Flexible Matter

A Real-Time Shape Exploration Employing Analogue and Digital Form-Finding of Tensile Structures

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The paper presents a research on real-time shape exploration employing analogue and digital form-finding and concludes with a proposal for a teaching methodology that led to an intensive student workshop which took place at Graz University of Technology during 2014. The aim was to experiment with analogue and digital tools in parallel, counter-informing the design process. The experiments involved physical form-finding following the tradition of Frei Otto at the Institute of Lightweight Structures in Stuttgart as well as computational form-finding employing mainly dynamic relaxation techniques of spring-particle systems. The combination of techniques and methodologies eventually led to a feedback loop across different media that explored both qualitative and quantitative characteristics of the projects at hand. By establishing feedback between digital media and physical prototypes, the creative process is immediately informed by the material characteristics and properties which in turn give rise to a real-time exploration of form. Simulations of physical forces for architectural form generation are increasingly gaining ground in architectural education as there is a broad selection of computational tools readily available that allow quick experiments to be conducted.

Keywords: Form-finding, Analogue-digital, Parametric design, Tensile structures, Kangaroo physics simulation

ANALOGUE COMPUTATION AND LEARNING BY DOING

Form-finding is a well-established method in architecture and engineering aiming to define the optimal geometry with respect to the structural behavior for certain boundary conditions. There is a long history of experimentation in this field, supported by scientific research and built examples. Frei Otto was the pioneer to research, study and categorize these structures, together with his team at the Institute for Lightweight Structures in Stuttgart. Their physical experiments and models have been documented in the famous volumes of IL books; although most of the IL series were published in the early 70s, which is much before the wide use of computational design in architecture, they remain an essential reading for
computational designers of our times.

For more than 15 years the morpho-ecological discourse has been influencing the work of architects and academics. According to Hensel and Menges, the term Morpho-Ecology is a correlation of morphogenesis (the birth of form) and ecology (the study of the relationships between organisms), a term that denominates a framework for architectural design rooted within a biological paradigm and giving rise to structures that are functional and performative (Hensel and Menges, 2007).

In the last few years the discourse is moving towards the overlaps between machine computation and material computation. Achim Menges affirms that current design research is moving towards "a synthesis of form, material, structure and performance in a process of integral materialisation, which finds its conceptual roots in the processes of becoming in nature" (Menges, 2012).

It is not a coincidence that also Frei Otto referred to his experiments as natural constructions, not merely for their morphological resemblance to natural forms but mainly because "these are constructions which reveal the processes of their creation with particular clarity. The form-finding processes are those which, given a set of conditions and following the prevailing laws of nature give rise to visible forms and constructions under experimental conditions. As they take place without human intervention they are also termed autonomous formation processes" (Barthel, 2005).

A tensioned membrane, just as a soap film, possesses a self-organizational property of finding its own form, it tries to minimize its material (energy) to span between the given borders. The pressure is the same on both sides, of the membrane or soap film, so the material system settles in a configuration with mean curvature as close to zero as possible. Thus a membrane is able to 'compute' form. De Landa describes it as an 'analog search algorithm'.

We refer to physical form-finding experiments as 'analogue computation' because the material 'computes' its form, it self-organizes to find a stable state for a given setting of boundaries, tension cables and anchor points. The design process inherently embeds performance criteria; there is a real-time exploration of optimized configurations. Each modification in the location of an anchor point or tensile force will have a direct repercussion on the form so that all forces acting upon the model are in equilibrium. Thus design decisions are taken by the material itself and the forces acting upon it.

In the framework of the student workshop presented in this paper, the challenge was to adopt an integral approach to computation that goes beyond a mere fascination with the medium. The aim was to address computation in its multiplicity negotiating material, structure, design, function. The focus was manifold; on one hand to address tensile structures and go beyond the established morphological vocabulary of hypars and vaults into more creative, non-standard and therefore unexplored geometric manifestations (See Figure 1). On the other hand we were concerned with the pedagogy of teaching construction technology and design to architecture students, the aim was to explore innovative teaching methods through a modus operandi of learning-by-doing, following the doctrines of Piaget, Papert and Montessori.

