Solar Spline

Expanding on traditional sun-sail typologies and Frei Otto’s lightweight approach with the help of computational design procedures

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This paper presents the design and production processes of a real world organic photovoltaic lightweight installation realized at the University and School of Art, Kassel. It revisits thereby, Frei Otto’s lightweight principles to establish design criteria. Furthermore, we present the possibilities of computational procedures for the design of contemporary lightweight structures within a speculative design setting. Last, we illustrate the benefits of these tools for the design of lightweight structures and the role they played in re-conceptualizing traditional sun-sail typologies within an interdisciplinary student team.

Keywords: Lightweight Structures, Form-Finding, Computational Design, Interdisciplinary Collaboration

INTRODUCTION

Shading structures that protect urban spaces from excessive sun exposure, such as the Roman velarium, have a long tradition in architecture, especially for hot countries. A version still in use today is the Spanish toldo (‘awning’) covering public street spaces. Heribert Hamann and José Luis Moro describe their performative potential in ‘IL 30: Vela, Toldos, Schattenzelte’ as protection against excessive insolation, protecting public spaces against air-borne dust and against glare. Moreover, they also, explicitly highlight their space-creating effects as most impressive (Hamann et al. 1984, p. 94). Sun-sails are architecturally active, in the sense that they allow us to create and control spatial effects that can be experienced (i.e. varying degrees of light, shadow, temperature, etc.).

Figure 1
Contemporary sun-sail in Nicosia, Cyprus, 2018

The design of more recent sun shading structures underlines this architectural potential, as structural interventions that provide better urban spaces in hot regions. Such sun sails examples include the Heart of Doha Project by Schlaich Bergermann and Partner in Qatar (Stein 2017, p.61), or Ocean’s MM-Tent.
Membrella (Hensel 2013, p. 107). The advantages of their performance seem therefore evident: inexpensive and flexible lightweight structures that provide for habitable shade (Fig 1).

However, most toldos, velas or sun-sail typologies do not yet combine their capacity for energy reflection (passive shading) with active energy generation. This simple and obvious observation sparked our research interest of developing and building a contemporary, one-to-one scale sun-shading typology that is also capable of harvesting energy. Furthermore, understanding the toldo typology as an architectural ‘space-creating’ and consequently three-dimensional structure we were not interested in just adding an additional photovoltaic layer to the existing fabric of sun-sails. Instead, it was our aim to re-think the traditional toldo typology as a contemporary, multi-functional solar structure with a high degree (technological and esthetic) of photovoltaic integration. The exploration of such design opportunities, especially for lightweight organic photovoltaics (OPV), supported by the use of computational design procedures is part of an ongoing research effort, at the faculty of architecture at the University of Kassel, department of experimental design and construction in close collaboration with the digital 3d technology lab at the School of Art, Kassel. The results presented here (Fig. 2) demonstrate both geometric flexibility and adjustability to different kinds of architectural constraints for ultra-lightweight OPV structures (Carl and Schein 2017, p. 1228)

This paper describes hereinafter our design approach and the computational procedures employed by an interdisciplinary (architecture, design, electrical engineering and information sciences) educational team in tackling the complexity of the Solar Spline project.

First, we will revisit Frei Otto’s lightweight principles to establish the criteria used by our team for conceptualizing, developing and actually building the Solar Spline structure. Second, we will outline how we gradually translated the principles of physical form-finding experiments into an associative geometry model that contained at the end all relevant information of the project, such as fabrication data, physical simulation, design representations or solar radiation analysis. Moreover, we will discuss how different computational design methods helped to develop and resolve the complexity of the project and collaterally informed the formation of an associative geometry model used for communication, simulation, representation and fabrication. Finally, we will critically evaluate the benefits of the computational procedures employed. Looking at the one end at the performance of our Solar Spline structure, and at the other end at the lightweight principles formulated by Frei Otto and his team.

**DESIGN FRAMEWORK: LIGHTWEIGHT PRINCIPLES AND MATERIAL COMPUTATION**

A key advantage of sun-sails is their small weight to surface area ratio, because they are pure tension structures that avoid compression and torque forces. As a result, considerably less material is required for their construction and they belong to the category of lightweight structures. Therefore, in the spirit of achieving lightness, both in an esthetics sense and as an actual reduction of material use, we decided to approach the organic PV elements not as a separate additional material layer, attached to a sun-sail structure. Instead, they treat the OPV modules as space-defining elements forming...
a three-dimensional shading structure: integrated OPV cloud instead of sun-sail membranes with added OPV modules. This approach exemplifies the idea of exploiting material properties (in our case the ‘lightness’ of organic photovoltaic cells) to an architectural advantage, thereby rethinking PV integration away from heavy elements (just think of all the silicon based glas-glas PV) towards the direction of ultra-lightweight structures. The 30 m² of ‘solar cloud’ are comprised of 300 OPV cells that seem to be suspended in midair. This ‘solar cloud’ is composed of a series of rope carriers which consist of thin aluminum tubes (d = 6 mm), acting both as compression members for the structure, and as a mount for an ultra-light, vacuum-formed carrier plane for the integration of the OPV modules. The weight of this ‘solar cloud’, including the tensile supporting structure, is less than 120kg.

