Constructing correctly in wood: new insights into timber technology approaches through purist and liberalist schools of thought.

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Constructing Correctly in Wood:

New Insights into timber technology approaches through Purist and Liberalist schools of thought.

Abstract:

Conventionally, technology-based articles focus on methods by which architects and engineers designed and built to present new methods, materials to evidence novelty in technical terms. This paper does not do that. Instead, through a current overview of past and present timber practices, it will present a new cultural perspective by looking at timber technology from purist and liberalist approaches. Indicating a moralistic sensibility of what "constructing correctly" in wood means to them, with these two attitudes implying inherent values, this paper seeks to project a new cultural dimension on technology. More importantly, the approaches convincingly reflects our relationship with digital technology, as timber culture and tradition come to terms with the inevitability of the digital age.

Keywords:

- Complex timber structures
- CNC and woodworking technology
- Wood design
- History of representation in wood design
- Timber gridshells
- Wooden architectures and timber structures survey

1. Introduction

Recent research by the authors into the design, fabrication and use of timber gridshells revealed contrasting polemical views of architectural timber use. Seen in the development of doubly-curved, thin shell structures over the last 50 years, these attitudes resonate with Pier Luigi Nervi's views on the "correct" application of technology, and are here categorized as *purist* and *liberalist* approaches to timber technologies.

This technology-related polemic of being *purist* in terms of timber gridshells was first identified and mentioned in the preface of a recent publication on timber gridshells, namely:

> *"….. There are 'purists' who accept as gridshells only… those formed from initially flat deployable grids of thin timber laths. However, nowadays the term is also freely and widely applied by many to be free-form timber grids assembled from sometimes relatively massive, single- or double-curved, engineered timber components, connected by sophisticated metal jointing systems."* (Chilton and Tang, 2017, xviii)

Clearly, technology-based definitions change and evolve alongside technological advances. The variation of cultural attitudes to technology held by different societies marks an intriguing phenomenon. Within the immediate realm of timber technology, where the acceptance, or indeed a simultaneous partial rejection, of technology in timber practices can unite or divide opinions, how do contemporary timber practices negotiate the influence of digital “advancements”? Similarly, how do timber artisans working with traditional methods respond to the introduction and infiltration of digital ideas? In the same grain, and *vice versa*, how do high-tech computational manufacturers of precision components learn the rudiments and assimilate the wisdom and intuitive material appreciation of the craftsperson?

What constitutes *constructional correctness* (as proposed by Pier Luigi Nervi, see below) must be prioritised to inculcate an understanding of the influence of technology on craft-based practices which combines both art and science. These are important questions deserving discussion and a considered elaboration because a confident appreciation of the different viewpoints will impact on future methods and technique development influencing future timber works and affect the way we restore/renovate past historic timber structures as well.

1.1 Constructing Correctly

In 1955, the reinforced concrete shell designer/constructor Pier Luigi Nervi raised the notion of constructing correctly through his acclaimed publication *Costruire Correttamente* (Nervi, 1955), a theme he continued to promote in his influential writings in the 1960s. In his book *Aesthetics and Technology in Building* he suggested that objective technical issues “…stability, durability, function and … economic efficiency…” are necessary conditions but that there is also a subjective aspect, which includes the aesthetic appearance of the structure (Nervi, 1965, p2-4). Although his remarks concentrated on his work in reinforced concrete, the idea of constructional correctness is appropriate and applicable to all materials and are timely in the field of timber technology. The term questions the relationship between historical and contemporary materials/products, construction methods and the context in which they are applied, including timber. The title of this present chapter borrows from Nervi’s idea, to launch some intriguing questions about our relationship to technology when working with wood.

Evidently, timber technology has advanced rapidly in recent years to the benefit of design, manufacturing and construction capabilities. This sees the previously unimaginable becoming constructible, especially with regards to increased accuracies of curved geometries. However, like the many other technologies that have made modern living easier (such as mobile telephones, apps, electricity, wi-fi and the internet), these “improvements” in timber technology are also guilty of disrupting our fundamental relationship with timber as a construction material. Some might argue that this may also change our material understanding of timber itself.

“Constructing Correctly” is timely and relevant, as we move towards new modes of production and as timber as a construction material evolves. This perspective is highlighted in the development of timber gridshells. Using design, fabrication and construction of timber gridshells over the years as examples, philosophies and approaches taken by designers with regards to this traditional construction material, are critically questioned to give a techno-cultural perspective of how we view the more traditional or new computer-aided methods of working with wood. To instigate a healthy debate, this chapter identifies alternative approaches to negotiate between the polemics and better understand the concerns and deliberations from both sides, at the same time reflects on the way timber technology is viewed, treated and applied.

