

Wooden membrane with integrated flexible photovoltaic foil

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Abstract

This paper presents a method to design lightweight architecture out of bent timber with integrated photovoltaic foil as a structural and waterproof building skin.

The first chapter explains the physical form-finding process of bent only configurations where material fatigue plays no relevant role in the long time load capacity of the architecture. The final configurations consist of pressure arches and tensile surfaces self-interlocking each other. The geometrical freedom of possible forms is primarily determined by the limits of bending plywood merged with photovoltaic foil into double curved forms.

The second chapter presents the benefits in the assembling process. Elastic bending behaviour of wood is used to build membrane-like structures without the necessity of any scaffold nor using heavy foundations. Parametric digital design – respectively the software rhino-grasshopper – supports the optimization of the forms providing digitally related construction files for an effective workflow simultaneously.

The last chapter analyses exemplarily one architecturally relevant configuration – a hybrid between a membrane and a shell – and presents the calculation of its electrical efficiency related to the form.

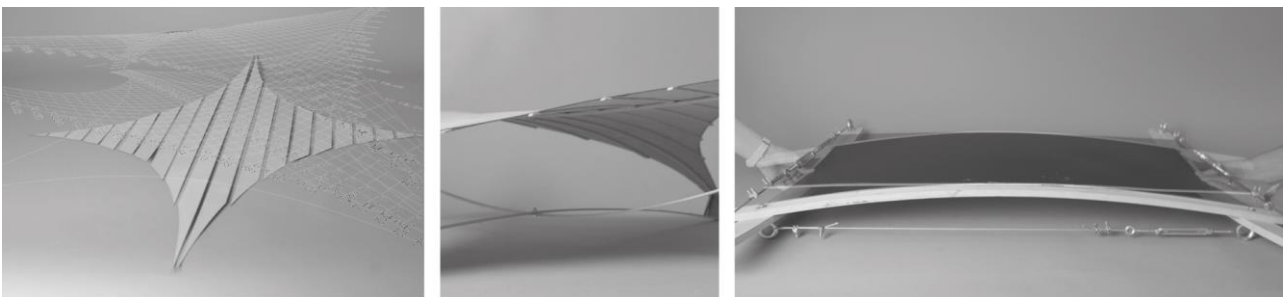


Figure 1: Collage: physical and parametric design to apply flexible PV-foil on structural wooden membranes

Keywords:

Integrated Photovoltaic, Sustainable Lightweight-Design, Assembling process, Active Bending Wood, Constructional Membranes, Wooden self-formed shell

1. Form-finding process

1.1 The form finding concept of bent wooden membranes

1.1.1 Initial situation and context

The basic idea to facilitate the building process of curved architecture by using the elastic bending behaviour of materials is an ancient concept and was recently rediscovered in contemporary architecture as summarized in the paper *Active Bending* from the year 2013 [1]. In 2015 Klasz has presented the built case study *A cloud for fresh snow* [2] explaining the concept to use membranes in a hybrid configuration with active bending wood. The benefit is that material fatigue of wood – the reducing bending force – plays no relevant role for the long time load capacity of the structures [3]. Based on this knowledge this paper presents the new concept to replace the textile membranes with wooden membranes including integrated photovoltaic foils. All components are planar wooden elements: The primary structure consists of longitudinal wooden boards. The secondary structure consists of thin planar plywood merged with photovoltaic foil.

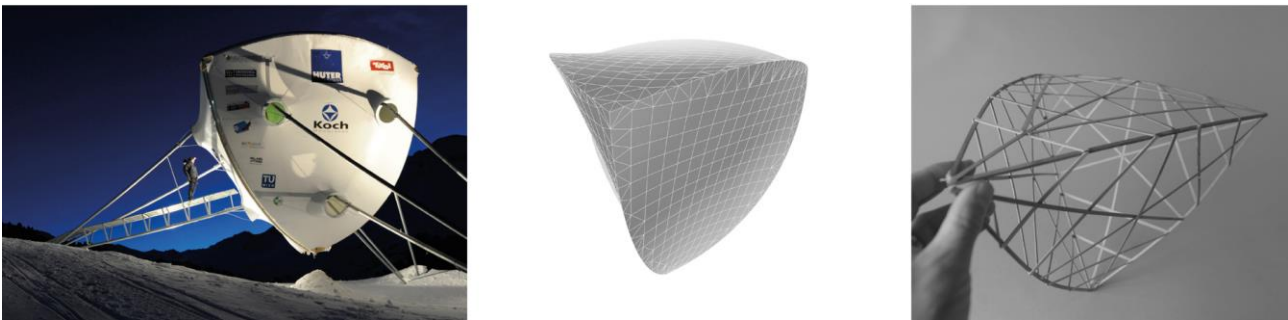


Figure 2: Collage Spherical tetrahedron: left: a cloud for fresh snow (wood + textile membrane); middle: geometry drawn with rhino-membrane; right: geometry built in a model out of straight wooden members

