Structural Design

A Systemic Approach

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The paper sketches out the idea of a systemic approach to structural design. Starting with the notion of complexity as interweaving of feedback loops it introduces a thermodynamic understanding of the problem of form-finding and discusses some implications for the design of building structures.

Keywords: structural design, systemic thinking, form-finding, thermodynamics, complexity

INTRODUCTION

Over the past twenty years, the introduction and integration of computational methods and techniques into architectural design and discourse has been paralleled by the almost ubiquitous presence of the notion of complexity in connection with applications of the digital: complex architectural geometry, complex fabrication, complex assembly, complex environmental performance, or complex urban analysis to name but a few. In this context, complexity is used synonymously as indication of an advanced level application to an otherwise well-known topic within architecture.

Such a connotation of the notion of complexity as advanced level application, however, stabilizes our current understanding of architecture. It veils the mind-changing potential of the digital and limits the conscious recognition of computation as a paradigmatic shift within the discipline. Architecture is taking part in an "intellectual revolution [that] is happening all around us, but few people are remarking on it. Computational thinking is influencing research in nearly all disciplines, both in the sciences and the humanities. . . . It is changing the way we think" (Bundy, 2007).

WOVEN COMPLEXITY

The etymological roots of the word complex can be traced back to the Latin complecti, from com- (with, together) and plectere (to weave, to twine). In its original meaning, therefore, complexity refers to an activity of weaving together independent threads into a new organized whole. This bringing together, however, is not a simple additive process as the actual weaving of material illustrates: the weft and the warp interact with each other, both threads deform and connect to one another by friction.

It is the coordinated accumulation of this active interaction that results in new properties of the overall configuration that is not apparent in the threads themselves. Such emergent properties like a specific spatial morphology or structural rigidity are used for example by the artist Joe Hogan in the creation of sculptures based on traditional basket weaving tech-
Figure 1
Principle of weaving based on embedding of weft thread into collection of warp threads and examples of possible weaving patterns; From Earth And Sky, woven sculpture, 2012, by Joe Hogan, Co Galway, Ireland (Photo: Rory Moore, Belfast, Northern Ireland).

Figure 2
Translation of a simple warp-weft configuration into the related connectivity matrix and according directed graph.

Techniques (Figure 1). Here, especially the resulting overall shape of the sculpture is often hard to predict as the bending stiffness of the willow changes along the thread as well as from thread to thread.

In general, the weaving pattern introduces an interdependency between neighboring threads which causes a feedback mechanism that influences the precise formation of each individual thread (Figure 2). That is, weaving can be seen as the construction of a network of threads with a large number of overlapping and interacting feedback loops. It is this feedback mechanism that guides the formation process as visible expression of the regulatory behavior and distribution effect caused by the circular interaction. An effect, explored in depth first by Norbert Wiener in his seminal book Cybernetics or Control and Communication in the Animal and the Machine published in 1948 (Wiener). Together with General Systems Theory, established by Ludwig von Bertalanffy in the 1940s, Wiener’s Cybernetics provided the foundation for the development of systemic thinking and systems theory up to the present (Stähle, 2009).

With this in mind, the notion of complexity has to be understood essentially as a systemic notion. It relates to pattern of interwoven simple relationship between a larger set of agents that allow for feedback loops as a form of exchange of information between the agents. Complexity describes the ability of a set of agents to organize itself into a new whole, of phase change, of re-organization into a new unity. Complexity, therefore, fundamentally is a transitional phenomena at the transformational stage between hierarchies of organization. It refers to the ability inherent in a system for organized construction, a construction of morphology or structural stability like in the example of the woven sculpture by Joe Hogan.
Paradigmatic shift in science from reductionism to systemic thinking and related concepts of exploration that have been taken up in digital architectural design with some temporal delay.