1.2 Constructing Correctly in Timber

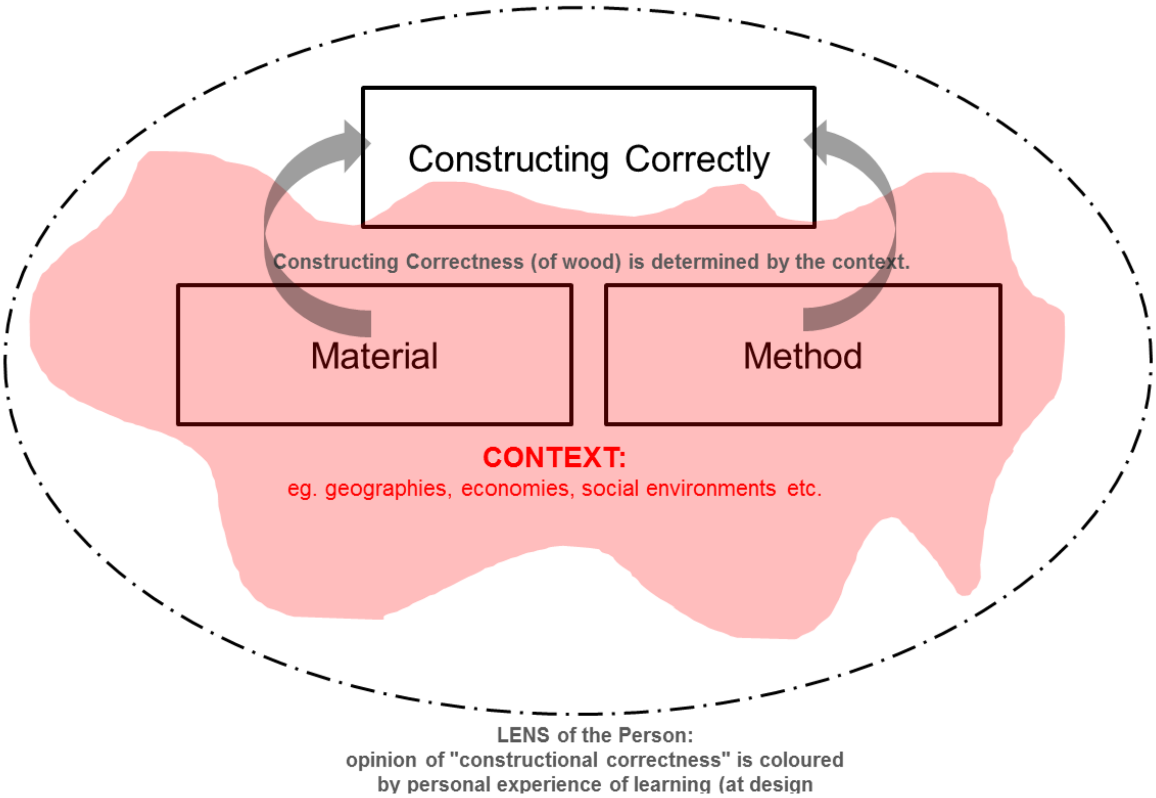

Figure 1: The idea of 'Constructing Correctly' is shaped by the values the individual places on material understanding and constructional methods within specific contexts such as location, aesthetics etc (Figure © Gabriel Tang)

As represented in Figure 1 above, "Constructing correctly" in timber suggests different elements of discussion. First, the material in question (in this case, timber) includes an understanding and appreciation of physical properties. Secondly, the method, which is concerned with how timber is used. These elements are influenced by personal experiences. Thirdly, this *correctness* is governed by the context in which material and fabrication methods are applied. In other words, the same technical solutions may be viewed differently, when assessed in different countries and/or socio-economic environments. A fourth element is the lens through which the judgment is viewed, including the opinions and values of the person putting forward his or her views. Although an objective judgment can be made, each person has the freedom to exercise his/her opinion on whether construction has been carried out "correctly" in terms of design, use, material treatment and/or construction method, aesthetics and appropriateness to context.

2. Context

Aspects of timber technologies described in figure 2 below present a perspective on how technology is solving previously unsolvable problems. It is widely accepted that digital innovation negates the need for a fundamental understanding of timber, leading to the need to touch, see, smell or be in physical contact with the material becoming redundant. Ultimately, this breeds a detached relationship from material understanding.

A level of subjectivity about the concept of constructional correctness is embedded within the discussion in this paper. What is judged as being correct or otherwise is unavoidably coloured by our personal stance of "constructional correctness" shaped by our personal experience.

Therefore, the following questions are posed: what does it mean to construct with timber in digital age of the 21st Century? Do we regard material completeness as being correct construction? For instance, should a "correct" timber building be on more than half of the primary structure's material being timber? Or should this be measured against what is the correct method of constructing structure?

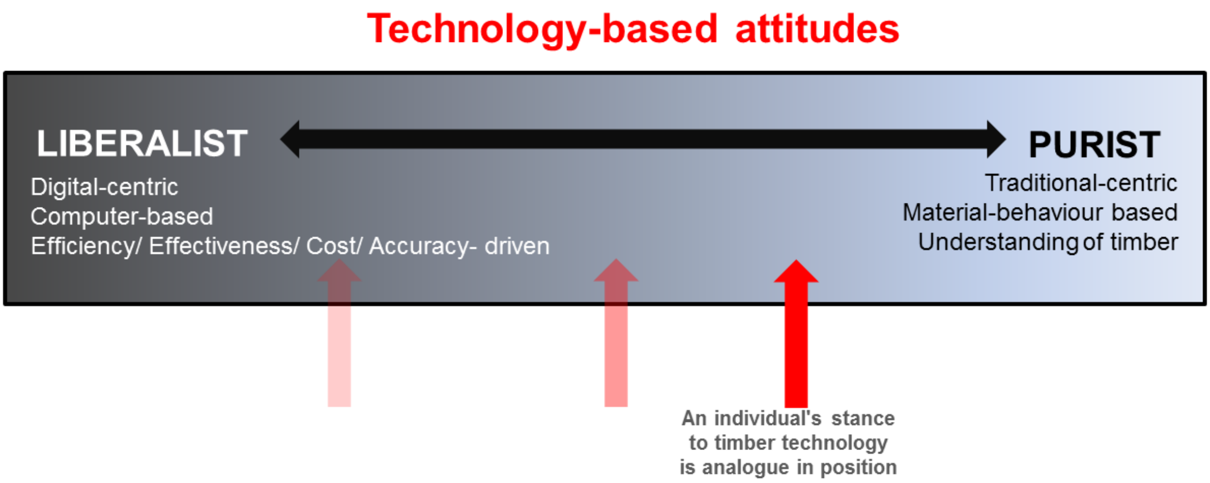

Figure 2: The Purist and Liberalist camps exhibit different attitudes to technology. Liberalist attitudes pertain to a view accepting computerization, digitization for increased productivity. On the other hand, Purist attitudes value traditional methods, timber characteristics and structural behaviour. This categorization is not binary, but allows each individual to position themselves on a varying scale in relationship to each school of thought. (Figure © Gabriel Tang)

