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The Digital Turn in Architecture 1992–2012
Edited by Mario Carpo
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Morphogenesis and Emergence (2004–2006)

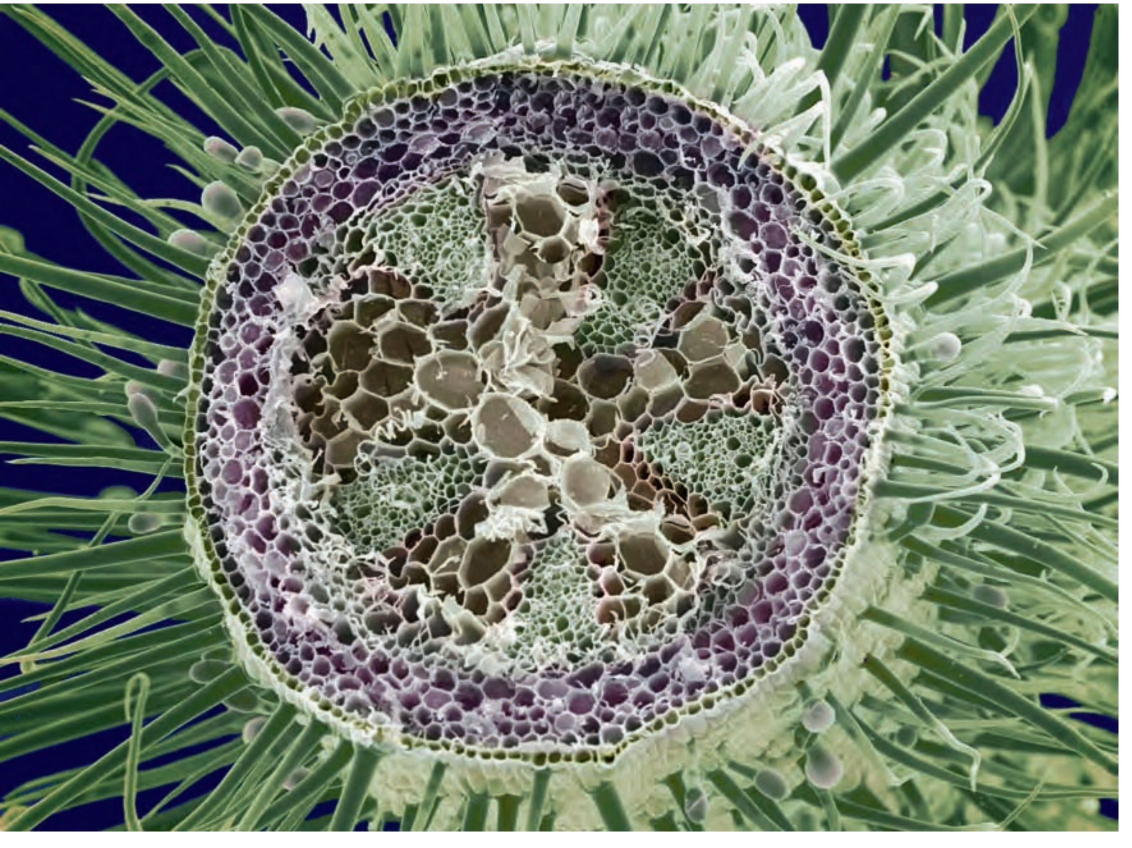
Michael Hensel, Achim Menges and Michael Weinstock

Morphogenesis and the theory of evolution have long provided a source of inspiration and an apt simile for computer-based design, with parametric script in lieu of genetic code, and the instantiation of script into different material events in lieu of the variations of phenotypes exposed to external (environmental) forces. The term 'emergence' derives from system theory, where it defines properties of a system which cannot be derived from the sum of its parts – a notion often associated with complexity theory, to the study of nonlinear behaviours and to self-organising systems. In the history of digital design theory such arguments have sometimes warranted romantic, spiritualistic or anti-technological interpretations of digitality, and have spurred similarly minded design strategies, but the 2004 *Emergence* issue of *AD*, followed by other *AD* Profiles guest-edited by the Emergence and Design Group in 2006 and 2008, signals a step in a different direction.

As they apply the principles of self-organisation to buildings seen as systems, or even eco-systems, both in their tectonic and thermodynamic aspects, Michael Hensel, Achim Menges and Michael Weinstock are keen to point out the difference between 'emergent' properties in life and in computation, and the gap between nature and machinic production. The introduction to the 2004 Profile refers in particular to the teaching and research undertaken by the team, and other associates, at the Architectural Association in London. The second essay, by Achim Menges (2006) applies the theories of self-organising systems to structural design, form finding and research on physical materials. The term often used by Menges in this context, 'performative', an apparent conflation of 'form' and 'performance', has been largely adopted by the design community and is still in use.

In Menges's theory, performativeness is the quality of material systems that perform through deformation, or which visibly deform to self-organise and resist new external forces (loads, for example). All materials deform under stress, and such deformations can and often must be carefully calculated, but in classic engineering the new visual configuration of structures after an elastic (reversible) deformation is seldom taken into account for design purposes. Conversely, Menges applies the logic of self-organising systems to structural systems of which the deformation under stress is the salient quality – figural as well as structural. This pertains to unusual or irregular materials such as soap bubbles and catenary ropes, but also to textiles, perforated membranes, post-tensioned timber tiles, paper strips or honeycombs (see the examples featured in the essay). The structural behaviour of such inelastic, anisotropic or nonhomogeneous materials or composite structures was until recently

impossible to calculate, and could only be approximated using physical models – often at real size, due to the non-scalability of structural tests. This is where digital modelling is now changing the game, as the behaviour of non-conventional ('nonlinear') materials, and even of irregular, natural materials, such as timber or stone, can now to some extent be calculated, and structures made with such materials can be designed and fabricated by digitally controlled machines – machines which can theoretically emulate the skills, adaptivity and alert manipulation of expert artisan makers.



Coloured scanning electron micrograph (SEM) of a section through the stem of a geranium plant. With the close-packed bundles of differentiated vessels and specialised cells, it is the perfect example of integration and differentiation in a plant stem. The geometrical arrangement and close-packed integration produces a complex structure, strong but flexible, and capable of differential movement. Photograph © Steve Gschmeissner/Science Photo Library.

MICHAEL HENSEL, ACHIM MENGES AND MICHAEL WEINSTOCK

Introduction to *Emergence: Morphogenetic Design Strategies* *AD* May–June 2004

Emergence and Morphogenesis

It makes little sense to characterise emergence as either solely abstract or purely a means of production; in emergence the two are inextricably intertwined. As used in the sciences, the term refers to the 'emergence' of forms and behaviour from the complex systems of the natural world. A substantial body of knowledge falls under this term, occurring in the overlapping domains of developmental biology, physical chemistry and mathematics.

The techniques and processes of emergence are intensely mathematical and have spread to other domains where the analysis and production of complex forms or behaviour are fundamental. In 'Morphogenesis and the Mathematics of Emergence', Michael Weinstock traces the origins of the concepts and provides an account of the mathematical basis of processes that produce emergent forms and behaviours, in nature and in computational environments. The mathematical models can be used for generating designs, evolving forms and structures in morphogenetic processes within our computational environments.

Morphogenetic strategies for design are not truly evolutionary unless they incorporate iterations of physical modelling, nor can we develop systems that utilise emergence without the inclusion of the self-organising material effects of form finding and the industrial logic of production. Emergence requires the recognition of buildings not as singular and fixed bodies, but as complex energy and material systems that have a life span, and exist as part of the environment of other buildings, and as an iteration of a long series that proceeds by evolutionary development towards an intelligent ecosystem.

Physical form-finding experiments in architecture are thought to have begun with Gaudí. Frei Otto's pioneering work on form finding is well documented and in 'Frei Otto in Conversation with the Emergence and Design Group' he discusses his development of modelling through form-finding techniques in the context of his interest in natural systems, the relation of experimental models to geometry, iterative mathematics and irregularity.

New form-finding methods are needed for the forms capable of change for the adaptation that emergence demands. In 'Finding Exotic Form' Michael Hensel, of OCEAN NORTH, presents the case for a digital and dynamic form-finding technique that suggests a material means of form adaptation in situ. His argument is developed through a design for the World Center for Human Concerns, an architectural study of a 'parasite building' in which structural and circulatory independence from the host is achieved through the skin of the draped volume.

Data, Genes and Speciation

The Emergence and Design Group, founded by Michael Weinstock, Achim Menges and Michael Hensel, present their case for a morphogenetic strategy in the design study of a high-rise building, placed in the context of their argument for integrating structural criteria and behaviour into material systems of vertical urbanism. In 'Fit Fabric' they propose high-rise buildings as surface structures, explore flexure and stiffness, and present models taken from natural structures for geometry, pattern, form and behaviour. Their evolutionary process has produced a design for high-rise structures in which a helical structural system and an intelligent skin are integrated into a versatile material system. The evolutionary technique here is the development of a population of forms from which the fittest is evolved.

The relation of an individual to a population and to a species is a matter of fierce debate, and within developmental biology the argument between Dawkins and Gould has extended for decades. In 'Types, Style and Phylogenesis' Farshid Moussavi and Alejandro Zaera-Polo of Foreign Office Architects discuss the systematisation of their work into a phylogram of species, and the implications of this new organisational paradigm regarding the methods and techniques that they have refined during their 10 years in practice. They discuss phylogenesis in the context of reflections on the architectural ideologies of 'type' and 'style', and explain their changing design approach in recent work.

