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ADVANCES IN DIGITAL DESIGN AND FABRICATION OF WOODEN ARCHITECTURE

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ROZWÓJ CYFROWYCH METOD PROJEKTOWANIA I FABRYKACJI W ARCHITEKTURZE DREWNIANEJ

Abstract

This paper deals with the possibilities of architectural design of wooden structures in the digital age. The first part of the paper presents the material-based design as a new approach to shaping free-form objects. The problem is that a new geometry requires new materials or a new approach to old, well-known building materials and structures. The lack of suitable materials to build curvilinear free-form surfaces has led to the use of traditional materials in new ways.

The second part describes the historical techniques of designing and manufacturing of curvilinear wooden forms. They were compared to digital tectonics as a new methodology in architectural design. Historically, architects and carpenters used the stereotomy method and manufactured non-standard wooden elements (e.g. guitarde dormers and balconies), taking into account the inherent properties of the material. Digital CAD/CAM technologies have radically changed the conceptual approach to architectural and engineering design. Architectural forms created with the use of digital parametric tools are considered in terms of geometry, material properties and means of production. Such well-known buildings as Chesa Futura in St Moritz (Switzerland) and Weltstadthaus in Cologne (Germany) were presented as model examples of digital tectonic design in wooden architecture.

In the Discussion, the paper presents the advantages of timber architecture. The new generation of high-performance wood materials offers unique architectural possibilities. The digital era led to the transformation of traditional tectonics into digital tectonics operating in terms of construction logic shaped according to the principles of digital design and fabrication tools. The CAD/CAM system is the basic formula of digital tectonic approach and it unveils inherent properties of wood as a natural material.

Streszczenie

Artykuł dotyczy możliwości projektowania architektonicznego konstrukcji drewnianych w epoce cyfrowej. W pierwszej części przedstawiono projektowanie materiałowe jako nowe podejście do kształtowania obiektów o formach swobodnych. Problem polega na tym, że nowa geometria wymaga nowych materiałów lub nowego podejścia do starych, dobrze znanych materiałów i konstrukcji budowlanych. Brak odpowiednich materiałów do budowy krzywoliniowych powierzchni o dowolnym kształcie doprowadził do wykorzystania tradycyjnych materiałów na nowe sposoby.

W drugiej części opisano historyczne techniki projektowania i wykonywania krzywoliniowych form drewnianych. Porównano je do cyfrowej tektoniki jako nowej metodologii projektowania architektonicznego. Historycznie architekci i mistrzowie ciesielscy stosowali metodę stereotomii i wykonywali niestandardowe elementy drewniane (np. lukarny i balkony typu guitarde) z uwzględnieniem naturalnych właściwości materiału. Cyfrowe technologie CAD/CAM radykalnie zmieniły podejście koncepcyjne do projektowania architektonicznego i inżynieryjnego. Formy architektoniczne tworzone za pomocą cyfrowych narzędzi parametrycznych rozpatrywane są pod względem geometrii, właściwości materiałowych i środków produkcji. Jako modelowe przykłady cyfrowego projektowania tektonicznego w architekturze drewnianej zaprezentowano znane budynki, takie jak Chesa Futura w St. Moritz w Szwajcarii i Weltstadthaus w Kolonii w Niemczech.

W zakończeniu pracy przedstawiono zalety architektury drewnianej. Nowa generacja wysokowydajnych materiałów drewnopochodnych oferuje wyjątkowe możliwości architektoniczne. Era cyfrowa doprowadziła do przekształcenia tradycyjnej tektoniki w tektonikę cyfrową operującą w kategoriach logiki konstrukcyjnej kształtowanej według zasad cyfrowych narzędzi projektowych i wytwórczych. System CAD/CAM jest podstawową formułą cyfrowego podejścia tektonicznego i uwypukla nieodłączne właściwości drewna jako materiału naturalnego.

Keywords: wooden architecture; wooden stereotomy; digital tectonics; CAD/CAM

Słowa kluczowe: architektura drewniana; stereotomia drewna; tektonika cyfrowa; CAD/CAM

INTRODUCTION

The digital revolution in architecture is manifested with the emergence of non-standard forms with a high degree of complexity. Digital design and production drew attention to the modernist dichotomy between structure and material, and imposed a whole new interpretation of materiality. Before the advent of the digital age, the dominant design approach was focused on geometry contributing to the primacy of form over material. Traditional ways of representing geometry were based on descriptive methods, which favoured Euclidean geometry and Cartesian space. The formal language based on a line and a right angle, a composition of simple geometric solids and flat elements, had a well-established tradition dating back to antiquity.

In the last decade, innovative theories and methods of digital design have brought a new meaning to the concept of architectural tectonics. The ideological revolution is dubbed with the technological one, and the multiplicity of approaches as well as creative attitudes suggest different design intentions. What they have in common is not only a desire to design curvilinear forms, but a tendency to use digital technologies to integrate creative design concepts with their uneasy implementation. In advanced digital design the architectural form is not drawn or created but rather calculated, which means that the designer invents internal parametric logic to model the form, function and structure of the building. Moreover, designing with digital tools requires formal, structural and material aspects present in the design from its earliest stages of mutual influence.

1. MATERIAL-BASED DESIGN

The curvilinear geometry of free forms in architectural designs poses new challenges for building materials. Commonly used and recognized materials are reconsidered in the context of their use in the construction of free-form buildings. Material-based design is a process of exploring associations between geometry, material behaviour and structural efficiency in architectural and engineering design. Solutions to these problems require the integration of traditional construction methods with an extensive use of design software [Oxman N., Rosenberg J. L., 2007]. Material-based design computation is developed and proposed as a set of computational strategies supporting the integration of form, material and structure by incorporating physical form-finding strategies with digital analysis and fabrication. In this approach, material precedes shape, and it is the structuring of material properties as a function of structural and environmental performance that generates the design form [Oxman, N., 2010].

Wood is one of the oldest building materials. However, apart from its indisputable advantages, it has numerous disadvantages which limit its use in construction. In traditional timber construction structural components made of solid timber are limited by the dimensions and quality of raw timber. The advent of modern technological solutions has led to the elimination of the disadvantages of wood and the resulting limitations to its application through the use of wood-based materials. Their characteristics (mechanical strength, resistance to moisture, dimensional stability) often exceed those of the wood they are made of. With new-generation wood-based materials, such as engineered wood products (EWPs), it is possible to achieve structural component dimensions impossible with solid timber. An important advantage of wood-based materials is the possibility of designing their properties at the production stage, which makes these materials more functional than solid timber. An important advantage of wood-based materials is that lower-quality or small-sized raw wood can be used for their production. All this makes the use of wood-based materials in construction compatible with the idea of sustainable construction, which promotes materials that are as natural as possible and at the same time provide structures with adequate strength, durability as well as thermal and acoustic comfort.