2.1 Purist View

In this research, through conversations with architects, engineers and builders, it was observed that their descriptions of timber gridshell structures described their stance and view of timber technology.

On the one hand, there are those, the purists, who believe in their perceived "correct" manner of construction, holding an innate understanding of timber's physical and mechanical characteristics, such as respect for grain direction and accommodation to bending characteristics. In this school of thought, value is placed on the skills of the craftsperson and fundamental material understanding of timber. Their view of constructing correctly may also be steeped in a preference for material purity (avoiding the excessive use of non-timber fastenings or adhesives, and/or complex fabrication and construction techniques).

The purist view respects traditional skills, craft and tooling in creating timber structures, be it simple or complex, imbued with an intuitive understanding of material properties and handling gained through years of experience working with wood. Purists place value on human craftsmanship, and may be opposed to the machine and mechanization.

In the context of this paper, a purist also believes in the fundamental understanding of material and holds a traditionalist approach steeped in historical precedent and rationale. The purist is averse to the influx of digital influences in timber technologists.

2.2 Liberalist View

On the opposite end of the spectrum, a contrasting approach is observed to incorporate a standpoint that celebrates innovative construction and fabrication methods largely brought about through digital technologies. It embraces the use of engineered timber products with increased strength and a typical ability to withstand thermal and moisture-induced deformations. Products such as cross-laminated timber (CLT), laminated veneer lumber (LVL) and glue-laminated (glulam) timbers, fast replacing steel or concrete to renewed claims of sustainability, are examples of how technology is changing our understanding of timber as a material. Held in high reverence in the liberalist school of thought, these products may not be viewed in the same light by the purist camp.

Alongside this phenomenon of new engineered timber materials, as machining technologies progress and new engineered timber products emerge, doubly-curved structures (such as timber gridshells) are no longer limited by the discernible characteristics of sawn timber and the traditional methods of using them. Instead, computer numerically controlled (CNC) milling machines are capable of rapidly producing single- and double-curved sections with repeated high geometric precision to a consistent standard not seen previously using traditional hand tools. Liberalists are positively influenced by the importation of technologies: machines, digital tools such as parametric design and digital form-finding, new engineered timber products, adhesives and fastenings.

This approach differs from the purist way of dealing with timber through the use of new machinery, associated method innovation and material improvements. With this new technology, timber structures can be accurately designed, precisely manufactured and efficiently assembled with improved adhesives and fastenings, signifying a shift in the function of the craftsperson in design and construction terms.

To some, this also elevates the role of digital technology, often at the cost of de-skilling (craftspeople) and de-materialization (of timber).

2.3 Spectrum

In between these extremes there lies a spectrum upon which the individual is able to take a stance. An example of the benefit of acceptance of digital fabrication, whilst using timber in its most basic form, is illustrated by the 10m diameter reciprocal frame roof installed at Hill Holt Wood, near Newark, UK, Figure 3. Here, locally-sourced debarked tree trunks were used to create interlaced spirals of mutually-supporting beams. Although the tree trunks were irregular in cross-section, once a reference centreline had been established precise CNC cutting and drilling of the simple lap joints was possible (Chilton *et al*, 2009). This would have been extremely difficult to achieve using a strictly traditional ‘purist’ method of setting out and cutting of joint profiles. This acceptance of digital technology, combined with an understanding of traditional woodworking methods is reflective of the inclusivity of a balanced approach.

Figure 3: Reciprocal frame timber roof at Hill Holt Wood, near Newark, UK, assembled from CNC machined tree trunks [Photograph © John Chilton]

3. Tectonics of Timber Assemblies

The word tectonic (deriving from the root-word of the Greek word tektōn (τέκτων), denoting a building artisan, in particular a carpenter (Wikipedia, 2018)) is relevant here. "Tectonic" has evolved to mean "the art of joining things" (Borbein, 1982) and is highly relevant to timber technology. The need to extend and join timbers to each other motivated timber technology.

Assembly Technology: A Crafted Dimension

Timber technology developed as a result of building from roughly cylindrical forms (tree trunks). The structural bundling of organic cells, a composite of cellulose fibres and lignin, provides strength to the material. Traditionally, trees are harvested and machined into planks and posts (Figure 4). Long building elements usually run along the grain of the timber to avoid cutting through fibres and maintain their superior structural capabilities.

Figure 4: Harvested raw timbers being debarked, processed and sawn into planks and board materials. Guizhou, China [Photograph © Gabriel Tang]

Throughout history, civilizations endeavoured to join discrete timber sections, at first without the use of metal fastenings, nails or adhesives. These inventive methods and innovations were driven by the lack of metal fastenings and jointing technology. These solutions and ancient wisdom were also limited by tools available for cutting timber members into shorter, more manageable sections.