'Emergent Technologies and Design' is a new Master of Architecture programme at the Architectural Association Graduate School, and is the first of its kind in the world. It was developed, and is directed, by Michael Weinstock and Michael Hensel. Achim Menges is the studio master. Professor Chris Wise, director of expedition engineering and chair of civil engineering design at Imperial College, London, is an eminent design engineer, and as external examiner to the masters programme evaluates the work of the graduating students. In 'Drunk in an Orgy of Technology' he reflects on their intoxication with technology, mathematics and computers, and their pioneering engagement with emergence. A short account of two MA dissertation projects is presented. 'Data-Graphics and Continuous Datasets', by Lina Martinson, explores the digital imaging, mapping and modelling of complex material systems. The increasing currency of complex morphological articulation in contemporary architecture requires the introduction of imaging technologies from medicine and science. 'HybGrid' by Sylvia Felipe and Jordi Truco, is an adaptable structure developed through a design strategy that combined digital and material processes. The structure has a multiplicity of stable states that link changing spatial requirements to a corresponding formal and structural articulation. The structure makes use of redundancy and elastic behaviour, which are further explored in the context of the article in 'Adaptable Equilibrium' by Wolf Mangelsdorf of Buro Happold, who also teaches in the Emergent Technologies and Design masters programme. He presents an argument, developed from the study of natural structures, for inbuilt redundancy and multiple load paths as primary requirements for the materialisation of the new concepts of adaptability and controlled dynamics.

Complex forms and systems emerge in nature from evolutionary processes, and their properties are developed incrementally through the processes that work upon successive versions of the genome and the phenome. In 'Evolutionary Computation and Artificial Life in Architecture', Dr Una-May O'Reilly of the Computer Science and Artificial Intelligence Lab at MIT, Martin Hemberg and Achim Menges explore the potential of genetic algorithms as design tools for architecture. The development of 'genetic engines' that model evolutionary and growth processes are demonstrated in the context of two morphogenetic design experiments. The argument for the combination of evolutionary computation with advanced digital modelling and the constraints of manufacturing techniques is developed.

Complex forms in architecture demand new tools and new approaches to design. In 'Engineering Design: Working with Advanced Geometries', Charles Walker, leader of the Advanced Geometry Unit (AGU) at Arup & Partners, in conversation with the Emergence and Design Group, discusses AGU's search for a new paradigm, for new organisational principles and the integration of physical and digital modelling in its processes. The collaboration with architects and artists includes Toyo Ito for the Serpentine Gallery Summer Pavilions in 2002, Anish Kapoor for the Marsyas sculpture in the Unilever series at Tate Modern, and David Adjaye for the British Pavilion at the Venice Biennale 2003. Each of these structures required an exploration into the phenomena of the 3-D bracing of interlocking planes, the algorithm as a generative tool, the buckling stability of flat plates, and the manipulation of stressed skins to achieve sculptural form.

Behaviour, Material and Environment

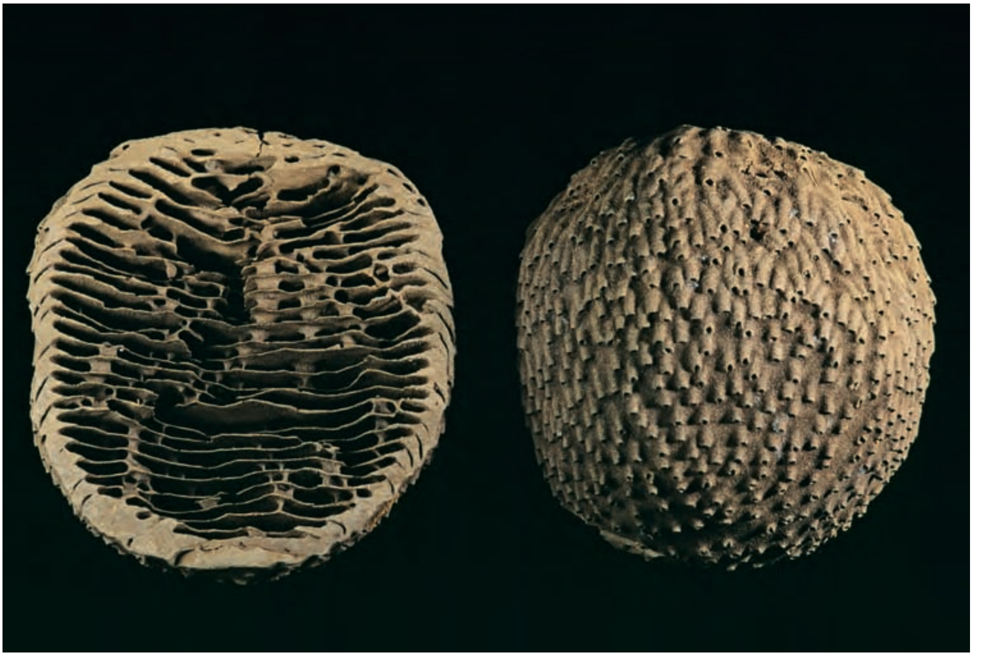
The emphasis on increasing density in mature urban conglomerates is a notable feature in the future strategies of many metropolitan and regional authorities. When very large numbers of people are concentrated in one place, the resources needed to maintain the environmental quality of public and private spaces increase exponentially. Social interaction is more complex and more intense, and this has to be ameliorated by spatial and infrastructural design that maximises qualitative as well as quantitative factors. Emergence provides models for life cycles, and the way in which different life cycles interact with each other in an ecosystem. This is the key to understanding the ecology of densely occupied environments in which topological, structural and programmatic integration facilitates human activities. In 'Morpho-Ecologies' Achim Menges presents two of his architectural research projects that explore the dynamic relations and behaviour of occupation patterns, environmental modulations and material systems.

In natural systems most sensing, decision-making and reactions are entirely local, and global behaviour is the product of local actions, with a high degree of functionality in the material itself. All natural material systems involve movement, often without muscles, to achieve adaptation and responsiveness. In 'Biodynamics' Professor George Jeronimidis examines natural dynamic systems, the material behaviour that enables adaptation, and presents the case for implementation of these models in architecture and engineering.

In natural morphogenesis the information or data of the genome and the physical materials drawn from the environment for the phenome are inextricably intertwined, one acting on the other, and each in turn producing the other. The logic of natural production studied in the sciences of emergence offers a model of seamless integration to replace the conventional separation of design and material production. The search for manufacturing and construction solutions for the complex geometry of contemporary architecture necessitates the development of new methods and tools, and this in turn demands the seamless integration of digital modelling and computer-aided manufacturing. Waagner

Biro is the manufacturing contractor best known for complex geometry constructions. In 'Manufacturing Complexity', Johann Sischka, in conversation with the Emergence and Design Group, discusses the construction strategies and methods of complex geometry structures, such as the dome of the German Reichstag and the roof of the Sony Center in Berlin, and the roof of the Great Court of the British Museum in London.

This issue could be divided into three sections which delineate the strategy for this initial exploration of emergence in architecture. In the first section, 'Emergence and Morphogenesis', the mathematical techniques for modelling the emergence of forms and behaviour from the complex systems of the natural world are juxtaposed with form-finding techniques for stable and dynamic material forms. In the second section, 'Data, Genes and Speciation', the focus is on geometry, pattern and behaviour, and the computational and material evolution of 'populations' and 'species' of architectural forms with complex behaviour. The third section, 'Behaviour, Material and Environment', is concentrated on the adaptive behaviour of natural and architectural material systems and the industrial potential for a seamless integration of their design and production.



Section of complex nest structure built by Apicotermes termites. 20 centimetres (8 inches) across, the structure is made from soil and woody material, with external holes to ventilate the horizontal layered passages, which are vertically connected by an internal spiral staircase. The complex form emerges from the collective behaviour of a large number of termites following very simple rules. Photograph © Pascal Goetgheluck/Science Photo Library.

Emergence Defined
A Mini-Bibliography

1 John Holland, ***Emergence: from Chaos to Order***, Oxford University Press (Oxford), 1998

'We are everywhere confronted with emergence in complex adaptive systems – ant colonies, networks of neurons, the immune system, the Internet, and the global economy, to name a few – where the behaviour of the whole is much more complex than the behaviour of the parts.'

'… it is unlikely that a topic as complicated as emergence will submit meekly to a concise definition, and I have no such definition to offer. I can, however, provide some markers that stake out the territory, along with some requirements for studying the terrain …'

Both quotes are from the opening chapter of *Emergence: from Chaos to Order*, 'Before We Proceed'. Holland's concentration on well-defined technical concepts as a foundation for a framework for studying emergence is excellent. He explores three kinds of concepts – purely mathematical concepts, systems and games concepts, and general informal concepts. Modelling is central to the book and to his discussion.

2 Steven Johnson, ***Emergence, the Connected Lives of Ants, Brains, Cities and Software***, Scribner (New York), 2001; Allen Lane/Penguin Press (London), 2001

In discussion of complex, adaptive systems:

'The movement from low-level rules to higher-level sophistication is what we call emergence', and '… a higher-level pattern arising out of parallel complex interactions between local agents'.

