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ARTICLE (PEER REVIEWED)

Applications of Timber and Wood-based Materials in Architectural Design using Multi-objective Optimisation Tools

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Abstract

Digital fabrication leads architects and structural engineers to modify the design optimisation methodology. The designers, as never before, are facing new technologies developed in the search for new materials based, among others, on wood components and the improvement of manufacturing methods at the same time. In this process, the material and manufacturing technology adjustment to desired aesthetic outcomes is possible not only by the material used but also by the self-organisation of the structure's optimisation. New fabrication techniques linked with topology optimising software change traditional load-bearing systems designing using timber and wood-based materials. Multi-objective optimisation research indicates that timber might be a comprehensive material based on various applications from low-tech to cutting-edge contemporary fabrication technologies. The article presents new tools and methods for the optimisation of structural elements. A case study based on interdisciplinary architectural and structural optimisation suggests the possible effective research-based design. Comparing contemporary buildings with wood load-bearing structures explains timber usage's diversity and characteristics in modern design.

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Keywords

Architectural Design Optimization; Digital Fabrication; Folding; Generative Design; Timber Manufacturing; Wood-based Materials

Introduction

Digital fabrication is prompting architects and structural engineers to modify their design optimisation methodologies. Designers, as never before, are faced with the development of new technologies in the search for new materials based on timber components and the improvement of manufacturing methods while adapting the material and manufacturing technology to the desired aesthetic effects. At the same time, it is possible by adjusting the material characteristics accordingly, but also by self-organising design optimisation. New manufacturing techniques combined with optimisation software change the traditional way of designing load-bearing structures made of timber and wood-based materials. Research on multivariant optimisation indicates that timber can be a versatile material with a wide range of applications from low-tech to advanced systems using additive fabrication from the wood-based composite filament. Influence of environmental requirements (design according to international organisations' strictures related to Sustainable Development), technological development of wood-based construction materials (micro-laminated and CLT), and development of modern tools (generative software, structural analysis, computer-controlled fabrication) resulted in a return of interest in timber and wood-based materials and their reuse as effective solutions (e.g., in high-rise buildings, large-surface coverings or freeform complex geometries) (Lara-Bocanegra, et al., 2014). The paper presents new tools and optimisation methods using these materials as structural elements and structural optimisation of freeform canopy pavilions.

SUSTAINABLE DESIGN

Visible changes in the construction sector are dictated by regulations, including those of the European Union. E.U. Development Strategy "Europe 2020" and earlier conventions: in Arhus, Helsinki, and Convention on Biological Diversity indicate the need for building industry to adapt to Sustainable Development Goals. It is required to improve the efficiency of energy consumption and reduce the consumption of greenhouse gases. It is estimated that concrete production is responsible for 8% of global anthropogenic carbon dioxide emissions to the atmosphere(Pantazis and Gerber, 2019). About 30% of the Earth's surface is now forested, with almost half of all forests located in developed countries. During growth, trees convert carbon dioxide into oxygen through photosynthesis so that even with the highly energy-intensive wood processing, the final wood components are low-energy and have a positive carbon footprint(Joseph, 2008; Padilla-Rivera, Amor and Martin, 2018). The drive to minimise non-environmental materials, increase renewable materials, stabilise the building process, and tighten regulations to follow Sustainability guidelines significantly influences many kinds of research for materials and technologies to use wood as a construction material.

Literature Review

Digitisation of the design method has changed the boundary conditions shaping architectural and structural design. A common computer-based platform that combines digital tools for design, optimisation, pre-production, and fabrication enables models with a complete cross-section of information (Klinger, 2013). However, while allowing for the exchange of interdisciplinary information, the BIM platform's use still does not provide the ability to shape the aesthetic expression of free forms. Greater design freedom and design differentiation are achieved using an interdisciplinary architectural and structural environment, including FEM-based structural calculations, which allow continuous surfaces to be discretised into a finite number of interdependent nodes (Tamke, 2015). Current research on timber and wood-based materials is mainly based on two research assumptions, looking for the work's structural logic and tectonics. The second research assumption is to look for wood materials' characteristics and shape structural elements using them (Weinand, 2017).

RESEARCH-BASED REVIEW

Contemporary architectural design with the use of digital tools is increasingly associated with concepts such as "new structuralism" and "non-standard architecture" (Lei-Chuan and Shan-Yau, 2012; Monier, Bignon and Duchanois, 2013). The use of irregular structural forms has given cause for interdisciplinary explorations at the intersections of morphology in architecture, structural optimisation, material engineering, and fabrication technology (Nilsson, 2007). The use of wood and wood-based materials and composites, with their help, is a solution that is increasingly common in research projects. Striving for the benefit of materials under the way a structure works is not a new issue. Innovative research is mainly based on choosing the material properties and manufacturing to use the most effective. Examples of prefabricated timber elements in the construction sector include cross-laminated timber (CLT) as a monolithic material (the glue content is about 0.6% of the element's total weight).

