digitized Grain* (iii) Christoph Schindler at al. *Serial Branches*, (iv) Ryan Luke Johns and Nicholas Foley *Bandsawn Bands*.

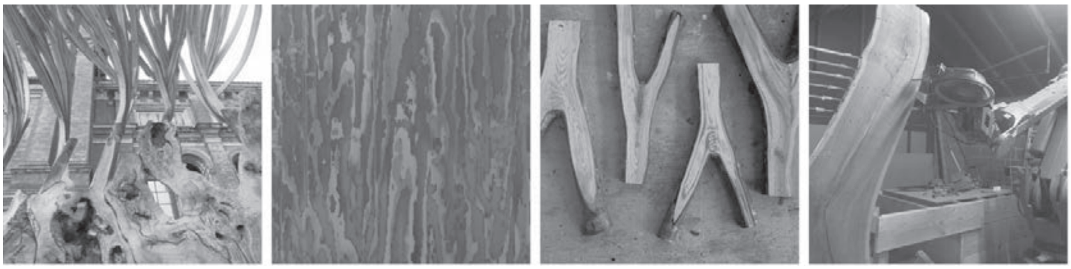

Figure 1.

The projects are of limited scale, ranging from a pavilion (i), through an art installation (ii) to furniture (iii, iv). Nevertheless, their innovative approach to the design process and technology points into a very promising direction for the material-oriented design in wood. They emancipate the material in the production of form, minimise the energy use in favour of the information use, and strive to challenge the commonplace design practice.

(i) Helen & Hard's project breaks away with the conventional design sequence: finding, scanning and digital modelling of the ash trees became the initial rather than the final design phase. As a result, the sketch phase was omitted as an inadequate work method for heterogeneous material: "[the] forms were dictated largely by the shapes of discarded branches, and therefore could never have been predicted in a preliminary sketch". Material idiosycrasies -- organic shapes, knots, holes and fibres -- led the design and construction (Stangeland & Kropf, 2012, pp. 172-179).

(ii) Yoshida's project seeks to translate the craftsman's interaction with natural materials into a fully automated *Scan-To-Production* process. The wood grain is digitally scanned, image-processed and transferred into motion paths for a CNC machine. As a result, the grain pattern of wood is replaced by polyester resin, based on colour analysis. "The Scan-To-Production (STP) process, through the use of digital scanning and robotic fabrication, proposes to take material irregularities as design input, to distinguish and create meaningful order from material *noise*" (Yoshida & In, 2013).

(iii) Schindler's project took inspiration from the Viking boatbuilders and vernacular joinery, where superior strength was achieved by using naturally forked hardwood pieces. As a result of a trial and error process a method was deviced to minimise the amount of information neccesary to compute the shpes for design: all branches were planed on both sides resulting in two parallel evenly distanced surfaces. The project demonstrates how "although we claim to explore the benefits of digital tools, our thinking is bound to the heritage of industrializaion: we are used to work with measurable geometry, minimal tolerance and reliable mateiral constraints" (Schindler, Tamke, Tabatabai, & Bereuter, 2013).

(iv) Johns and Foley in their project reverse the commonplace logic of digital manufacture: "rather than transferring material, (…) from a curved tree into dimensional lumber which is then re-machined into curvilinear digitally designed geometry" the authors "take the tree as the starting point for design and move directly to digital fabrication. This leap in the production sequence enables more sustainable material efficiency while simultaneously conferring the natural aesthetic advantage of *beauty's found geometries.*" The devised technique uses a robotically operated bandsaw to cut series of strips following the curvatures "which, when rotated and laminated can approximate doubly-curved and digitally defined geometry". As a result of the "close relationship between available material and designed geometry" the process yields "practically zero-waste". Interestingly, some tool operations are closely connected to material features, e.g. the robot cut speed is programmed as a value proportionate to the curvature of the cut, resultant from the grain pattern (Johns & Foley, 2014).

In all these examples the material properties are equal rights partners to the designer. Helen & Hard (i) or Yoshida (ii) partly cede responsibility regarding the design to the material. Should the material had different features, it would have resulted in different shapes or patterns. In this case one cannot fully claim the authorship. A hypothesis can be formulated as to whether is this a necessary trade-off, the *natural contract*, where -- by *surrendering to the material* – we can access new territories of unknown architecture, effects, affects and effectiveness? The projects seem to tentatively confirm this hypothesis. As Johns and Foley (iv) say their method is "one of few woodworking techniques which are explicitly not subtractive, but transformative" (Johns & Foley, 2014, p. 25) indicating the potential for the approach regarding minimising waste in digital manufacture. Strikingly, this applies to other presented projects: Helen & Hard (i) or Schindler (iii) also dodge waste and pollution. Intricate forms are result of naturally grown shapes and mindful handling of information, rather than sculptural milling. In this regard all four projects rely on 3-dimensional and 2-dimensional scans and digital image or model processing to form a *nature-culture hybrid,* used as a starting point for the design. It is telling that none of the projects could stick to the conventional design method, where a conceptual sketch through iterations becomes a working drawing. Not only drawings representing final forms were difficult or impossible to produce, but also obsolete. For the final product more important were process sequences and strategies regarding digitising and operating material information.

The Swelling Vault – a self-bending shape

I argue that -- however the presented projects are legitimate examples of New Materialism of wood – there still is undiscovered potential under the framework of material-oriented design. One yet little explored area remains the utilisation of dynamic, or kinetic, relations informing design. I pose that such approach opens design towards harnessing emergent phenomena. By emergence in this context I understand a process where form is produced through interaction between small components, while the meaningful properties of the form are not exhibited by the components themselves.

In order to illustrate the approach, as well as investigate its implications, I[7] carried out an experiment together with the students of design at the Hochschule Luzern. The main goal was to device a method for harvesting phenomena resultant from kinetics of material behaviour, and thus to extend the notion of material-oriented design in wood.

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

The aforementioned DeLanda sees digital simulations as prerequisite for harnessing emergent phenomena:

> [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 (…). [S]imulations can play the role of laboratory experiments in the study of emergence complementing the role of mathematics in deciphering the structure of possibility spaces. And philosophy can be the mechanism through which these insights can be synthesized into an emergent materialist worldview that finally does justice to the creative powers of matter and energy. (DeLanda, 2011, p. 6)

It was decided to lay two different patterns: checkered, using square blocks laid with alternating grain orientation; and herringbone, using elongated rectangular blocks (Figure 2). As a connection between the blocks The Lamello Joining System (biscuit joint) was chosen and no adhesives were applied.

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[7] The project was made possible thanks to the invitation and support from the Hochschule Luzern, Design & Kunst, and especially Christoph Schindler and Sebastian Kraft.

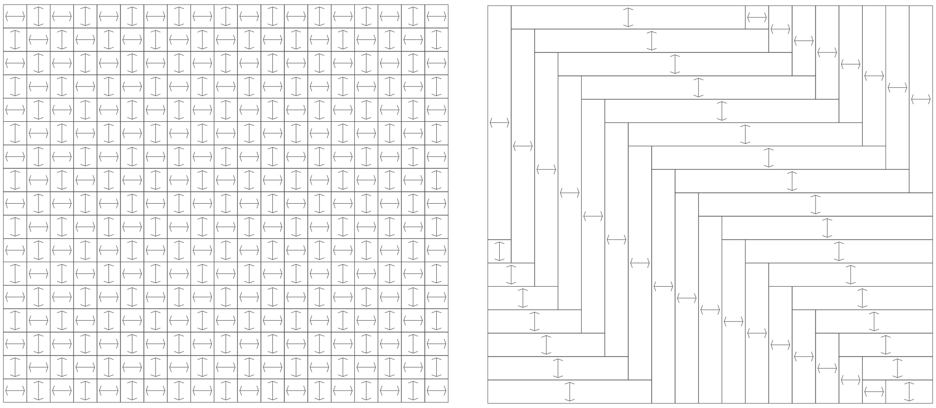

Figure 2.