This is a good general read, covering many fields. In particular the second section, covering what Johnson identifies as the four principles of emergence – local interaction of neighbours, pattern recognition, feedback and indirect control – are a good, if general, introduction. The book also offers a short history of the intellectual development of what Johnson calls 'the bottom-up mindset'.

3 'Self-Organisation, Emergence and the Architecture of Complexity', Francis Heylighen in ***Proceedings of the 1st European Conference on System Science***, Paris

'Emergence is a classical concept in systems theory, where it denotes the principle that the global properties defining higher order systems or "wholes" (e.g. boundaries, organization, control …) can in general not be reduced to the properties of the lower order subsystems or "parts". Such irreducible properties are called emergent.'

'The spontaneous creation of an "organised whole" out of a "disordered" collection of interacting parts, as witnessed in self-organising systems in physics, chemistry, biology, sociology … is a basic part of dynamical emergence.'

This interesting paper concentrates on the dynamics and evolution of emergent properties.

Michael Hensel, Achim Menges, Michael Weinstock, 'Introduction', *Emergence: Morphogenetic Design Strategies*, **Michael Hensel, Achim Menges and Michael Weinstock (guest-editors),** *AD* **Profile 169,** *AD* **74, May–June 2004, pp 6–9.**

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ACHIM MENGES **Polymorphism** *AD* March–April 2006

Natural morphogenesis, the process of evolutionary development and growth, generates polymorphic systems that obtain their complex organisation and shape from the interaction of system-intrinsic material capacities and external environmental influences and forces. The resulting, continuously changing, complex structures are hierarchical arrangements of relatively simple material components organised through successive series of propagated and differentiated subassemblies from which the system's performative abilities emerge.

A striking aspect of natural morphogenesis is that formation and materialisation processes are always inherently and inseparably related. In stark contrast to these integral development processes of material form, architecture as a material practice is mainly based on design approaches that are characterised by a hierarchical relationship that prioritises the generation of form over its subsequent materialisation. Equipped with representational tools intended for explicit, scalar geometric descriptions, the architect creates a scheme through a range of design criteria that leave the inherent morphological and performative capacities of the employed material systems largely unconsidered. Ways of materialisation, production and construction are strategised and devised as top-down engineered, material solutions only after defining the shape of the building and the location of tectonic elements.

An alternative morphogenetic approach to architectural design entails unfolding morphological complexity and performative capacity from material constituents without differentiating between formation and materialisation processes. Over the last five years I have pursued related design research through projects and also in educational collaboration with various colleagues at the Architectural Association (AA) and other schools. Based on concepts of developmental biology and biomimetic engineering, the core of such a morphogenetic approach is an understanding of material systems not as derivatives of standardised building systems and elements facilitating the construction of pre-established design schemes, but rather as generative drivers in the design process.

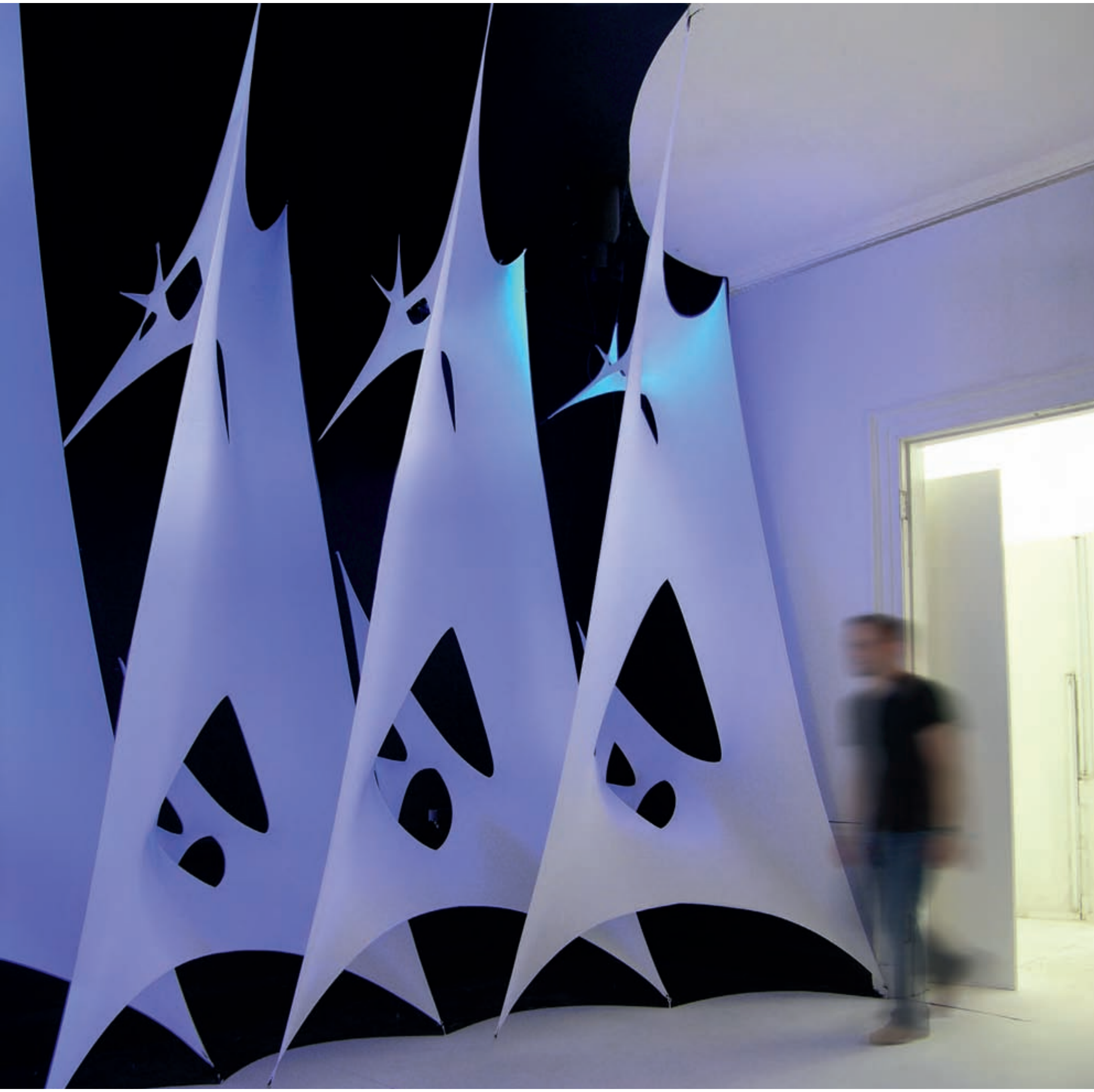
Extending the concept of a material system by embedding its material characteristics, geometric behaviour, manufacturing constraints and assembly logics allows for deriving and elaborating a design through the system's intrinsic performative capacities. This promotes an understanding of form, materials and structure not as separate elements, but rather as complex interrelations in polymorphic systems resulting from the response to varied input and environmental influences and derived through the logics and constraints of advanced manufacturing processes. This demands new modes of integrating design techniques, production technologies and system performance, a cross-section of which will be discussed here. Through a series of five morphogenetic design experiments ranging from homologous systems[1] to polytypic species,[2] the characteristics of integral form-generation processes enabled through parametric association, differential actuation, dynamic relaxation, algorithmic definition and digital growth will be examined. Discussing the organisational potentialities and spatial opportunities that arise from such a design approach would go beyond the scope of this article.[3] The focus is therefore placed on presenting relevant tools and methods for such an integral approach to design.

Form-Finding and Dynamic Relaxation: Membrane Morphologies

The disconnection of form generation and subsequent materialisation emblematic for current design approaches manifests itself in the 'hard control' that the architect needs to exert on the constructs he or she designs. Before any material realisation can take place, the designer must define the precise location and exact shape of all elements, geometrically controlling the maximum amount of points needed to describe the system to be constructed. However, such a design method fails to notice the potential of using the capacity for self-organisation inherent to material systems. This suggests a design process based on the strategic 'soft control' of minimal definition that instrumentalises the behaviour of a material system in the formation process. Integrating the logics of form, material and structure was investigated in a series of membrane structures[4] developed by Michael Hensel and myself as exhibition installations for different locations. Membrane structures are of particular interest for such an exploration, as any resultant morphology is intrinsically related to the material characteristics and the formation process of pretensioning. Thus a viable design method cannot be based on geometric hard control over a maximum number of points of the system, but should be based on the local exertion of force on strategic points.