Inspiration from active forms, such as cable, membrane, or arch constructions, is used to search for form-finding using timber as a flexible material and adapts to the structure's forces (Bletzinger, et al., 2010). Examples of studies that used optimisation based on bending-active segments include the 2010 and 2015/16 ICD/ITKE experimental pavilions (Sonntag, Bechert and Knippers, 2017; Nabaei,Baravel and Weinand, 2013). The optimisation of spatial structures using wooden material can be seen in the search for geometries in which it is possible to minimise the intricate structural details connecting the elements. An example of such examination is traditional construction patterns, e.g., wicker baskets (Figure.1). The old Japanese art of basket weaving - kagome, which consists of interweaving symmetrically arranged in a triangular or triangular-hexagonal grid, has become an inspiration for the search for architectural objects of both small scale and large scale objects such as, e.g., Centre Pompidou Metz in France (Ayres, Martin and Zwierzycki, 2018).

Research on the use of wood as a construction material and applying suitable manufacturing load-bearing elements was also conducted during the exhibition pavilion project in Landesagrtenshau, Germany (Schwinn, 2017), where a 50 mm thick structure was used. The supporting structure consisted of flat,

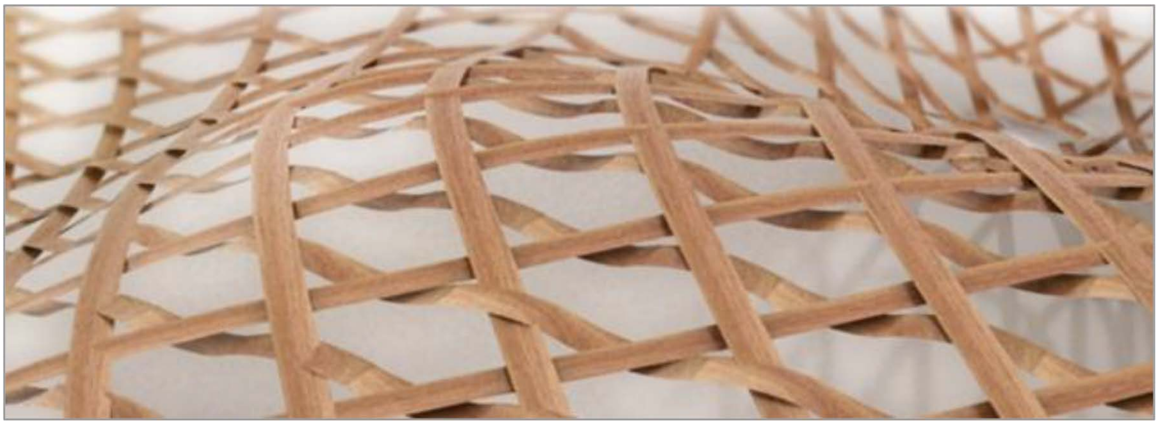

Figure 1. Kagome, a system of weaving elements without the need to use complicated connection details, a basic Kagome pattern consisting of three main directions of braided elements, courtesy: Marius Tsiliakos

mainly hexagonal panels (of irregular shape) optimised concerning shape and fabrication. The panels were connected by finger joints, cut out by a KUKA robot, and secured against shifting with nails in specially shaped sockets. The walls of the pavilion, as a year-round object, were designed as three-layer, consisting of a load-bearing part (plywood with a thickness of 50 mm), the insulation part (35 mm wood fibreboard), and the outer finishing layer (plywood with a thickness of 10 mm).

The use of modern fabrication technologies in wooden structures was also the inspiration for designing the BUGA summer pavilion. The research objective was to develop an architecturally aesthetic and structurally logical biomimetic timber shell. According to the principle, the structure based on three end supports, with a span of 30 m, assumed the minimisation of material: "Materials are expensive, and shape is cheap" (Pawlyn, 2016). Each wooden segment comprises two thin panels covered by a ring of edge beams at the top and bottom to minimise material and weight, creating large-scale hollow wood boxes with polygonal forms. A large opening in the bottom panel provides a distinctive architectural element and access to hidden connections during assembly. The lightweight building components are connected by finger joints that mimic the morphological principles of the anatomical features found on the sea urchin panels' edges. In its assembled state, the shell acts as a form-active structure through its expressive double-curved geometry.

DESIGN-BASED

In the service-cultural architecture of the 20th and 21st centuries, experimental buildings based on free-form algorithms characterise the spectacular realisations of leading architects. The search for patterns that minimise material use in Nature while achieving significant efficiency has become a marker of biomimicry and sustainable development guidelines. The search for unique forms is increasingly being combined in practical design with the search for optimal material. Respect for the environment, minimising carbon footprint, greenhouse gas emissions directed designers' attention to searching for construction materials in natural wood and conglomerates with wood and wood-based materials. A two-pronged search is evident: in the use of wood as a construction material in traditional construction, e.g., residential buildings (single-family houses built using wooden structures produce several times less carbon dioxide than reinforced concrete structures), and the use of wood in unique structures.