After laying out the patterns warm water was poured on (Figure 3), and the pieces were left to soak in for the wood to swell. A few days later the surfaces have bulged up, the checkered patterned shape was rather regular and domed (Figure 4), while the herringbone formed a conical, almost ruled surface (Figure 4). Both resultant shapes were very strong. Four people weighting ca. 280 kg could step on a 3.2 m^2 piece not causing any damage (Figure 3).

Figure 3.

It remains to be tested to what degree the deformation is reversible when the moisture content drops. Should it reverse too much, the surface could be sealed to fix it in the warped shape.

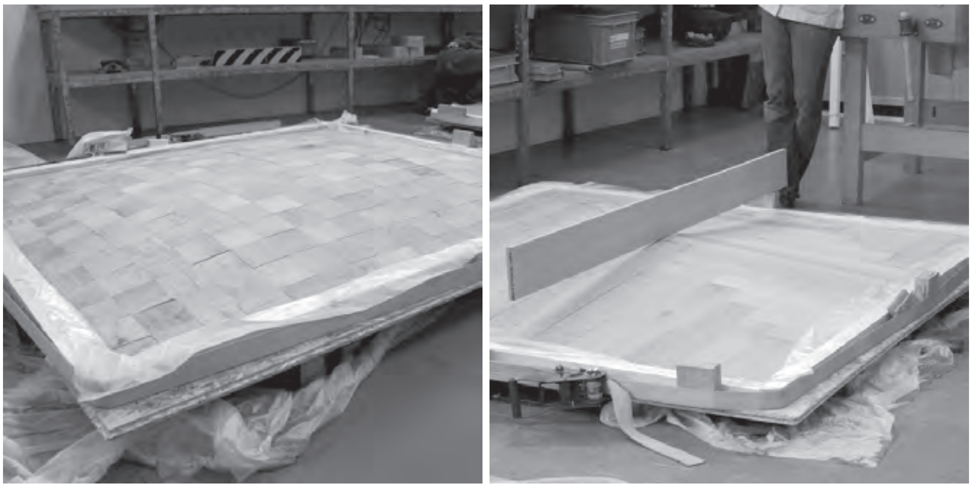

Figure 4.

In parallel, a digital simulation model was devised to compare the results with the empirical tests. Swelling of wood was estimated using a formula based on the equation from Covington and Fewell (1975). Comparison of the estimated elongation of the surface (1730.6 mm) to the empirical (1726.7 mm) yields only 0.2% discrepancy, and results in ca. 6% discrepancy between the measured 132 mm and calculated 140 mm for the sagitta (Figure 5, where solid line indicates measured and dashed line estimated shape). As for now, the digital simulation is only operational to predict the bulging for checkered patterns. Had the model been fully working, it would have been possible to predict resultant 3-dimensional forms from flat patterns.

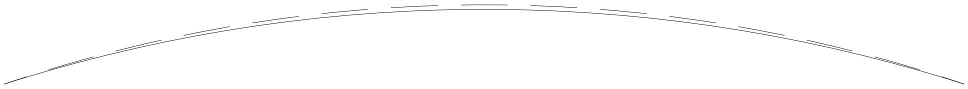

Figure 5.

Material takes command. Discussion

New ontology

The Swelling Vault project explores the symmetrical and reciprocal relation of the *natural contract*. In the process of forming neither the designer's nor the material agency could be seen as superior. In this view, the concepts of agency and intentionality are decoupled. The form is emergent, where its main property – the curvature -- is not reducible to the properties of its constituent parts. The system behaviour is anticipated by means of computer simulation.

The reciprocal relation between the designer and the material can be describes as a *dance of agency*, where none of those two could be omitted nor prioritised. Any imbalance would invalidate the process. However the designer and the material are equally valid, there obviously are important differences between them. At different stages of the process one or the other comes to the fore: the designer in the preparatory stage specifying the layout of the blocks in order to achieve – within tolerances -- desired result, and the material in the final stage, where the totality of material and environmental factors give the vault its final shape.

A prerequisite for the balance to be operational is that the material is seen and used in the *ontological* terms. Not only pieces of other material looking like wood, but even some other species of wood, would not perform the task. For the *natural contract* to be valid, a total understanding and acceptance of the material behaviour is necessary. In a way, that may be seen as yet another come back of the clichéd 18th century concept of *truth to materials*[8], this time in a purely *ontological* understanding of material without any references to moral values.

Bio-cybernetic process

The project harnesses an emergent, moisture induced phenomenon, rather than uses external energy for forming. Therefore it conforms to the bio-cybernetic and biomimetic models. The shape, achieved with negligible use of energy and waste, becomes *cheap.* The *ju-jitsu principle* is applied in the process as the ability not only to accept setbacks but also to turn them into advantages. In the project the material characteristic usually seen as disadvantageous -- moisture related dimensional instability -- is exploited. The change of perspective, allowed by the countercultural design approach, allowed not only to *even up* or *compensate* for it, but also to turn it into design strategy. And even more, this strategy results in palpable and quantifiable gains – the shape is achieved with a minimal *environmental rucksack*.

Not unlike in the case of the four aforementioned projects, also the *Swelling Vault* required rethinking of the design process. The predominant design methods are rooted in the Renaissance, when design was concerned with imitation of objects. Quite the contrary, the process captured dynamic relations, where the shape could be specified only within the material limitations. Within the system not all forms are possible, and any simulated design negotiated between the designer and the material is only a simulated approximation. The designer’s control is through material selection, shaping of the wooden blocks and laying them out in various orientations and patterns. The simulation as a design method allows only for interaction through a trial and error process. One possible way of development may be application of a strategy called reverse engineering: a shape would be specified by a designer, than computer program would generate the best possible shape match, and choose the appropriate material and pattern.

As a result of the project, two conclusions concerning the design process arose: digital tools are essential for simulation of the *dance of agencies* at the early design stage, and as this prediction cannot be 100% accurate, appropriate tolerances must be embedded in the design.

Cultural performance

Are we, designers, loosing control over the designs by including material *actants* in the *nature-culture hybrid* process? Sharing the authorship with – to some degree – unpredictable, and also demanding *partner*, may seem counterproductive towards achieving design goals. The approach bears resemblances with the *digital turn* in architecture, that

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[8] The concept of *truth to materials* surfaced for the first time in Italy in the mid-18th century when Carlo Lodoli (1690-1761), as a countermeasure to the Baroque and the influence of the Classics, formulated an entirely new notion of truth, not understood in the Classical sense as synonymous with beauty, but associated with consistency. For Lodoli the form of the ornaments must be consistent with the materials in which they were made (Forty, 2000, pp. 294, 296).

have already questioned the Modernist idea of the standard and the Renaissance idea of the author (Carpo, 2009, p. 53). In exchange – besides the aforementioned energy and material savings -- it offers a return to the pre-industrial and pre-modern models: the relation between the subject and object of design in the digital chain mirrors the Medieval master builder approach, or the distributed authorship of *Wikipedia* echoes the Medieval manuscript read-and-write mode. In particular the later brings similar controversy as the *nature-culture hybrid* process due to its inconsistencies and unreliability. Obviously *Encyclopaedia Brittanica* is much more stable and reliable, but cannot match *Wikipedia* in speed of reaction or availability. Analogically, the available *Swelling Vault* shapes are limited by the system capacity to take shapes, and its final shape is a few per cent off the predicted height, but it has been achieved with a negligible *environmental rucksack*. I propose to see it as a necessary trade-off that has to be made if we want to access the benefits that come with this approach.