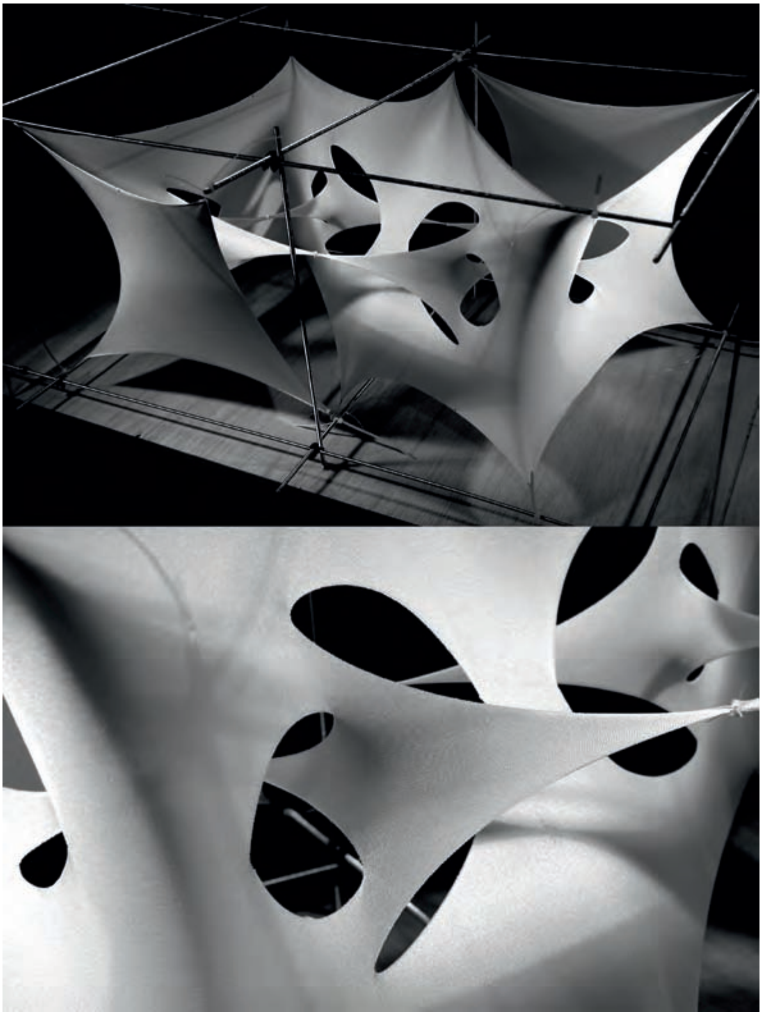
Form-finding, as pioneered by Frei Otto,[5] is a design technique that utilises the self-organisation of material systems under the influence of extrinsic forces. In membrane structures, the displacement of particular boundary points and the consequent pretensioning force are correlated with the material and form, in that the form of the structure can be found as the state of equilibrium of internal resistances and external forces. Form-finding processes for membranes can be physically modelled and simulated through digital dynamic relaxation. The latter involves a digital mesh that settles into an equilibrium state through iterative calculations based on the specific elasticity and material make-up of the membrane – isotropic in case of foils, anisotropic in case of fabrics – combined with the designation of boundary points and related forces. The same software applications can usually also generate the associated cutting patterns if the membrane is to be constructed from relatively nonelastic material.

In the project presented here, the material consists of nylon fabric with different elasticity in the warp and weft direction. An additional design aspect was the introduction of holes cut into the fabric that considerably alter the behaviour of the membrane. These holes were critical as they expanded the performance range of the system. While traditional form-finding methods focus on structural behaviour of material form resulting in monoparametric assessment criteria, the aim of this project was the exploration of a multiparametric approach. Thus the additional capacity of the perforated membrane system to modulate visual permeability as a differentiated exhibition screen was understood as being intrinsically related to the structural form. In order to instrumentalise this relation, two operations were of critical importance for the design process: first, the parametric specification and subsequent confection of each membrane patch defined by boundary points and cutting lines expressed within the object coordinate space of the patch and, second, the pretensioning action defined through the relocation of the object boundary



Michael Hensel and Achim Menges, Diploma Unit 4 - Architectural Association, form-finding and dynamic relaxation. Initial form-finding experiment of 'minimal hole' configuration. 'Membrane Morphologies 02' installed at the Architectural Association, London. Photograph © Achim Menges.

points towards anchor points described in the coordinate space of the exhibition room. Feeding back information between examining different values of local parametric variables and testing altering positions for the anchor-point coordinates creates multiple membrane morphologies that all remain coherent with the construction logics of the system. A specific configuration can be developed through corroborating and negotiating different behavioural characteristics and specific performance requirements. The resulting membrane morphology settles into a stable state of unity between form and force. At the same time the correlated complex curvature of the membrane and the opening of the holes provide for different degrees of visual permeability resulting in the varied exposure of the exhibits.



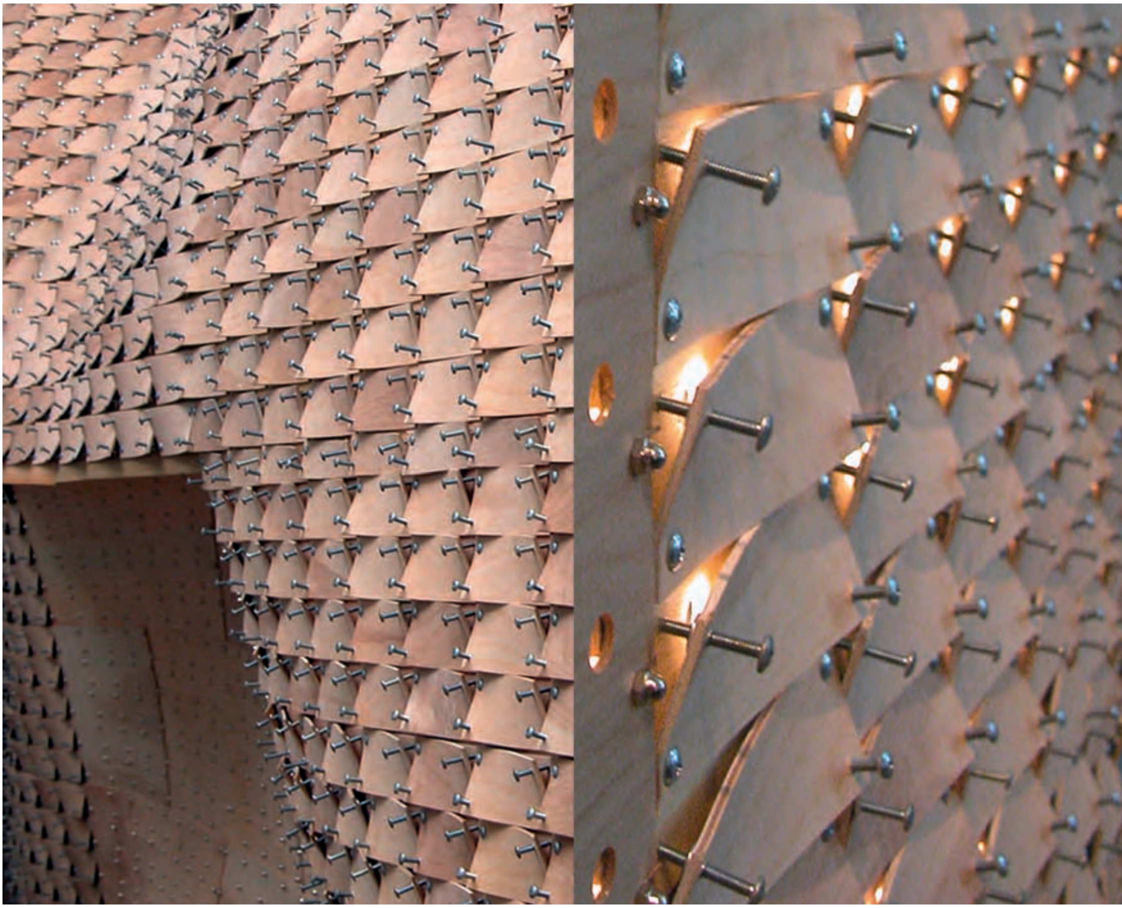
Michael Hensel and Achim Menges, form-finding and dynamic relaxation. Close-up view of 'minimal hole' configuration. 'Membrane Morphologies 02' installed at the Architectural Association, London. Photographs © Michael Hensel.

Differential Surface Actuation: Metapatch Project

In most form-finding processes, operations focus on the exertion of force on strategic system-points, which leads to a 'global' manipulation of the overall system. In this context, 'global' refers to the entirety of a system, while 'local' describes a sublocation. It is important to realise that the self-organising capacity of material systems is not limited to 'global' form-finding processes such as the one mentioned above. It can also be deployed in a 'local' manner. One such exploration is the project developed by Joseph Kellner and David Newton[6] in the context of the Generative Proto-Architectures studio led by Michael Hensel and myself at Rice School of Architecture. This experiment was driven by the hypothesis that the material capacity of a system consisting of uniform elements can be employed to achieve variable yet stable configurations with complex curvature through a vast array of local actuations.

Initial tests confirmed that a series of very simple rectangular wooden elements fastened to a larger sheet of timber can be deployed as local actuators. Each rectangular element is attached to a larger patch by four bolts, one in each corner. While two of the bolts in opposite corners are permanently fixed and thereby define the length of the diagonal line between them, the other two bolts remain adjustable. Tightening these two bolts increases the distance between the element's corners and the patch begins to bend. As each larger patch is covered with arrays of elements, the incremental induction of curvature results in a global (de)formation. Detailed investigations of the correlation of element and patch variables such as size, thickness and fibre orientation, actuator locations and torque lead to taxonomy of geometric patterns and generated system behaviour. This data enabled scripting of the parametric definition, assembly sequence and actuation protocols for a large prototype construction.