Freeform structures made of glulam like the Metropol Parasol in Seville are a free-standing structure with an area of 12,670 m2 and a height of 28.50 m and is an important tourist attraction the main viewpoints. Mayer Architects' structure incorporates commercial and recreational functions, housing market halls, cafés, restaurants, and an observation deck. The architects Shigeru Ban and Kengo Kuma gained their recognition thanks to, among others, the use of wood as the primary material in their objects. In their projects, they both look for unique forms based on the principles of geometric divisions of spatial grids, and their structures often gain lightness precisely thanks to the use of, among others, laminated wood structures. An example of Europe's largest free-form, timber-framed building is the headquarters of Swatch and Omega. The structure with a total area of 25,000 m2 is designed as a support-free hall with a quadrilateral glulam grid structure made of 7, 700 unique elements.

MULTI-OBJECTIVE OPTIMISATION TECHNIQUES

The formulation of tasks applies to the transfer of information, analysis, and conclusions on the achievements of architecture based on new solutions, both in terms of aesthetic and function, economic and practice aspects, as a result of the continuous development and innovative technological solutions, practical demonstration of their growing influence on the architectural and structural works. Knowledge and understanding of the issues traditionally associated with architectural and urban design, such as technical infrastructure, communication, natural environment, landscape architecture necessary for social, economic, ecological, biotechnological, historical, cultural, legal, and other conditions of engineering activity are fundamental skills. Due to the increasing requirements in environmental protection, the presentation of new technologies should be a comprehensive sustainable development circle, not only the design, maintenance, and monitoring of the condition of facilities. Multi-objective architectural optimisations consist of many architectural factors, such as social, economic, ecological, biotechnological, historical, cultural, legal, and other conditions, but cannot be limited to them. New possibilities in designing technologies require material engineering, digital fabrication, topological optimisation, often beyond architects' knowledge and interests. During recent technological development, the designing process undergoes re-formulation (Oxman, 2017). Architectural Design Optimization utilises parametric script language (Jabi, et al., 2017), topological and generative methods (Aish and Woodbury, 2005), and changing designing conditions.

Review and Comparative Analysis of Selected Contemporary Fabrication Techniques

Figure 2. Timber based structural designing, a) Lookout Tower Helsinki Finland, Avanto Architects, 2001, courtesy: Avanto Architects, photo: Jussi Tiainen, b) Sunny Hills Minato Japan, Kengo Kuma & Associates, 2013, courtesy: Kengo Kuma and Associates, c) Pudelma Pavilion Turku, Finland, Rosenfield K., 2011, courtesy: Taavi Henttonen, d) Botanical Pavilion, Melbourne, Australia, Tom Ross, 2020, Courtesy: Tom Ross

Modern digital fabrication allows structural components to be made with unprecedented precision. An advantage of these technologies is that the representation of structural elements becomes redundant in technical drawing documentation. A CAD/CAM collaboration allows both smaller-scale working models and finished products to be produced using file-to-factory technology. Essential details of connections in wooden structures, using precision CNC milling machines, allow minimising additional joining elements, using the structure's work and the links, such as the finger joint.

Table 1. Examples of selected contemporary fabrication techniques

Rok	Author	Location	Material, technology, and algorithm
2020	Kengo Kuma Geoff Nees	Botanical Pavilion, Melbourne, Australia	Timber elements overlapped like a jigsaw puzzle without the need for meta-log brackets. An algorithm was developed to combine small pieces into a structural whole. (Figure 2d).
2019	Voll Arkitekter	Mjøstårnet Brumuddal Norway	Cross laminated timber (CLT) The 85.4 m high timber tower's main body comprises large-scale glulam trusses along the facades, internal columns, and beams. The trusses provide the required stiffness and also transfer global vertical and horizontal forces.
2019	ICD Research Building /Prototypes	Urbach Tower Urbach Germany	Bentwood components. Industrial standards for technical drying were developed. This project uses natural deformation caused by moisture and the drying process. In contrast to the bending process (which is mechanical and has been known for centuries), this method programs the wooden elements to transform themselves into predetermined shapes.
2019	Hanaa Dahy, Piotr Baszyński, Jan Petrš University of Stuttgart	Experimental Biocomposite Pavilion Stuttgart Germany	Double-curved, parametrically designed segmental shell. Three curved, crossed wood beams support Single-curvature wood and biocomposite elements. Natural fibre-reinforced polymers (NRFP) were used for research and education.
2018	Efilena Baseta Klaus Bollinger University of Applied Arts Vienna	Self-formation of mesh coatings, Vienna, Austria	The two-wire bar structure uses active bending work. The elements were created by an industrial computerised numerical control (CNC) milling process of wooden strips.
2017	ICD/ITKE University of Stuttgart	Sewn Timber Shell Research Pavilion Stuttgart	NCN milling is a manufacturing technique for thin plywood sheets. A custom digital modelling design tool was used to derive a three-layer system that integrates material properties, manufacturing considerations, and assembly sequence.
2016	SHoP Architects	3D Printed Bamboo Pavilion for Design Miami, USA	The pavilion was printed from biodegradable bamboo felt. Almost 5500 kg of PLA reinforced with bamboo was used. Picture: University's website, 2016, Description of the Sewn timber Shell viewed 20 March 2021,