The role of model making in architectural education is well established in the academic curriculum and new digital media have brought a new dimension to traditional model-making (Stavric et al., 2013). Brett Steele, director of the Architectural Association in London, alludes to the common belief that "architecture is only ever learned by getting your hands dirty" (Self and Walker, 2010). He explains that this is done through the construction of physical prototypes, 1:1 models, whose "working difficulties and eventual results offer the designers vital insight and understanding into how they take a next tentative step forward". In an attempt to contribute to the ongoing discourse about what lies in the intersection of analogue and digital media in the design process, we realize that there is a conceptual gap when design thinking is addressed. The technological develop-
ments in CAD/CAM have achieved a seamless transfer of information from designing to making, a file-to-factory continuum from the computer screen to the CNC machine. However, the creative process itself is not so easy to trace; very often thoughts are fragmented, discontinuous, yet creative, jumping from one idea to another, taking one informed decision, followed by a random or controversial design gesture. In the same fashion, a designer implements different media during the design process, "Prototypes and other types of expressions such as sketches, diagrams, and scenarios, are the means by which the designer builds the connection between fields of knowledge and progresses toward a product" (Stappers, 2007). It is not possible to come up with a cartography of how a design idea is developed. Many agree that a design process is iterative, including trial and error, multiplicity of sketches media. As Parthenios explains in his paper for the Critical Digital Conference at the Graduate School of Design at Harvard, "conceptual design is not a linear process, it consists of sub-processes which are individual but interact with each other" (Parthenios, 2005). Our aim here is not to delve in the mysteries of design creativity; it is rather to provide access to diverse media for design experimentation and set up a workshop framework where student work is more self-guided, "with the student given greater opportunity to test their own assertions and to build their own confidence and repertoire of design experimentation" (Self and Walker, 2010).
THE SET-UP FOR ANALOGUE EXPERIMENTS

Following the tradition of Frei Otto, during "Flexible Matter" workshop at Graz University of Technology, the analogue experiments were carried out on a measured plexiglass frame where elastic textile (with elasticity in both directions) was tensioned. If the tension forces are isotropic on the surface, i.e. the same T value in all directions and in every point on the surface, the membrane will tend to adopt the form of a minimal surface (a surface with zero Mean Curvature). The first set of experiments involved measured models and the form-finding of typical tensile structure primitives, such as the Hypar, Conic and Barrel Vault, together with possible combinations of the above. Thus, already from the initial design stages, the elasticity and material characteristics led to a vocabulary of possible formations within the broader category of tensile structures. This set of experiments also studied the repercussion of a 2D cutting pattern on the 3D form, understanding the translation of forces into geometry, the continuity and discontinuity of force transfer as a design gesture. The physical models and material tests were carefully studied and documented in order to extract a first set of observations regarding material behavior.

BIBLIOGRAPHICAL RESEARCH THROUGH MAKING

There is an immense body of research on tensile structures and numerous built examples throughout the history of architecture. It would be an omission not to study the relevant bibliography in depth. In this context studying the bibliography does not merely mean to gather information from published media. The nature of the subject matter at hand requires further action. Considering a pedagogical approach of learning by doing, the students investigated the case studies by making models, by understanding the morphogenetic principles that govern the construction (See Figure 2). This was not an exercise about copying the external form, it was rather an exercise about understanding the principles that generate the form. A hands-on approach offers a tacit knowledge which combined with the theoretical background leads to more informed decisions. As Koskinen explains a design process "may start from theories, methods, and fieldwork findings, and just as often it begins with playing with materials, technology, and design precedents [...] Without this culture of doing, many things of interest to designers would go unnoticed" (Koskinen et al., 2011) With this attitude in mind the workshop's experimentation departed from known case studies to further evolve into original design ideas on a second stage. The built examples that were used as case studies were drawn from various different periods of architectural history, thus ranging from the Institute of Lightweight Structures in Stuttgart (Figure 3) to the Paradise Pavilion by Chris Bosse.
DYNAMIC RELAXATION FOR FORM GENERATION

Extracting the underlying generative logic of the analogue experiments and understanding the forces in play is the first step towards building a digital setup that simulates the physical behavior. Solving similar problems with Dynamic Relaxation of spring-particle systems has been used for over three decades in the engineering world (Day, 1965), however the recent integration of visual algorithms such as Kangaroo Physics in Grasshopper (Piker, 2013) has resulted in a very user-friendly and intuitive tool in the hands of architects (see Figure 4).

