## The tectonics of timber architecture in the digital age

Good buildings that are immediately convincing and in which one feels at ease, that surprise and astound us, have one thing in common – a successful synthesis of technology and spatial design. The art of deploying construction technology in such a way that it forms an integral component of the design and actively helps to shape it is what Kenneth Frampton defines as tectonics.[1] Tectonics can be conceived as construction technology's potential for poetic expression. Technology is deployed not only to find an optimal solution for a structure; it also influences the sensual experience of space.[2] Tectonics is rooted in timber building because the Greek word *tecton* signifies 'carpenter', or 'builder' in general. The art of the carpenter thus hallmarks all of architecture. Three main factors determine a building's tectonics: the material, the tools, that is to say, the technical possibilities for working with the material, and the design. The use of computers has led to sweeping changes chiefly in the processing of the material and in the design process. At the same time, timber as a material is also continually being developed further, opening up new technical and design possibilities. In order to make tectonic potential in the digital age easier to understand, we will briefly describe how the interplay of material, fabrication technology and design has changed over the course of time, and what impact these changes have had on the tectonics of timber building. Finally, we will show how digital design tools can support the tectonic quality of timber buildings, illustrating this point with a few examples.

### The tectonics of timber architecture as reflected in its production conditions

"Le progrès humain est marqué par une extériorisation progressive des fonctions, depuis les couteaux et les haches en pierre qui permettaient d'étendre les capacités de la main humaine jusqu'à l'extériorisation des fonctions mentales au moyen de l'ordinateur."[3]

In order to trace how the interplay between material, fabrication technology and design has developed, we will largely follow the architectural periodisation model conceived by Christoph Schindler.[4] Production engineering is posited therein as a system that transfers information onto a workpiece with the help of energy, whereby the information describes the form and shaping of the workpiece. Two caesuras are defined within production engineering in which more and more human skills are taken over by machines. In the first step, the machine replaces human hands (hand-tool technology) in guiding the workpiece and tool (machine-tool technology) and in the next, the machine also takes charge of the variable control of information (information-tool technology). This transformation is accompanied by increasing specialisation: the universal carpenter is replaced by a team of highly specialised experts. In parallel, the design techniques change as well: from the elevation that the carpenter and builder draft on site, to the application of standardised laws of descriptive geometry, and finally onward to parametricised geometry that no longer defines the form, but rather its framework.

The history of timber building can be divided into three phases, each of which harbours its own tectonic potential: the wooden (hand-tool technology), the industrial (machine-tool technology) and the digital age (information-tool technology).

### The wooden age

In the wooden age, tectonics were omnipresent. This period was characterised by the unity of design, execution and material. The carpenter was in charge of both execution and planning. He was the *archi tekton*, the 'head builder', who conceived, designed and processed the workpiece, taking into account the specific properties of wood in his planning and execution, and leaving his personal signature on the workpiece through his manual labours with axe and saw. The planning of timber structures was very simple and involved only generalised specifications. For half-timbered buildings, for example, all the project plans known to us today date from the eighteenth century or later. As a rule, the client came to an agreement with the master carpenter on a few fundamental aspects of the building, such as size, number of storeys, interior divisions and number of doors and windows.[5] Once the typology of the structure had been established, the rest all followed from the traditional rules governing the material and its natural dimensions, as well as from the type of construction, typical solutions for details, and the geometric proportions of the whole. The carpenter built up the components directly atop the drawing floor on a scale of 1:1. In the process, he worked with the wood's natural growth patterns, adapting the building's design to fit as necessary. Each element was individually finished to connect smoothly with the neighbouring parts. Absolute dimensions played no role here; instead, the constructional thinking proceeded according to proportions. The details of a particular building varied according to the local carpentry tradition and the region. Although design and construction followed fixed rules, these left a relatively large margin for creative freedom, leading to a variety of individual solutions, which were, however, all moulded by the same ground rules.

The type of construction (log or half-timbered) thus influenced the individual variations in traditional manual workmanship – in other words, the signature of the carpenter – which can be considered the tectonics of the wooden age; spatial aspects remained secondary here.