Table 1. continued

Rok	Author	Location	Material, technology, and algorithm
2015	Timber Construction Laboratory IBOIS, EPFL	Interlocking Folded Plate Lausanne Switzerland	Origami was the inspiration for the panel pavilion design based on folding, built from laminated wood panels. The assembly of the double-bent folding panels required multiple edges of each element to be joined simultaneously, which impacted the rigidity of the geometry and the whole object and the panel joints.
2013	Kengo Kuma & Associates	Sunny Hills Minato Japan	Wooden elements 60 x 60 mm It was constructed using the "Jigoku-Gumi" joining system, a traditional method used in Japanese wooden architecture. (Figure 2b)
2012	Politecnico di Torino University of Torino	Fractal Forest Monalisa Pavilion MadeExpo2012 Milan, Italy	The fractal algorithm represents a growing poplar tree from the seed to the tree. Computational and parametric techniques were used to realise the concept in design form.
2011	Columbia University, University of Oulu Aalto University	Pudelma Pavilion Turku, Finland	Woven wood construction Kerto-wood glued in layers. (Figure 2c)
2011	ICD Research Building/ Prototype	Research Pavilion Stuttgart Germany	Robotically manufactured timber structures. Flexibly bendable, tongue-and-groove jointed wood panels. Using a seven-axis robot helped create efficient mono-material joints for structural components connecting wood panels at different angles.
2001	Avanto Architects	Lookout Tower Helsinki Finland	Lattice construction of 72 glulam slats, bent and twisted in place from seven pre-formed types. (Figure 2a)

The Characteristics of Manufacturing Fabrication Methods of Timber and Wood-based Materials

CNC TECHNOLOGIES

Subtractive fabrication allows the use of technologically and economically affordable materials based mainly on flat or single curved structural elements (Sonntag, Bechert and Knippers, 2017). Splitting a continuous structure requires connecting elements that can change the way forces propagate in the structure. However, this allows for economical solutions, smaller working areas, and significant waste elements when shaping free-form structures.

3D printing in the 20th century has become one of the tools to produce structural components; however, most 3D printing materials so far have been based on environmentally unfriendly petroleum-based products such as thermosets, thermoplastic polymers, and their composites. The apparent trend of searching for sand, clay, or soil has started using environmentally friendly biomaterials. While optimising the material used, additive technologies remain the most efficient, using up to 100% of the material. Widely used in the construction industry, NFPC (natural fibre plastic composites) are easily moldable materials, which is why they have become the basis for research on 3D printing using fibres from wood processing waste. Depending on the given elements' purpose, various admixtures are used to stiffen the finished product, and the primary bonding material is bioplastic Polylactide (PLA)(Tan, et al., 2017).

TECHNICAL ASPECTS AND MATERIALS SPECIFICATION OF WOOD-BASED MATERIALS

As a natural material and the construction material, wood neutralises a significant amount of carbon dioxide from the atmosphere during growth. Wood in its natural anisotropic state is characterised by compressive and tensile strength, depending on its position relative to the grain. At the microscale, in the form of fibres, its material properties remain unchanged. The use of threads in combination with plastic allows the precise design of the composite's characteristics and parameters, which can be seen in the broad application of both the felt for printing and elements prepared in the form of glued boards (plywood, CLT).

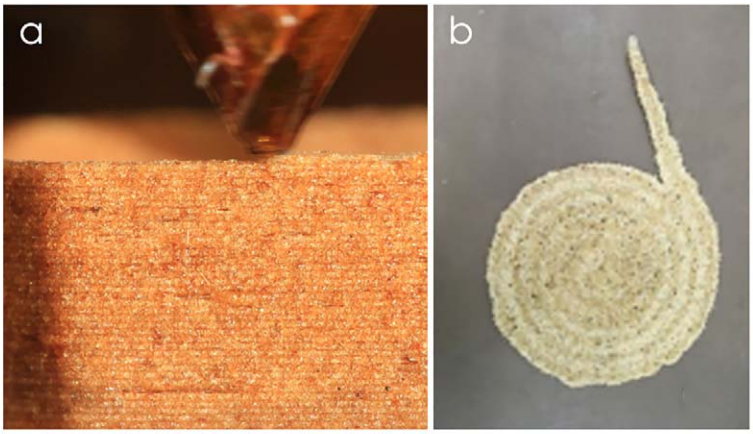

Figure 3. Timber fibres composites, a) Wood-based fibres typically combine a PLA base material with wood dust, cork, and other pulverised wood derivatives (Tao et al., 2017), courtesy: Jeremie Francois, b) the ILF process, 3D printing with wood fibre composites, courtesy: Klaudius Henke.