In contrast to grid shells like the *Multihalle Mannheim* by Frei Otto in 1975 or the *Polydôme* at the *Campus Lausanne* [4] by Julius Natterer (see Fig. 3) this paper presents statically self-interlocking configurations replacing heavy foundations and simplifying the assembling process. The main difference concerning the assembling is that the final form is realized from the beginning of the installation process by bent timber-boards in a self-organizing process. The second difference deals with the building skin: Instead of putting a waterproof layer on top after the construction is finished – like done in Mannheim and Lausanne – the new concept consist in using waterproof *PV-wood-panels* as a structural building skin. The basic typologies (see chapter 1.2.1 and 1.2.2.) present solutions, where the structural skin works in the final configuration statically as a membrane and not as a grid shell. Hybrid typologies (see chapter 1.2.3.) include both: membrane-like surfaces and grid-shells merging into each other smoothly.

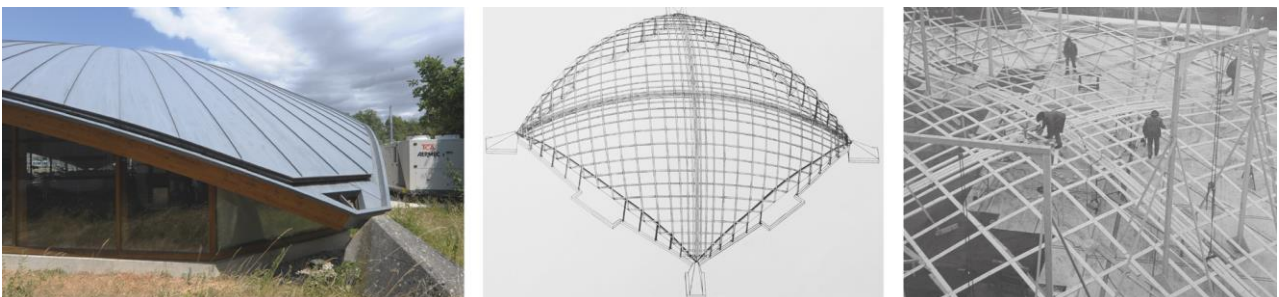


Figure 3: Polydôme at the Campus EPFL Lausanne by J. Natterer; left: Photo: W. Klasz 2015; middle: axonometry of the structure; right: photo of the assembling process of the straight wooden members up to 19m; images middle and right see *Schweizer Baublatt* 1992 [4].

1.1.2 Bent primary structure

Active Bending simplifies setting up the curved primary structures. In the final configuration, these elements are held in position by the membrane-like secondary structure and therefore these compressed bows (pressure arches) have geometrically no moment-forces – although the remaining elasticity supports in the redundant structure the stiffness according to different load cases. Relevant load cases to dimension these elements are those during the assembling process. The self-weight of the elements limits the upscaling of this concept (see perspectives). Selected boards of the secondary structure are installed to get the primary structure bent in its wanted position (see Fig. 4 – image in the middle). In other words, parts of the secondary structure bend the primary boards in their position, while finding their own position simultaneously.

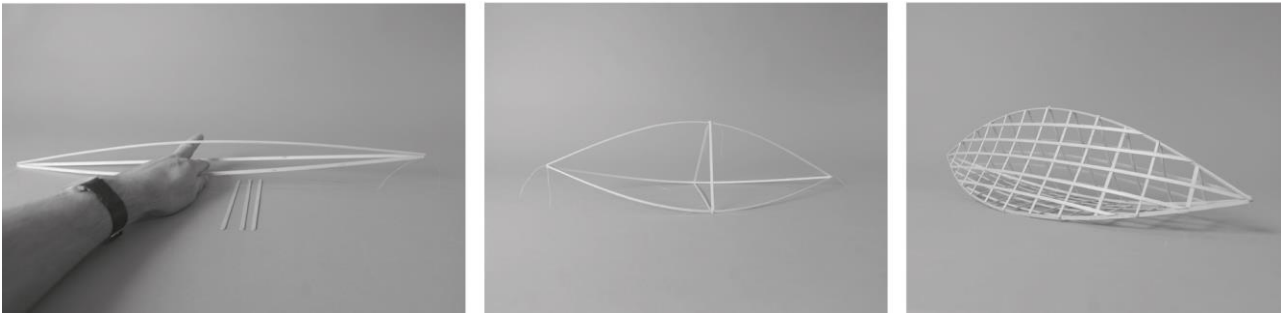


Figure 4: Collage onion-like structure: left: three primary wooden members joined at the ends to each other; middle: three members of the secondary structure bend the primary members; right: the longitudinal secondary members bend the vertical ones easily in the membrane-like configuration.