As the discussed projects may suggest, the unpredictability and idiosyncrasy resulting from the approach is a design opportunity. Design that follows material yields objects that cannot be reproduced, thus resulting in *cultural performance* not seen since the pre-industrial times. Just like the subject-object relation in design process or the question of authorship, the cultural role of material in material-oriented design takes after the pre-Modern and pre-industrial models. Are we ready for the material to take command?

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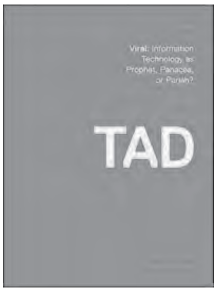
Appendix 7: WÓJCIK, M. 2017. Three Experiments in Wood and Computational Design. Technology | Architecture + Design, 1.



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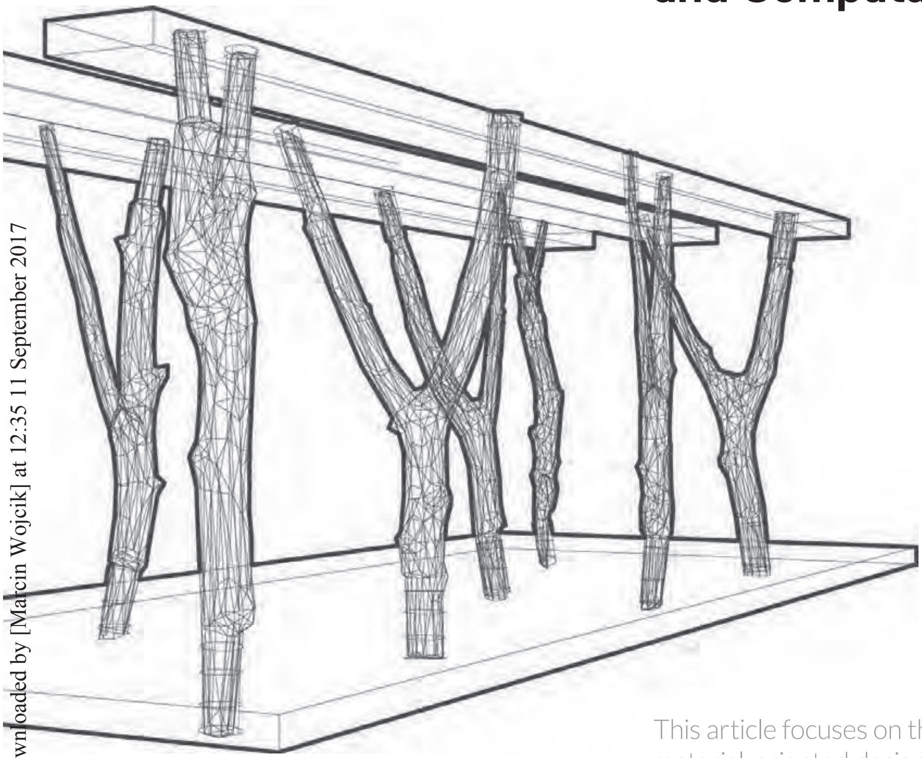
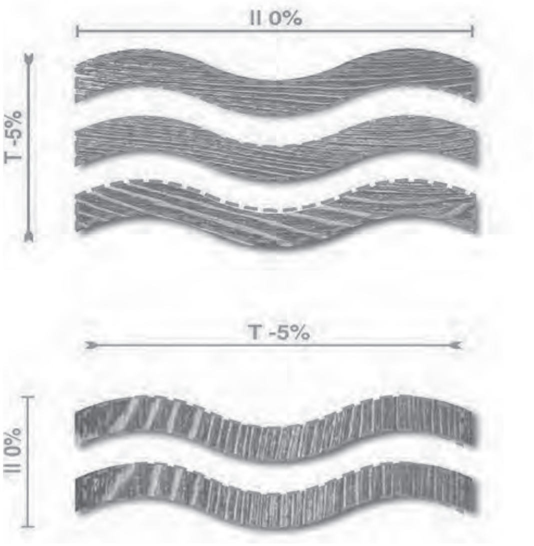


This article focuses on the relationships among material-oriented design, digital technologies, and environmentally responsible construction. It argues that computational design methods and digital manufacturing have the capacity to open new opportunities for design and can lead to more sustainable practices. 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.

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

▽ Figure 2. Tangential (T) and longitudinal (II) shrinkage as connection mechanism (orange lines indicate sizes after shrinking). Drawing by the author.



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 examples discussed, *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 (1514–77), Carlo Lodoli (1690–1761), Viollet-le-Duc (1814–79), Auguste Choisy (1841–1909), Adolf Loos (1870–1933), Frank Lloyd Wright (1867–1959), and Louis Kahn (1901–74). 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 hinged 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 twentieth century, such as 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 itself 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 they were not subject to strict technical scrutiny. Notwithstanding the lack of technical standards and testing, they prove the potential of the approach and set the stage for further replication, development, and improvement. In this light, aside from 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

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 nonbiodegradable synthetic polymer. CLT panel construction systems rely on metal connectors for assembly. These solutions are problematic when the entire life cycle and recycling of the component are considered.[1]

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 Brettstapel, 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 (http://www.brettstapel.org).

A similar principle is employed in the production of NUR-HOLZ (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 the 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 (http://www.nur-holz.com).

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 pine, a substandard 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 (Figure 1). Anisotropic shrinkage is where wood shrinks

△ Figure 3. BackToBack: dry-in-wet. Photograph by the author.

△ Figure 4. BackToBack: dry-in-wet. Photograph by the author.

at different rates tangentially, radially, and longitudinally to the log axis.

Norway spruce was chosen for the experiment. The acquired roundwood was frozen and processed while still green. Our test pieces indicated 5 percent tangential shrinkage[2] after 2 weeks of keeping the wood at room humidity and temperature.[3]

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. (1) 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. (2) 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 side (Figure 2).[4]

(1) 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 (Figures 3 and 4). A series of linear 20-mm incisions were cut at various angles to the halved-log axis on the bark side. Dry pine boards 20×120 mm were used as inserts. The resulting interstitial spaces between the boards could be used for thermal insulation, for example, 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 explores the distribution, geometry, and dimensions of these incisions and inserts by testing multiple variants.

(2) 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 (Figures 5 and 6). A series of waving incisions were CNC cut perpendicular to the halved-log axis on the bark side, in order to produce actively shrinking areas of the panel, harnessing the tangential wood shrinkage.[5]

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: (1) it did not permit sufficient precision to accurately assess the results, and (2) as a result of the conical, half-round cross section and irregularity of the individual logs,

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

△ Figure 6. BackToBack: wet-in-wet. Photograph by the author.

additional work time was required to readjust the machines.

The problems mentioned above 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 rpm[6] produced very smooth surfaces, where no manual work was required. As a cutting tool, a standard flat nose milling bit was used.