New construction systems rely on a high degree of prefabrication. Wood and wood-based composite materials are especially suitable for prefabricating large structural elements and components because of the ease they can be worked with, the techniques used to join them, and the light weight of elements making them easy to transport. Innovative wood-based materials combined with the means of digital technology have led to a renewed interest among architects in tectonic expression, material properties, and the ability to produce a desired form and spatial effects with both new materials and innovative applications of conventional materials. A particularly interesting trajectory is the pursuit of the material and the tectonic unity of structure, function and skin (as per Vitruvius' modern expression: *firmitas, utilitas* and *venustas*), which ensures the variability of volume, shape, composition, texture and appearance into a single material product.

2. WOODEN STEREOTOMY VS. DIGITAL TECTONICS

Stereotomy (from Greek: στερεός (*stereós*) – solid and τομή (*tomē*) – cut) is a term defining the division of three-dimensional solids into smaller geometrically defined particular shapes. Stereotomy in architecture is typically referred to such materials as stone or wood that are cut to be assembled into complex structures (walls, vaults, arches, etc.). In engineering drawing, the term stereotomy is synonymous with descriptive geometry and deals with two-dimensional representations of three-dimensional objects. Plane views and perspective drawings of solids are used to describe and analyse their properties for engineering and manufacturing purposes.

The concepts of stereotomy and tectonics, introduced by Gotfried Semper, in relation to an architectural object in their basic framework, only seem to be mutually exclusive. However, for analytical purposes, a division into stereotomic and tectonic architecture can be adopted. The interdependence of tectonics and stereotomy, in the Semperian sense, is described by the Swedish historian of architecture Elias Cornell in the book entitled *Rummet i arkitekturen* (Space in Architecture) published in 1996. In the introduction to this book, he distinguishes the aspects relevant to architecture regarding these two concepts. He believes that architecture in its external appearance is tectonic through its construction, and stereotomic in terms of space. Tectonics translates to a clearly erected building structure composed of components and parts that do not necessarily have to be figurative. Cornell understands stereotomy as what has been spread, suspended in between. He also notes that stereotomy and tectonics, although conceptually different, rarely overlap, but are most often considered together. These concepts are important for Cornell when architecture is treated as the art of creating form and at the same time interpreted in terms of architectural space [Cornell, E., 1996].

Stereotomic architecture can be understood as one in which the force of gravity runs undisturbed in its structural system, as the continuity of the structure is maintained, and it is complete. It is massive, stone, heavy architecture. The buildings rest firmly on the ground, as if born from it. Stereotomic architecture seeks light, pierces its thick walls made of modular, masonry elements, so that the light falls into them. This is the architecture of the podium, the base and the stylobate. It is also an architectural representation of a cave. Stereotomy in construction is the ability to make a stone or ceramic fittings an element or a masonry structural system – usually complex, such as an arch, buttress arch, rib or vault coating, dome coating, coffered ceiling, window tracery, buttress, staircase, or carpentry joints connecting elements of a wooden structure.

In tectonic architecture the force of gravity runs discontinuously, its structural system is connected at nodal points where the construction is rhythmic and syncopated. It is light-weight architecture shaped on the basis of a skeleton resembling a tree. The tectonic architecture rests lightly on the ground as on tiptoes. It is architecture that defends itself against light, in which the excess of its openings should be covered to control the light that floods into it. This is the architecture of the housing of the human hearth – a tent or a hut. A model example of tectonic architecture designed according to the rules of geometry and mathematics is a Gothic cathedral.

3.1. Stereotomy of wood

Stereotomy is the art and technique of cutting three-dimensional solids into shapes. The English term follows the French *stéréotomie* derived from the Greek words for 'solid' and 'to cut'. The French master carpenter Louis Mazerolle and at the same time an author of the 1866 treatise, *Traité Théorique et Pratique de Charpente*, defined the term as 'the art of representing objects in section, elevation, and plan in order to cut them out.' Employing working drawings to design and fabricate structures both simple and complex, it can be thought of as a 'universal language' for three-dimensional space. Stereotomy has long been used in the design and construction of wooden historic buildings in Europe, including cathedrals, castles and palaces. Stereotomy, as applied by French master carpenters, is commonly referred to as *l'art du trait*. This term, roughly translated as 'the art of the line', was first used by *Les Compagnons du Devoir*, an ancient French craft guild system with possible origins predating the 12th century. German carpenters, *Zimmermänner*, refer to the knowledge and practice of stereotomy as *Schiften*. Miyadaiku, Japanese temple carpenters, refer to it as *kikujutu*. As an art and collection of techniques, stereotomy reflects empirical knowledge that has developed into a genuine intellectual discipline. As it cultivates independent problem solving, stereotomy is relevant and practical on any worksite. For eight centuries, *l'art du trait* has been used in France to determine and express, through precise working drawings, the real values of details in a structure. By using this method, a carpenter can determine all the dimensions and angles required, prior to assembly, or even layout, of any components. This can be accomplished through using full-size working drawings, often lofted on the floor, or scaled down drawings [P. Moore, 2021, 10].

In the 18th century, in the Loire Valley in France, a distinctive type of curvilinear dormers and balconies developed. Their name *guitarde* referred to an instrument because their curved lines resembled the shape of a guitar. The curvilinear form was the result of the use of a circular or elliptical plan and deformation (e.g. by rotating the initial solid). In the past, a masterpiece referred to a piece of work produced by an apprentice or journeyman aspiring to become a master craftsman in the old European guild system. Crafting an element of such a degree of complexity was a demonstration of carpentry art, which was not possible without careful mapping of the complicated geometry of individual elements. Dormers owed their popularity to the possibility of lighting the attic rooms above the eave line of the building. The earliest dormers were functional and simple, but over time they took on more and more magnificent forms, providing an effective aesthetic impression. The first documented example of elaborate wooden dormers is a pair of *guitarde* dormers designed and built in 1765 by Nicolas Fourneau, a master carpenter from Rouen, Normandy. Fourneau is also the author of an influential treatise on carpentry *L'art du feature de charpenterie* published in 1767, in which he presented working drawings of *guitarde* dormers. Fourneau's treatise was the culmination of nearly twenty years of teaching advanced carpentry techniques using stereotomic methods. Stereotomy, meaning the application of complex geometry to construction methods, is commonly referred to in the French tradition as *l'art du trait* ('the art of the line'). Similar concepts exist in Germany (*Schiften*) and Japan (*Kikujutsu*). Wooden stereotomy, as an art and a set of techniques, reflects empirical knowledge that has developed into an intellectual discipline. As a method of cultivating independent problem solving, stereotomy has been essential in woodworking and carpentry tradition [Moore P., 2022].