**The industrial age**

Characteristic features of the industrial age are standardisation and specialisation. In order to rationalise production processes and hence increase turnover, the guidance of workpiece and tool was transferred to machines, which however continued to be under human control. The prerequisite for this development was the production of large quantities, as every readjustment of the machine slowed down the production process. The components were hence standardised and no longer adapted individually, becoming in effect interchangeable. Standardisation also called for a homogenisation of materials: wood in its natural state was taken apart, broken down and then glued together again in order to cancel out its anisotropy and the inhomogeneity of its growth patterns. The development of panel-shaped plywoods opened up new paths for timber engineering. At the same time, the age of industrialisation brought greater specialisation amongst builders: the carpenter was now often entrusted only with execution, whilst design and technical planning were in the hands of the architect and the engineer. For the specialists to be able to understand one another and coordinate a project, they needed to speak a common language – that of descriptive geometry – and to use precise units of measurement, and the standard metre was thus set down as the authoritative measure at the end of the eighteenth century.

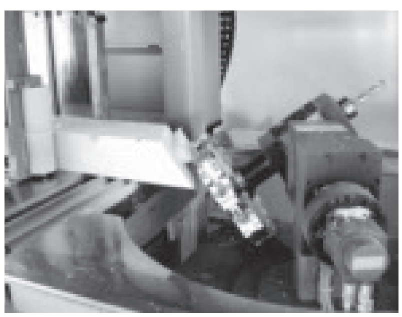
This all led to new conditions for timber building. First of all, the standard dimensional lumber known as 'two-by-fours' (boards measuring 2 x 4 inches) gave rise to balloon frame construction, in which the carpenter's own signature wood joining was replaced by nails, and where planks covered both sides of the close-knit frame, hiding the tectonics that were previously evident in the construction. Timber also played a key role in the development of modular building systems. These are based on a uniform grid into which

modules are fitted. The grid's dimensions are extremely conspicuous in timber frame construction. Here, it is no longer the explicit construction and joints that characterise the tectonics of a building, but rather the presence of the construction grid, whether in the pattern of joints visible in the modules or in the rhythm of openings and their subdivisions.
The development of plywood panels led to increasingly larger formats, in which surfaces took on a more prominent role. While at the beginning of this development, small-format plywood panels were deployed primarily as planking and for bracing, the ability to produce larger panels ushered in a reversal of the roles of bar-shaped and panel-shaped members: the panel was now used for load transfer and the bar for bracing. This opens up new freedom for designing spaces and facades, while also presenting the architects with fresh challenges.[6] Tectonic quality is no longer determined by the construction grid or the artful joining of bar-shaped elements. What does plywood panel tectonics look like? What distinguishes it from other panel-shaped materials?

**The digital age**

In contrast with the industrial age, which was characterised by standardised production, the hallmark of the digital age is a strong tendency towards individualisation, precipitated, on the one hand, by the electronic control of production machines, and on the other, by new, parameterisable design tools.
The ability to control machines with the help of a computer code eliminates the need for serial production. The information dictating the form of a workpiece, which the human previously provided through a one-time machine setting, is now directly integrated into the machine. The information flow from the control program is variable, meaning that components of various shapes can be manufactured without any time losses in production.

The first machines to be controlled via a digital information flow were the looms developed by Jacquard, in which the digital signal was not, however, generated electronically, but rather by a punch card. The first digitally controlled joinery machines for timber construction came out in the 1980s, first for joining bar-shaped elements only, although these were soon followed by huge portal machines capable of cutting and joining workpieces of virtually any form. These are distinguished not only by electronically variable control, but also by their universal applications. Thanks to an automatic workpiece exchanger, the machine can be loaded with practically any workpiece and can mill, drill and saw it.
The functions of the portal machining centres are not completely unlimited, however, because their processing capabilities depend on the mobility of the tool head, the size of the work area, and the tools with which the machine is equipped. Machines with three directions of movement can move along only the three spatial axes X, Y and Z. Cutting a piece on a slant to the horizontal plane XY on such a machine is either extremely time-consuming or impossible. This calls for a machine with five directions of movement in which the tool head, like a human wrist, can be rotated around two axes. The machine is operated by means of an internal machine code generated by a special program. This means that the machine cannot simply be fed a data set that describes the shape of the workpiece geometrically; instead, the form of the workpiece must first be translated into movements made by the appropriate tools. Operating and programming the machine requires the relevant knowledge, which leads once again to specialisation in the field of carpentry. The easy machinability of wood makes it an ideal material for digitally controlled processing portals. For this reason, the timber industry is well equipped with such machinery, and timber is taking on the status of a high-tech material.

left: Hermann Kaufmann, Olpererhütte mountain lodge, 2006; right: Hans Hundegger Maschinenbau GmbH, Hawangen