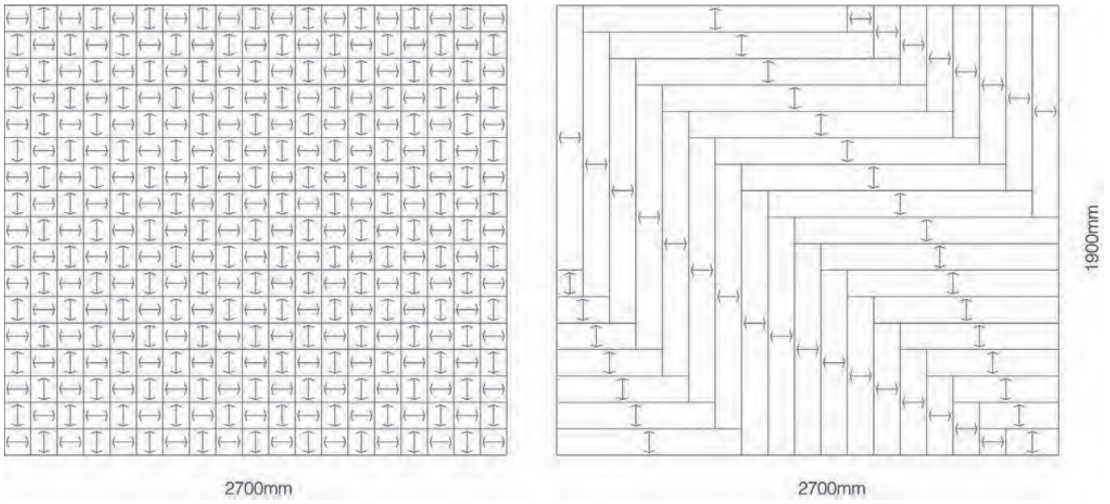
The width of the incisions shrank after drying and tightened on the receiving ribs resulting from the identical incisions cut parallel to the log axis on the corresponding passive elements of the panel. The incisions along the log axis were passive, as the longitudinal shrinkage ratio is negligible.

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 before 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, although 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 percent).

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 US and EU regulations restrict their use and caution against exposure to them.



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

▷ Figure 8. The Swelling Vault: increasing moisture content in wood. Photograph by the author.

▷ Figure 9. The Swelling Vault: the herringbone pattern bulging. Photograph by Sebastian Kraft. Reproduced with permission.

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 Pavilion, FRAC Centre Orleans, by Institute of Computational Design, Universität Stuttgart (Achim Menges, Oliver David Krieg, Steffen Reichert, 2013, http://www.achimmenges.net/?p=5612). The pavilion contains apertures that open or close based on curling of the wood skin induced by changes in humidity of 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 percent.

In order to compare results, two identical 1,700×1,900 mm oriented strand board (OSB) bases with edge constraints were constructed. It was decided to lay two different patterns: *checkered*, using 100×100 mm square blocks laid with alternating grain orientation; and *herringbone*, using 1,000×100 mm elongated rectangular blocks. The edge blocks had to be cut to fit in the base (Figure 7).

These patterns were 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 100×100 mm module. Connections between the blocks used the Lamello Joining System (biscuit joint), and no adhesives were applied.

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.

It was estimated that about 15 liters of water per piece would increase the moisture content of the wood up to approximately 30 percent. 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 8).

Results

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

Four people weighing approximately 280 kg could step on the 3.2 m^2 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 9).

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 plug-ins.[7] In the program, 2D block patterns were drawn with the swelling direction of each block programmed as a compressed spring. The rest of the 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 shape.[8]

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,

and

FSP = fiber saturation point.

For our case, each block measures 100 mm across the grain, so:

$OD = 100$ mm.

For European oak (*Quercus robur*), tangential shrinkage from green to 12 percent moisture content amounts to 7.5 percent and radial to 4 percent (Dinwoodie 2000, 59). 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 percent was assumed. Therefore,

$SV = 0.0575.$

The average measurement of the final moisture content equaled 27 percent, while the initial was 8 percent; thus,

$CMC = 0.19.$

Fiber saturation point at 30 percent 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:

$DC = 100 \times 0.0575 \times 0.19 / 0.3 = 3.6\ mm.$

Comparison of the simulated elongation of the surface (1730.6 mm) to the empirical (1726.7 mm) yielded a discrepancy of only 0.2 percent and resulted in a discrepancy of approximately 6 percent between the measured 132 mm and simulated 140 mm for the sagitta.[9]

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.

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 the architectural form. This experiment used an opposite logic, where the 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 irregularly grown form. Such natural forms cause problems because 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, 145–49).

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, 133–34). The first algorithmic model for computer simulation of branching patterns employing the concept of *cellular automata* was proposed by the Polish-American mathematician Stanisław Ulam (1909–84) 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 WholeTrees Architecture & Structures,[10] 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 (2014–16; Figure 10).

While this 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 Victoria and Albert Museum in London in 2010. The project breaks from the conventional design process in beginning the design by first finding, scanning, and digitally modeling 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, 172–79).

The Woodchip Barn (2015–16), designed and built by students of the Design & Make program at the Architectural Association School of Architecture in London (Figure 11), strives to explore the boundaries of applications of this material at full architectural scale.[11] 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 before harvesting. Based on the criteria of the structure, twenty-five 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.

◁ Figure 10. WholeTrees Architecture & Structures, Festival Foods Grocery Store in Madison, Wisconsin. Architect: Bark Design Architects; contractor: Tri-North Builders. © WholeTrees Architecture & Structures. Reproduced with permission.

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 with Y-shaped branches, which were collected in the forest. The material was cut to 40 cm length using a band saw. All ends of the branches were rounded with a tenon cutter. A typical tenon cutting blade 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.

The horizontal slabs were made out of polyurethane, because of 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

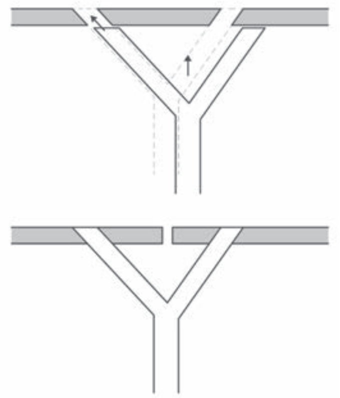
The goal of the Y-timbers project was to produce a 1:10 model of a construction system using forked timbers as columns with connecting horizontal beams or slabs. The joint between the column and the beam was based on mortise and tenon techniques.

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 (Figure 12). To this end, a design strategy was devised that resolves the problem by connecting two beams on top of a Y-shape. 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 modeling, and drilling holes using 5-axis CNC milling. A desktop size robotic arm AL5D with an Arduino microcontroller[12] 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 13). 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. It was then possible to lay out the branches accordingly to the design intent and locate the mortise positions and orientations in the slabs. Finally, an industrial Motoman robotic arm was used to mill the oblique holes in the polyurethane slabs (Figure 14).[13]

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 a use for the innate strength of the naturally grown forked shapes of timbers.



△ Figure 11. Architectural Association School of Architecture, the Woodchip Barn, Hooke Park near London. © Architectural Association School of Architecture. Reproduced with permission.

△ Figure 12. Y-timbers, connection problem. Drawing by the author.

Discussion

A summary of the three experiments is presented in Table 1.

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 the versatility of robotic milling.

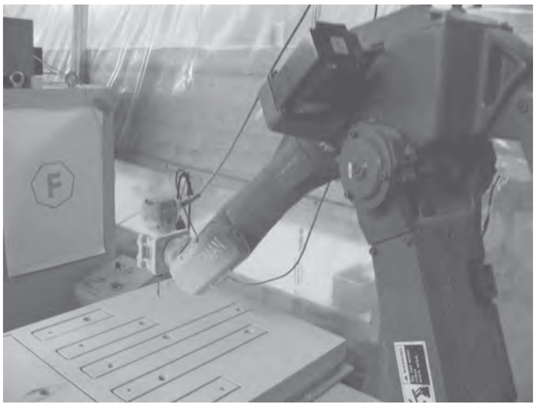
While the Swelling Vault experiment did not require digital fabrication, it used computation as a means to control the process. As discussed earlier, bulging of multiple parquet blocks is an emergent phenomenon, in which the final shape cannot be intuitively predicted. Thus the emphasis in this method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

△ Figure 13. Y-timbers, 3D scanning, April 2016. Photograph by Jan Strumiłło. Reproduced with permission.



△ Figure 14. Y-timbers, robotic milling, June 2016. Photograph by the author.

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 and improvement of the environmental impact, and market viability testing.