The configuration tested as a large-scale prototype consists of initially flat, identical timber patches onto which equal elements with actuator bolts are attached on one side. According to the particular distribution of actuator positions, the elements are connected to the patches and the patches are assembled into a larger structure with different orientations of the element's clad sides. The resulting material system consists of 48 identical patches, 1920 equal elements and 7680 bolts. After assembly, the structure is initially entirely flat. Through the subsequent incremental actuation of fastening delineated bolts it then rises into a stable, self-supporting state with alternating convex and concave curvature. Changes to variables within this actuation protocol allow for articulating and testing multiple emergent states and their inherent performative capacity. As the patches are perforated by drilled hole-patterns, the performative modulation of porosity and the adjustment of structural capacity through curvature are intrinsically correlated with the manipulation of the system's material and geometric behaviour. Developing an integral technique of form generating and making based on the material capacity and local actuation of the system enabled a variable, complex morphology derived through the materiality, geometry and interaction of amazingly simple material elements.



Joseph Kellner and David Newton, (supervised by Michael Hensel and Achim Menges), Protoarchitecture Studio Rice School of Architecture 2004. Differential surface actuation, Metapatch prototype at the *Modulations* exhibition, Rice School of Architecture, Houston, US, November 2004 and close-up view of actuation elements and patches. Photograph Chad Loucks. © Achim Menges/Chad Loucks.

Component Differentiation and Proliferation: Paper-Strip Experiment

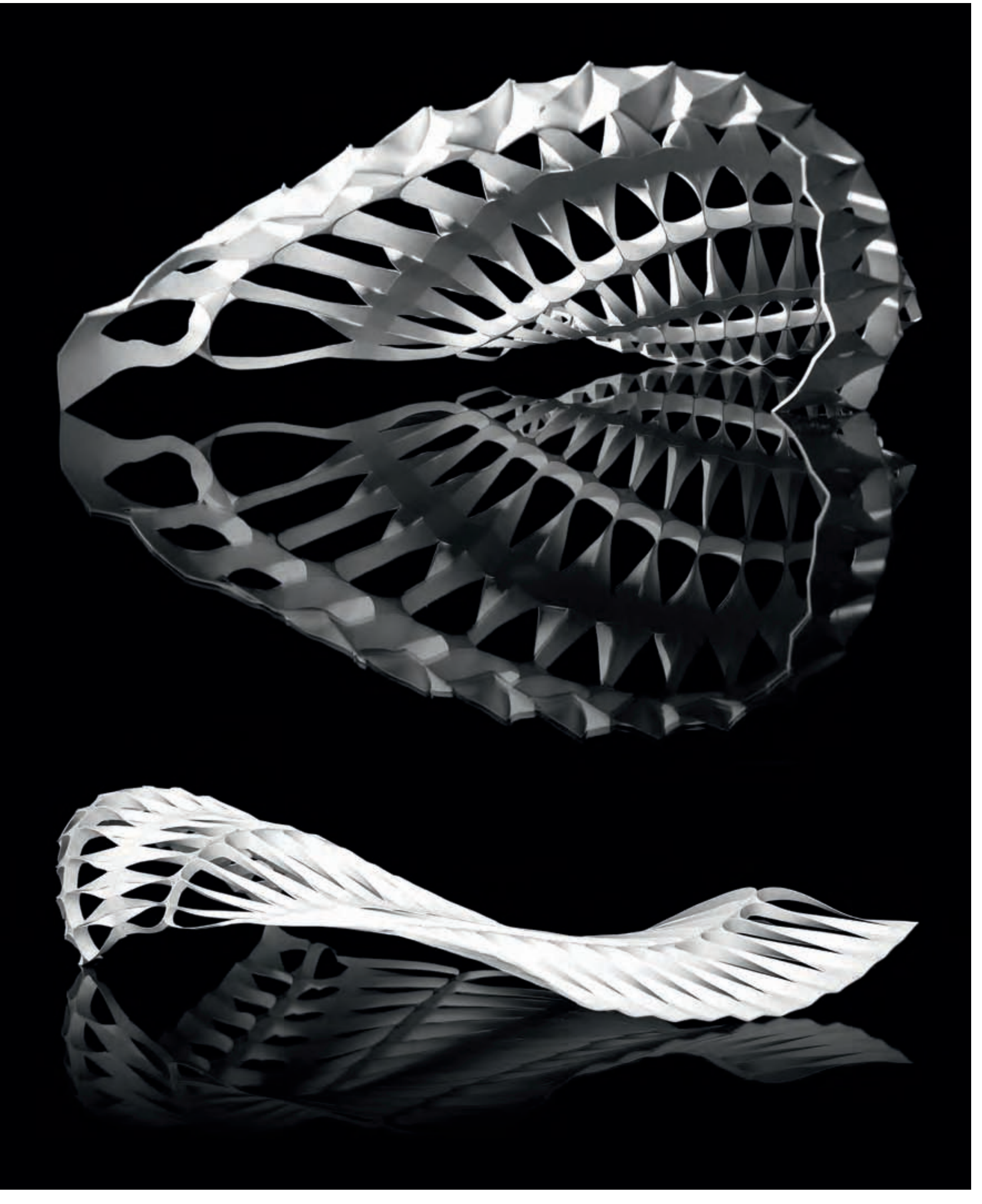
A third approach towards polymorphous material systems is component differentiation and proliferation. While the experiment explained above relied on the differential actuation of equal components, the following morphogenetic technique is based on parametric components defined through geometric relationships. The proliferation of different instantiations of a parametric component generates a material system with differentiated sublocations. I developed such a design process through an experiment[7] based on very simple material components, namely twisted and bent paper-strips.

In this project, a digital component is defined as an open and extendable geometric framework based on the 'logics' of a material system that integrates the possibilities and limits of making, and the self-forming tendencies and constraints of the material. Through elaborate physical studies of the behaviour of twisted and bent paper-strips, the essential geometric features, such as points of curvature, developability of the surface and tangency alignments were captured in a digital component. This component describes the nonmetric geometric associations of a single paper-strip as part of a component collective and thereby anticipates the process of assembly and integration into a larger system. In other words, through parametric geometric relationships the digital component ensures that any morphology generated can be materialised as strips cut from sheet material.

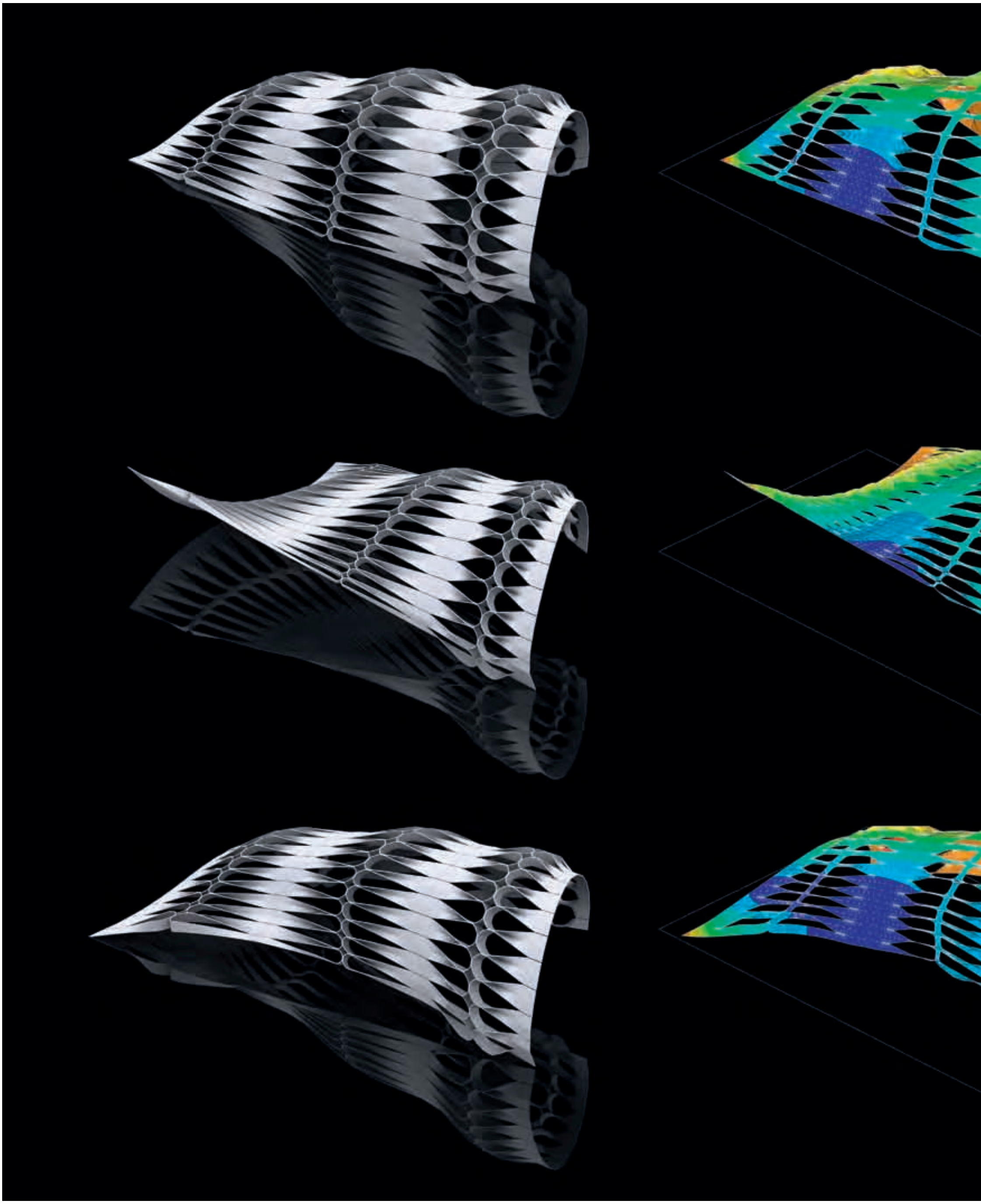
A larger system can then be established through a process of proliferating components into polymorphic populations. For this, a variable 'proliferation environment' is defined to provide the constraints for the accretion of components as well as stimuli/inputs for their individual morphologies. An algorithm drives the distribution of components with three possible modes of proliferation: first, an outward proliferation of a component into a population that increases in number until the environment's boundaries are reached, second, an inward proliferation within the initial system's setup and, third, a hierarchical proliferation based on environments/inputs for secondary, tertiary, etc, systems. These three proliferation modes can also be deployed in combination, leading to nested populations of component systems.