In Norway and Northern Russia, logs are primitively shaped and with ends cut into throats and notches slot together without the need for metal nails or additional timber dowelling. Traditional Norwegian stave construction was developed to connect round timber sections to form locked and stable joints (Herzog, Natterer, Schweitzer, Volz and Winter 2012). Similarly, in Japan and China, ancient timber structures are also constructed through precise hand-crafting, cutting and shaping to form connections that secure the discrete structural elements (Herzog *et al*, 2012; Sumiyoshi and Matsui, 1991), without mechanical fixings, Figure 5. The application of technology here is low and the quality of the construction depended on the skill and experience of the artisan, the craftsperson. Although apparently primitive in method, the construction was based on fundamental understanding of timber. To the purist, this can be deemed a "correct" way of building in a specific context without excessive metal fastenings.

Figure 5: Traditional tenon and mortise joints, Maogong, China [Photograph © Gabriel Tang]

To analyze and understand the intent and procedures associated with timber processing, it is imperative to form a holistic view of *constructing correctly*. The evolution of timber technology stemmed from the need to join and extend. Often, in pre-digital societies, this knowledge evolved as it was passed down from master to student over many generations. Therefore, tectonics, recognized here by Borbein's (1982) definition, as a way of joining things together, is clearly integral to the art, and science, of timber technology.

3.1 The changing characteristics of wood

With the influence of scientific advances on timber technology, the philosophical question "What do designers want timber to be?" is an intriguing question. In recent years, timber has established itself as a key material for use in sustainable construction due its low embodied energy, the carbon that it sequesters, its ability to be reused and the fact that it is a renewable resource. This is demonstrated in projects such as the GlaxoSmithKline (GSK) Sustainable Chemistry Building at the University of Nottingham, Figure 6, which is expected to be ‘carbon-neutral’ after 25 years due to the renewable energy technology incorporated and the extensive use of engineered timber in its construction (Chilton, 2015).

Figure 6: The ‘carbon neutral’ GlaxoSmithKline (GSK) Sustainable Chemistry Building, University of Nottingham, UK, under construction, 24th July 2014, which has predominantly timber structure and cladding above ground [Photograph ©John Chilton]

Of all construction materials, especially when compared to steel and concrete, wood from a living tree is most closely linked to human beings physiologically. A natural material, figures resulting from growth rings and the way in which the timber is cut, irregularities and imperfections such as knots and shakes, add to its visual charm, lending it a psychological warmth. Timber is also breathable and reacts to relative humidity, expanding and contracting in volume. This variability and environmental responsiveness is often accepted as an attractive characteristic of green timber but requires careful detailing to accommodate possible movement.

However, timber as a natural material is shedding its shortcomings of being a material marred by (sometimes beautiful) defects such as knots, and lacking in uniformity due to the opportunities offered by engineered timber-based materials.

New technology has resulted in a shift in structural ability and pre-conceived material understanding. Whilst retaining their timber appearance, new timber products such as CLT are behaving more like steel, technology generates new materials by drawing on qualities from the best of both. This mis-match, often frowned upon by the purist school, sees technology solving problems, which pose the question of material honesty and their relationship to the materials's basic provision, both structural and aesthetical. These unfamiliar qualities quite easily split purists from liberalist schools with the latter being receptive to new improvements through new technology.

3.2 New Timber products

Engineered timber products such as cross-laminated timber (CLT) are becoming more widely available in the market. With key benefits of enhanced strength and reduced dimensional movement, when compared to raw timber, the engineered timber products appear to be very attractive indeed. Manufactured in large (up to 16.6m x 2.95m) boards, consisting of a minimum of three plys of crosswise-orientated timbers glued together (KLH Massivholz GmbH, 2012), extensive structural elements such as walls and floors, can be assembled easily and rapidly. Building openings such as windows and floors can be robotically milled to high precision, as used in the GlaxoSmithKline (GSK) Sustainable

Chemistry Building, Figure 6. These new products are also more thermally and moisture-stable materials minimising the uncontrolled movement of the material.

The issue is how this technology changes our acceptance and recognition of what timber is. This is an interesting phenomenon, as technology dematerializes timber in its application in architecture, as engineered timber products enhance the properties of plain timber.

3.3 Fastenings

The capabilities of fastenings and attachments of one timber section to another parallel the development of cutting technologies. These days, contemporary architects are choosing to celebrate the art and the honesty of attaching different sections of timbers together.