The necessity of performing 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 not only her approach to aesthetics, tolerances, and 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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Acknowledgments

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Notes

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

	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 three experiments.

partying out in a demolition process. Thus, only about 0.03 percent 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. For Norway spruce, depending on the sources consulted (Dinwoodie 2000; Falk 2010), tangential shrinkage amounts to between 4 and 7.8 percent, radial to between 2 and 3.6 percent, and longitudinal to between <0.1 and 0.3 percent.
3. Approximately: relative humidity = 30–40 percent, temperature = 20°–22°C.
4. The active side of the panel is the part that shrinks, while the passive side is the part that does not shrink.
5. See https://vimeo.com/192351147.
6. In FabLab's milling machine setup, 18,000 rpm is available as a standard (Shopbot PRS Alpha with HSD 4HP spindle).
7. 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).
8. See https://vimeo.com/192333690, https://vimeo.com/192333694.
9. Sagitta is the distance from the midpoint of an arc to the midpoint of its chord (http://www.merriam-webster.com).
10. See http://www.wholetrees.com.
11. See http://designandmake.aaschool.ac.uk/woodchip-barn/.
12. Arduino is a do-it-yourself microcontroller kit for prototyping digital devices (http://www.arduino.org).
13. See https://vimeo.com/192430402.

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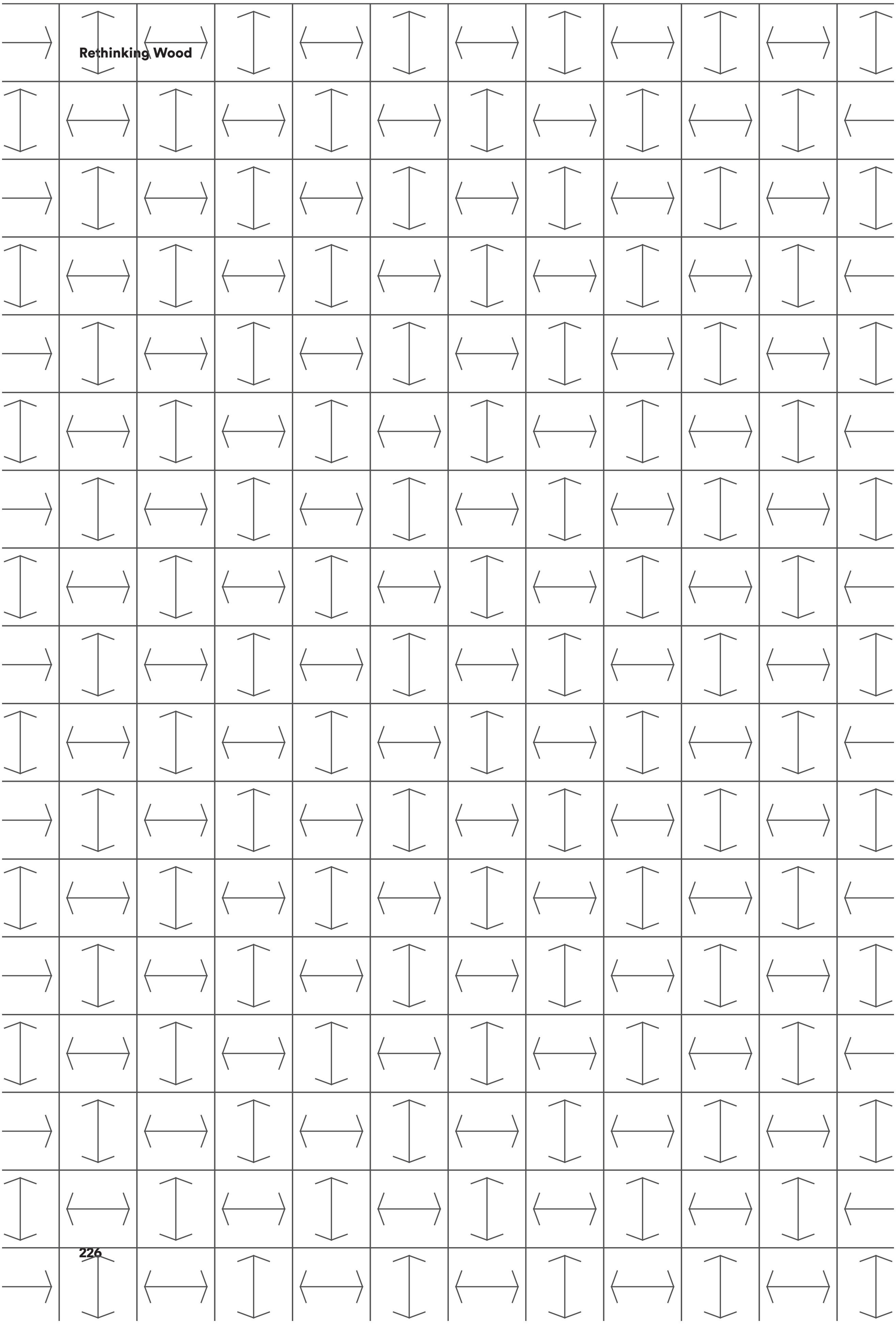
Appendix 8: WÓJCIK, M. (2019) The (D)efficiencies of Wood. In: HUDERT, M., PFEIFFER S. (ed.) Rethinking Wood. Future Dimensions of Timber Assemblies. Springer.



The (D)Efficiencies Of Wood

Marcin Wójcik

Wood, one of the oldest building materials, has recently received renewed attention as a result of the increased interest in sustainable construction. However, today the predominant method of using wood in construction is based on seeing it as passive during the design and form-giving processes. The efficiency of this method requires suppressing inherent traits of the material and behaviors, such as irregular shapes or dimensional instability, and renders them as deficiencies, which have to be overcome. The processes of adapting wood for the needs of modern building are energy expensive, use toxic chemicals, and produce waste, all of which defeats the purpose of sustainable construction.

An alternative approach suggested below is based on reversing this predominant relationship of design and materials, with a view to turn the material's deficiencies to efficiencies. In this new approach, the innate traits and behavior of the material guide the design and are used to support the form-giving process, with a goal of reducing the environmental impact of construction.

The relationship of design and material

The Western tradition of formal architecture and design prioritizes ideas over their manifestations. In line with this hierarchical construct, the form is superior to the material, and the formal approaches to design are favored over materialistic ones.[1] What follows is that the existing methods of design are not capable of embracing the material-

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[1] This approach is rooted in the ancient Greek philosophy. For Plato (c. 428–348 BC), the form was an idea or eidos that achieved a higher, ontological status, while the material world was only an image of this real world. Aristotelean (384–322 BC) hylomorphism characterized every thing as consisting of two intrinsic principles, one potential, hylē (matter), and one actual, morphē (form), where matter had the capacity to become an object, while remaining passive in the form-giving process. In the first architectural theoretical treatise De architectura (Ten Books on Architecture), the Roman author and architect Marcus Vitruvius Pollio (c. 80–15 BC) posited that the first dwelling was built in the forest, with branches and trees, and the forms resulting from wooden construction were directly transpositioned to stone construction, and formed the base of the Classical orders, what adhered to the Aristotelean and Platonic models. Western formal architecture has been founded on the assumption that materials can be interchangeable, while their role is subservient to form.

istic perspective, e.g. material behavior, such as movement present in timber, eludes the means of design methods,[2] from working drawings to building information models (BIM). Similarly, naturally grown irregular shapes of wood are incongruent with the predominant manufacturing and assembly methods, which require materials of regular and repeatable shapes yielding interchangeable parts and components. In this light, many inherent material characteristics are seen as deficiencies, which are being overcome with substantial energy, material, and chemical treatment input, resulting in environmental degradation. Current design methods based on static representations and divorce of design and construction do not support the approach where material characteristics play an active role in the form-giving process.