The ‘solar cloud’ is carried by two separate, pre-stressed tension ropes of roughly 70m length (d = 20mm), whose three-dimensional figure was inspired by the mapping of the sun path in solar analysis software. The supporting ropes are anchored between a group of trees and on the ground by an array of thin, almost invisible dark cables (d = 2mm). These thin cables also determine the shape of the ‘spline’-like geometry of the two suspension ropes. In contrast to double curved minimal surface geometries, mostly used for sail-like membranes, the linear elements of this approach could be easily controlled and true length measurements determined by spring particle simulations for fabrication.

One lightweight principle formulated by Otto states that forms resulting from natural forces (i.e. gravity) ‘show the connection between form, force and mass’ (Otto 1996, p. 12). We observed this connection for the form-finding principles of the Solar Spline carrier ropes, but also for the behavior of the Solar Spline structure’s interaction with environmental forces.

In general, the lack of stiffness, rigidity or material strength under load is considered disadvantageous for building structures, resulting in bending, buckling or breaking. However, in our case, the soft and ‘fuzzy’ articulation of structural components increases the robustness to external forces, such as down- or updraft winds and snow loads considerably. Similar to a leave of grass or the branches of a tree, the elasticity of the components react to environmental forces like wind or snow loads through movement (i.e. slight inclinations of the OPV carrier panels is enough to allow for snow to slide off). These principles, combined with the permeable nature of the OPV cloud, constitute a light and resilient structure. Solar Spline withstood for example two summer storms with wind speeds of up to 100 km/h. Moreover, the aggregate and permeable nature of the ‘solar cloud’ decreased also the overall tension forces to address, in comparison to traditional sun sails with a greater surface area. As a result, considerably less material could be used for construction in comparison to structures that are more rigid.

Frei Otto and his team based their most prominent research on the observation of natural principles to formulate methods and ideas for the design of such lightweight structures. For Otto they are ‘most of the times [...] the result of [...] optimization processes which follow the principles of reducing their proper mass, for whatever reason. This is what we [Otto] call the lightweight principle’ (Otto 1996, p. 11).

In reference, we employed analogue form-finding procedures to determine the shape of the ‘spline-like’ carrier ropes at the beginning of our studio to observe structural and geometric principles based on gravity and material properties (Fig. 3). These form-finding methods employed are well established for educational curricula and defined as material computational by Manuel de Landa (De Landa). This both expedited design decisions and helped students to understand the underlying principles that generate form, but also to appreciate architectural design methods, which link material behavior with representation (Carl 2016, p. 595).
Next, we outline the setup of our associative geometry model that represents at the end of the design process all relevant design decisions for the entire structure.

**COMPUTATIONAL PROCEDURES: ADDRESSING COMPLEXITY BY ASSOCIATIVE GEOMETRY MODELLING**

Analogue form-finding procedures helped both to establish and elaborate first design concepts and to understand lightweight form-finding principles of tensile structures. The physical methods chosen have well know counterparts in the virtual world. Dynamic relaxation algorithms that are well suited to simulate and evaluate quality and partially quantity of tensile architectures.

Therefore, we established, rather easy, several computational procedures that applied the logic of these first analogue structural formations. First, the geometry of the two spline-like carrier ropes was determined, after various small-scale physical models led to some general understanding of controlling the shape of these carrier ropes. The analogue form-finding models represent physical forces, but also relevant functional and esthetic design decisions.

Transferring the relevant reference geometries (in our case the location of only 16 anchor points - four per segment of the structure) allowed us to simulate the geometry of these ropes also in the digital realm (Fig. 4 and 5). Daniel Piker’s off-the-shelf Rhino Grasshopper plug-in Kangaroo 2 was well enough suited for this task.

While such spring particle systems, based upon the principles of Hooke’s law, simulate tensile behaviors, this does not mean that all detailed parameters of material stiffness and plasticity - and consequently structural deformation - do equate to real world parameters. However, the results of physical material tests are accurate enough to mediate between simulation logic and real world behavior, thus establishing a feedback loop between digital and analogue models (Carl 2016, p. 596). To give an example: The necessary parameters for bearing capac-
ity to pre-tension ratio of the carrier ropes were determined through a series of carefully documented 1:1 experiments, combining data with quantitative meaning (in our case load deformation) with the more general outcomes (i.e. overall length of the carrier ropes) of the employed digital simulation model.

Of course, it would have been possible to use tools that are more precise (i.e. structural finite element software) to grasp objects by means of figures in static calculation. However, we agree with Otto that in the end the accuracy of calculations is generally a question of how much work we want to invest and of how exact we want our result to be (Otto 1996, p. 34). The simulated geometry relaxation of Kangaroo2 in combination with physical material tests provided an accurate enough ‘loose fit’ that allowed a team of architects to approximate the carrier rope behavior and to develop a geometry accurate enough for construction and fabrication (Fig. 6).