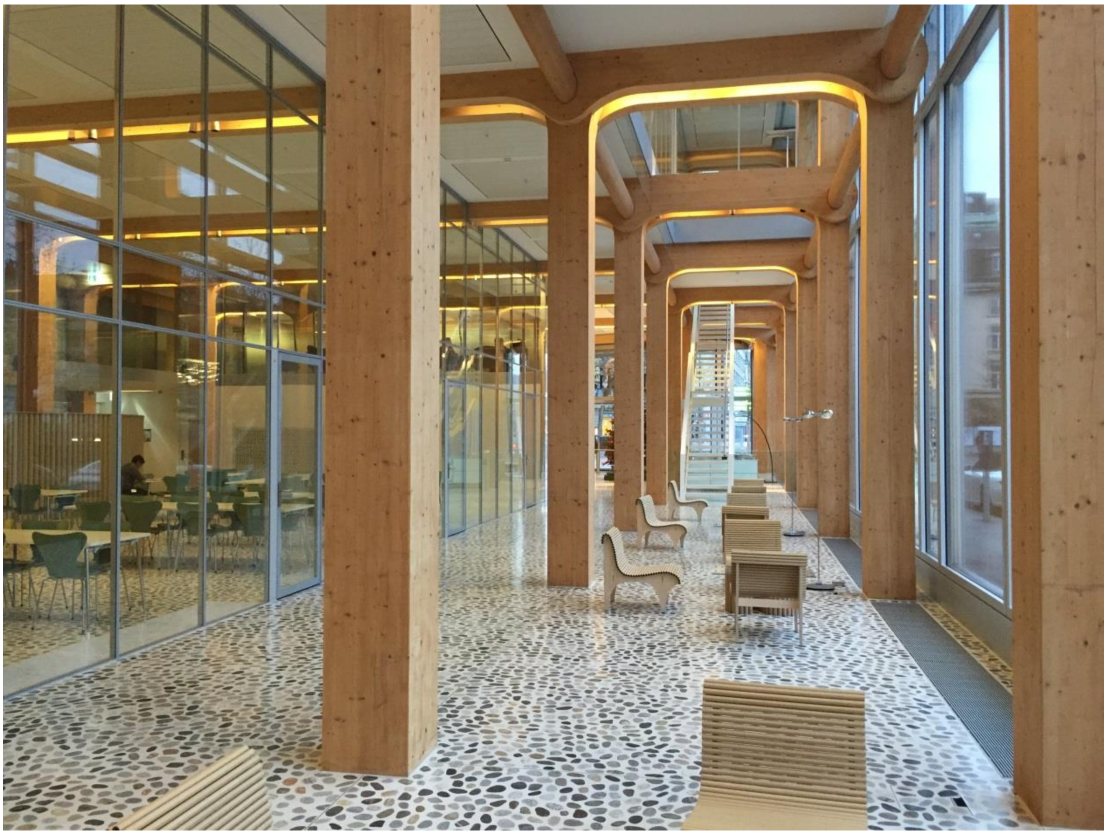

Figure 7: Interior of the Tamedia Headquarters Building, Switzerland (Source: https://commons.wikimedia.org/wiki/File:Tamedia-Verlagshaus.jpg)

The use of iron straps, coach bolts and nails which secured cathedral roof trusses in the middle-ages in Europe saw new material, construction tools and methods in improving construction. What was pure and completely made of timber was now married to technology.

Of course, the use of metal plates, bolts, screws and nails is now common, but they are often held in hostile regard by purist timber craftspeople. A recent example of such thinking is seen in the Tamedia Headquarters Building, in Switzerland (Figure 7), completed in 2013, where, despite embracing the use of engineered timber, the architect Shigeru Ban tried to minimize the number of metal connections in the 7-storey office building. Key joints between floor beams and columns in the multi-storey frame were formed with large transverse oval glulam timber dowels spanning between the columns (Antemann, 2014).

Express or Repress

The philosophy of material and constructional honesty has been discussed since Adolf Loos' essay *Ornament and Crime* that laid down the foundation for new architectural movements with regards to ornamentation (Loos, 1913). Timber fastening design raises questions of how these "foreign" metal connections should be treated – either hidden from view or be acknowledged as tectonic and visual features. The honesty of expressing timber connection responds to our aesthetic values and where we place this. Flitch plates securing two or more pieces of wood together are often hidden from view, while pinned connections are expressed. Both exposed and concealed metal connectors are clearly illustrated in the Timber Wave Sculpture designed by Amanda Levete Architects and constructed by Cowley Timberworks, exhibited outside the Victoria and Albert Museum, London, UK, in 2011, Figure 8. The proliferation or excessive use of metal fastenings in timber connections, to the technology purist, evades the question of timber joining relying on technology rather than through skills and patience. To express or conceal fastenings is a bone of contention as their visual proliferation may suggest the dilution of craftsmanship.

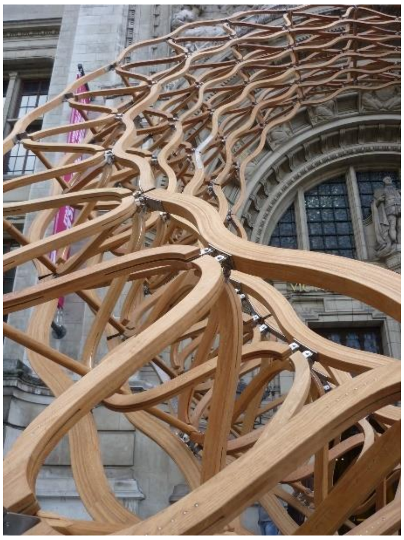

Figure 8: The Timber Wave Sculpture designed by Amanda Levete Architects and constructed by Cowley Timberworks, Victoria and Albert Museum, London, UK, 2011 demonstrates the expression of metal fastenings and flitch plate connections. [Photograph: © Gabriel Tang]

4. Timber Gridshells

The evolution of timber gridshell design and construction not only reflects the development of timber technologies, it also allows us to learn about ourselves in terms of the values that we place on our relationship with technology.

Ideas associated with innovation in the design and manufacture of timber assemblies discussed earlier are clearly applicable to the development and evolution of timber gridshells as a genre. The notion of the liberalist versus purist traditions reflects our position in relation to material and construction methods used.

Gridshell structures are beautiful and expressive. Through their tectonic expression of doubly-curved volumes, they define interesting curved spaces. Their development is a close reflection of the advance in architectural technology over the last 50 years, from the first engineered timber gridshell, constructed in Essen, in 1962 (Hennicke and Shaur, 1974) to present day structures, such as the French Pavilion for the Milan Expo, in 2015 (Chilton and Tang, 2017) made possible through the extensive help of digital technology.