In 1871, master carpenter Pierre-François Guillon created a practical vocational school in Romanèche-Thorins that taught a special drawing technique enabling the mapping of curvilinear forms in technical and executive drawings. The method referred to the idea of stereotomy used in wooden construction. The school known as *d'École de Trait* ('school of the line') was located in Romanèche-Thorins in the department of Saône-et-Loire in Burgundy, and over half a century dozens of apprentices were educated there. The method created by Pierre-François Guillon refers to the idea of stereotomy by: considering the target shape of the element as a three-dimensional solid that is a combination of smaller-sized elements. The solid is considered in terms of careful division into smaller fragments, which enables subsequent assembly as architectural elements (walls, brackets, flights of stairs, vaults, roofs), freeing the shape of the element from the material properties of wood in terms of its dimensions resulting from the geometry of the wood raw material (e.g. profile, log length).

The stereotomy consisted in the appropriate marking of the manual processing of raw, unprocessed wood, which allowed for the emergence of a designed assembly element from the solid, exactly matching the neighbouring elements. For this purpose, 1:1 scale drawings, templates corresponding to the projection of a given surface or a three-dimensional model representing the target shape, were made. Then the cutting lines were traced or drawn (using a compass, a square and a ruler) on the levelled surface of the raw material. Further processing of the solid consisted in the precise execution of the joint (invisible after assembly), ensuring the fit and proper cooperation of individual elements. Originally this was achieved with full-size drawings often drawn on the substrate. With the development of mechanization and technology, the method of using scale drawings was developed.

The pre-industrial use of timber in architecture and boat building actively exploited particular characteristics and geometric forms by matching them to function within a structure. Conversely, the 19th-century industrialization of construction led to homogenized materials – particularly steel – and a corresponding design attitude in which standardization was favoured, driven in part by the professional split of the architect and engineer professions, and the consequent abstraction and rationalization of the description of material properties for structural analysis. The variability of wood was counter to engineering's aim for precision and certainty, and its reductive tendency to codify and seek standardization in how a material is described and applied. This reductive attitude irreversibly led to the loss of the earlier tradition based on informal knowledge and intuitive capacity held by the craftsperson and, indeed, the creative engineer [DeLanda M., 2004].

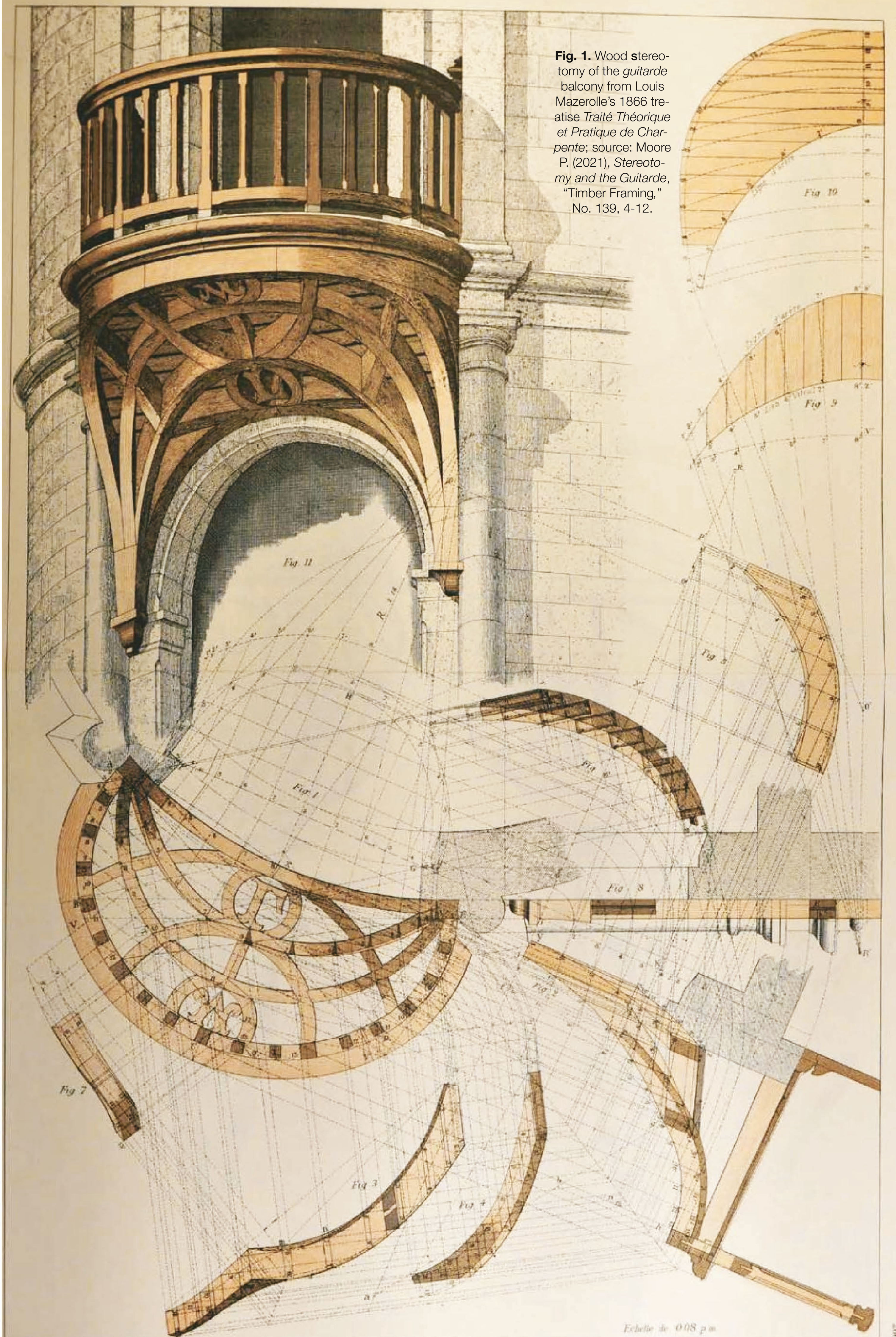
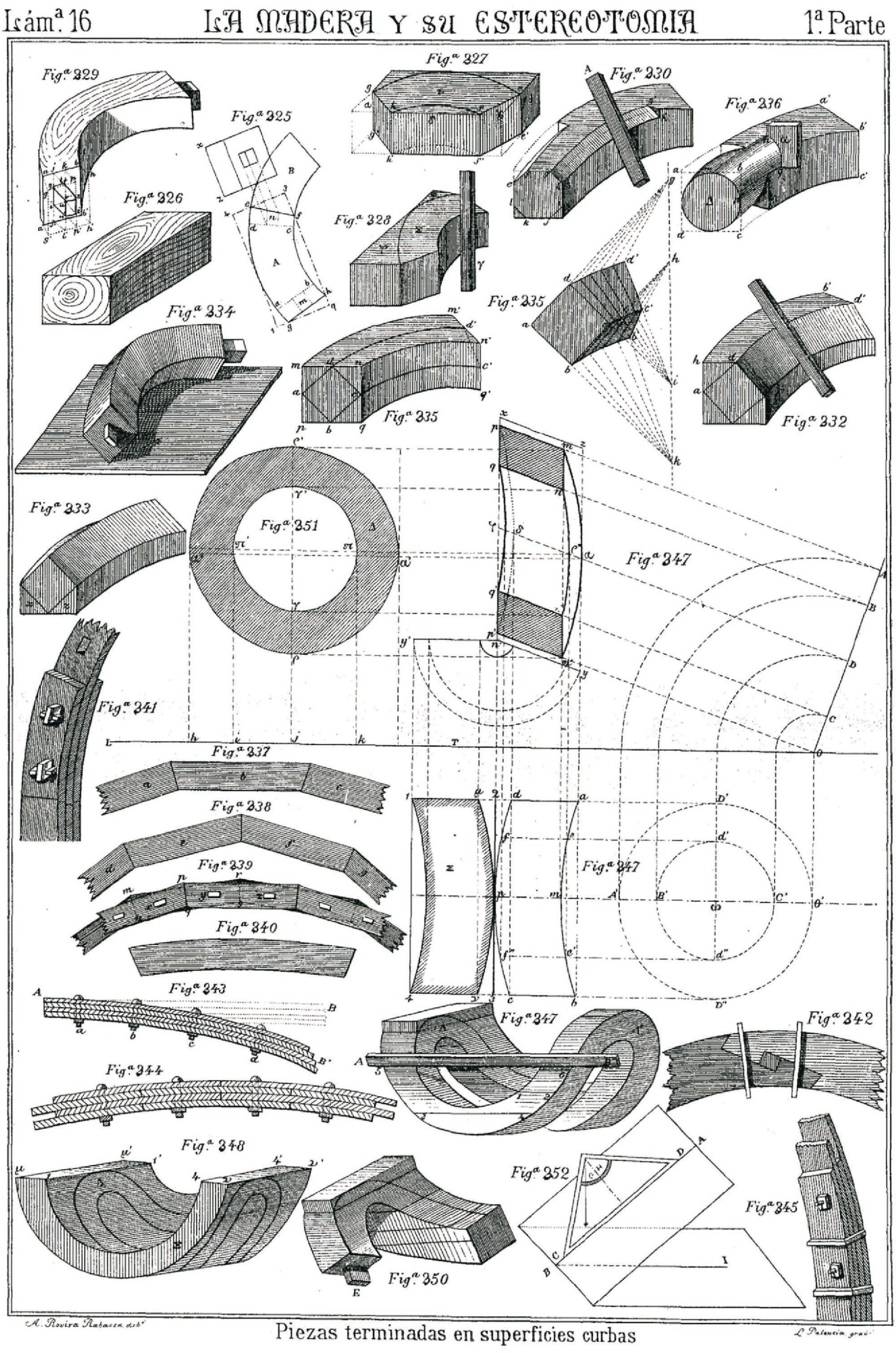