1.1.3 Bent secondary water-prove membrane-like structure

The secondary structure is continuously completed causing the more and more precise form-finding of the primary structure and the whole configuration. After having installed a tight grid of boards the thin plywood sheets with integrated photovoltaic-foil are fixed to the structure. One benefit is, that all sheets are cut out of plane plywood without any pre-curving in the third dimension. The other advantage is the easy installation of these parts to the grid and the individually possible maintenance. In the final configuration, they work statically as membranes with mainly tensile forces, whereas the outer primary bows have pressure forces only. The more the bending force of the wood releases (increasing material fatigue) the more precisely the materials find the wanted self-interlocking position. This process can be improved by pre-stressing the tensile surfaces, which can effectively be done by a prolongation of the outer primary beams (the detailing will be done in ongoing applied research on the planned full-scale case study – see perspectives.)

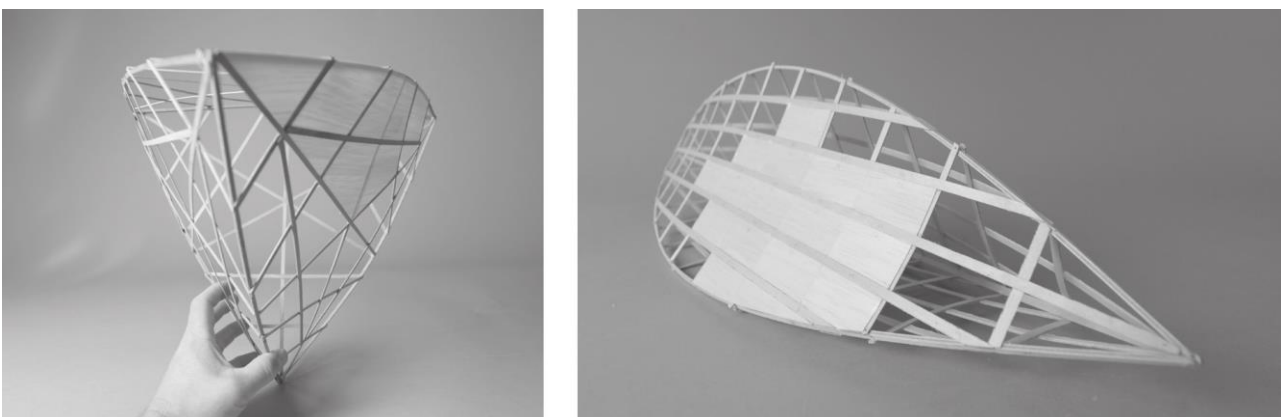


Figure 5: Statically self-interlocking models with partly fixed membrane-like elements out of thin plywood left: spherical tetrahedron; right: onion-like configuration.

1.1.4 Limits and freedom of bending the PV - wood panel

The Austrian company *Sunplugged* is developing in ongoing research machines to produce flexible photovoltaic foil of a width of 40cm and a length of maximum 200cm. The foils can be produced in any planar form and fixed so precisely to each other that it cannot be seen visually from a distance of more than one meter. As the investigation of the behaviour and function of the foil is more precise with one single piece of foil (less complexity – no connection points) the dimension for the test-panel is chosen with 40cm to 80cm – a possible grid for several full-scale projects.

The photovoltaic-foil – thermally covered with a waterproof translucent material – is glued to a 4mm sheet of birch-plywood. In order to simulate different curvatures the wooden grid of boards of a cross section of 60mm to 12mm is bent by steel cables fixed with screws at each corner of the test-panel (see Fig. 6).