Geodesic line, IBOIS, EPFL

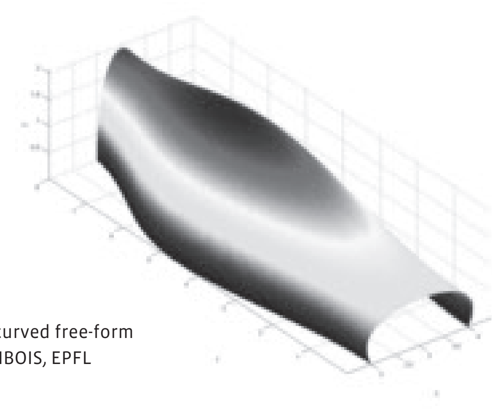
In the early days of CAD (computer-aided design), the computer served above all as a digital drawing board, and was still used to design the traditional ground plan and section. Almost imperceptibly, however, new tools found their way into the arsenal, such as the digital curve template and the Bézier curve. These were developed by French mathematicians Pierre Bézier and Paul de Casteljau to design automotive bodies. While descriptive geometry clearly grew out of the craftsmanship techniques of carpenters and stonemasons,[7] the Bézier and spline curves did not originate in the field of building construction. As design tools always leave their stamp on the form taken by the architecture made with their help, the question now is how architects will handle the new tools,[8] and how the resulting forms can be translated into the construction of buildings. In the case of the two-dimensional Bézier curve, this would appear relatively simple, while by contrast the handling and structural application of the three-dimensional NURBS surfaces (NURBS = non-uniform rational B-spline) are much more complex. This tool likewise traces its origins to the automotive industry, but today enjoys extremely widespread use, for example in computer graphics and product design. NURBS surfaces are exactly defined mathematically but do not underlie any structural logic. The questions of how such a form can be carved up into individual building components, and which support structure is appropriate for the form, often present the architect or engineer with insurmountable obstacles, as he or she is not in possession of the requisite mathematical knowledge. The solutions arrived at for subdividing the form are therefore often pragmatic, but also somewhat banal: it is cut into parallel slices,[9] not always an optimal solution from the tectonic standpoint. Another possibility is to work with a specialist who can help to master the geometric and structural problems. The question here is to what extent the architect can then still actively shape the tectonics of the building, and whether structural considerations might call the form into question and result in the need to modify it.

An important step in this direction is offered by parametric models. These make it possible to change form and building components without the need to draw everything all over again. When the overall form is altered, the components are adjusted to fit the new shape. In a parametric model, the form per se is no longer drawn, but rather a process is defined that generates the form and its constituent components. The form can be generated and modified by controlling predetermined parameters. What is decisive here is not the chosen form, but how the process for form generation has been set up and what parameters control the process. Echoing the idea of the genetic code, the form-generation process is known as 'genotyping'. As in nature, the genotype establishes a certain spectrum within which it is possible to define a number of individual forms: the phenotypes.[10] Such design processes provide an opportunity to incorporate the properties of the materials and the support structure, as well as construction and fabrication techniques, as parameters into the process. This lends tectonics a new topicality: the parametric model is capable of mediating between space and technology.[11]

Driven by increases in efficiency and standardisation, natural wood is making way more and more for homogenised plywood, with panel-shaped timber elements taking on ever greater importance. Many natural properties of the material, such as its easy machinability, low weight and appealing surface structure, are maintained in its plywood version. This makes timber extremely attractive and versatile to use, both for digitally controlled production and in interior design.

Digitally controlled production makes it possible to manufacture individualised building components economically. As in hand-





Double-curved free-form surface, IBOIS, EPFL

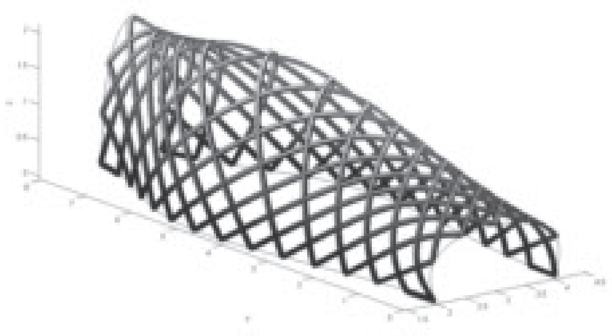
craftsmanship, the various parts are adapted to fit together and thus form a network of relationships. Parametric drafting tools also follow a logic of relationships that constitute the genetic framework for the form. This creates a connection between design and production.
Whereas in the 'wooden age' described above, knowledge and skill lay in the hands of the carpenter, in the digital age, they are distributed among a number of specialists, which calls for a great deal of effort in planning and coordination. Planning can be rationalised through the integration of material-specific, constructional and fabrication-specific parameters in the design tools. The intelligent conception of design tools like these is extremely time-consuming and is hardly worthwhile for just one project. However, because parametric design tools can generate several solutions that always take into account specific sets of requirements, it would seem justifiable to develop drafting processes that can be applied in diverse projects. Parametric design processes resemble modular building systems in this respect, the difference being that, when they are designed well, they offer a much higher degree of flexibility. As in modular building systems, the identity of a project's authors becomes blurred: are they the developers of the digital tool, or those who use it?[12]