Fig. 1. Wood **s**tereotomy of the *guitarde* balcony from Louis Mazerolle's 1866 treatise *Traité Théorique et Pratique de Charpente*; source: Moore P. (2021), *Stereotomy and the Guitarde*, "Timber Framing," No. 139, 4-12.



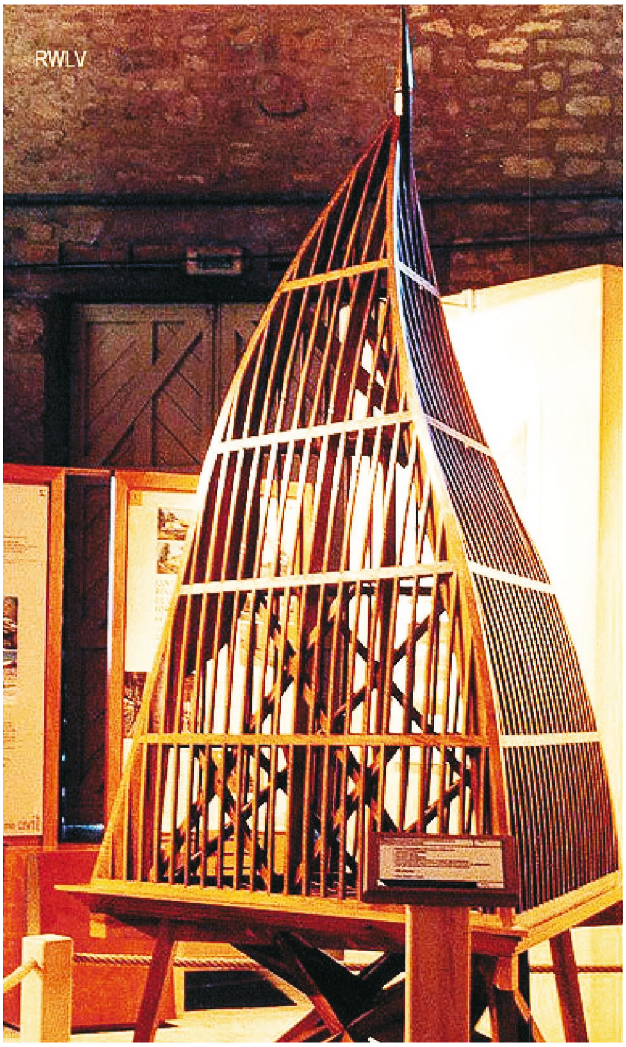
Lám.ª 16 LA MADERA Y SU ESTEREOTOMIA 1.ª Parte

Piezas terminadas en superficies curbas

Fig. 2. Wood stereotomy in Antoni Rovira and Rabassa's 1990 treatise *La madera y su estereotomia*;
source: Tellia F. (2018), *Stereotomy and architectural design at Foster + Partners*, "Nexus Network Journal," vol. 20, no. 3, 605-626.

Fig. 3. *Guitarde* dormers in France; source: Historical Carpentry (2017)

Fig. 4. a, b, c, d. Contemporary wooden architectural models crafted using wooden stereotomy; source: Exposition de chefs-d'oeuvre de Compagnons (2002).



3.2. Digital Tectonic

Digital tectonic design is a fresh approach to architectural design methodology that emerged with the development of CAD tools. Tectonic design is focused on materiality and assemblies of structural elements. Emerging digital technologies challenge architects to explore innovative methods and procedures for practicing architecture to promote building design using structural elements specifically tailored to material properties. Advanced computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies have a significant impact on design and manufacturing in architecture [Leach N., Turnbull D., Williams C., 2004].