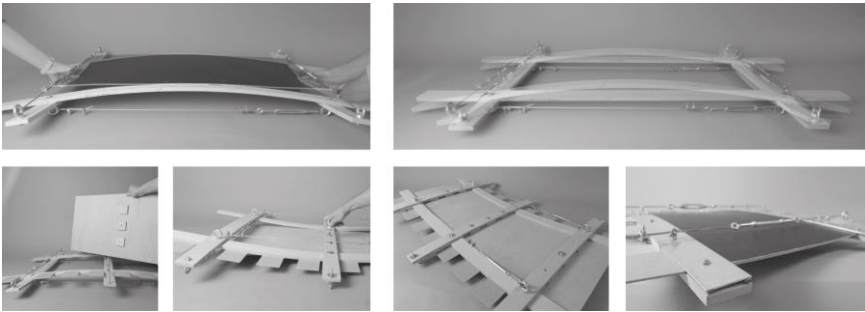


Figure 6: Prototype 01 of a bent PV-wood-panel with a low-tech water-prove assembling system

1.2 Self-interlocking configurations and potential applications

1.2.1 Spherical tetrahedron

The spherical tetrahedron (see Fig. 7) is a space-symmetrical form out of six pressure arches and four membranes statically self-interlocking each other. The commissioned research lab *A cloud for fresh snow* uses this basic form in a more complex configuration adding 3 high points at each façade-surface. For a habitable use of this structures the roof can be realized in a wooden PV-membrane with an offset wooden layer (as can be seen in a different configuration in Fig. 12) providing a stronger resistance against snow-loads. During the assembling, the first layer works statically like a membrane and with the wooden offset-layer the roof becomes a self-formed shell-structure. Turning the form upside down and scaled in the vertical dimension (see Fig. 7 - below), it can be developed for example as a *hard tent* – lifted off the ground.

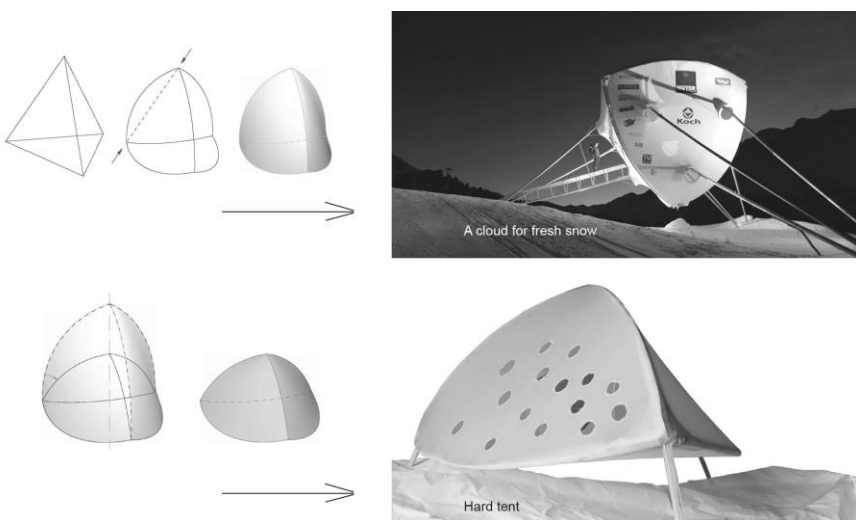


Figure 7: Spherical tetrahedron and applied variations

above: commissioned research lab "A cloud for fresh snow" 2015 [2 und 3].

below: project "Hard tent" 2015 by W. Klasz + M. Stefanova, V. Menegon, J. Marx, C. Harm

1.2.2 Onion-like structure

The onion-like structure is an axial symmetrical form consisting of three pressure arches and three membranes statically self-interlocking each other. The proportions and curvatures can be adapted to the different applications of longitudinal spatial solutions. Figure 8 shows exemplarily two applications in the field of product design: A self-formed sledge and a self-formed wooden kayak – both easily built up purely using the skin as a structure without any ribs.

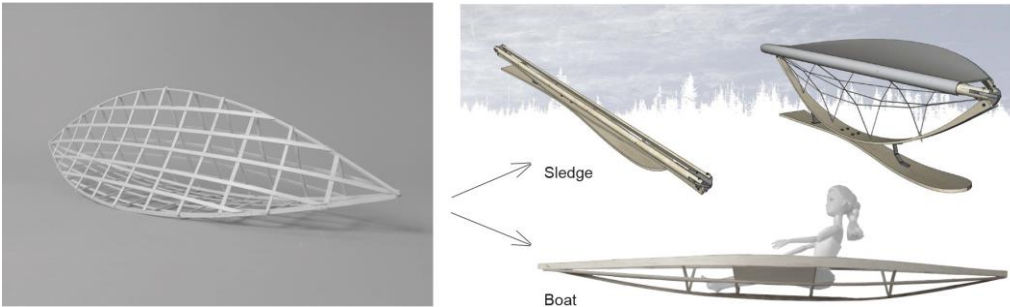


Figure 8: Onion-like structure and applied variations
right above: Compact sledge 2015 by W. Klasz + N. Meyer, T. Wopfner
right below: Concept model by W. Klasz for a bent only self-interlocking kayak