**SYSTEMIC BEHAVIOR**

Systemic thinking is a holistic thinking that caused a paradigmatic shift in science by questioning the universality of reductionism as scientific method of exploration. Since the 1950s, this shift has been triggered by the availability of computational means which made it possible to handle and explore a large set of interaction between various quantifiable entities (Mussmann, 1995). The possibility to explore in more depth the self-regulating effect of feedback has resulted in a successive modification or even replacement of reductionism as the predominant paradigm of research thinking. That is, the mechanistic understanding of nature and the continuous top-down reduction of the whole into parts has been exchanged from patterns of local interaction to the overall global arrangement of the parts as an emergent bottom-up property of the system (Figure 3). Starting in the late 1980s it is not surprising that architects became interested in these systemic models of nature due to potentially new methods of spatial organization and form-generation provided by computers and appropriate software (Weinstock, 2010). As a result, over the past decade, systemic notions and concepts from science have diffused into architectural discourse and are currently being explored for design purposes.

One of the main applications of the self-regulating capacity of systems has been in the development of computational tools for form-finding of long-span roof structures and lightweight structures, a classical problem in structural design, at the conceptual stage of the design process. Such structures transfer their loads purely through axial or in-plane forces and the shape is determined primarily by the flow of forces in space. This distribution of forces in space is typically not known in advance and therefore a formation process is required (Veenendaal & Block, 2012).
Before the availability of computational tools, physical experiments were used to determine the shape. Probably the best-known examples are the hanging chain model by Antonio Gaudi for the Colònia Güell in Barcelona or Heinz Isler’s membrane models for thin-walled shell buildings (Kotnik, 2011). These experimental form-finding methods can be approximated computationally by particle-spring systems, a multibody system method (Kilian & Ochsendorf, 2005). One of the first tools created to explore particle-spring systems as a method of form-finding was CADenary, a simulation tool built mainly by Axel Kilian in 2002. It gained popularity due to the intuitive understandability and the interactive character of the particle-spring system but lacked features to make it into a versatile design tool. Some of these design limitations have been overcome by Kangaroo, a popular physics engine for Rhinoceros developed by Daniel Piker that allows an interactive simulation and form-finding (Piker, 2013).

One of the big shortcomings of the particle-spring approach is that the described method of form-finding is only valid for tension-only respectively compression-only structures like membranes or shells. In more general cases, the underlying dynamic relaxation process does not converge. The same limitation is true for other existing methods of form-finding in structural design like the Thrust Network Analysis (Block & Ochsendorf, 2007) embedded into Rhinovault, a form-finding software by Philippe Block.

The reason for this limitation is that particle-spring systems are highly ordered systems: the relation between neighboring particles is very restrictive and aims for balancing out of uneven force distribution resulting in pure compression or tension within each neighborhood of a particle and no rapid change of the surface geometry. This means all neighborhoods of the surface have to be similar in their geometric quality. If, on the other hand, compression and tension are available within the same neighborhood of a particle then rapid change of the surface geometry is possible and various equilibrium solutions of the system can exist (Figure 4). This means, the systemic behavior of structures in general is much more intricate than the existing methods of form-finding are able to capture. Compression and tension function as pushing-and-pulling effect in the formation process of structural systems and it is well-known from the study of dynamic systems in physics and biology that it is the simultaneity of pushing and pulling within a system which is responsible for the emergence of new phenomena and configurations (Mayfield, 2013).

**THERMODYNAMIC FORM-FINDING**

In order to overcome the limitations of the existing methods of form-finding it is, therefore, suggested that a new systemic approach to structural design is required for a better understanding of formation process in structural systems.

Starting point of such a new approach is the
observation that in engineering the understanding of the system under consideration is defined by the free body diagram, an isolated description of the part of the structural system and all the forces acting upon it (Muttoni, 2006). The primary goal of this diagram is the detailed examination of the force distribution within the structural system at static equilibrium. Hence, it describes a fixed situation, the situation at the end of the formation process. Form-finding, however, is a dynamic process and is driven by constant change of the configuration. In the case of the particle-spring system this change is provoked by a residual force at each of the particles, a lumped mass, that introduces some kinetic energy into the system (Figure 5). The process of change continues till all the energy has dissipated and structural equilibrium is achieved. By introducing this residual force and the initial configuration into the diagram, the free body diagram transforms into a diagram of an open system with the external forces as exchange of energy of the system with the surrounding and the residual forces as internal energy flow. This reading of the diagram introduces a thermodynamic perspective into structural design and with it the interpretation of the above mentioned form-finding methods as near-equilibrium systems.