As Branko Kolarevic states: 'In contemporary architectural design, digital media is increasingly being used not as a representational tool for visualization but as a generative tool for the derivation of form and its transformation ñ the digital morphogenesis. In a radical departure from centuries old traditions and norms of architectural design, digitally-generated forms are not designed or drawn as the conventional understanding of these terms would have it, but they are calculated by the chosen generative computational method. Instead of modelling an external form, designers articulate an internal generative logic, which then produces, in an automatic fashion, a range of possibilities from which the designer could choose an appropriate formal proposition for further development.' [Kolarevic B., 2003].

Although mathematicians studied non-Euclidean geometries since the 17th century, their use in architecture using new construction technologies based on reinforced concrete, cast iron and steel, did not develop on a larger scale until the 1950s-1970s. The recognized types of non-Euclidean geometries are: hyperbolic geometry (also referred to as saddle geometry or Bolyai-Lobaczewski geometry), elliptical geometry, spherical geometry and Riemann geometry, which is a generalization of the above. These are the geometries of space with negative and positive Gaussian curvature, respectively. Euclidean geometry is the geometry of 'flat' spaces with zero curvature, also called parabolic geometry. Creative research for original and economical types of structures and their practical applications were ahead of aesthetic theories that would link the design process and execution with a new paradigm in science and economics as well as progress in the field of understanding geometry. It was only in the 1990s that spatial structures deviating from orthogonal geometry began to be perceived as one of the symptoms of the transition from the mechanistic era to the holistic era based on the science of complexity, the development of information technology and the strategy of sustainable development. The problem of creating architecture based on non-Euclidean geometries was, however, more complex, while the texts of theoreticians usually reduced it to organic form and spatial relations.

Aa a consequence, a new design practice has developed. The use of digital technologies makes it possible to dynamically combine design intent and intent for contextual information. This allows architects to create projects with a high degree of complexity that directly involve individual contexts related to the designed building, such as the structure or the envelope. The design process is organized in an information system, i.e. it has a multi-level structure that allows the user to process input information into output information using procedures and models. Designing free architectural forms involves the need to solve many geometrical, structural and material problems. This requires developing stages of optimization to achieve a viable and affordable solution. In the conceptual design phase, maximum results can be achieved with the use of digital graphics and Virtual Reality [Śliwecki B., 2021].

The rapid development of advanced digital design aids has facilitated the design of highly complex custom forms. Digital designs of any form are characterized by high formal and procedural complexity, which – to a large extent – owe their existence to the introduction of advanced digital design and manufacturing technologies. The shift from mechanical to digital forces architects to reposition themselves: architects generate digital information, which can be used not only in designing and fabricating building components but also in embedding behaviours into buildings. This implies that, similar to the way that industrial design and fabrication with its concepts of standardization and serial production influenced modernist architecture, digital design and fabrication influences contemporary architecture. While standardization focused on the processes of rationalization of form, mass customization – as a new paradigm that replaces mass-production – addresses non-standard, complex, and flexible designs.

Since the beginning of the 21st century computer-aided design (CAD) and computer-aided manufacturing (CAM) have been developing as separate fields following the advancement of computer technology. CAD drawing software such as Autocad, 3Dmax, FormZ, Maya, and so on, as well as CAM technology, such as computer numerical control (CNC), rapid prototyping (RP), laser cutter, 3D scanner, were mainly used in other fields than architecture during the early days. These included industrial design, shipbuilding, aerospace and movie industries. However, 1992 marked the start of a revolutionary trend in computer-aided technology as CAD/CAM started making waves in the architecture and construction fields as well. At the time, Frank Gehry applied CAD/CAM digital techniques in the design and construction process of his Barcelona Fish sculpture, in effect digitizing the whole design process. With the aid of CAD/CAM, there has been greater freedom and liberty in the design form as the design process has been progressively digitized. In recent years, increasing numbers of researchers and architects have started probing the ways CAD/CAM technologies are supplementing the design process, culminating in the study of digital fabrication. Currently, a lot of attention is being focused on CAD/CAM fabrication within the field of architecture. This is because computer technology has not only influenced and changed the design process, but has also impacted the approach to and process of building construction [Lim C. K., 2010].

The scope of the architect's work has once again expanded and reached the digital chain of production systems. The manner in which executive drawings for CNC machines will be prepared is interdependent on the use of the NURBS surface geometry and the numerical polygon mesh. Huge potential lies in the area of developing structurally and materially effective and flexible methods of cooperation between an architectural office and a smart factory. This situation strongly signals how intensively industrial production drives innovation in the architectural design of wooden structures.

The architectural industry is ready for this kind of challenge. Systemic design in architecture understood as 'the process of creating forms that manifest a changeable physical arrangement, organization and form in response to functional conditions' has been present in architectural discourse and practice since the 1960s. Pioneers in this area were Christopher Alexander, Buckminster Fuller, Yona Friedman and in Poland – Adam M. Szymski and Stefan Wrona. The works of the above-mentioned authors contributed to the expansion of knowledge and skills in using a computer in architectural design. The process is conducted in the cause-and-effect aspect with the use of computer technologies supporting design, which ensures the development of innovative solutions with a high degree of efficiency.

The combination of digital technology and wood is revolutionizing the way buildings are designed and built. The convergence of mass timber with a design approach called design for manufacture and assembly (DFMA) enables architects, engineers and contractors to create buildings that are more affordable, of higher quality and better for the environment. DFMA is used as a basis for concurrent engineering studies to provide guidance to the design team in simplifying the product structure, to reduce manufacturing and assembly costs, and to quantify improvements. The practice of applying DFMA is to identify, quantify and eliminate waste or inefficiency in architectural and structural design, benefiting from the combination of two methodologies: Design for Manufacture, which means the design for ease of manufacture of the parts that will form a product, and Design for Assembly, which means the design of the product for ease of assembly deriving creative ideas at the same time.

Wood has been used in architecture for millennia, but the material has never been as modern as it is today. According to Hani Buri and Yves Weinand, different technological eras have always influenced the tectonics of wood structures since the artisanal 'wooden age' to our current 'digital age'. Wood is easily machinable; therefore it provides an ideal material for digitally controlled CNC processing. Wood-built architecture provides a wide field for experimentation in digital design and manufacturing techniques. Structural wood, which has excellent engineering properties, is also a renewable, environmentally friendly, healthy and locally available raw material. The production of wood consumes much less energy and generates less pollution than the production of other building materials. In addition, compared to many types of solid wood and wood-based materials, it is much easier to process.

The architectural free-forms are defined by the envelope of the parametric surface generated in the NURBS modelling software (e.g. Rhinoceross) in the computer's memory. Parameterization of the geometry of such a form is possible thanks to visual programming tools (Grasshopper) and supporting script programming languages (Python, Visual Basic, C#). Object-oriented programming (OOP) defines a programme using objects that define state (data, attributes) and behaviour (procedures, methods). An object-oriented computer programme is a collection of such objects that communicate with each other to perform tasks. This approach is different from traditional procedural programming, where data and procedures are not directly related to each other. OOP allows to write and reuse programmes or script fragments. Moving away from text-based programming in favour of a graphically has refined and intuitive interface increased the functionality of the platform and expanded the group of potential users. It has enabled the transfer of programming technologies to the area of architecture design. Architects have been successfully using the latest programming solutions since the beginning of 21st century.