1.2.3 Redundant hybrid forms between a shell and a membrane

This third typology bases on the concept to merge bent pressure arches planar with membrane-like surfaces in a configuration of two self-interlocking four point sails. The bending only assembling method determines the primarily form-finding parameters and leads away from the four point sails. The resulting forms work in some areas statically like a shell and in others like a membrane – depending on the load cases. This has a relevance in terms of wanted redundant constructions providing the necessary security for users.

Figure 9 shows on the left hand side a parametrically designed basic form. On the right hand side, the more complex form of the self-formed PV-wood-lounge represents one possible application [5].

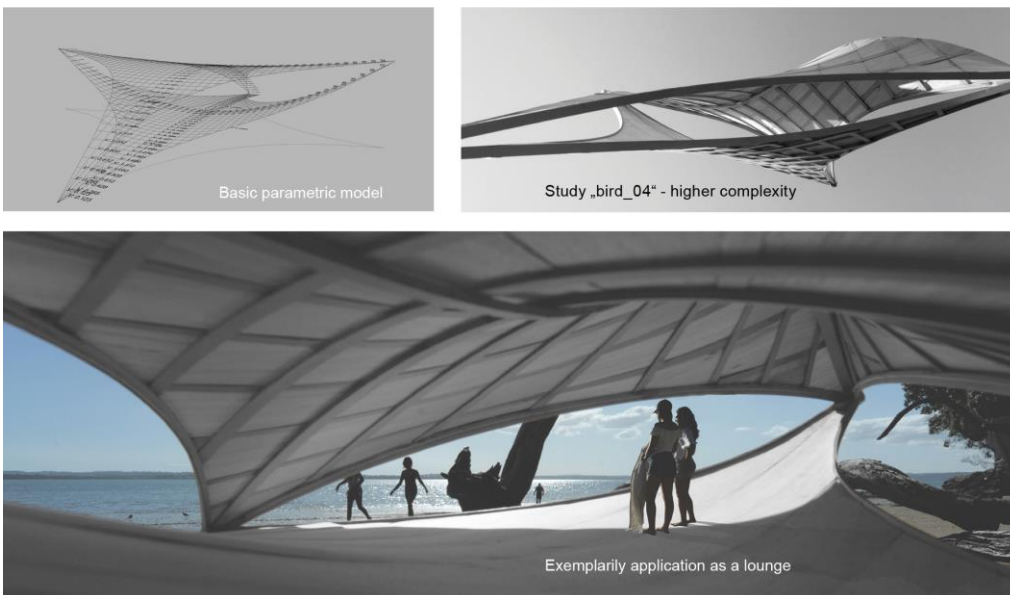


Figure 9: A self-formed lounge [5] – developed by W. Klasz as an exemplarily architectural application for the wood – PV panels in a self-forming and statically self-interlocking configuration (note: the basic parametric model was done after the experimental physical studies).