This hierarchical relationship of design and materials has recently begun to change as a result of pressures put on the building industry from two directions: on the one hand by the necessity for sustainable construction, and on the other by emerging fields of material science, such as nanotechnology, which has led to developing new types of materials. Today, new material developments should both focus on novel functional qualities of new materials, and minimize their harm to the environment. Architects, in turn, are being increasingly obliged to consider materials in terms of their performance standards, including environmental impact, as well as their appearance.[3]

The elevated importance, and the new role of materials, has not yet fully affected the methods of the architectural design profession, which is still following the logic of static representations and regular, repeatable shapes. Wood is a material characterized by movement and irregularities, offering a potential for testing a new design approach, one that uses these characteristics as design strategies. This new approach is based on reversing the well-established hierarchy of design and material. The goal of the approach is to make the most of wood as a sustainable, energy neutral, and smart material.

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[2] In architecture, design methods are based on separating the design and its object. The process begun in the Renaissance with the Neoplatonic thought, which identified beauty as the independence of form from matter (Forty 2000, p.151). In the mid-fifteenth century, Leon Batista Alberti (1404–1472) in De re aedificatoria (On the Art of Building), the first book on architecture written after the Classical antiquity, made the distinction between lineaments, which are the product of thought, and matter, which is the product of Nature (Alberti [1443–1452] 1988, p.5), and noted that it is possible to project forms in the mind without recourse to the material (Alberti, [1443–1452] 1988, p.7). The distinction between the design and its object was facilitated by the introduction of drawing as a design method in 1470s and perspective drawing in 1500s. These inventions paved the way for architectural design as representation, distancing the architect from the material world. It enabled the reduction of the materials to the white space between the lines delineating the forms in projective drawings. Since Alberti, architecture has been a separate field from construction, and design could be conceived as abstracted from materials.

[3] To illustrate how this entered the profession, Katie Lloyd Thomas brings the example of the changes in material specification in the U.K. in 1960s, since then materials have to conform to particular performance standards (fire-rating or acoustic separation) rather than be specified by kind (Thomas 2007, p.7).

From deficiencies to efficiencies

The new design approach to wood construction uses the material's inherent traits and behaviors as a starting point for design, and by doing so, uses the undesired aspects of the material to find productive solutions, thus turning deficiencies to efficiencies. Possible strategies for the application of two categories of such deficiencies are outlined below: dynamic, based on material behavior, and static, based on material geometric and structural features.

Wood behavior as a design strategy

Wood is a hygroscopic material, attaining moisture content in equilibrium with the water vapor pressure and temperature of the surrounding atmosphere. Due to this feature, it is not dimensionally stable. Wood expands and contracts under changing moisture content in relation to its environment. The movement in timber is anisotropic, dependent on the fiber direction (Figure 1). The degree of anisotropy is further dependent on the tree species and the way the log was converted. At the microscopic level, anisotropy is a result of the alignment of cells as well as the orientation of the microfibrils in the middle layer of the secondary cell wall. Transverse and longitudinal (across and along the grain) degree of anisotropy of timber shrinkage due to water relationships amounts to approximately 40:1 (Dinwoodie 2000). The pressure force of moisture-induced swelling of wood amounts to over a tonne per square centimeter. This property was already known in the ancient Egypt and was used there for splitting large blocks of stone (Rowell 2012).

At the scale of a building component, dimensional instability, related to absorbing and releasing moisture from the atmosphere, is measured in millimeters, and occurs between seasons, and even nights and days. It is often seen as disadvantage, and the modern-day

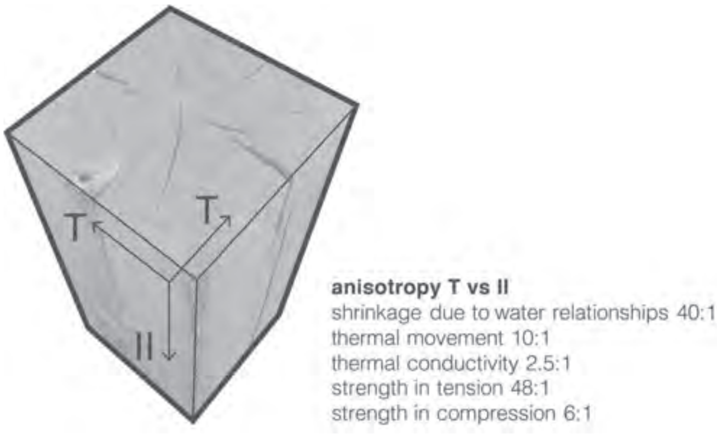

Figure 1: Anisotropy of wood: T-transverse, II-longitudinal direction (Author).

construction industry is focused on minimizing its problematic effects. Various manufactured wood products (Figure 2) have been developed with the goal of offsetting the dimensional instability of wood by randomizing the material behavior. The array of these products is enormous and widely used, including plywood (developed in ancient Egypt and reintroduced in its modern form in the 1830s), glued laminated timber/glulam (developed in the 1860s and introduced in the 1900s), chipboard (introduced in the 1930s), medium-density fiberboard/MDF (introduced in the 1960s), oriented strand board/OSB (introduced in the 1970s), and cross-laminated timber/CLT (developed in the 1970s and introduced in the 1990s). Other strategies involve the application of various oil-based or alkyl-based finishes, heating the timber for short periods of time to high temperatures (250–350° C), or chemical treatments (Dinwoodie 2000). The common trait of all these strategies is their extensive use of external energy and chemicals, including toxicants.

A new generation of researchers and designers, working at the intersection of computer science and physical materials, is beginning to explore the potential of using material behaviors as a design strategy. In the 2010s Skylar Tibbits, the director of the MIT Self-Assembly Lab, popularized the terms “4D printing” and “programmable materials.” These concepts can be characterized as intelligent assembly systems and are based on producing customized, smart materials by multi-material printing, or putting together independent parts or components. By sensing and reacting to their environments, these materials are able to transform and change shape over time and find their structures and functionalities without further human or machine guidance. However, there has already been extensive research in the area of self-assembly. The novelty of this approach lies in the focus on applications in large-scale structures, where substantial reductions can be sought

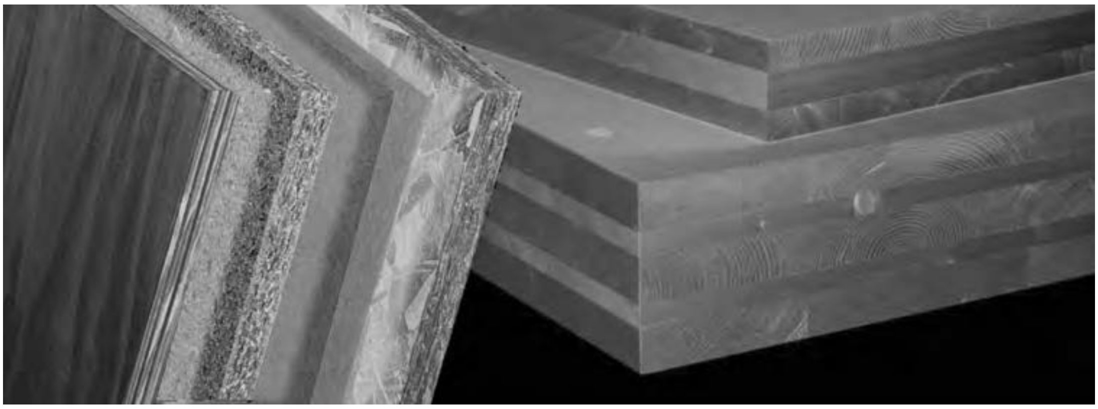

Figure 2: The array of manufactured wood products: plywood, chipboard, MDF, OSB, and CLT (Author).

with respect to the energy, cost, and time consumption during the construction of buildings and infrastructure (Tibbits 2011). One logical consequence of this new conceptual framework for the field of architecture is that the notion of smart materials can be extended onto all building materials, where any material property or behavior that results in dimensional change can be used as design, or forming strategy, as long as it can be predicted and harnessed.