4. CASE STUDIES

The creation of complex forms in contemporary architecture and the development of digital design tools combined with computer technology and CNC woodworking have given designers new opportunities to shape architectural forms. Curvilinear architecture rejects Cartesian geometry and the conventional language of Euclidean shapes. There are several manufacturing strategies used for 2D manufacturing. These often include contouring, triangulation (or polygon tessellation), use of lines, expandable surfaces and unfolding. They all rely on the extraction of two-dimensional, planar components from the geometrically complex surfaces or solids that make up the form of the building. The challenge in two-dimensional interpretation is choosing the right geometric approximation that preserves the basic characteristics of the initial three-dimensional free-form model. The choice of the manufacturing strategy depends on the tectonic definition of structure, envelope, combination of the two, etc.

4.1. Chesa Futura

The perfect example of digital tectonic in architectural design is Chesa Futura ('house of the future' in Romansh language) in St. Moritz, Switzerland. The building was designed by Foster + Partners and completed in 2004. The project combines computer-based design and manufacturing tools with centuries-old building technology to create an environmentally friendly residential building. Its glulam structure is covered with hand-crafted wooden shingles. In Switzerland timber construction is particularly appropriate as it follows traditions developed and refined over the centuries. The building's larch shingles naturally react to the elements, turning silver grey over time, and should last a hundred years without maintenance. It is a structure of three residential floors and two levels of parking located below the ground level. Despite its small size, the site is located on the edge of a steep slope, which overlooks St. Moritz towards the lake. Reacting to this location and the weather conditions of the Engadine valley, the building's bubble-like form allows the south-facing balconies to open up to sunlight and views, while the north façade is more enclosed, with deep window openings in the Engadine tradition. In St. Moritz, where snow lies on the ground for many months, there is a tradition of raising buildings to avoid the danger of wood rotting due to prolonged exposure to moisture. This tradition is reinterpreted here by erecting the building on stilts and allowing the ground plane to flow uninterruptedly beneath it – a move that also allows temporary dwellers to enjoy views that would otherwise be denied [Fantoni M., 2003].

Chesa Futura in St Moritz faced extreme challenges due to a combination of unfavourable climatic conditions and a desire to use natural, traditional materials in new ways to create a futuristic form that would optimize the potential of the site with its limited and steep gradient. The building is a bean-shaped wooden form raised above the ground on steel supports. The curvilinear form resulted from a response to the potential of the place while adapting to its limitations. Initial design sketches were interpreted and formalized as a parametric model, which the team then referenced to track changes in both directions. The parametric version of the cross-section underwent several changes, which was also confirmed by parallel planning studies [Chaszar A., 2004].

Although covered with wood shingles, cut by hand and fixed in place, the glue laminated timber frame and wall panels were prefabricated in Germany using advanced CNC machines. The manufacturing process was based on the executive extracted from the 3D model, which included multiple offsets, cuts and diffs, so that accurate geometry could be obtained for each component. Even with the experience of the previous Foster + Partner projects, it became clear that in order to design Chesa Futura, it would be necessary to design a modelling process that was based on a full understanding of the underlying technologies. The free form was only controlled by a schematic plan and cross-section, which were rationalized as tangential arcs and then connected to act together as parametric templates. This provided a simple control mechanism to explore and resolve the complex interactions between internal spatial and external contextual relationships in a fine-tuning process that took many months. In order to create a free-form surface arc, transition points were locked into inclined planes to define paths along which the variation profile could be routed by the generative script. Any change in the two defining templates regenerated the entire form, but always as a smooth surface with continuous curvature and precise definition. Thanks to the use of parametric templates consisting of rational curves, the obtained form was interpreted by the solid modeller as a mathematical surface for which precise displacements could be easily obtained. This approach ensured the precision and robustness required to reliably drive CNC machines during the manufacturing process [Kolarevic B., 2003].

Norman Foster's Chesa Futura can be regarded as a certain manifesto of architecture made of wood not only in the Engadine but also in other parts of the world. Contrary to the pattern of growth that distorts the edges of so many growing communities, it shows

Fig. 5. a, b, c, d, e. Foster + Partners – Chesa Futura Parametric model of Weltstadthaus, Cologne; source: Fantoni M. (2003).

how new buildings can be inserted into the existing grain of increased density, while preserving local building techniques and protecting the environment [Tellia, F., 2018].

4.2. Weltstadthaus

The Weltstadthaus is a department store designed by the Renzo Piano Building Workshop and located in the centre of Cologne on Schildergasse, the city's most important shopping street. The building was completed in 2005. With a length of 130 m, a width of 60 m and an area of approx. 23,000 m^2, the building bridges the gap between Cologne's modern and historic architecture. The oval, glazed façade faces the late-Gothic Antonian church, while the main part of the building refers to the cubic volumes of the surrounding buildings from the 1970s. The streamlined, reflective façade of the Weltstadthaus building, interacting with its surroundings, is an attractive complement to the city space. The free-from surface was determined in the process of optimizing the load distribution and material properties of the wooden structure. The façade construction consists of 66 multi-layered wooden arches spaced approx. 2.5 m apart and connected with a steel ridge at a height of approx. 28 m. The number of layers of Siberian larch boards forming the rib sections of the structure has been selected in accordance with the prevailing stresses. In the highest part of the structure, where bending and compressive forces occur, 4 layers of boards were used, 3 layers on the third and second floors, and 2 layers on the first floor. Each curved larch plank forming a 6 cm thick arch profile was precisely matched with sliding cast iron connectors, allowing the elements to move and dynamically adapt to dynamic loads (e.g. wind pressure). The 4,900 m^2 double-curved façade is covered with 6,800 quadrangular flat glass panels. Each of them has an individualized shape developed on the basis of a parametric façade model. The complex geometry of the structure of the glass façade required absolute precision in the execution of individual elements. The horizontal and vertical segmentation of the panels was optimized so that the gaps between the edges of the flat panels could be covered by the frame [K. Januszkiewicz, Paszkowska N., 2015].

The Weltstadthaus building is an example of performative architecture that arises in response to environmental conditions and the characteristics of the material which it is made from. The 21st-century performative architecture is designed with the active participation of digital technologies. Form is no longer perceived as shape and material. Forming in digital 3D space starts with free-form surface modelling of the designed object. Attention is paid to considering the effects of many different IT processes shaping the form in terms of its behaviour and cooperation with the environment. Such qualitative assessments of design concepts can be carried out thanks to improvements in graphical output and visualization techniques. By overlapping (superpositions) of different analytical evaluations, design proposals can be compared to select relatively simple solutions that yield optimal results [K. Januszkiewicz, 2021].