2. Simplified assembling process

2.1 Using elastic bending to largely self-form the wooden membrane-like structures

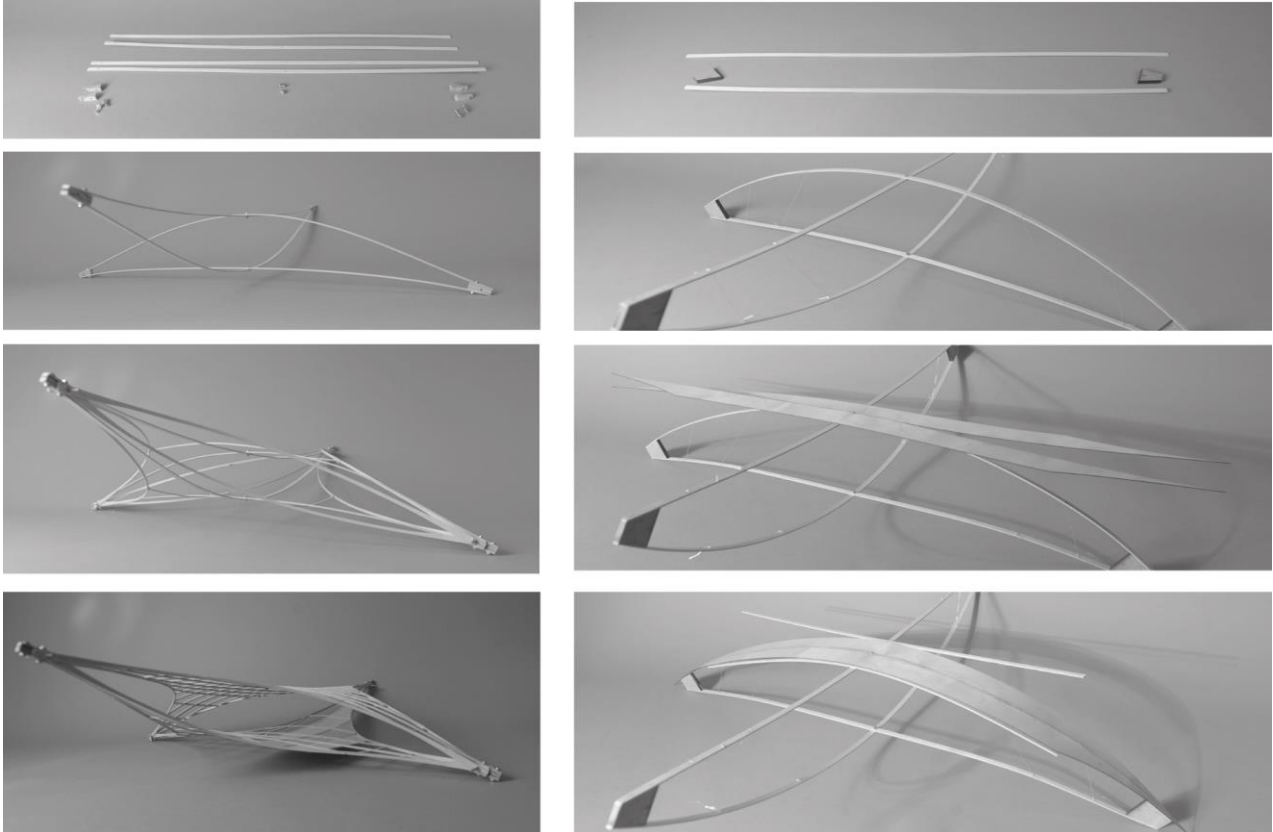


Figure 10: Collage of bent only structures comparing: left: Assembly with boundary bows; right Assembly by bending the PV-Wood panels without boundary bows (primarily bows only – based on the parametric model)

The concept to simplify the assembling of double curved wooden structures bases on the idea to install the architecture without a scaffold and without ribs by providing a self-formed primary framing, which merges with the finale structure visually and statically fully integrated. Instead of putting photovoltaic at the end onto the structure, the PV-wood-panels – respectively the longitudinal boards (see Fig. 10 right hand side) are used themselves to let the structure emerge in the wanted form.

2.2 Using parametric digital design to optimize efficiency

The artistically and statically optimized form-finding is done experimentally with the help of scaled physical models following the elastic bending behavior of wood (see Fig. 10 left side). Using the software rhinograsshopper this forms are defined and controlled digitally in a second step. Efficiency is optimized by the designer on three levels: statically, aesthetically and energetically.

A holistic approach for sustainable design bases on the concept that aesthetics plays an important role in the socio-cultural acceptance and as such in the lifecycle of a building [6]. The designer David Trubridge [7] stresses the fact that *beauty matters* (title of many of his public speeches). This expert on bending wood uses physical studies and digital design-tools always simultaneously in the field of furniture and lighting design. The beauty of the assembling process has a close relation to the aesthetics of the built structures. Aesthetics and self-formed assembling have a close relation. Parametric digital design enables the changing of proportions due to the specific user, the different bending behavior of local materials and due to different site-conditions.