The resulting system remains open to 'local' manipulation of individual components, 'regional' manipulation of component collectives and 'global' manipulations of the component system, proliferation environment and distribution algorithm. The parametric associations of and between components, collectives and the overall system allow the rapid implementation of these manipulations, leading to a multitude of self-updating system instances. Situated in a simulated environment of external forces, the system's behavioural tendencies then reveal its performative capacity. For example, exposing multiple system instances to digitally simulated light flow enables the registration of interrelations between parametric manipulations and the modulation of light levels upon and beyond the system.

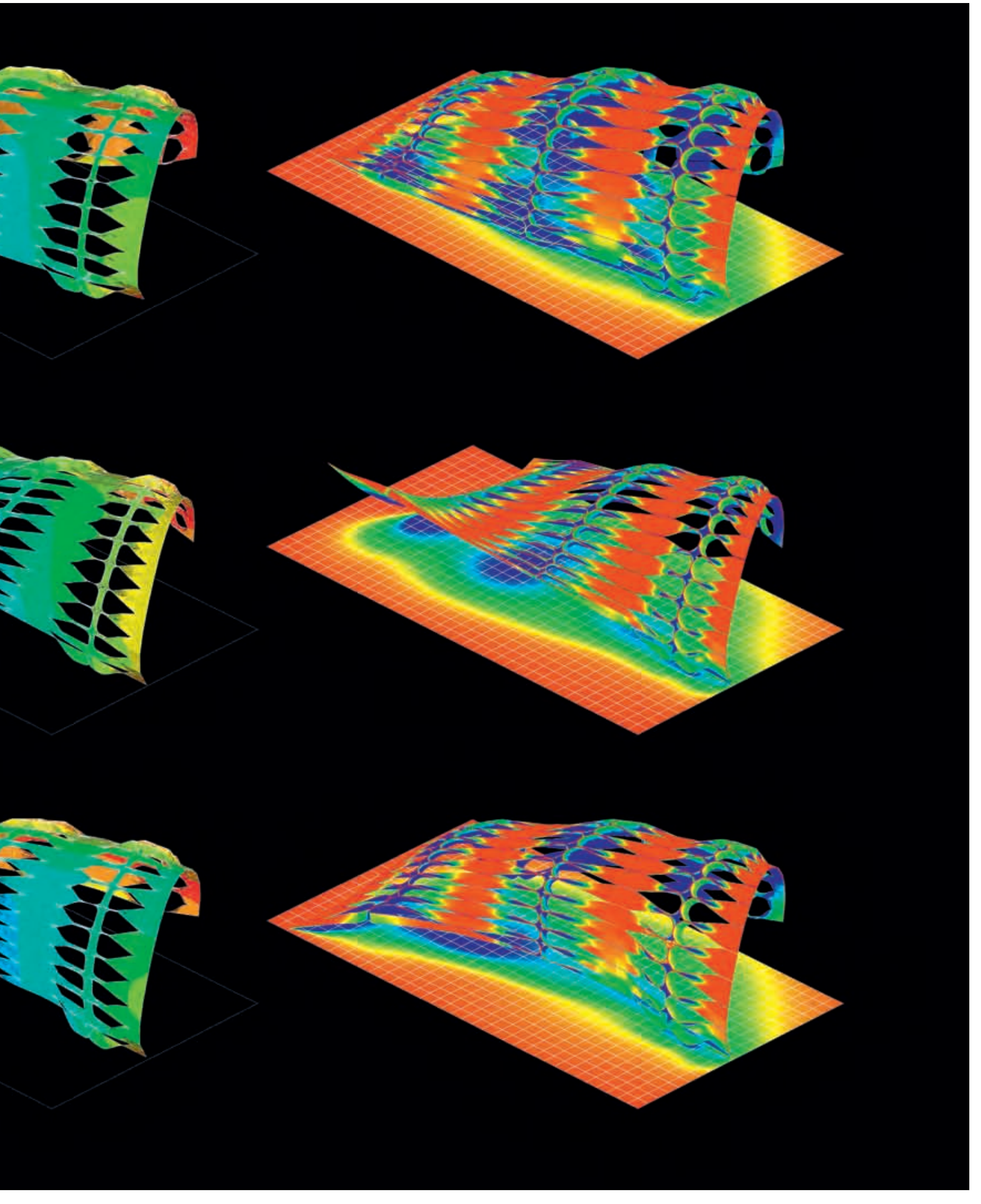
Additional digital structural analyses of the same instances reveal the related load-bearing behaviour of the system. These behavioural tendencies of the system interacting with external forces and modulating transmitted flows can be traced across various parametrically defined individual morphologies. The resulting patterns of force



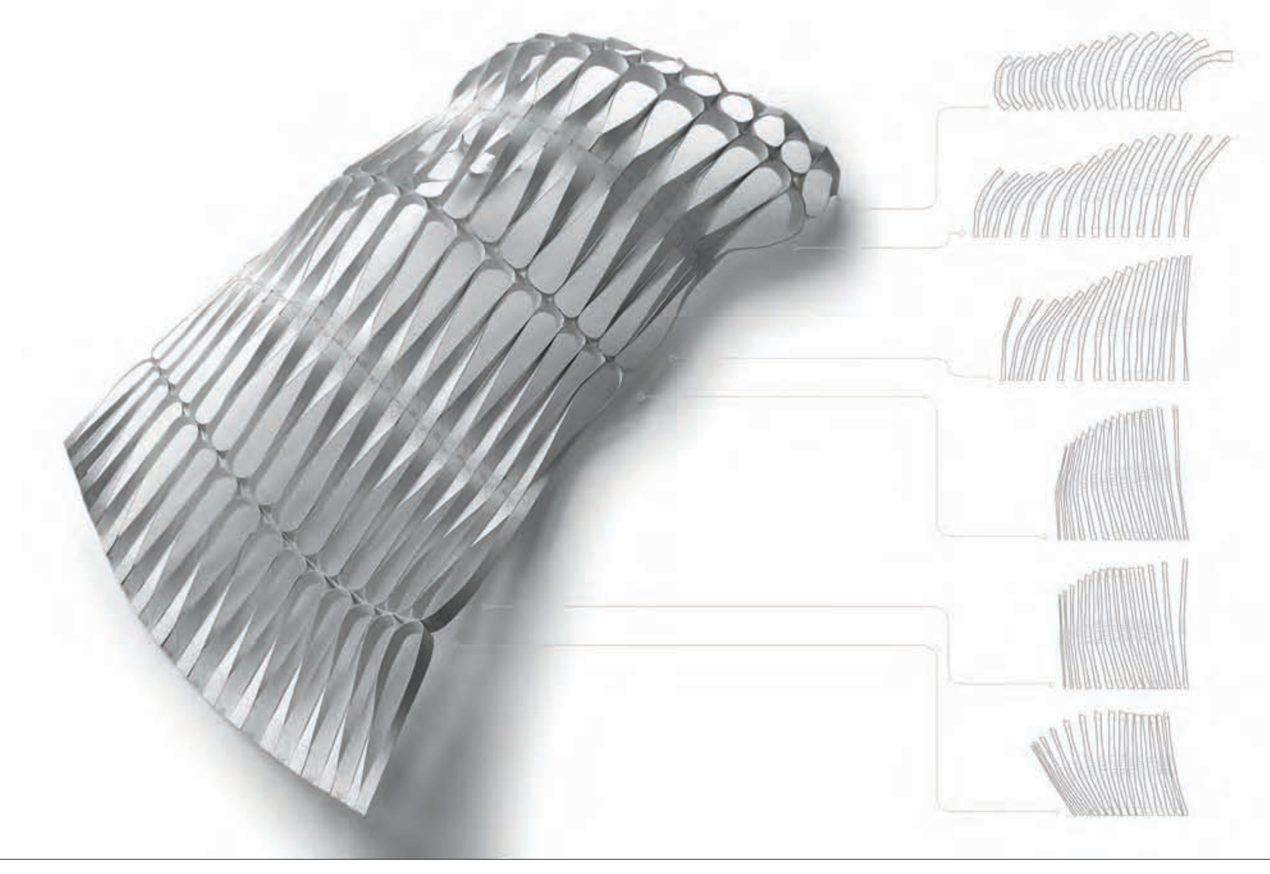
Achim Menges, component differentiation and proliferation. Physical test model of paper-strip system derived through a parametric process embedding the material characteristics, manufacturing constraints and assembly logics observed in physical tests. Photograph © Achim Menges.