Research Methodology

The technologies and materials presented in the previous chapters are currently used to design small-scale objects, such as canopies, small pavilions, or small architectural and seasonal buildings. The use of contemporary rapid prototyping techniques combines with the inspiration of structures taken from the natural world. However, natural patterns are not often directly implementable in structures. Recent interdisciplinary research creates new research tasks: searching for implementation methods of bionic structures, lightweight and durable systems (Aziz and El Sherif, 2016; Mizobuti and Vieira Junior, 2020). Engaging in using timber as a construction material are structures with plate arrangements, found, among others, in folding. Following Meyer, et al., "*the fold is becoming a conceptual tool to address the realm of contexts and perspectives in architecture*" (Meyer, Duchanois and Bignon, 2015, p.447). Based on the literature of the

Table 2. Examples of wood and wood-based materials used in subtractive and additive technologies

Material	Technology
Subtractive Technologies	
CNC	Subtractive CNC technologies involve removing, cutting/milling unwanted material to obtain the required form. Subtractive technologies are relatively inexpensive and make it possible to produce significant unit-sized elements, generating quite a large percentage of waste.
LVL- Laminated veneer lumber	It has applications in load bearing structures and uses multiple layers of thin wood bonded together with adhesives. It is typically used for face members, beams, rim plates, and edge moulding materials. LVL offers several advantages over typical milled lumber: Made in the factory under controlled conditions, it is more robust, straighter, and more uniform. Its composite Nature is much less likely to warp, twist, bow, or shrink than regular lumber. LVL is a type of composite structural lumber comparable to glulam but with higher allowable stresses.
CLT- cross-laminated timber (Falk, Von Buelow and Kirkegaard, 2012)	It consists of wooden boards glued lengthwise and crosswise (wood 99%, glue 1%) with a maximum of 3, 25 x 16 m. Adhesives used for gluing the panels do not contain formaldehyde and are entirely ecological. Cross gluing gives mechanical strength. Structural elements are monolithic, which means that they can withstand high loads in different directions. Components glued in this way do not crack or shorten. CLT panels can be used for both exterior and interior walls, as well as ceilings and roofs (Buck, et al., 2016).
Additive technologies	
CNC	In additive technologies, CNC involves adding material in layers to achieve the required shape. Additive technologies are relatively expensive and mostly rely on polymers. Current research into adapting CNC machines to print structural components and materials such as concrete, steel, and biodegradable wood fibre composites suggests that this technology will compete with subtractive technologies.
ILF- Individual Layer fabrication (Henke, et al., 2021)	In the ILF process, three-dimensional parts are printed and then laminated, unlike LOM (laminated object manufacturing), where pieces are created by printing in layers rather than cutting out parts and then laminating them (Henke, et al., 2021) (Figure 3b).
PLA (Polylactic Acid filament)	Wood-based fibres typically combine a PLA base material with wood dust, cork, and other pulverised wood derivatives (Tao, et al., 2017) (Figure 3a).
high-performance cellulosic fibres	Cellulose is an organic compound that is a major structural component of green plants. Chitin, a long-chain polymer, is the primary component of the exoskeletons of shrimp and fungal cells. As extremely abundant and renewable materials, both substances are attractive alternatives to synthetic polymers, especially those made with fossil fuels such as ABS. Their natural composition also makes chitin and cellulose a viable option for biomedical research.

Table 2. continued

Material	Technology
Additive technologies	
FLAM-Fungal-line adhesive material (Sanandiya, et al., 2018)	FLAM is a fully biodegradable and, therefore, eco-friendly material. It consists of a combination of cellulose and chitin, the two most common natural polymers. The cost of producing this material is meagre ($2/kg). As a material that can be used, 3D printing is characterised by high strength and stiffness. Currently, its technical parameters are comparable to high-end, rigid polyurethane foam, e.g., PCF-30 used to produce, among others, synthetic bones.
Continuous Timber Fibre Placement, Solid-wood Mono-filament (Dawod, et al., 2019)	The primary material in the production of this filament is annual willow shoots. Their main property is their considerable flexibility. After mechanical cutting of shoots into elements with a thickness of about 0.7 - 1.4 mm and a length of 1.2 - 1.4 m, they are subjected to gluing and spatial bonding to form a continuous fibre.

subject (Sonntag, Bechert and Knippers, 2017; Stefańska, 2020; Grey, Scarpa and Chenk, 2019), and in particular, geometries on the shape of origami (Curletto and Gambarotta, 2016; Cehula and Průša, 2020; Schenk and Guest, 2011), the analysis of the pavilion canopy open using folding techniques was adopted as the object of research in this paper. Following Liu and Paulino, bar structures were analysed to frame the triangular panels that form the canopy (Liu and Paulino, 2017). With a simplified function and form, the structural system was analysed for the structure's total weight.

The literature review indicates that wood materials in structures with complex forms are becoming more popular, thanks to the developing fabrication technologies and multi-objective optimisation tools and techniques. The presented research aims to search for pavilion roofing shape using structural elements made of glued laminated timber in topological transformations to optimise the used material at the preliminary design stage. Analysis of architectural objects and technological possibilities allowed observing how important topological shaping of load-bearing structures shapes contemporary forms. Multivariate optimisations serve to minimise the production time or the amount of used material and the applied technology. The primary optimisation parameters indicate the need to integrate interdisciplinary research teams, particularly the possibility to optimise the structure already in the preliminary design phase.