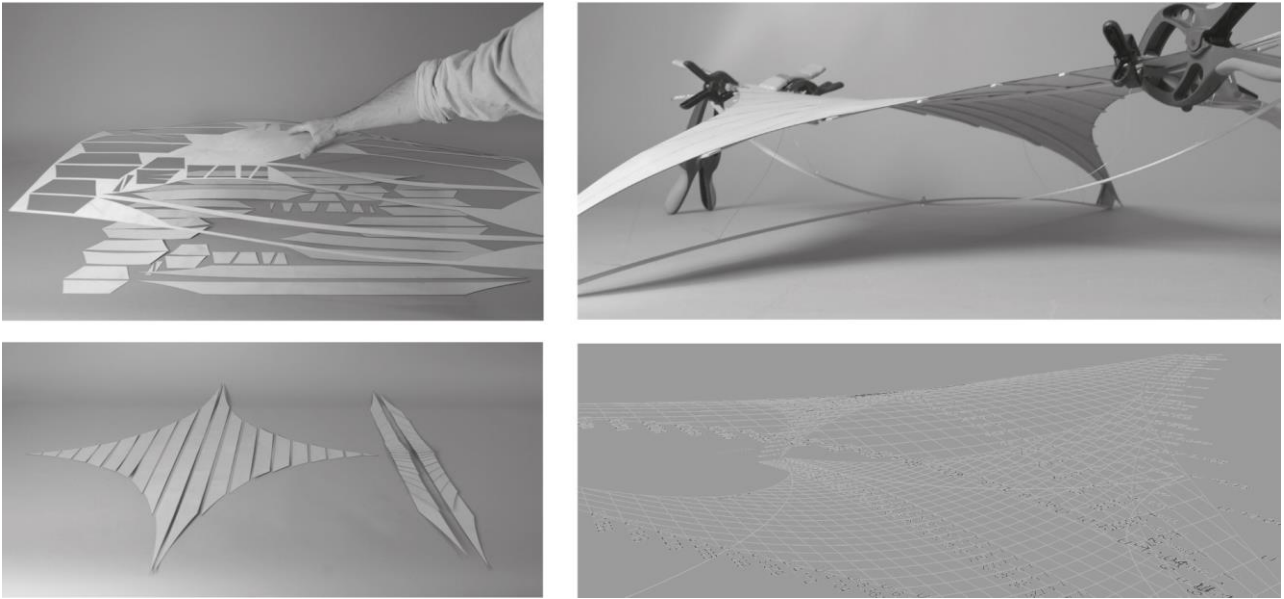


Figure 11: Laser-cut PV-wood-panels optimized in form and dimension by digital parametric design

Statically the optimization bases on the concept of a redundant structure. Some areas of the structure (Fig. 11, 12) work statically like a wooden membrane, others temporarily or locally like a grid-shell and in the final configuration as a composite-shell consisting of two wooden double bent surfaces – one inside and one outside merged with the flexible PV-foil providing the waterproof skin. Depending on the positioning of the foundation points and the load-cases the surface works statically as a membrane or a shell (a deeper research on this topic will be done in ongoing investigations – see perspectives).



Figure 12: Fixing the second wooden-surface onto the structure providing a self-formed composite shell

3. Electrical Energy Concept

3.1 Electrical self-supply and waterproof roofing versus optimized orientation

Based on the explained concept of fully integrated photovoltaic foil in the structural building skin, the focus of the electrical concept is to achieve a holistic solution achieving energy gaining surfaces during the whole day and during different seasons. The fact that in this case some areas are only during specific times electrically efficient, is compensated with the general benefit of providing a waterproof structural building skin.

This skin may be the structural roof as shown in the concept of a summer lounge (Fig. 13 left) or it may be a double curved structurally working parapet as shown in the concept of a winter-chalet (Fig.13 right). The basic digital parametrical model (Fig. 9 top left) can be used to develop customized applications in the interdisciplinary team, where the client and the site play an important role, too. The holistic solution is found in a self-forming design process [8].

3.2 Case Study: A self-formed lounge

The *self-formed lounge* presents exemplarily the application of structurally working PV-wood-panels. Architecture is about putting material into the best relation to each other providing attractive space for humans. The concept follows the idea of a natural leaf: A leaf combines structure, skin and photosynthesis in a functional and aesthetical appealing way and it grows without any scaffold. The case study *a self-formed lounge* tries to apply this approach for energetically self-sufficient self-formed bent only architecture.