The research into 4D timber construction carried out by the Institute for Computational Design at the University of Stuttgart is a direct application of these ideas to wood construction (Wood et al. 2016). Under the direction of Achim Menges, the team identified the major scale limitation of the current research in self-forming and self-assembling systems, based on materials, such as shape memory alloys, heat curling carbon fiber composites, or phase or state-changing polymers, is caused by the immense quantity of required external actuation energy. Wood's ability to shrink and swell with high force in response to the energy-neutral change of moisture content in its environment presents an opportunity to develop large-scale, self-constructed timber surfaces. The team develops bending methods for timber surfaces based on the principle of bilayer-responsive material systems, where the curvature results from combining layers with different coefficients of expansion. The method harnesses wood's anisotropic moisture-induced movement by combining active with restrictive elements or layers using opposing fiber orientations. The resultant curvature is controlled by the orientation, length, thickness, and initial configuration of the elements (Figure 3). The system behavior is determined by integrated simulation, visualization, and computational design methods.

The 4D timber experiments, however performed on prototypes not larger than 1 by 1.5 m, suggest that the anisotropy present in wood

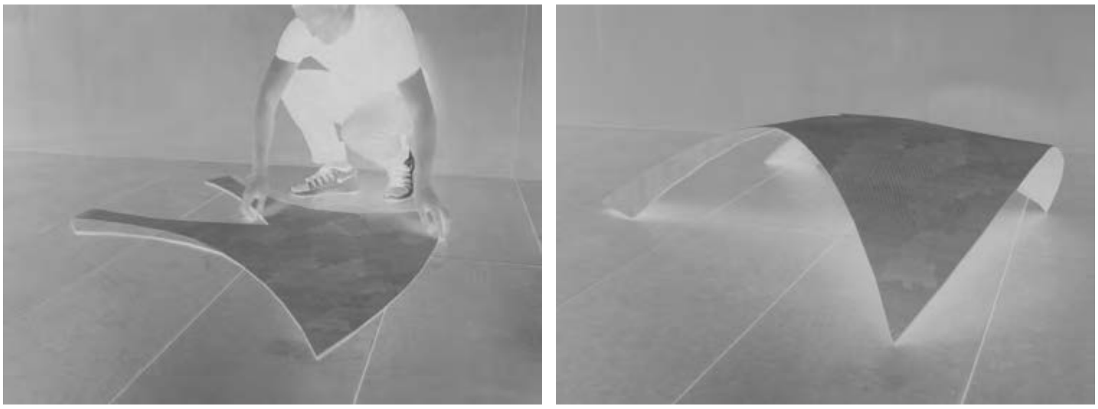

Figure 3: 4D timber construction prototype: self-constructing surface from flat to double-curved (© ICD, University of Stuttgart).

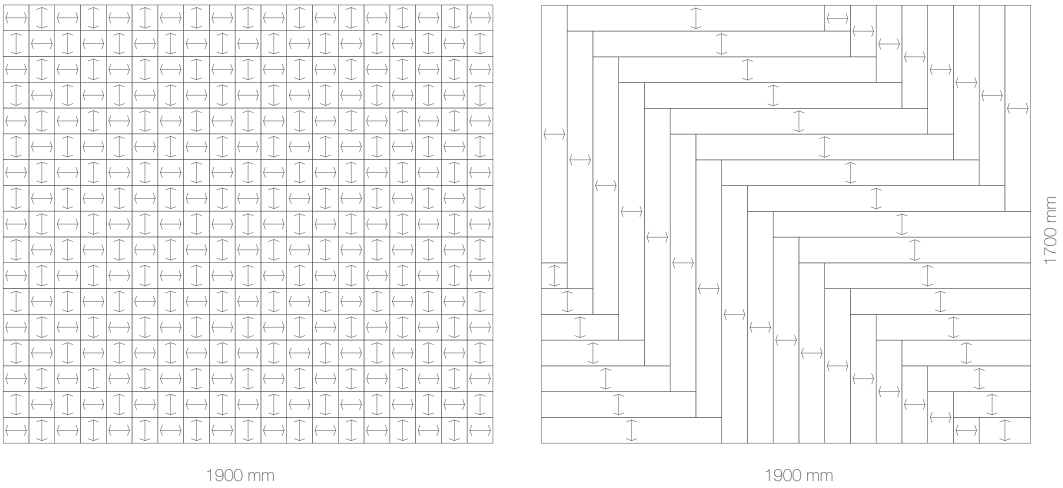

Figure 4. The Swelling Vault, checkered and herringbone block patterns, arrows indicate the swelling directions (Author).

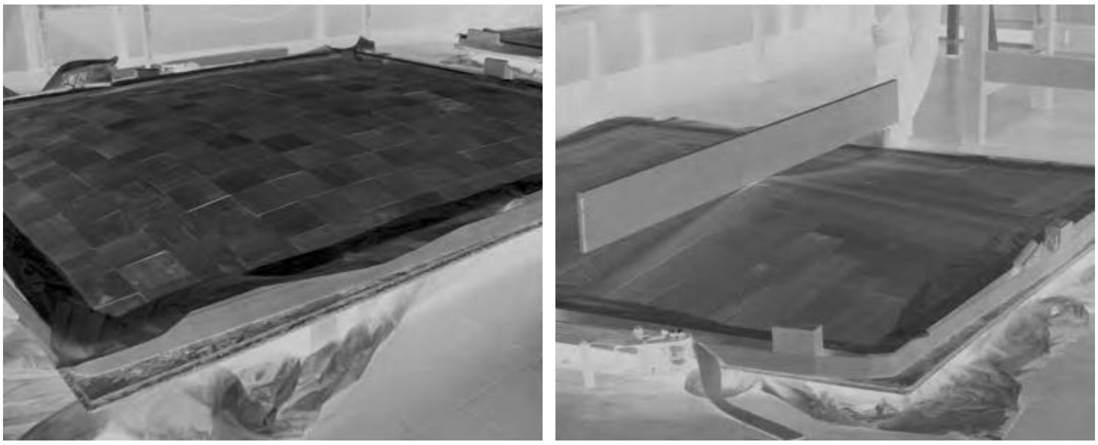

Figure 5. Domed and conical bulged shapes (Marcin Wójcik and HSLU Lucerne) Photo: Sebastian Kraft

can be used to control the process and effectively become a generative means to create form, where the force and directionality of wood movement can be used to form double curved shells at the full architectural scale. To test the viability of this approach, an experiment was carried out (Wójcik 2017) together with students from the Lucerne School of Art and Design at the Lucerne University of Applied Sciences and Arts (HSLU)[4] which was inspired by the fact that after flooding parquet floors assume various bulged shapes. The tested aspect of the phenomenon was whether the bulged geometries are generated by the initial condition of the blocks shapes and their mutual relations in block patterns. Two, identical 1.7 × 1.9 m bases with edge constraints were built, on which two different patterns of parquet blocks were laid out: one checkered, using 100 × 100 mm square blocks laid with alternating grain orientation; and one herringbone, using 1000 × 100 mm elongated rectangular 20-mm-thick oak parquet blocks (Figure 4).

Water was poured on both pieces, then left to soak in. After a few days, the bulging was significant: the checkered pattern bulged to 120–132 mm, forming a regular and domed shape (Figure 5 left), while the herringbone pattern bulged to 108–113 mm forming a conical surface which was much more stable than the dome (Figure 5 right). In parallel to 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 plugins.[5] 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 shape. The discrepancy between the measured and the simulated bulging was approximately six percent. The experiment indicated that a flat layout pattern of wood blocks dictates the bulged 3D shape when the blocks swell. This shape can possibly be predicted by means of digital simulation. This method might then be used to form double-curved wooden elements or formworks without using wasteful, and energy intensive, processes.