Achim Menges, geometric manipulations of the parametric system (left) and related patterns of structural behaviour (centre: contour plots of finite element analysis under gravity load) and modulation of light conditions (right: geographically specific illuminance analysis on the system and a register surface for an overcast sky). Illustrations © Achim Menges.



distribution and conditions of varying luminous intensity can inform further cycles of local, regional and global parametric manipulations. Continually informing the open parametric framework of component definition and proliferation yields an increasing differentiation with the capacity for negotiating multiple-performance criteria within one system. The important point is that the outlined parametric design technique permits the recognition of patterns of geometric behaviour and related performative capacities of the polymorphous component population. In continued feedback with the external environment, these behavioural tendencies can then inform the ontogenetic development of a specific system through the parametric differentiation of its sublocations. And these processes of differentiation will always remain consistent with the constraints of materialisation, fabrication and assembly of the paper-strips.

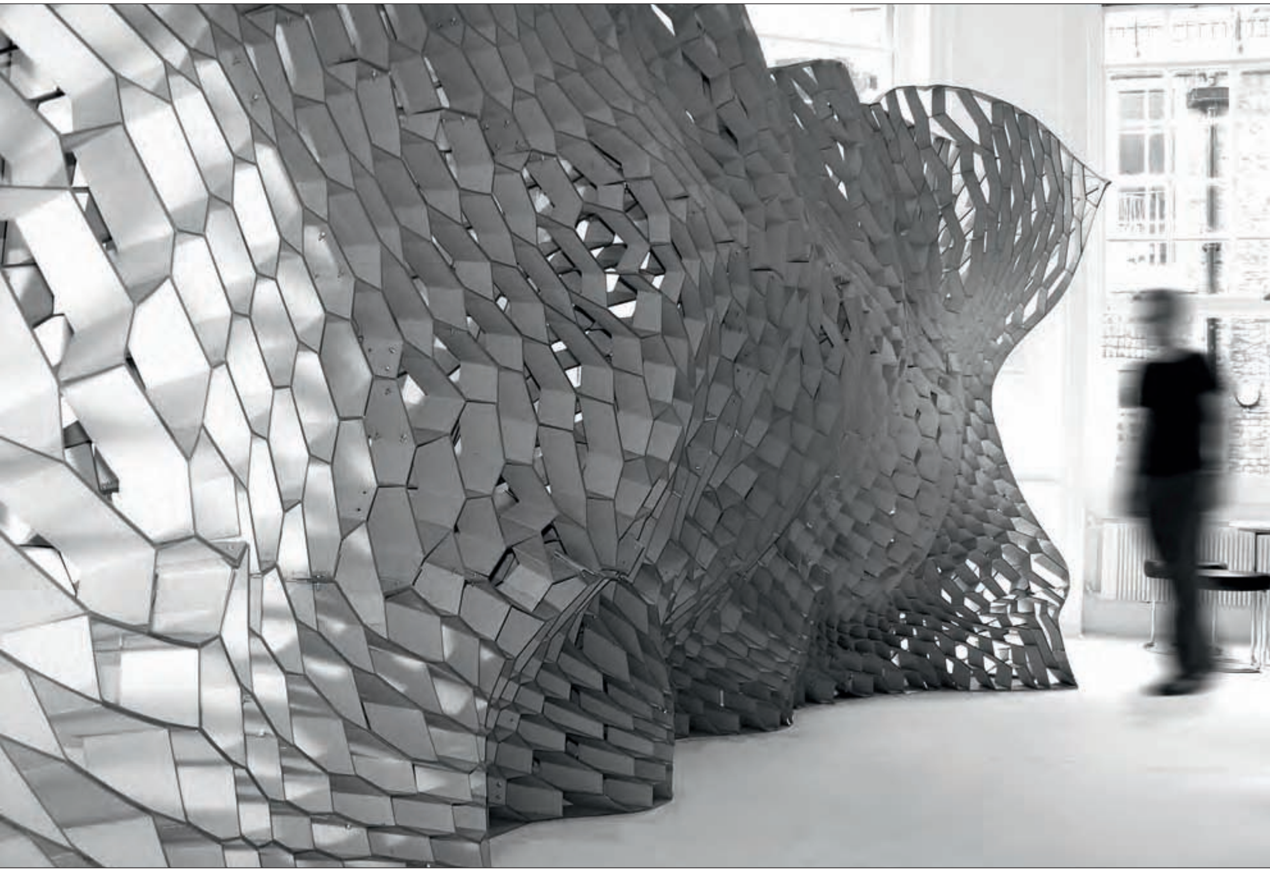


Achim Menges, physical test model of a population of 90 paper-strip components and related strip-cut patterns. Photograph © Achim Menges.

Generative Algorithmic Definition: Honeycomb Morphologies

Another technique for the development of a polymorphous cellular structure has been researched by Andrew Kudless for his Masters dissertation[8] as part of the AA Emergent Technologies and Design programme led by Michael Weinstock, Michael Hensel and myself. While in the paper-strip experiment the material, manufacturing and assembly logics were embedded in a digital component corresponding to the physical element to be proliferated into a larger population, the focus in this project is to algorithmically generate a coherent honeycomb system able to colonise variable geometric envelopes within the limits of fabrication.

Standard honeycomb systems are limited to planar or regularly curved geometry due to their equal cell sizes resulting from the constraints of industrial mass-production. However, computer-aided manufacturing (CAM) processes allow for a greatly increased range of

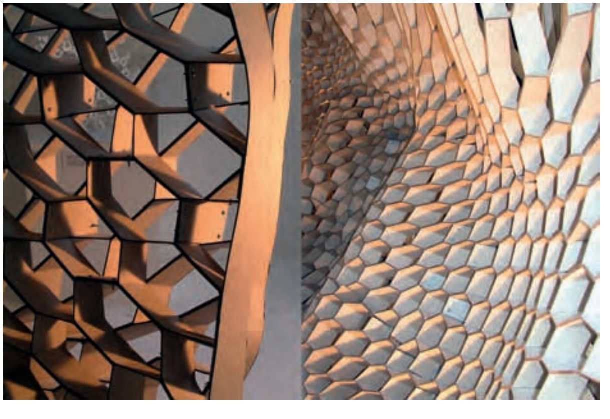


Master-project by Andrew Kudless, EmTech (Michael Hensel, Achim Menges, Michael Weinstock), Architectural Association. Generative algorithmic definition, algorithmically derived honeycomb prototype in which each cell is unique in shape, size and depth, allowing for changing cell densities and double-curved global geometry. Photograph © Achim Menges.

geometries if the production logics become an integral part of the form-generation process. In this particular case, the embedding of manufacturing constraints in the rules of deriving the system required the consideration of three aspects for the construction of a large-scale prototype. First, to ensure topological continuity all generated cells need to remain hexagonal and tangential with the adjacent cell walls. Second, folded material strips of which the system consists are cut from planar sheet material with a laser, therefore the possible generation of elements must be linked to the constraints of the related production technique, namely two-dimensional cutting of limited size and the specific material properties such as, for example, the folding behaviour. The third important point is the anticipation of required assembly logistics through labelling all elements and inherently defining the construction sequence by the uniqueness of each pair of matching cell walls.

Based on these aspects, the resultant digital generation process comprises the following sequence. In order to define the eventual vertices of the honeycomb strips, points are digitally mapped across a surface that is defined by the designer and remains open to geometric manipulations. The parametrically defined correlation of point distribution and geometric surface characteristics can also be altered. An algorithmic procedure that connects the distributed points creates the required folded strip lines. Looping this algorithm across all points forms the honeycomb mesh, and this procedure is repeated across an offset point distribution to generate a system wire-frame model. In a following step the defined honeycomb strips are unfolded, labelled and nested to prepare for subsequent production.

This integral form-generation and fabrication process can create honeycomb systems in which each cell can be unique in shape, size and depth, allowing for changing cell densities and a large range of irregularly curved global geometries. The resultant differentiation in the honeycomb has considerable performance consequences, as the system now carries the capacity for adaptation to specific structural, environmental and other forces not only within the overall system, but locally across different sublocations of varying cell size, depth and orientation. Embedding the possibilities and constraints of material and production technology, the form-generation technique and its parametric definition become, per se, the main interface of negotiating multiple-performance criteria.



Master-project by Andrew Kudless, EmTech (Michael Hensel, Achim Menges, Michael Weinstock), Architectural Association. Generative algorithmic definition, close-up views showing planar connection tabs between honeycomb layers (left) and double-curved global surface articulation (right). Left: Photograph © Sue Barr/ AA; Right: Photograph © Achim Menges.