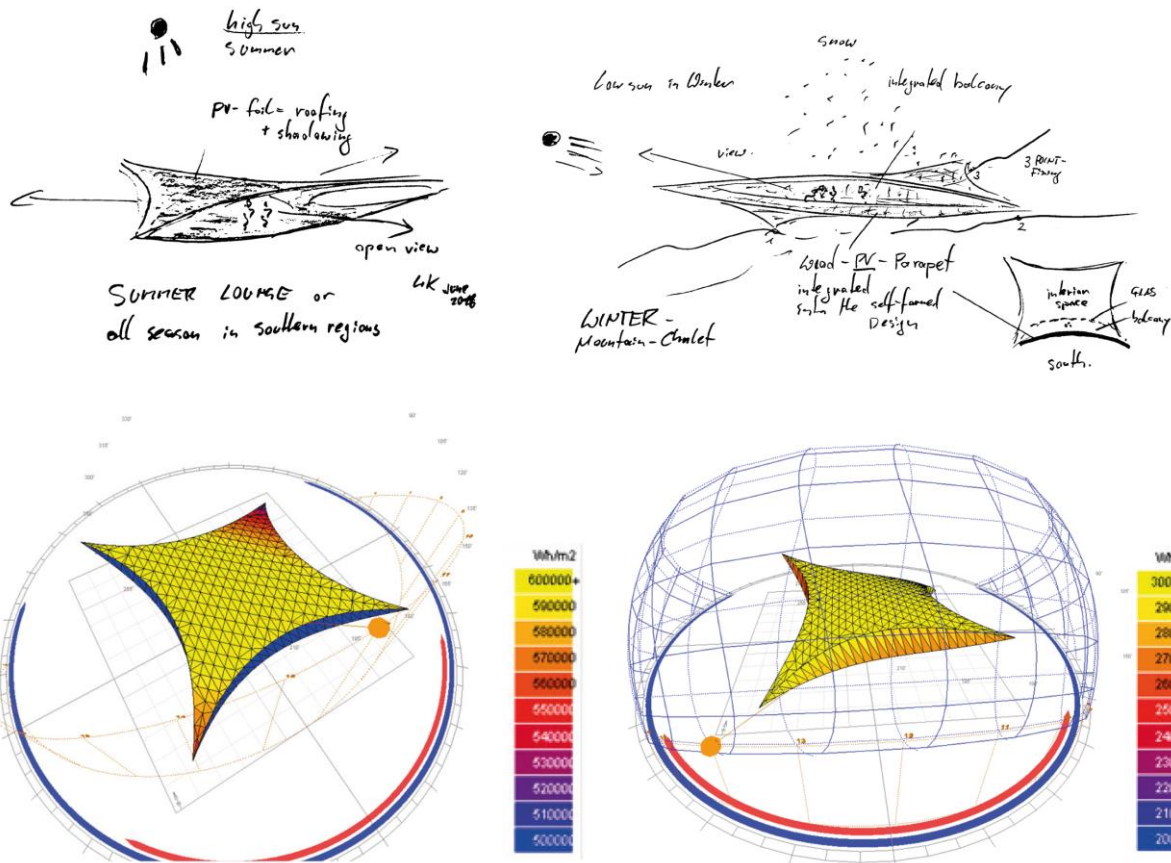


Figure 13: A self-formed Lounge – Analyzing the coherence between structural PV-wood-panels and the architectural concept: Conceptual sketches for possible summer and winter applications by W. Klasz; Analyses of Efficiency of surfaces based on the location Innsbruck by P. Sevela (left: summer, right: winter)

4. Summary

This paper proves following integrated solution in a conceptual stage: flexible photovoltaic foil - glued to flat plywood - provides a PV-wood-panel, which serves as a structural building skin. Three types of geometrical configurations – all of them able to be assembled out of flat bent wood without any scaffold, foundation or ribs necessary – present a new fully integrated light weight wooden design language. Due to different applications, membrane-like surfaces become a shell by fixing an offset wooden layer. Parametric digital design control allows an effective adaption to the specific use and site and it provides production files simultaneously making the double curved statically self-interlocking and self-formed structures affordable and competitive.

5. Perspectives

The interdisciplinary group (conceptual designer, parametrical expert, timber engineer, developer of the flexible PV-foil and engineer for energy-efficient buildings) works in ongoing research on the presented topic focusing on the optimization for a full-scale prototype. The research focuses following issue: How and how far can materiality and energy be reduced in the production and assembling process of the presented self-interlocking bent only configurations? Secondly, the limits in scaling up this structures – related to their holistic efficiency – will be investigated.

6. Acknowledgement

This work was partly supported by the *Austrian Klima-und Energiefonds* within the framework of the research project *SynerCIS- Synergizing Austrian Breakthrough Innovations for CI(G)S solar cells*.

The flexible PV-foil for the bending-test was given by Andreas Zimmermann, CEO of www.sunplugged.at. Special thanks also to the Workshop team at Unitec, NZ, to the Workshop-Team at the unit Structure & Design, University of Innsbruck, to David Trubridge and to Dr. Switbert Greiner - Founder of art-engineering.net.

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