Achim Menges presents a range of morphogenetic design techniques and technologies that synthesise processes of formation and materialisation. Through a series of design experiments, he explains his research into 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 of advanced manufacturing processes.
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 processes and devised as top-down engineered, material solutions only after defining the shape of the building and the location of tectonic elements.

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 to polytypic species, 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. 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 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 – isotropic in case of foils, anisotropic in case of fabrics – found as the state of equilibrium of internal resistances and material and form, in that the form of the structure 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 – 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 points towards anchor points described in the coordinate space of the exhibition room. Feeding back information between examining different values of local

Form-finding and dynamic relaxation
Clockwise from top left: Initial form-finding experiment (top) and close-up view of ‘minimal hole’ configuration (bottom); ‘Membrane Morphologies 02’ installed at the Architectural Association, London; close-up view of

membrane installation resulting from parametrically defined patch specification, cut location and pretensioning action; digital model form found through dynamic relaxation processes (left) and related specification and installation of ‘Membrane Morphologies 02’ (right).
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.

**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 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.

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 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

Differential surface actuation
Top to bottom: Close-up view of actuation elements and patches (left) and resulting light transmission patterns (right); Metapatch prototype at the ‘Modulations’ exhibition, Rice School of Architecture, Houston, US, November 2004; parametric definition and actuation protocol for full-scale prototype.
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 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.

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 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 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.

Digital Growth and Ontogenetic Drifts: Fibrous Surfaces
The final project synthesises the presented methods of component differentiation and mapped propagation with digitally simulated growth. This collaborative project, 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 interprets 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 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 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. 

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.

Above: View of fibrous self-interlocking surface structure.
Notes
1. Homologous systems share an evolutionary transformation from the same 'ancestral' state.
2. Polytypic species are species that comprise several subspecies or variants.
11. Ontogenetic drifts are the developmental changes in form and function that are inseparable from growth.