Topological optimisations were performed using glulam rods with a variable cross-section (VCC) as the structural material to minimise the material usage. The initial geometry of the structural mesh divisions was designed so that the mesh's subsequent transformations would allow the nodes' location to change only in the Z-axis. This allowed the effectiveness of the applied principal curves forming the free-form structure geometry to be tested. The structures were based on folded plates structures existing in architectural designing, such as Yokohama International Passenger Terminal, designed by Foreign Office Architects (FOA) in 1995 (Moussavi and Polo, 1995), Timber Construction Laboratory, and Vidy-Lausanne Timber Pavilion in Switzerland, design by Yves Weinand Architectures Sarl and Atelier Cube in 2017. Form-finding testing was carried out using the early designing stage tools (Grasshopper/Rhinoceros), while geometry dimensioning was carried out in the Robot Structural Analysis tool.

The study was based on the following designing assumptions – set as multi-objective optimisation factors, presented in the optimisation flowchart (Figure. 5):

- a pavilion shape canopies were based on rectangular geometry, each with the covering area of 400 m2;
- each structure had four supports at its corners; the systems were statically determined;
- Solid glue-laminated timber (G.L. 22C) bars were used as a homogeneous material;
- each structure was loaded with the same combination of loads (dead load, service load, snow, and wind load) according to E.C.;
- According to aesthetical results, the pavilion canopies' total height was restricted to 4.0 – 8.0 m, the entrance height in all variants was limited to 3.0 – 7.0 m (one meter less than the full height).

A base geometry consists of a triangular mesh; all the joints' X and Y coordinates remain the same (Figure 6). The variable coordinates on Z-axis depend on the total height of a pavilion canopy and principal arch curvature.

Two-stage analyses of various reticulated canopy pavilions were carried out:

-adopting freeform structures to various curvatures, based on catenary (Figure 4a), paraboloid (Figure 4b) and segment of a circle (Figure 4c) arches.

-adjusting folding plate heights to structural optimisation.

The analysed structures were designed as homogenous glue-laminated timber bars with the properties of G.L. 22C material. Due to polycarbonate as a covering material and variable geometry, acceptable global deformations were set as 8 cm, developed in detail in individual variants. In the conducted analyses, the adopted optimisation criteria were the minimum total weight [kg].

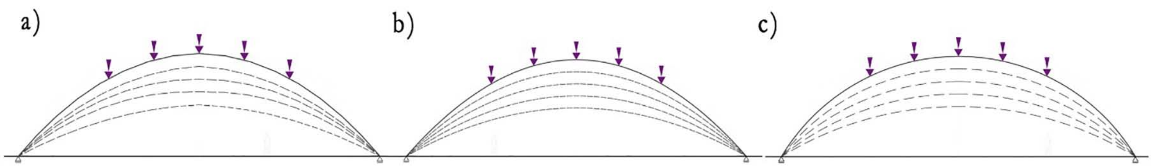

Figure 4. Different arch curvatures as the base geometries of the structures: a) catenary arch, b) paraboloid arch, c) segment of a circular arch