Naturally grown shapes of wood as a design strategy

Historically, joiners and carpenters must have frequently faced the problem of putting irregular timber to good use. For instance, in medieval English joinery, slightly curved trees were split in half to make

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[4] The project was possible thanks to the invitation and support provided by Christoph Schindler and Sebastian Kraft from HSLU.

[5] 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).

Figure 7: Festival Foods Grocery Store in Madison, WI, WholeTrees Architecture & Structures with Bark Design Architects and Tri-North Builders (©WholeTrees)

Diameter
Base Diameter 0 in
Mid Diameter 0 in
Branch Diameter 1 0 in
Branch Diameter 2 0 in

Branch Span
Number of Branches 0
Branch Span 0 ft
Branch Angle 0 °

Height or Length
Total Length 0 ft
Trunk Length 0 ft
Branch Length 0 ft

Figure 8: Robotic fabrication of the Woodchip Barn, Hooke Park near London, Architectural Association School of Architecture (© AA, Design+Make).

rafters and joists, where the split was used as the straight surface to which other elements could be attached, while more considerably curved trees were longitudinally halved and the two matching mirror-image halves placed symmetrically in a frame (Figure 6, left) as tie beams, braces, or crucks (Harris 1979).

Viking boat and shipbuilders used naturally curved timbers for stems, keels, ribs, and knees of the boats, while tholes and keelsons required forked timbers, selected for the job at hand. Wood for the curved components was sourced from isolated oaks, free to grow outwards and produce crooked timbers (Graham-Campbell 1980). Historically, carpenters frequently used naturally fork-shaped pieces of wood 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, known as konstrukcja sochowa (Ruszczyk 2014) and Norwegian bent construction (cross frame), known as grindverk (Drange et al. 1992).

Naturally grown, forked shapes of wood offer innate strength, knowledge of which was exploited by builders in the past, but was not convenient for industrialized production. For the efficiency of the industrialized construction methods, it is more important to use uniform material profiles than to take advantage of the strength of an irregularly grown form. Such natural forms cause problems as they are incompatible with standard machinery, are difficult to address in design when no two branching pieces are identical, and they do not lend themselves easily to structural performance calculations. Nevertheless, recent developments in digital fabrication and computational analysis and design methods suggest it may be possible to reverse this well-established logic.

In the 2010s, the US Forest Products Laboratory in collaboration with the WholeTrees Architecture and Structures[6] performed testing and analysis to establish the structural parameters of branching timbers. This enabled the WholeTrees group to design and build large structures using round and forked timbers, such as the Festival Foods Grocery Store in Madison, WI, USA (2014–2016), with eighty-six round wood wing trusses spanning over eighteen meters supported by twelve unmilled ash columns with forked ends (Figure 7). A project of this scale required a more methodical approach than the previously used system of felling single trees and bringing them to the warehouse for individual scanning and analysis. In 2015, WholeTrees approached Mandli, a company that deals with the design and development of specialized digital imaging, data collection equipment, and operational methodologies. Mandli suggested using Maverick, a highly portable

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[6] See http://www.wholetrees.com.

[7] See https://www.mandli.com/maverick-by-teledyne-optech/.

mobile mapping system which combines LiDAR, a high-definition 3D environmental scanning with 360-degree imaging, and an integrated position and orientation system. A Maverick-equipped car was driven through the area where the trees were being collected. Based on the gathered information, a specialized software was used to identify the trees that fitted the WholeTrees requirements. The entire process proved to be successful, very quick, and cost-efficient.

The Woodchip Barn[8] (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 architectural applications of forked timbers through the integration of 3D scanning, robotic fabrication, and form-finding techniques combined with traditional wood construction knowledge. The structural spine of the project is formed by a truss composed of interconnected forked beech trees, where the Y-shaped fork junctions are used structurally, so that the natural strength of these joints is exploited. Analogously to the process applied by WholeTrees and Mandli, trees from a local forest had been 3D scanned prior to harvesting in order to produce a database of available material. Based on the criteria of the structure, twenty-five 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.

The discussed design methods draw upon digital fabrication and simulation. The flexibility, repeatability, and precision of digital fabrication on the one hand, and the capacity to foresee the effects of material behavior, as well as the interactions among multiple components, by digital simulation on the other, open possibilities for new design methods and techniques. While the currently dominant approach to design is grounded in fifteenth century methods, such as using drawings as means of design and representation, and the role of wood as construction material is based on the nineteenth century industrial paradigm, where materials are standardized, homogenized, and generally passive in the form-giving processes, the new digital design and manufacturing methods allow not only the acknowledgement of material characteristics, but also the inclusion of them in the processes of form generation. This new inclusive process has the capacity to support the active role of materials in construction, understood literally, as is the case of wood movement, or more metaphorically, as is the case of taking advantage of its naturally grown shapes.

The presented design strategies transform the commonplace perception of material characteristics, such as dimensional instability and geometric irregularity. As a result, many of our assumptions regard-

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[8] See http://designandmake.aaschool.ac.uk/woodchip-barn/.

ing design, and the role of materiality in it, are questioned. The main novelty lies in reversing the well-established, hierarchical relationship of design and material. While the design tradition stemming from the Classical times prioritizes form over the material it is made from, in the presented examples, the resultant forms are determined by static material traits and dynamic behaviors. In this light, it not surprising that they refer to vernacular construction rather than formal architecture. As imposing forms over materials is a process that requires external energy, material or chemicals inputs, it is conceivable that the over two-millennia-long design tradition contributed to the environmental degradation we are witnessing today. The discussed examples suggest that there is indeed an alternative method of using wood in construction, one that is based on radical rethinking of the role of the material in design and construction. A change of perspective on this role is necessary, as merely improving existing techniques is not enough to prevent the environmental harm caused by the construction industry. When the perspective is reversed, material traits and behaviors can be seen as design potentials, leading to effective solutions, rather than as deficiencies to overcome. This new method, as one that is working together with, rather than against the natural properties of the material, can transform wood into a truly sustainable material.

Marcin Wójcik

REFRAMING WOOD CONSTRUCITON

Innovation in architecture through activating material properties with the use of digital technologies

This thesis focuses on the relationships between material-centred design, digital technologies and environmentally-responsible practice with respect to wood construction. It argues that computational design methods and digital manufacturing have the capacity to reframe wood construction, open new opportunities for design, and lead to more sustainable practices.

Wood is the building material that frames this research. The long tradition of using wood in construction and its cultural connotations, as well as its heterogeneous structure and its often-unpredictable behaviour, make it a case in point for material-centred design. Today, the predominant approach to wood construction is adaptation to industrialised processes that suppress individual material properties. The thesis proposes to reframe wood construction in order to offer an alternative design method that uses material properties and behaviours as valid design factors.

The ultimate goal of the thesis is to reorient architecture towards sustainable construction methods. The thesis identifies that digital technologies have not yet embraced materiality and that digital advances in architecture provide an opportunity for including material parameters as valid design factors. This thesis proposes that digital technologies have the potential to access various latent and palpable potentialities of the material that can deliver design solutions with lower environmental impact.

Marcin Wójcik is an architect, researcher, and educator with over 20 years' professional experience. He is a Lecturer in the school of architecture at TU Dublin, where he is teaching at the BArch and MArch levels. His academic and professional interests include computational design, digital fabrication, and material-centred design. He holds a Master in Advanced Studies (Dipl. ETHZ in Arch.) degree from ETH Zurich (2004) with specialisation in Computer Aided Architectural Design, and an MSc in Architecture degree (mgr. inz. arch.) from Szczecin University of Technology (1996).

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