4.1 Definition

Supporting either a purist or liberalist view of contemporary timber and digital technology, opinions on the definition of what constitutes a timber gridshell are divided.

The classic and highly-specific example can be illustrated by the definition of a gridshell given in 1974 by Hennicke and Schaur, namely:

> *"The gridshell is a spatially curved framework of rods and rigid joints. The rod elements form a planar grid with rectangular meshes and constant spacing between the knots [nodes]. The form of the gridshell is determined by inverting the form of a flexible hanging net. To invert the catenary so that it becomes the thrust line of an arch free of moments is an idealization. Analogously, inverting the form of a hanging net yields the support surface of a grid shell free of moments."* (Hennicke and Schaur, 1974, p26)

This definition, detailed and prescriptive, supports a purist view. It records the method/technology/technique applied in the 1970s to create efficient gridshell shapes. In terms of components, it defines a spatially curved framework of rods and rigid joints based on a grid with regular spacing between the nodes setting up a mesh with distinct square pattern. Additionally, it also describes the method by which this flat mesh arrives at its doubly-curved shape; its deformation by inverting the form of a flexible hanging mesh to generate a line theoretically free of moments. [In fact, due to the difference between a flexible net and a grid of continuous timber laths, moments are induced in the gridshell – it is a bending active structure.] This definition was made at the infancy of digitization and described the derivation of efficient shapes through physical model-making.

Of course, over 50 years on, in 2018, digital form-finding via software such as dynamic relaxation or particle spring methods, exerts their influence on the design methods, superseding the method by which 'moment-free' shell forms are generated, providing time and material savings when compared to designing through physical model-making.

In 2000, Steve Johnson, of Edward Cullinan Architects (now Cullinan Studio) presented his interpretation of what constitutes a gridshell:

> *A shell is a natural, extremely strong structure. A gridshell is essentially a shell with holes, but with its structure concentrated into strips"* (Johnson, 2000)

Johnson's definition appeals to liberalist thinkers by an implicit approval of contemporary technology. The definition described what gridshells are, and was not overly concerned with how they were designed or built. In this case, design methods, structural analysis and physical construction were left open-ended. The definition left room for improvement that enabled innovations and new techniques to be developed in the future. This description is hence sufficiently broad to include projects such as the Kaeng Krachan Elephant Park perforated timber shell, completed in 2014 at Zürich Zoo (Figure 9), which, although appearing to be a gridshell made from wide strips with irregular grid geometry, is actually formed from approximately 600 CNC-cut flat panels of CLT in three layers (Lennartz, and Jacob-Freitag, 2016, p.31).

Figure 9: Interior view of the Kaeng Krachan Elephant Park shell, completed in 2014 at Zürich Zoo (Source: https://commons.wikimedia.org/wiki/File:Zoo_Z%C3%BCrich_Kaeng_Krachan_Elefantenpark_2.JPG, By Albinfo [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)], from Wikimedia Commons)

From these definitions, two main families of gridshells are commonly derived: those made from gridmats of long, thin timber laths – a purist application of timber - that are actively-bent during deployment; and those that are assembled from thicker, shorter, more rigid components assembled directly in the final shell. firmly supporting a liberalist attitude. Rigid timber gridshells free the designer from constraints experienced by their actively-bent predecessors, in particular the regular grid and the requirement for deployability and shaping of the gridmat- a result of technological improvements – supporting a liberalist standpoint.

4.2 Technology

Advancement in timber technology has directly affected the appearance of timber gridshells and how they are designed and constructed.

Mechanized Lath Production

The development of improved timber adhesives allowed long laths of timber to be produced rapidly and efficiently. During the construction of the Weald and Downland Jerwood gridshell (Figure 10), digitized machinery, specifically a Grecon/Dimter SUPRA E continuous feed finger-jointing machine (Harris, Haskins and Roynon, 2008), was used to detect and remove knots and other imperfections in the oak laths. The resulting laths had a reduced propensity to break when bent during the gridshell forming, although there were still 145 breakages in the 10000 joints (Harris *et al*, 2003, p. 438). Automation and mechanization has influenced the efficiency and methods by which these structures are designed, parts pre-fabricated and joined together.

Fig 10: The Weald and Downland Jerwood Gridshell, Singleton, Chichester, UK designed by Studio Cullinan and constructed by Green Oak Carpentry Company 2003 [Photograph © Gabriel Tang]

Design Control and Production of Curved Elements

As gridshells derive strength from curvature, the production of timber components curved in more than one direction remains a perennial challenge. This is achieved with increasing ease due to the assistance of new timber technology and digital manufacturing. Precision routers, milling machines and cutting of timber sections have also made timber elements with complex surface definitions possible.

For example, the production of curved elements using specialized routers allows the designer to produce complex timber sections accurately. It was reported that for a 20 m timber member fabricated for the Pompidou Metz, a 3-4mm tolerance was measured (Döbele, 2017). One may see this integration of computer aided design and fabrication process as leaving the craftsperson/builder in a precarious position; and for purists to question the true value of the timber craftsperson, in striving for absolute precision and efficiency in a material that inherently and traditionally bears a higher degree of tolerance and movement.

Safety and Method of gridshell construction

In early examples, timber gridshells were constructed by deploying gridmats of timbers with square grid patterns. For the Mannheim Multihalle, 1975, (Happold and Liddell, 1975), Figure 11, western hemlock laths were end-to-end finger jointed into lengths up to 40m before assembly to form the gridmat. The regular gridmat was then deformed through shearing the grid and actively bending the laths to form strong shell forms with double curvatures. Once the predicted shell geometry was achieved, the grid was fixed at the edges and restrained with diagonally placed pairs of 6mm diameter stainless steel cables (Figure 12) to prevent it from deforming back into its original flat mat. This method of installation, however, induced high bending stresses in the timber laths, which resulted in many breakages.