The form of the Weltstadthaus department store was conceived in the mind of Renzo Piano and recorded in the architect's sketches. The computer, on the other hand, as an active, 'intellectual' design tool, remained the direct cause and condition of this design concept in practice. The concept project of Weltstadthaus was initially digitally modelled in response to the location conditions on Schildergasse and the requirements of the retail chain Peek & Cloppenburg (investor) to ensure accessibility. Parametric CAD models made by architect and geometry specialist Arnold Walz were used to optimize the structural solution and to solve the complex geometry of façade. Arnold Walz is the pioneer in development of parametric modelling for construction planning, and helped to improve workmanship and precision of some of the most advanced buildings of the past years such as the Mercedes Benz Museum in Stuttgart, Zentrum Paul Klee in Bern, the new Porsche Museum in Stuttgart, the Smithsonian Institution in Washington, the Lufthansa Headquarters Frankfurt and many others. In parametric design of the Weltstadthaus façade was defined by only two curves: the horizontal curve of the building outline defining its projection on the situation and the curve defining the ridge of the building. Having these two curves, it is easy to determine the surface and its divisions, which are defined by only a few algorithmic rules. The aim was to find an optimal and harmonious division of the double-curved façade, convenient for the structural system and the system of external glass panels. Writing a script that describes the relationship between curves and developing rules takes less time than drawing a 3D façade using a mouse and a computer. With a script, new 3D options for façade were generated by modifying curves or rules. It was enough to describe parametrically only one element of the adopted structural system, and the programme generated the geometry of all 6,800 glass panes, although none of them was repeatable. In addition to the description of the two curves (horizontal and vertical), Walz also needed to determine four characteristic points required to divide the form into segments. It was about determining the geometry of 46 load-be-

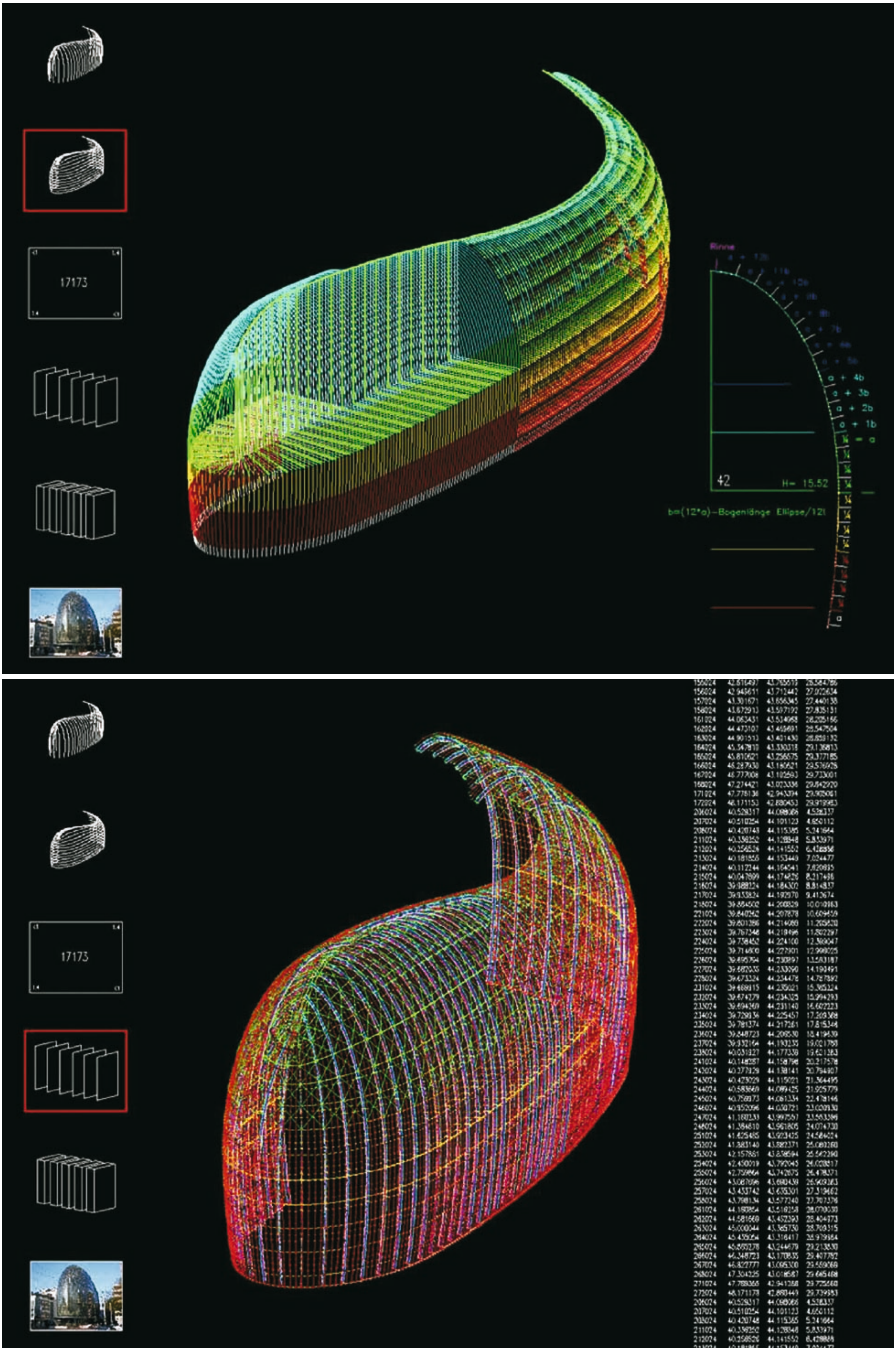


Fig. 6. a, b. Renzo Piano Building Workshop – parametric model of the Weltstadthaus, Cologne; source: Januszkiewicz K**.** (2012).

Fig. 7. a, b, c, d. Renzo Piano Building Workshop – the Weltstadthaus, Cologne; source: Januszkiewicz K**.** (2012).

aring ribs and the geometry of the division into segments of the glass cover (which is visible on parametric models) and their spatial correlation. The segments of the glass casing were optimized so that the distances between the panels could be absorbed by the metal frames of the flat glass panes. Three-dimensional CAD models prepared by Walz were used in manufacturing performed by CNC robots.

