ABSTRACT
This work-in-progress action research paper describes the development of a novel computa-
tion-driven design method for low-tech producible, structurally optimized, suspended
wooden roofs based on near-catenary-shaped glue-laminated beams. The paper positions
itself in a post-digital architectural context with as goal to introduce recent technolog-
ic advances into developing construction contexts characterized by limited production
means. The paper starts by evaluating the pre-existing practical, procedural, and economic
drivers behind the design and fabrication of curved glue-laminated beams—one of the
most ecologically sustainable structural elements commonly available. A method is
proposed that employs genetic algorithms to simplify the fabrication of a suspended roof
structure’s range of weight-saving, catenary-shaped beams. To minimize the number
of costly high-strength steel pressure vise setups required for their individual produc-
tion, idealized curve geometries are minimally tweaked until a single, reusable jig setup
becomes possible. When combined with a wooden roof underfloor, tectonic systems that
employ such beams have the potential to dramatically reduce structure material require-
ments while producing architecturally engaging and spatially complex nonstandard space.
The method’s validity, applicability, and architectural design opportunity space is tested,
evaluated, and discussed through a conceptual architectural design project proposal that
operates as demonstrator. The paper concludes by addressing future research direc-
tions and architectural advantages that the proposed design and fabrication methodology
brings, especially for developing construction contexts with limited access to digital fabri-
cation technology.
INTRODUCTION
With computational power continuously reducing in cost and its direct access becoming increasingly easy worldwide, architects’ modus operandi is profoundly changing. Yet, the challenge remains how to maximize this new resource’s potential in everyday construction, especially in contexts without access to high-tech manufacturing technologies like robotic or digital fabrication. This work-in-progress action research paper situates itself within the context of ‘Post-digital Architecture,’ defined as ‘architecture that addresses the humanization of digital technologies through interplay between digital and analogue cultural and material systems, between virtual and physical reality, between high-tech and high-touch experiences, between the local and the global’ (Crolla 2018).

The study’s objective is to expand the practically feasible design solution space for light-weight, structurally optimized, suspended wooden roof structures. This is done through direct numeric control over their specific geometry definitions, while remaining within a cost-effective operational model. Rather than viewing implementation processes as components of a construction process that is consecutive and supplementary to the initial architectural design process, this study hypothesizes that direct control over the wooden members' geometric definition—for a specifically optimized fabrication setup—can positively link the design and construction solution space for hyper-efficient wooden roof architecture, even in contexts of limited means. The aim is to increase the design agency of architects interested in producing spatially engaging, nonstandard, yet environmentally and economically sustainable work.

This paper challenges conventional procedures and the sequence of architectural design and construction and aims to functionally repurpose available digital means for contemporary architecture praxis. By including the expansion of encoded aspects from both the design and construction context into the architects’ scope (Mitchell 2004), the assumption is that he/she can directly positively affect the traditional workflow of a construction project and can capitalize on production efficiencies beyond the typical, geometrically constrained architectural solutions dictated by today’s mass-production construction economy.

BACKGROUND
Glue-laminated Beams
Glue-laminated (glulam) beams are structural engineered wood products composed by layering treated lumber and bonding it together with moisture-resistant adhesives. Large glulam members can be manufactured from smaller wood pieces, reducing reliability on old growth-dependent solid-sawn timber. Combined with the related cross-laminated timber (CLT), which has its layers glued together with the grain alternating at 90 degrees angles for each layer, the stronger glulam offers viable options for mass timber construction.

In addition to benefits in structural performance, fire resistance, sound absorption, dimensional stability, geometric versatility, and availability, glulam beams have clear environmental benefits compared to, for example, steel frames (Sandin et al. 2014). The manufacture of steel beams can take 2-3 times more energy and 6-12 times more fossil fuels than manufacturing glulam beams of equivalent structural performance (Petersen and Solberg 2002). As part of a globally increasing and urgent interest in ecologically responsible construction, the impact from studies in the practical architectural design opportunities for glulam can be substantial.