Figure 11: Mannheim Multihalle was created by pushing up gridmats from the ground [Photograph © Gabriel Tang]

Figure 12: Mannheim Multihalle was restrained by a diagonal network of twin 6mm diameter stainless steel wire ties installed at 4.5m centres. (Happold and Liddell, 1975) after the gridmats were pushed up from the ground. [Photograph © Gabriel Tang]

This revealed several shortcomings when judged by current construction standards of safety. Similar sized gridshells erected for the Silk Road Expo' in Nara, Japan, in 1988 (Sakamoto, 1992), used an alternative technique, where prefabricated sections of pre-bent laths (Melaragno, 1991) were craned into position and connected in the air. For the Weald and Downland Jerwood gridshell, shown in Figure 10, a new method was employed, by which the flat gridmat was assembled at high level and deformed into the final form through gravitational force and jacking (Harris et al, 2003).

In the case for the Savill Garden gridshell (Windsor Great Park, UK, 2005) (Figure 13), the larch gridmat was assembled at roof level. In order to reduce the possibility of breakage, laths were bent to a much reduced curvature compared to the Mannheim Multihalle, and restrained with a double layer of 12mm plywood boards (Harris, Haskins and Roynon, 2008; Chilton and Tang, 2017).

Figure 13: The Savill Garden gridshell completed in 2005 was restrained by a double layer of plywood working in shear. [Photograph © Gabriel Tang]

More recently, shorter and thicker components, prefabricated and pre-formed to curved gridshell geometry, have been assembled directly on temporary supports or assembled into larger sections on jigs before craning and connection to the previously installed sections. Examples include: Pompidou Metz, France, 2010 (Lewis, 2011); Haesley Nine Bridges Golf Clubhouse, South Korea, 2010 (Scheurer, 2010); France Pavilion Milan Expo, 2015 (Scheurer, Simonin and Stehling, 2015); and La Seine Musicale, near Paris, 2017 (Chilton and Tang, 2017). These developing methods, are enabled only by advances in digital fabrication and engineered timber production, have greatly improved the safety of the construction process, in light of lessons learnt from the Mannheim gridshell.

Off-Site Construction

Pre-fabrication and off-site construction using engineered timber has played a major part in the movement from purist to liberalist attitudes to the realization of timber gridshells. It was implemented for the gridshell canopies produced for the Hannover World Expo 2000 designed by Thomas Herzog and engineered by Julius Natterer. Each of the approximately 19m by 19m quadrants of the canopy was manufactured off-site and then delivered to site for assembly (Natterer, Burger, Müller, and Natterer, 2002).

Computer technology enabled sections of timbers with bespoke straight sides and specially curved sides to be constructed and holes milled for connection. Being able to divide digitally a curved surface into smaller and discrete components also meant that traditional method of actively bending with fixed intersections is no longer necessary (Chilton and Tang, 2017).

Digital technology used in design and fabrication is effective in shortening construction time, removing the need for manoeuvring space (in deployable gridshells) bearing a positive impact on project cost and complexity in construction. It has allowed designers to incorporate complex ‘woven’ jointing into gridshells, such as at the Haesley Nine Bridges Golf Clubhouse and La Seine Musicale, whilst minimising the use of mechanical fixings.

5. Discussion: Constructional Correctness

5.1 Structural Values

Gridshells designed in accordance with the ‘purist’ definition allow the structure to transfer dead and live loads efficiently, with no bending moments (theoretically) under the primary load condition (usually shell self-weight). Through their doubly-curved geometry, if correctly determined, they can do this whilst avoiding buckling in compression. Traditionally, this allows shells to achieve spectacular thinness relative to their span.

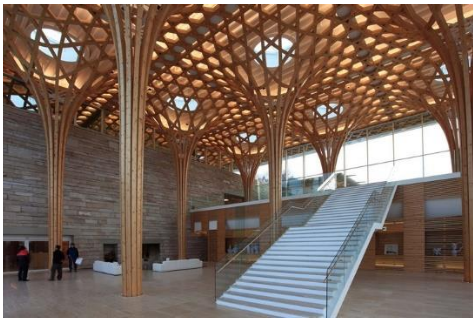

Fig 14: The Haesley Nine Bridges building, South Korea by Shigeru Ban, 2010 (copyright Jong Oh Kim https://www.arch2o.com/haesley-nine-bridges-club-house-kyeong-sik-yoon/)

Such structural logic and purity allows bending-active gridshell structures to span considerable distances. However, gridshells conforming to the looser definition of ‘a shell with holes’, especially more recent examples formed by connecting rigid timber components, are heavily dependent on digital fabrication techniques. Because curved components can be fabricated directly, they no longer need to be flexible – in fact they are thicker and can resist bending - the prime structural concern to create a wide-spanning column free environment is no longer the motivation of the shell designer, but the typology becomes valued primarily for its aesthetics. The application of timber gridshells with internal columns can be applied to projects not restricted to clear spanning purpose as very aptly demonstrated by Shigeru Ban’s Haesley Nine Bridges project in South Korea (2010), Figure 14.

The question of whether this construction is correct is a subjective one, highly dependent on the background and understanding of such structures by the individual. The purist may prefer the gridshell to be thinner to enclose a barrier free environment internally. A liberalist view sees the aesthetic and design benefits of how it can create an interesting architectural experience.