The Weltstadthaus structural solution is an excellent example of experimenting with well-known materials in anticipation of new materials for the architectural skin. The development of digital tools today is moving towards the integration of various options, so that a single comprehensive programme is created that allows the designer to study the behaviour of the building in various aspects. These include structural analysis, material behaviour, thermodynamics, lighting and acoustics. Such an integrated suite of digital tools would provide needed feedback in evaluating the behaviour of the structure in interaction with the simulated environment. It would also be a generative driver in the design process. The computational models here would describe the behaviour, not the shape. This would enable the designer to imagine structural and material systems as a synergistic result of IT mediation [Kolarevic B., Malkawi A. M., 2008].

DISCUSSION

Wood, one of the oldest building materials used by man, has been present in construction since the beginning of the history of architecture. The growing global demand for sustainable construction has renewed interest in timber construction. Wood is an easy-to-work material, and wooden building components exhibit a high strength-to-weight ratio, making them rational and efficient in prefabricated building structures and envelopes. The wooden construction elements are lightweight yet strong and durable, making them highly efficient. The flexibility of the material allows even double-curved surfaces to be cold bent to a certain extent. Thin layers of wood can be joined to form curved glued beams, made to measure with high precision.

As a construction material, wood is characterized by many advantages: low density, a high degree of strength and stiffness, low thermal and electrical conductivity, and chemical durability. However, it is an anisotropic material that contains structural elements of varying stiffness and strength. When moisture levels increase, it is characterized by the variability of its mechanical properties and creep resulting from rheological properties. Therefore, it is important to understand how the mechanical properties of wood vary depending on its heterogeneity, the orientation of the sample in relation to the directions of anisotropy and its natural disadvantages.

Digital technology embodied in Computer Controlled Manufacturing (CNC) redefines and adds a new dimension to timber construction. By combining computer-aided design (CAD), computer-aided engineering (CAE) and computer-aided manufacturing (CAM), even complex curved shapes including all connection details can be manufactured at high speed with impeccable precision. Meanwhile, technological advances in high-strength joints, digital manufacturing, and the introduction of glued laminated timber, CLT (cross-laminated timber), LVL (veneer lumber), PSL (parallel lumber), LSL (laminated strand lumber), OSL (laminated oriented strands) and roof and floor trusses, provide the means to use wood in a way that was previously unheard of. With a widening range of wood-based materials architects are embracing the ‘beginning of the timber era’. Wooden structures are a mirror of processing technology over the centuries. Hardly any other method of construction illustrates more comprehensively the relationship between architectural design, processing technology and manufacturing methods. Good physico-mechanical properties, ease of shaping and a trouble-free manufacturing process, combined with the unique ecological potential of wood, make wooden structures attractive again for architects and engineers. The natural properties of wood fibres combined with smart engineering provide a variety of perfectly adapted engineered wood products (EWPs). Scientists and architects around the world are re-thinking this material, improving its properties and expanding its range of application, in the hope to develop an environmentally friendly substitute to the performant, but energy intensive, engineered materials.

Digital CAD and CAM technologies have radically changed not only the conceptual approach in architecture but also in structural and material design. Curvilinear architectural forms created with the use of digital design tools based on NURBS (Non-Uniform Rational B-Spline) curves and surfaces pose new challenges for designers and the construction industry today. Digital tectonics is an evolving methodology that integrates the use of design software with traditional construction methods. A variety of computer-linked fabrication techniques have become an integral part of the design process, while new digital tools allow engineers and architects to understand in much greater detail the behaviour of digital surfaces that bear loads and shape new architectural forms. Digital tectonic design is seen as a systematic use of geometric and spatial rules, in conjunction with details and components directly related to contemporary construction. It is an approach focused on the role and use of materials and technologies in architectural design in the 21st century [G. Baliński, K. Januszkiewicz, 2016].

Wood has been used in architecture for thousands of years. Standard ways of using wood include both well-established traditional technologies (log and frame construction) as well as engineered ones (glulam, mass timber). Wood industry is still constantly evolving and innovating, finding new ways to use this material to provide flexible, beautiful, sustainable solutions for the construction and design industry. Paradoxically, it is perceived nowadays as a modern, high-performance material. Wood is increasingly used in free-form architectural designs due to research of high-strength composite materials and new ways of designing timber structures using computer numerical control (CNC) manufacturing tools. It has many advantages over other technologically advanced building materials. It is a common, easily available raw material and, unlike many other building materials, completely renewable, which is of additional importance for the protection of the natural environment. New tools and strategies for parametric design and digital fabrication methods are changing the way we use wood in architectural design.

After decades of relative crisis, wooden architecture is experiencing its renaissance. The lack of appropriate materials for the implementation of free forms meant that the materials known for a long time began to be used in a new way. Conventional materials today require a technological re-examination in terms of finding the form and efficiency of load transfer. It is about the differentiation of the material structure in response to the complex geometry of the free-form architecture. The long and rich tradition of wooden construction is being rediscovered, which, in addition to functional and structural values, is an important element of the cultural landscape. The interest in this material is rooted in the growing ecological awareness of investors, as well as its versatility. This trend also contributes to the rapid development of wooden structures, modern technologies and creative architectural solutions. Timber used in innovative construction and connection techniques can be found in impressive buildings designed by architects such as Renzo Piano, Norman Foster, Frank Gehry, Jürgen Meyer and Shigeru Ban.

The digital era brought unprecedented opportunities and led to the transformation of traditional tectonics into digital tectonics operating in terms of construction logic shaped according to the principles of digital design and fabrication tools. The combination of digital design and fabrication processes in the formula of digital tectonics does not change the character and nature of wood as a material. To a much greater extent, these systems use the integral and inherent features of wood and its material properties (physical, chemical, aesthetic). Material orientation is a prerequisite for the use of wood in the implementation of free forms in architecture.

The traditional tectonics of wooden architecture does not have the conceptual apparatus necessary to understand and describe the architecture created thanks to digital design and fabrication processes. In the case of traditional technologies, the material was perceived not only in technical terms, but also in cultural and sensory ones. In digital tectonics, the material is now in the centre of attention. The implementation of free forms based on the NURBS geometry in accordance with its assumptions requires a completely different way of treating wood as a building material and a closer connection of the material aspect with the geometry of the architectural form and production technology. In the practice of designing objects with non-standard geometry from wood, the huge potential of wood for implementation in digital tectonics is determined by:

- favourable material properties (physical, mechanical, chemical, aesthetic);
- ease of processing and high prefabrication potential;
- flexibility of use at any scale;
- ecological potential (low ecological footprint);
- globally rooted in architectural tradition.

The reductionist approach to the material has been forced by the development of centralized wood processing on an industrial scale, in which the variability of wood characteristics is deliberately averaged to achieve high consistency of wood-based product properties. Obviously, this has pragmatic advantages, but an approach based on standardization rather than specific and often hidden properties leads to a reduction in the value and architectural potential of wood. In the 21st century there appear a growing number of voices that paradigms based on centralized mass production and rationalized engineering standards are outdated, whereas new technologies and techniques allow for the use of non-standard varieties of wood forms and properties.

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