In comparison to the analogue form-finding models, the associative model helped us to inform more specific aspects of our design and thus to develop and answer to design question of a higher degree of complexity - from early design stages until the generation of fabrication data.

In contrast to the membrane surface of traditional sun-sails, Solar Spline consists of a three-dimensional shading structure that seamlessly integrates the OPV modules. The density, shape and orientation of this ‘solar cloud’, consisting of large number of elements, would have been hard to test and design without an associate geometry setup and the utilization of solar analysis tools. Linking the associative geometry model with Grasshopper Ladybug solar analysis provided instant visual and numerical feedback for evaluation (insolation and shading capacity). It was therefore easy to generate and evaluate different densities, shapes, colors and quantities for the OPV cloud. Thus, the computation procedures facilitate a high degree of design flexibility for adjusting the ‘solar cloud’s’ permeability and orientation for different locations and scenarios (Fig. 7).

Another crucial aspect of this approach is that, the all required manufacturing and assembly information could be stored in this associative geometry model. This information included for instance all data to determine the required rope lengths or data for water jet cutting of steel plates for the fabrication of the nodal points. Therefore, it was not necessary to prepare additional, time-consuming construction documentation. Solar Spline took only four months from conception to completion. This demonstrates that it is quite possible to tackle complex projects with a small team and budget within a tight timeframe.

**DISCUSSION AND CONCLUSION**

Revisiting Frei Otto’s lightweight design approach, helped us to use less material and energy for the design and fabrication of the Solar Spline OPV structure. Moreover, this approach relays not solely on reducing mass. The definition of lightweight structure as
Figure 6
Associative geometry model, containing all relevant information (top) fabrication of components, according to parametric data (bottom)
formulated by Otto and his team includes also other criteria:

- Structures that use less material and energy
- Forms that are the result of natural forces (i.e. gravity), showing the relationships between architectural form, force and mass.
- Structures that are simultaneously optimized and esthetically pleasing

The Solar Spline installation meets all these criteria. First, the overall weight is less than 120 kg for approx. 30m² of canopy and can be considered ultra-light. Second, analogue and digital form-finding methods are at the core of the design procedures. Lastly, the three-dimensional setup of our ‘solar cloud’ extends-in comparison with traditional membrane or sun-sail structures- the scope of climatic and architectural functions considerably. The open and permeable nature of the photovoltaic array allows not only heat loads to escape, but - equally important- it creates a structure that is also esthetically light. Thus, we conclude that the Solar Spline typology is simultaneously optimized and esthetically pleasing. In the words of Frei Otto: ‘Thanks to the “lightweight principle” it may even be possible to find some explanation for “aesthetics“ which are inherent in objects (Otto 1996, p. 11).

As Otto predicted, the computational procedures we employed played a major role in designing this truly multi-functional structure that allowed us to successfully combine ecological with esthetic concerns (Fig. 8).

‘Only by directly coupling the analytical reper- tory with the methods of designing and constructing, especially by integrating automatically running pro- cesses of optimizing and selection of the positive, we it be possible to take the further steps of developing towards constructions which will be lighter, more ef- fective from the point of view of energy and perhaps also aesthetic.’ (Otto 1996, p. 13)

Reflecting on the precision, accuracy and workflow of our computational procedures, we became aware of two findings.

First, combining various computational techni- ques within one associative geometry model car- ries indeed the potential to have a transformative ef- fect on the design and construction of lightweight structures. These computational procedures helped us to expand the established conceptual vocabulary of the sun-sail typology, to question assumptions and understanding of space and form, and to implement an efficient set of digital fabrication.

Second, ‘automatically running processes of optimizing’ should not be employed in a linear way, but instead in a continuous, iterative process that constantly links them with analogue methods and testing. Just to give one example: Being overtly confident about the precision of our spring particle simulation setup, we neglected to model the cable-carriers of the ‘solar cloud’ in detail. A single towing rope only represented each cable-carrier in the associative geometry model. Even though the basic principles and stresses of these cable carriers had been verified with real world tests, it slipped our attention to adjust the associative geometry setup to the final shape of the cloud. This resulted in a needlessly complicated assembly, because the center of gravity of the cable-carrier elements was placed too high and the elements therefore became less stable.

Nevertheless, we conclude: The Solar Spline project demonstrates, that pairing the correct ana- logue and computational procedures, mutually in- forming each other, helped us to transform and ex- pand the architectural typology of sun-sails (Fig. 9), lightweight construction and fabrication techniques considerably.
ACKNOWLEDGMENTS:
This project was made possible through the generous support of the Opvius GmbH and Cable net manufacturer Carl Stahl GmbH. Furthermore, we thank the ‘Lehre für einen Nachhaltigen Campus’ for their funding of interdisciplinary student work. Students who participated in the Solar Spline project are: Wassim Daaboul, Mahmoud Dames, Grischa Göbel, Annemarie Kroworsch, Elena Mateev, Steffen Och, Mario Scherf, Lisa Schreiber, Ahmed Teftafeh, Tuantai Truong, Bastian Wiesel. Special thanks goes to Annemarie Kroworsch for her dedication and enthusiasm.

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