In an attempt to mimic the physical behavior of a material system, we translate physical properties into mathematical equations that generate the geometry in the computational environment. Thus an elastic textile can be represented by a spring-particle system, translating mesh vertices to particles and mesh edges to springs, in other words a system of points and lines. Though the code is not visible to the user, the core is based on an algorithm that iteratively computes forces, velocity and lengths of springs that behave according to Hooke’s Law. Having obtained an understanding of the forces acting upon the models the students were able to build their own definitions, compare the results to the physical models and rectify any of the two. In several cases the form-finding experiments revealed some unpredictable results that emerged from the self-organizational capacity of the system to regulate and distribute forces to reach equilibrium. As Piker explains "one great advantage of physically based methods is that we have a natural feel for them, and this intuitive quality lends itself well to the design process [...]through the application of real-world physics we can make computational tools that really work with us to design in a way that is both creative and practical" (Piker, 2013).

OBSERVATIONS ON THE DESIGN PROCESS

Our attempt to introduce bibliographical research through making highlighted a series of findings. Students did get their “hands dirty” and acquired experiential knowledge about tensile structures. The process involved less thinking and more making, they faced problems and developed strategies to solve them. Unlike traditional bibliographical research which is carried out individually, in this learning environment individual learning led to collective knowledge gain in the workshop as everyone learnt from each other's experiments and case studies. With this process, we established a common working language and an initial understanding of structural performance in order to proceed as a group to the next stage of creative process. The students were therefore able to take informed decisions. They had already developed certain fluency with analogue and digital skills, therefore they were not any longer concerned with learning the tools. Aware of the potential of the material system at hand in a conscious and intuitive level, they were liberated from the restrictions of the tools and motivated to pursue their design ideas.

AN INTEGRAL DESIGN APPROACH

For the final phase of the workshop the students worked on their own design ideas. During the development of the projects they implemented in parallel analogue and digital media. There was a conceptual feedback across media which aided students to take informed design decisions. It is important to clarify that we are not looking at analogue-digital processes as two competing strategies, but as complementary tools that provide different type of input yet interrelated one with another. Analogue tools proved more efficient with handling qualitative characteristics of the design, transmitting the atmosphere of the architecture, understanding empirically the forces act-
ing upon the structure and dealing with issues of assembly and detailing. On the other hand digital tools can handle huge amounts of data, making them appropriate for handling quantitative characteristics of the design, they allow quick changes but they require certain experience with real-world physical forces so that the user can calibrate the values for drag, spring force and edge conditions. They are abstracted and idealized representations of lightweight structures and as such they allow for quick sketches. When the design is finalized the analogue and digital approaches look very similar to each other, almost identical, however what is crucial to underline here is that design decisions took place on both media, meaning that the design was not finalized on the computer and then transferred to the textile, or the opposite. Explorations were taking place in parallel in both media driving the design to solutions that were both aesthetically pleasing and structurally stable, so that it can be further developed into an architectural artefact. In particular the use of prototypes in early design stages conveys a lot of embedded design information. However, as Stappers explains, "the value of prototypes as carriers of knowledge can be implicit or hidden. They embody solutions, but the problems they solve may not be recognized"(Stappers, 2007). Therefore they represent great design tools for an exploratory phase of design ideation.

This paper wishes to present the results of the aforementioned intensive hands-on workshop and raise new questions on design methodologies and contemporary architectural educational agendas. The aim was to intrinsically involve analogue and digital design processes, not as separate routines, but as an integrated design approach were the two media counter-inform each other from the very beginning of the design lifecycle.

Understanding the association between geometry and material behavior, the elastic properties of membranes or computational spring meshes and the obtained form, leads to a 'synergetic approach to design integrating form, structure, material and environment' (Oxman and Rosenberg, 2007)

The presented projects (Figures 5,6,7) show an overview of the techniques and methodologies investigated during "Flexible Matter" workshop that took place in May 2014 at the Institute of Architecture and Media at Graz University of Technology. It addresses issues of design research through praxis, and design processes that encourage creative design thinking towards an integral approach in architecture, which integrates material behavior, functionality, material economy, aesthetics and optimized structural performance.

Figure 5
Architectural application of a digitally form-found membrane

Figure 6
Experimental digital form-finding model simulated in Kangaroo plugin for Rhino-Grasshopper
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