**The tectonics of digitally designed timber construction: bending, weaving, folding**

Based on selected projects carried out at the Laboratory for Timber Constructions (IBOIS) at the EPFL Lausanne, it is possible to show how parametric design tools can be created that are specifically tailored to timber and its material properties. Tectonics – the interplay of architectural expression, efficiency and the construction of support structures – is the focus of research and teaching at IBOIS.[13] New plywood materials and processing technologies along with the new possibilities for depicting and calculating support structures play an important role here. The aim is an efficient interlinking of design and construction that integrates the architectural, support-structure-related and production requirements, leading to sustainable and high-quality solutions.

**Bending and weaving**

Thanks to its natural fibre structure, wood is an extremely elastic material and easy to bend. This property can be utilised in construction and form generation. Timber rib shells take their cue from the elastic qualities of wood. They build on a grid of ribs crossing in space, with each rib made up of curved screwed lamellate boards.
A board with a rectangular cross-section can be bent and twisted only along its weak axis and can therefore take on only certain forms in space. If one attempts to attach a board so that it clings as closely as possible to a given form, the board will seek out its own path along the surface of the form. If the form is a cylinder, the board will twist along its central axis into a helix. In mathematical terms, the central axis corresponds to the shortest route between two points on a surface, the so-called geodesic line. For volumes such as cylinder and sphere, the geodesic lines can be analytically determined relatively easily, but the same does not apply to free-form surfaces such as NURBS. In collaboration with



Timber rib shell along the geodesic lines of the free-form surface, IBOIS, EPFL

Arch construction made of woven wooden strips, IBOIS, EPFL the Department of Geometry, IBOIS developed a model that is able to calculate the geodesic lines on a free-form surface.[14] The engineer and architect are able to steer parameters such as the number of ribs and the start and end point, in this way jointly shaping the load-bearing abilities and the form of the ribbed shell. Depending on the cross-section desired by the engineer and the resulting number of ribs, the program can calculate the required board lengths and the geometry of the intersections and transmit the data directly to the producer.

The bending of timber also plays an important role in another type of timber construction developed by IBOIS, which is based on the principles of textile technologies.[15] Textiles are regarded as one of the first human craftsmanship accomplishments and have been used since prehistoric times in the construction of dwellings. In this project, the fundamental principle behind all textile technologies, the crossing of two elements, is transferred onto two strips of plywood. The interlocking of the two double-bending surfaces creates a volume somewhere between arch and bowl. The basic module can be deployed as support element or combined in multiple ways to create larger structures. The weaving together of a large number of elements has the advantage of creating a system effect: the failure of individual elements does not lead to the failure of the overall system, which makes the support structure more robust. The precise geometric description of the base module is extremely complex and has not yet been solved satisfactorily. Currently, attempts are being made to mechanically simulate the joining process. What is interesting about this example is that the material and its distortion are the determining factors for the form-generation process. This procedure is, on the one hand, a guarantee of a tectonic quality of the form, but represents, on the other, a challenge for the mathematicians and engineers who have to generate and calculate that form digitally. The example also demonstrates that form and construction technologies like these can be developed only in research laboratories and in interdisciplinary cooperation.

**Folds**

Another inspiration for the research work at IBOIS was plywood panels, in particular glue-laminated timber. Glulam panels have good strength values and are manufactured in dimensions that make interesting applications possible in the construction of support structures, including for folded structures. With their load-bearing and spatial/sculptural effect, folded structures are attractive for engineers and architects alike.[16] The folds increase the stiffness of a thin surface, which means they can be used not only to cover a space but also as a load-bearing element. The rhythm of the folds as well as the play of light and shadow along the folded surfaces can be deployed in a targeted fashion to create the desired interior ambience. At the same time, the load-bearing capacity of the folded structure can be influenced by changing the depth and incline of the folds. We therefore set ourselves the goal of developing a method for rapid spatial description and modification of such folded structures. The point of departure for our work was origami, the Japanese art of paper-folding. Origami uses simple, basic techniques that by way of geometric variations give rise to an astounding variety of forms and generate complex forms rationally and with simple means. We wanted to transfer these properties to the construction of folded structures made of glulam. Through intuitive paper-folding, suitable folding patterns were determined and their geometry analysed in order to be able to depict them in a 3D drawing program. That led to the generation of folding structures with a computer-assisted drawing program. It was important here to create tools that could be integrated into the design process and with which