5.2 Material Values

Structural purity (pure compression action) for gridshells is often not the main driver. Aesthetically and poetically, the Savill Garden gridshell (2005), Figure 15, appears to hover at an approximate height of 10m above the ground. To allow this, the shallow gridshell was restrained by a 400mm diameter steel ring beam, in turn supported by V-shaped 8 metre long circular hollow section steel legs.

Fig 15: The Savill Garden gridshell, completed in 2005, is raised above ground by 8m long steel columns and the shallow gridshell structure is restrained by a 400mm diameter tubular ring beam. [Photograph © Gabriel Tang]

To some purists, the use of the highly conspicuous ring beam would suggest a demeaning use of a (relatively flat) gridshell as their strength generally lies in their shape. However, the Savill Garden gridshell was designed to realize an aesthetic vision and architectural concept, thereby demonstrating the adaptability of gridshells in timber, accepted by liberalists in recognizing the dexterity in accommodating different concepts. On the other hand, some purists would frown upon the excessive use of non-timber materials in the timber gridshell structure, questioning the material identity of the structure.

In more rigid gridshells, digital technologies enable the milling of glulam timbers into complex curves in more than one direction. Although the milling process can be programmed to minimise cutting of continuous wood fibres, timber components are not necessarily shaped with the same respect for the material as they would have been in a pre-computer age. These timber sections often need to be of greater size in order to accommodate bending moments that result from geometries that did not necessarily conform to natural load paths.

This also implies that the idea of the shell harnessing the shape (curvature) to produce a structurally efficient form for load transfer may be compromised. Purists would reject this. Conversely, this may be acceptable to the liberalists who appreciate the potential architectural merits of the less than structurally perfect gridshell form.

5.3 Aesthetics

One major aesthetic concern of timber gridshells rests with their external cladding, a problem perennially experienced by all doubly-curved surfaces. They lend themselves to the application of flexible membranes that can be patterned to conform with curvature. Some may be quick to point out that the roof of the Weald and Downland gridshell, with flat boarding being too complicated or even hiding the elegant doubly curved structure beneath.

Technological advancement in materials has allowed gridshells to become lighter visually by widening of grids. Compared to earlier gridshells, based on a 0.5m x 0.5m grid, the Waitomo Glowworm Caves Visitor Centre gridshell, 2010, (NZ Wood, undated) in New Zealand, appears much lighter and more transparent. Some may question the identity of the building, whether it is in fact an ETFE roof (purist) rather than a timber one (liberalist) by the sheer visual appearance (timber grid size of 4.25m) and the large expanse of the membrane material.

Timber tectonics and connections imbue ideas of construction methods and material understanding. The connections are traditionally expressed in deployable gridshells by virtue of their gridmat and deformation process. Timber gridshells, due to their constructional nature are tectonically expressive. The methods by which they are constructed or put together can become a design feature easily.

5.4 Economy

Material economy is an important issue in our resource conscious environment. Traditional actively-bent timber gridshells are constructed from rectangular-sawn laths with little wastage of material – this fulfils a purist view of their creation. However, digitally controlled processes now permit knots and other imperfections to be detected and removed from laths. Subsequently, finger-jointing with modern adhesives create long laths with enhanced properties compared to the base material – thus requiring a more flexible interpretation of the purist view.

In the manufacture of the rigid gridshells, laminations of small dimension are sawn and planed smooth before assembly and gluing to create larger glulam sections. Subsequently, in order to form double-curved components, such as that found in the Pompidou Metz and Haesley Nine Bridges Golf Clubhouse roofs, requires the removal of a substantial volume of material, potentially milling across and against the grain. However, with the aid of digital control of the milling processes it is possible to optimize the orientation of the final piece within the original glulam timber block to minimise the impact of this. These digitally-controlled processes are more acceptable to the liberalist viewpoint.

7. Conclusion

Pier Luigi Nervi’s notion of constructing correctly is relevant and significant in contemporary technology discourses. It has been argued here that his idea is subject to the values we place on material, method and the immediate context. Key timber gridshell projects have illustrated how different variations, developments and overall evolution of these structures are met with different attitudes depending on an individual’s value on technology. One's view is not binary in nature, but sits on a sliding scale between a purist or liberalist standpoint concerning the application of digital timber technology.

This discussion proves that the degree of acceptance of technological change in timber architecture is subject to our personal position in terms of values we place on material and technology. As we negotiate between increased use of digital design, fabrication and our craft tradition, this represents a cultural understanding of the craftsperson's relationship to technology, also raise the question of what, in our opinion, represents correct or incorrect construction.

Technology can be considered a double-edged sword. The influence of digital technology on timber practice is clear. Timber gridshells, intrinsically linked to technical capability, have evolved in the last half century - changing in shape, size and complexity - to document this change of timber technology and reflect the way such structures are designed, components fabricated and eventually assembled. Their design and construction method divides and unites opinions. To some (the purists), the traditional methods of designing and construction qualifies a gridshell as a pure structure. To others (the liberalists), the use of design tools, new materials and design methods are acceptable to qualify similar structures as gridshell structures. Significantly, these new material and methods are the direct or indirect results of digital technologies.

Therefore, digital tools of design and manufacture will continue to exert a strong influence on timber technology. As the digital wrestles with traditional ways of designing and constructing, the understanding of timber as a material must not be neglected by the next generation of designers and craftspeople which oversees a continued celebration and healthy adaptation of the characteristics and qualities of timber in both natural and engineered forms, in the spirit of *Constructing Correctly*.

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