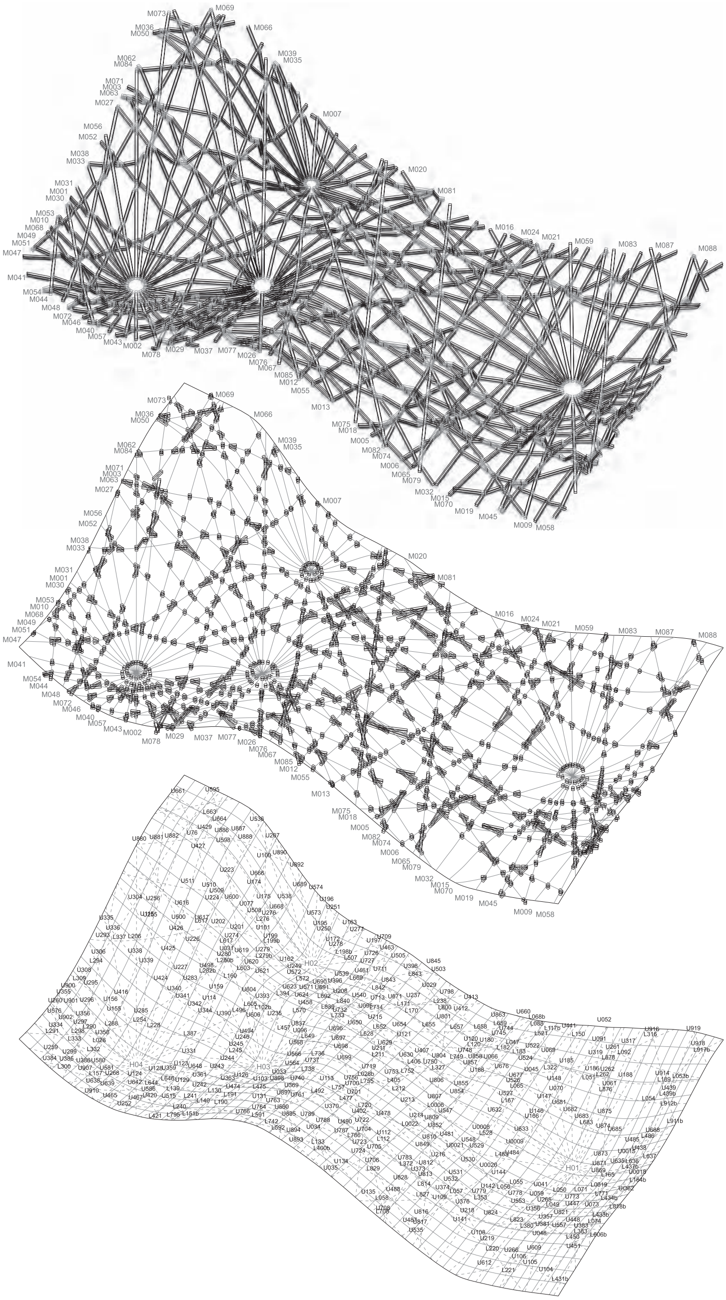
Digital Growth and Ontogenetic Drifts: Fibrous Surfaces

The final project synthesises the presented methods of component differentiation and mapped propagation with digitally simulated growth.[9] This collaborative project,[10] developed by Sylvia Felipe, Jordi Truco and myself together with Emmanuel Rufo and Udo Thoennissen, aims to evolve a differentiated surface structure consisting of a dense network of interlocking members from a basic array of simple, straight elements. To achieve complexity in the resultant material system the exploration focuses on advanced digital generation techniques in concert with relatively common computer numerically controlled (CNC) production processes.

The basic system constituent is defined as a jagged, planar strip cut from sheet material on a three-axis CNC router. In a parametric software application a generic digital component is established through the geometric relationships that remain invariant in all possible instances of the material element and the variable production constraints of the intended machining technology and process. Each particular implementation of the parametric component in the system to be digitally constructed is then based on three interrelated inputs. Primary input influencing the particular geometry of a specific system type is given by a Gestalt envelope that describes the system's overall extent and shape. This envelope is defined by a geometric surface grown in a digitally simulated environment of forces. The digital growth process employed for the generation of the surface is based on extended Lindenmayer systems (L-systems), which produce form through the interaction of two factors: a geometric seed combined with rewriting rules that specify how elements of the shape change, and a process that repeatedly reinterprets the rules with respect to the current shape.

In this particular case the surface is represented by a graph data structure constituted by a set of edges, vertices and regions. Since all edges are constantly rewritten during the digital growth process, all parts of the surface continuously change until the ontogenetic drifts[11] settle into a stable configuration. Based on the growing surface, another input for the implementation of the material elements is generated. In response to particular geometric surface features such as global undulation and regional curvature, a variable distribution algorithm establishes a network of lines on the surface indicating the position of each element and the related node type. Digital components then populate the system accordingly and construct a virtual solid model. In the resultant organisation, crossing members only intersect if they are perpendicular due to the embedded manufacturing constraints. If not, they pass under or over crossing elements, not dissimilar to a bird's nest, and thereby form a geometrically defined, self-interlocking, stable structure.

This complex correlation of geometric definition, structural behaviour and production logics does not only remain coherent in a single system, such as the tested prototype with almost 90 members and 1000 joints, but is integral to the generation process itself. This is of particular importance if one considers that the surface defining the critical morphogenetic input is constructed through a bottom-up process in which all parts respond to local interactions and the environment. As these internal and external interactions are complex and the interpretation of the L-systems is nonlinear, the outcome of the growth process remains open-ended. This continual change, combined with the long-chain dependencies of the subsequent generation



Achim Menges, digital growth and ontogenetic drifts. Diagram: the surface geometry generated through a digital growth process based on extended Lindenmayer systems (bottom) provides the geometric data for an algorithmic distribution of parametric components (centre), which results in a complex network of self-interlocking straight members (top) that are immediately ready for production. Illustrations © Achim Menges.

methods, enables the growth of different system types of member organisation, system topology and consequent performative capacity. Such an integral design approach begins to expand the notion of performative polymorphic systems towards digital typogenesis.

While the five experiments presented here remain in a proto-architectural state awaiting implementation in a specific architectural context, the related morphogenetic design techniques and technologies allow for the rethinking of the nature of currently established design processes. A design approach utilising such methods enables architects to define specific material systems through the combined logics of formation and materialisation. It promotes replacing the creation of specific shapes subsequently rationalised for realisation and superimposed functions, through the unfolding of performative capacities inherent to the material arrangements and constructs we derive. Most importantly, it encourages the fundamental rethinking of our current mechanical approaches to sustainability and a related functionalist understanding of efficiency.

Notes

1 Homologous systems share an evolutionary transformation from the same 'ancestral' state.
2 Polytypic species are species that comprise several subspecies or variants.
3 The organisational potentialities of complex built environments have been outlined in Achim Menges, 'Morpho-ecologies: Approaching Complex Environments', *Emergence: Morphogenetic Design Strategies*, *AD* 74, No 3, 2004, pp 48–53.
4 'Membrane Morphologies' Morphogenetic Design Experiment 04, April 2004 to Sept 2005. Phase 01: Physical and Digital Form-Finding Developments (Michael Hensel and Achim Menges, with Giorgos Kailis and Nikolaos Stathopoulos). Phase 02: Exhibition installation at the AA School of Architecture, London, 2004 (Michael Hensel and Achim Menges, with Tiffany Beriro, Edouard Cabay and Valeria Segovia). Phase 03: Exhibition installation at Rice School of Architecture, Houston, 2004 (Michael Hensel and Achim Menges).
5 See 'Frei Otto in Conversation with the Emergent and Design Group', *AD Emergence: Morphogenetic Design Strategies*, pp 19–25.
6 Joseph Kellner and David Newton, 'Metapatch' project, Generative Proto-Architectures Studio, Rice School of Architecture, Houston, September to December 2004. Visiting professors: Michael Hensel and Achim Menges. Visiting staff: Neri Oxman and Andrew Kudless.
7 'Paper-Strip Morphologies' Morphogenetic Design Experiment 03, April 2004 to April 2005. Phase 01: Physical and Digital Form-Finding Developments (Achim Menges with Andrew Kudless, Ranidia Leeman and Michuan Xu). Phase 02: Parametric Set-Up and Proliferation (Achim Menges); Finite Element Analysis (Nikolaos Stathopoulos).
8 Andrew Kudless, 'Manifold – Honeycomb Morphologies', MA dissertation project, Emergent Technologies and Design Masters programme, AA Graduate School of Architecture, London, 2004. Programme directors: Michael Hensel and Michael Weinstock. Studio master: Achim Menges.
9 See Dr Una-May O'Reilly, Martin Hemberg and Achim Menges, 'Evolutionary Computation and Artificial Life in Architecture', *AD Emergence: Morphogenetic Design Strategies*, pp 48–53.
10 'Fibrous Surfaces' Morphogenetic Design Experiment 05, June 2004 to October 2005. Phase 01: 'Integral Envelopes' Workshop (Sylvia Felipe, Achim Menges, Jordi Truco, Emmanuel Rufo and Udo Thoennissen), ESARQ International University of Catalunya, Barcelona. Phase 02: Algorithmic Distribution and Material Tests (Emmanuel Rufo, Sylvia Felipe, Achim Menges, Udo Thoennissen and Jordi Truco). Phase 03: Material Prototype (Emmanuel Rufo, Sylvia Felipe, Achim Menges and Jordi Truco).
11 Ontogenetic drifts are the developmental changes in form and function that are inseparable from growth.

Achim Menges, 'Polymorphism', Michael Hensel, Achim Menges, and Michael Weinstock (guest-editors), *Techniques and Technologies in Morphogenetic Design*, *AD* Profile 180, *AD* 76, March–April 2006, pp 78–87.
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