Textile base module, IBOIS, EPFL

the architect is familiar: the form of the folded structures is defined by one line each in the ground plan (riffling profile) and in the section (cross-section profile). Using this method, a variety of different forms can be created in a short space of time and adapted to fit both the architectural and structural planning requirements. For example, the load-bearing capacity can be influenced by varying the form of the riffling profile, which defines the height and incline of the folds. The method we developed enabled us to rapidly model complex folding structures, to export their geometry directly to a structural engineering program or a computer-controlled joinery machine, and hence to rationalise the design and production process.

The chapel for the deaconesses of Saint-Loup, in Pompaples (figs. p. 66f.), is the first building designed using the method IBOIS developed for modelling folded structures.[17] The geometry of the chapel integrates the spatial shell, support structure, construction, acoustics and lighting into a homogenous form and is determined in the main by the design tool used.[18] The aim was for the chapel to express a certain straightforwardness and simplicity, as well as being fast and economical to build. This led to the choice of a trapezoidal cross-section profile made up of three segments – two walls and a roof. The number of panels and joinings could thus be minimised.

The space is meant to recall a simple church nave with a round apse, which is why the riffling profile that determines the form in the ground plan is slightly curved. This compresses the space towards the altar, vertically pushing up the folds, which consist of a continuous, unwinding surface. The incremental transition from horizontal to vertical space gives the chapel a clear direction and meaning that is meant to symbolise the transcending of earthbound humanity towards achieving spirituality.

In an initial design phase, a row of parallel folds formed the folded structure, giving the spatial shell the necessary load-bearing capacity. The folds articulate the space like the columns or piers in a traditional church nave. In the definitive design, every second fold was then slanted. This creates an interplay between opposing large and small folds that enlivens both the facade and the interior. It also has the advantage that the roof folds are slanted, letting rainwater run off. The irregularity of the folds improves the acoustics and lighting of the space. The variously inclined wood panels reflect the light falling in through the gable facade and cast a subtle sequence of shadows throughout the room.

In the Chapel of Saint-Loup, it was possible, thanks to the precise arrangement of the geometry of the folded structure, to successfully integrate the architectural, structural engineering and production requirements into the design process. The new and independent architectural form that resulted would have been difficult to realise without the help of digital modelling. Executing it using glulam panels made it possible to build the spatial shell, support structure and interior out of a single layer. It was possible to rationalise the production process because the digital files for cutting the panels were created directly using a parametric design tool and then delivered to the producer.

The project is the outcome of a fruitful collaboration between architects, researchers and engineers. It shows that the successful integration of the specifications for the materials and support structure into a parametric design tool can lead to a constructive dialogue between spatial design and technology – the prerequisite for tectonic quality.

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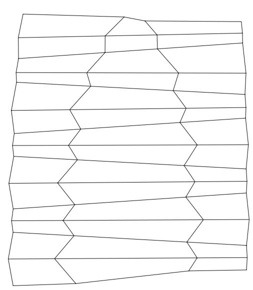
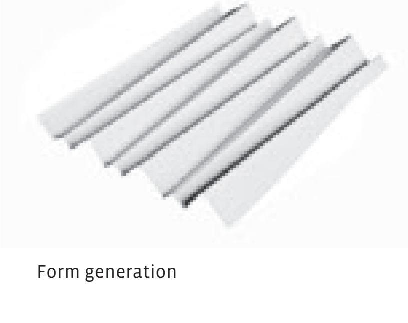
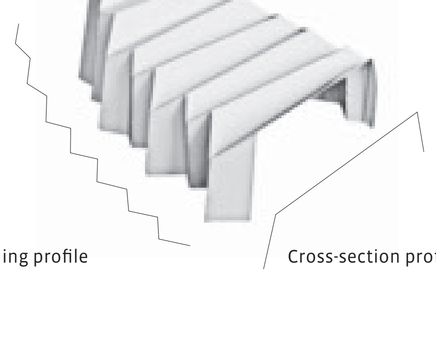


SHEL, Chapel of Saint-Loup, Pompaples, 2008, developing the outer shell



Form generation



Riffling profile

Cross-section profile

## Notes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