Glulam beams are frequently used in the building industry in the form of both straight and curved members. Large-scale curved glulam beams are typically not produced using computer-numerically-controlled fabrication equipment, but instead often rely on a rather labor-intensive process. A common manufacturing method employs large reusable jigs built up from a series of high-strength steel pressure vises that are arranged according to the desired curvature. Inside this jig, layers of treated, pre-fabricated wood strips are laminated, glued, and pressed together. Each jig setup can only produce one specific shape, reducing the practically feasible architectural design solution space and limiting the possible structural performance optimization through form.

Tried-and-tested methods for glulam production are slowly being exported from the developed world and integrated into developing construction economies, like Malaysia’s (How, Sik and Anwar 2016). For example, the Forest Research Institute of Malaysia (Institut Penyelidikan Perhutanan Malaysia - FRIM) produced their first curved hardwood glulam structure in August 2018. This structure is a simple, single-span wooden bridge made from two identical curved balau beams with a constant curvature radius of 25m and spanning 11m (Figure 2).

Structural Optimization of Curvature
The structural advantages of working with curved glulam beams as opposed to straight beams becomes evident when comparing the material weight requirements for two setups with identical load scenarios but differing beam geometries. The software Karamba3D© is a parametric...
A structural modeler that operates as an add-on to the procedural modeler Grasshopper©, a plugin to the NURBS modeling software Rhinoceros© (Preisinger 2016). We used Karamba3D to evaluate, optimize, and compare constant section profiles of identical load scenarios of 10kN/m applied on straight and curved beams that span 20m. Since the fabrication complexity doesn’t substantially increase if we abandon constant curvature—working with circle arc segments—catenary curves were introduced. A catenary curve is the curve that an idealized hanging chain or cable assumes under its own weight when supported only at its ends. Results reveal that an optimized catenary-shaped beam, operating under pure tension, can require up to 90% less material than its straight counterpart in a given load condition (Figure 3). Slight deviations from the perfect catenary geometry still result in substantial material savings.

Frei Otto’s Wilkhahn Manufacturing Pavilions

Applications of catenary-shaped structures can be found throughout recent architectural history, with notable examples including the David S. Ingalls Skating Rink (Eero Saarinen, New Haven, USA, 1958) or the Yoyogi National Stadium (Kenzo Tange, Tokyo, Japan, 1964), both using lightweight, suspended steel roof members. Wooden precedents are less common but can be found in Frei Otto’s Wilkhahn Manufacturing Pavilions (Bad Münster, Germany, 1988) (Figure 4). This project consists of four identical pavilions used as office space. Their roofs structurally combine a series of uniquely shaped catenary glulam beams with a doubly-curved wooden roof underfloor that is made from standardized tongue-and-groove shuttering, both suspended from glulam edge beams and a triangular central truss (Otto and Nerdinger 2005).

Objective

With the Wilkhahn Manufacturing Pavilions as a starting point, the objective of this design research project was to find a design and fabrication method that dramatically simplifies the construction of the uniquely shaped catenary glulam beams needed for this tectonic system. The goal is to provide architects operating in developing/low-tech construction contexts access to the structural, environmental, and spatial benefits of this hyper-light-weight wooden roof typology and to explore its design potential.

METHODS

Evolutionary Jig Optimization

All catenary lines are similar. Their equation in cartesian coordinates is \( y = a \cdot \cosh(x/a) = (a/2) \cdot (e^{x/a} + e^{-x/a}) \), which results in a line of constantly changing curvature. Changing the parameter ‘a’ is equivalent to uniformly scaling the curve. Hence, for a doubly-curved roof built up from a series of unique catenary lines, no single jig setup is possible that can produce all required curves precisely.