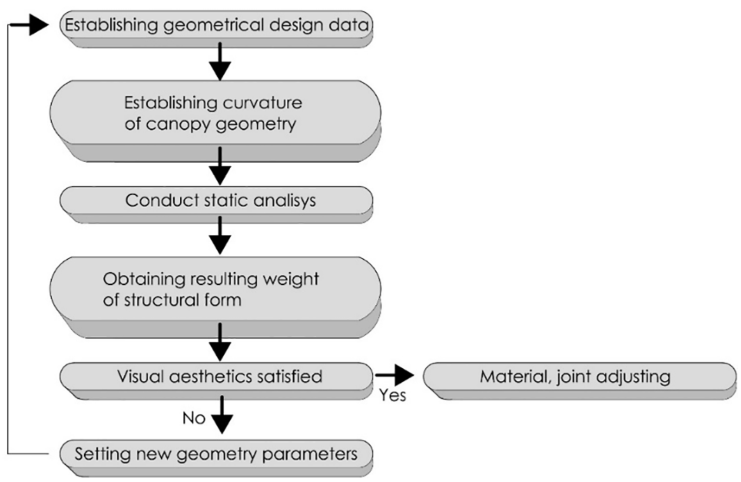

Figure 5. Form-finding analysis flowchart

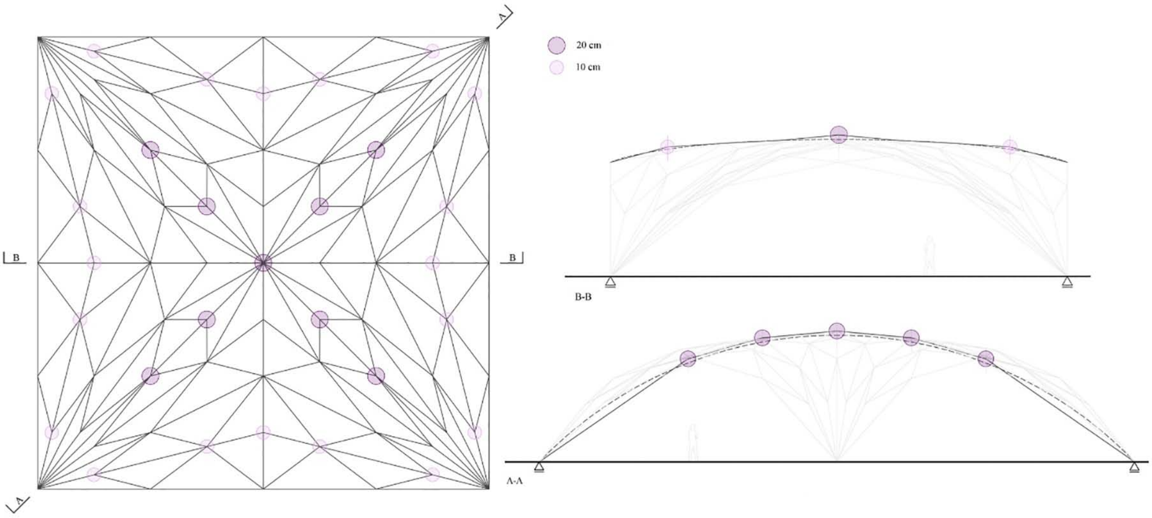

Figure 6. Folding adjustments analysis

Findings

The determining parameter in geometry optimisation was the minimisation of the total weight of the whole structure. In the case study, a population of geometries with a height between 4.0 and 8.0 m was calculated. Only resultant characteristic geometries with a height change of 1.0 m were presented in the tables (Table 1 and Table 2).

The results show a tendency in structure behaviour, two parameters in each resulting variant were calculated: changeable weight of the whole structure and a factor of weight divided by the canopy's total area. Factor k=1,0 presented the first analysed geometry (variant: catenary arch with a total height of 4.0 m). A factor k_i defines the proportion of the weight of particular geometries to the first variant, according to the formula:

$$k_i = \frac{k_n}{k_{ref}}$$

where:

k_i-weight factor of the tested variant (unitless)

k_{ref}-weight of variant: catenary arch with a total height of 4.0 m [kg]

k_n- weight of structures of the n-variant in kg

The second factor analysed in the study m_i represents the dependence of the structures' total weight with the variable area of the canopy of each variant studied (variable depending on the full height of the pavilion and the folding used). The smaller the factor is, the least material is needed to fabricate the canopy.

STUDY I-ADOPTING FREEFORM STRUCTURES TO VARIOUS CURVATURES, BASED ON CATENARY, PARABOLOID, AND THE SEGMENT OF A CIRCLE ARCHES

Comparing all the variants in study I (Table 1) indicates the tendency that the best structures were found among paraboloid-based arches in all the height types of the structures, with the best variant with the curvature height of the structures 8.0 m. Higher than 8.0 m structures were not analysed because of aesthetic and functional reasons.

Table 3. Results of various curvatures adopted to the initial grid (author's compilation)

FACTORS	The total height of the structure				
	4.0	5.0	6.0	7.0	8.0
Basic arch geometry: catenary					
Weight factor of the tested variants k_i (unitless)	1.0	0.94	0.74	0.70	0.87
Weight to the total area of the canopy in the variants m_i kg/m^2	11.35	10.21	7.83	7.13	8.03
Basic arch geometry: paraboloid					
Weight factor of the tested variants k_i (unitless)	0.75	0.73	0.76	0.79	0.62
Weight to the total area of the canopy in the variants m_i kg/m^2	8.51	8.04	8.14	8.15	6.11
Basic arch geometry: the segment of a circle					
Weight factor of the tested variants k_i (unitless)	0.94	0.83	0.98	1.12	1.12
Weight to the total area of the canopy in the variants m_i kg/m^2	10.71	9.05	10.26	11.01	10.44

STUDY II- ADJUSTING FOLDING PLATES HEIGHTS TO STRUCTURAL OPTIMISATION

Table 4. Results of various folding sizes adapted to the initial grid (author's compilation)

FACTORS	The total height of the structure				
	4.0	5.0	6.0	7.0	8.0
Basic arch geometry: catenary, main arches raised by 20cm					
Weight factor of the tested variants k_i (unitless)	0.97	0.84	0.78	0.75	0.78
Weight to the total area of the canopy in the variants m_i kg/m^2	10.97	9.09	8.19	7.68	7.55
Basic arch geometry: paraboloid, main arches raised by 20cm					
Weight factor of the tested variants k_i (unitless)	0.82	0.74	0.73	0.69	0.62
Weight to the total area of the canopy in the variants m_i kg/m^2	9.27	8.09	7.77	7.08	6.10
Basic arch geometry: the segment of a circle, main arches raised by 20cm					
Weight factor of the tested variants k_i (unitless)	0.95	0.96	1.03	1.05	1.19
Weight to the total area of the canopy in the variants m_i kg/m^2	10.76	10.43	10.66	10.31	11.02

Study II (Table 2) aimed to identify the beneficial aspects of folded plate systems in the freeform structures. Comparing all variants indicates that folding systems show no improvement in mass minimisation results in structures based on circle segments. In catenary arch-based structures both k_i and m_i

improvement to a certain extent is visible. Variants based on paraboloid arches remain the most effective, as in the previous study. However, improved performance is only seen in structures with higher overall heights.