Such systems tend to evolve towards equilibrium, a special state that has been the focus of multi-body research for a century. Yet much of the richness of the world arises from conditions far from equilibrium (Schneider & Sagan, 2005). Phenomena such as turbulence, earthquakes, fracture, and life itself occur as phenomena far from equilibrium. Subjecting materials to conditions far from equilibrium leads to otherwise unattainable properties. This is also true in structural systems.

As mentioned above: one of the essential prerequisites for the existing form-finding methods is the assumption of flow of forces through the system purely through axial or in-plane forces. On one hand, this enables an efficient use but on the other hand it reduces the typology of shapes to a minimum. If more material is introduced into the system then other types of inner force flow get possible like in the case of a beam where non-axial forces lead to the simultaneity of compression and tension in the same material section and consequentially to bending of the beam (Figure 5). In the case of the particle-spring system residual forces dissipate into movement, in the case of the beam energy does not dissipate out of the system but remains within, stored as elastic deformation respectively bending stress.

Thermodynamically, bending can be understood as dissipation of energy within the system that is the resulting deformation is a morphological reaction of the system to the flow of energy through space. This interpretation seem to be farfetched. However, locally compression and tension define opposite directionality. In a material section with compression and tension like for example in the redirection of the force flow around a cut the resulting bending can be seen as a local turbulence pattern around the cut. This pattern of energy dissipation resembles the flow of wind around an obstacle like for example a wall (Figure 6).

Consequently, the inner flow of forces as phenomena of mechanics shares some similarity with the flow of energy as phenomena of thermodynamics. An insight that forms the basis for constructal theory, a general theory on the formation of pattern
Based on plasticity theory the flow of forces can be manipulated following simple geometric operations like the redirection of forces: The direct flow of inner forces between two external loads (a) can be redirected within the material by adding an internal force that pushes the flow out of its preferred line and compensating the additional force to ensure equilibrium in the system (b). The resulting configuration of forces can be understood as pattern of turbulent dissipation of energy (c). The discrete turbulence pattern in force flows resembles in an abstract way the patterns of energy dissipation - visible in the local increase of wind speed - that occur in the flow of wind around an obstacle like a wall (d).

**CONCLUSION: DESIGN OF STRUCTURE**

Clearly, the implied similarity of flow pattern still requires a lot of in depth research before it can be made operative and a thermodynamic approach to structural design is only sketched out in a very rough way. But it already starts to point towards a possible direct link between ongoing research within science and architectural design based on formation process. And even at this infant state of development some conclusion can made regarding the implications for our current understanding of structural design.

At the moment, teaching and design of building structures still is based on a reductionistic paradigm of hierarchy of structural systems governed by the idea of accumulation of forces from top to bottom primarily along linear elements. This has fostered a move from surface to line that is the replacement of massive walls by linear structure and the development of building elements and fixed typologies as structural solutions. The implied tendency towards lightness and dematerialization of structure has diminished the potential of building structures to function outside of the mono-functional purpose of providing structural stability.

Within a systemic paradigm building structures are perceived differently. Based on a thermodynamic ambition building structure should be spread into space in order to maximize the possibility for the even distribution of loads. Animal architecture like for example bird nests exemplify this very well (Figure 7): out of the interweaving of soft and flexible material structural stability emerges as complex property like in the initial example of the basket weaving. At the same time the weaving enables a flexible adaptation of the material system to the environmental conditions and the spatial requirements. This step-by-step construction is a formation process that results in a structural system that not only fulfils a mono-functional purpose but is also the generator of the space as well as shading device and thermal regulation.

A system design of structural systems aims at such kind of polyvalent use of the building structure. Systemic structural design, therefore, has to be non-hierarchical and cannot be based on typologies but
rather has to be based on first principles as generative driver of the design. Systemic thinking in structural design is the move away from the static iconography of form towards the dynamic and procedural of formation. It is the move away from structural design towards design of structures!

Figure 7
Nest of a Baya bird in Southeast Asia and nest construct of Social Weaver in South Africa.

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