An evolutionary algorithm was developed to derive, from input geometry, a single jig setup that allows the closest manufacturing approximation of any given set of input curves. This algorithm uses the standard Galapagos©...
add-on to Rhino’s Grasshopper software, which allows for straightforward evolutionary optimal solution identification within a multi-dimensional field (Rutten 2013). Eight parameters (three angles and five distances) are used within a polar coordinate system to define the five control points of the NURBS curve that will define the eventual jig (Figure 5). Required input curves are procedurally positioned along this NURBS curve at the location that resulted in the lowest cumulative distance between an evenly set spread of input curve points and the NURBS curve, i.e. they are positioned at the NURBS curve segment that most closely resemble the input curve. The evolutionary solver then changes the eight input parameters with the aim to minimize the cumulative distance between all curves and their respective approximative NURBS curve segment. Once the optimal total NURBS curve is defined, only the segment that combines all required catenary approximations is kept to produce the jig.

Case Study: Re-design of the Wilkhahn Manufacturing Pavilions Roof Structure
As a case study, one quarter of one of the four identical and symmetrical roofs of the Wilkhahn Manufacturing pavilions was redesigned according to this method. One single jig setup was identified that allows for the production of all beams. The beams measure up to 12.55m in length. The maximum difference between the original optimal catenary curves and the final NURBS curves extracted from jig segments was 30.3mm; the average maximum difference per beam was 16.6mm (Figures 6 and 7). This difference is minimal and results in a relatively minor increase in required material to respond to the structural load requirements. Deviations are also small enough to not inhibit the production of a continuous wooden roof under-floor. A 1:10 scale model jig was used to manufacture the prototype beams of the structure (Figure 8).

RESULTS: DEMONSTRATOR
To identify the extent and opportunities of the method’s architectural design solution space, an architectural demonstrator project was developed. The selected conceptual design brief involved the architectural design of a Visitor and Education center for FRIM—located next to their Wood Lamination Laboratory—to be constructed from wood using only the locally available manufacturing technology.

The final design was built up from two interconnected roof structures covering an area of around 3,825 m². The large overhanging roof structures operate as shading devices for the smaller internal programmatic entities, which include exhibition areas, reception, lecture hall, a café, and an outdoor playground.
The roof is built up from 177 small-sectioned glulam beams, measuring up to 32m, suspended from heavier glulam perimeter-hinged arches that are supported by columns. For the manufacturing, the laboratory would only be required to set up five jig configurations for the suspended beams and three jigs for the perimeter structure.

The design demonstrator reveals how the highly structurally, ecologically and economically optimized tectonic production process still allows for widely varying and exciting spatial moments because of constantly changing double curvature of the roof geometry (Figures 1 and 9). Ample possible architectural opportunities remain that allow for the very flexible response to site, brief, program and context, even when only limited means of production are available.

**DISCUSSION**

The initial research findings discussed in this paper demonstrate the structural and architectural potential from the covered design and manufacturing methodology. A novel yet practical architectural design language can herewith be introduced to a local developing construction context while maintaining benefits of structural, ecological, and economical optimization.

Future collaborative research projects will be set up with partner institutes in developing construction contexts to allow for the more rigorous and complete investigation of the study’s elements. These will include the further refinement of the evolutionary solvers, the integration of the roof underfloor in the structural analysis, the systematic solving of architectural details related to the tectonic system, etc.

**CONCLUSION**

This paper illustrates, through an initial optimization study of hyper-light-weight suspended wooden roof structures, that the strategic application of computational design technology away from often inhibitive expensive digital fabrication technology and towards low-tech implementation contexts can enable a dramatic architectural expansion of the locally feasible construction solution space. By including encoded aspects of construction systems into the scope of the architect, architectural and spatial design freedom can be expanded while remaining economically, economically, and socially viable.

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**REFERENCES**


8 1:10 scale-model prototyping of GluLam beams from a single jig setup.

9 Physical 1:75 scale model of the demonstrator design project: Exterior and interior model perspectives.


IMAGE CREDITS

Figure 2: © Forest Research Institute of Malaysia (Institut Penyelidikan Perhutanan Malaysia - FRIM)
Figure 4: © Wilkhahn Image Data Base
All other drawings and images by the authors.

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