Based on contemporary interdisciplinary design trends, the research conducted in this paper indicates the need for multivariate optimisation, especially free-form structures. In the initial design phase, introducing interdisciplinary dependencies allows recognising several dependencies assigned to a given structural system's boundary conditions. The research indicates that architectural-structural research's suggested direction should be continued, using algorithmic design with simultaneous structural analysis of objects searching for material-cost- and time-efficient architectural buildings. The research results on free-form structures shaped by different curves (catenary, paraboloid, and segment-of-a-circle arches) indicate significant efficiency of systems based on parabolic arches. The search for material minimalization visible in Nature becomes an essential structural and architectural optimisation aspect in the XXI century (Dixit, Stefańska and Musiuk, 2020). Structural transformations based on natural patterns such as folding systems (Patil and Vaijapurkar, 2007; Mousanezhad, Kamrava and Vaziri, 2017; Kresling, 2012) remain an amusing aspect of designing both in architectural aesthetic and structural logic. The case study results indicate that structural efficiency becomes more efficient while organising the structural curvature at first. The final efficiency remains optimal while the initial force flow is designed according to the architectural form-folding systems. The future perspective to more in-depth optimisation processes could be a task to better understand Nature pattern implementations into the structural and architectural designing process and fabrication techniques. The challenging requirements in such processes are still understanding rapid prototyping procedures and implementing still non-structural timber material variables into standard architectural designing.

Structural and architectural optimisations in terms of free form designing become the significant aspect of efficient designing. The paper research results indicate that small algorithmic changes in generative designing scripts might improve the structure's weight by up to 40%. A presented case study favours forms based on paraboloid arches as a non-obvious choice in architectural practice nowadays (Figure 7).

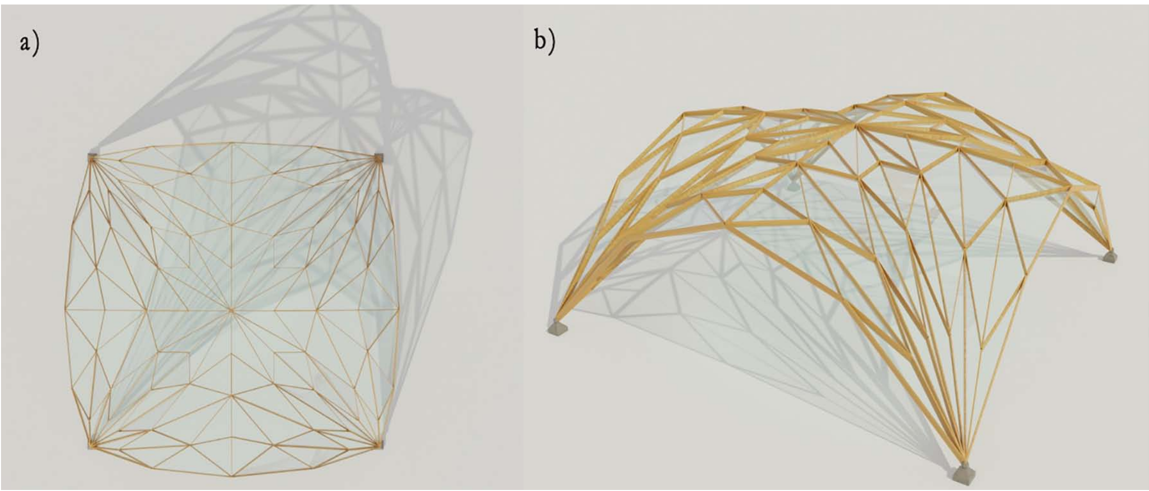

Figure 7. The most lightweight variant is the structure shape scheme after full-shape optimisation in the Robot Structural Analysis program, a) plan, b) 3D view.

Conclusion

The practical use of CNC tooling achieves unprecedented precision while saving time and material. In addition to the economic factor (Dixit, et al., 2019; Dixit and Sharma, 2020), the manufacturing process considers sustainable construction to reduce carbon footprint and ecological considerations and achieve the highest sustainable construction standard through precision manufacturing. Pro-environmental solutions based on Nature patterns are becoming an essential link for interdisciplinary collaboration, especially with renewable materials like wood and its composites. Currently, digital fabrication is a costly and labour-intensive phenomenon, requiring researchers experienced in working with specific prototyping methods. In contrast, emergent structures fabricated in an interdisciplinary environment can yield significant savings in the future, and ongoing research brings us closer to a deeper understanding of these complex processes.

The timber uses as a non-homogeneous material has allowed research into the complex fabrication of structural elements, materials design to meet production technology demands, and complex free-form architectural forms. The interdisciplinarity of the issues undertaken in the research work, supported by several multivariate optimisations, allows achieving architectural objects that imitate visual patterns borrowed from Nature and how they work under given loads, thus improving efficiency and reducing the cost of construction of unique individualised architectural forms.

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