Manufacturing Diversity

Recent developments of digital fabrication and computer-aided manufacturing (CAM) in the building sector have a profound impact on architecture as a material practice. In this article, Achim Menges describes advanced processes of steel, timber and membrane fabrication and construction through an investigation of the pioneering work of world-leading manufacturing companies Covertex, Finnforest Merk, Octatube Space Structures, Seele and Skyspan.

Covertex, pneumatic cladding installation for the Allianz Arena, Munich, Germany, 2004.
Architecture as a material practice is changing rapidly through the increasing number of geometrically complex designs accomplished by leading practices, and through a growing interest in a built environment that is becoming much more diverse than in the days of mass production and standardisation of building elements and systems. The key concepts underlying these developments are, for example, variation or differentiation leading to varied building elements and systems that are similar in degree, together with an increasingly integral relation between building systems and elements that are different in kind.

The work of leading manufacturing companies in the building sector confirms the contemporary belief that computer-aided manufacturing (CAM) processes are playing a critical role in a potential paradigm shift from mass production and its inherent standardisation, to the conception and production of differentiated building elements and systems. Thus it seems to be critical now to understand digital production as a strategic aspect of the design process rather than a merely facilitative activity; especially as CAM is not at all a recent technological development.

Initially developed with the support of the US military to overcome the limitations of mechanised mass production in the 1950s, the first generation of computer-controlled automation introduced numerical control (NC) to machines for metalworking applications. Over the following four decades, derivate systems, now referred to as computer numerical control (CNC), have been developed for a much wider range of materials and a variety of scales, and still constitute the basis for most CAM applications. The arrival of microprocessors in the 1970s, the development of personal computers (PCs) in the 1980s, and the associated proliferation of desktop computing and related use of computer-aided design (CAD) applications, had profound effects on the dissemination of CAM.

The resulting transfer and integration of digital manufacturing and its increasing affordability has begun to significantly transform the building industry. The seemingly contradictory ambition of differentiation and economy of designers and manufacturers alike is becoming resolved by the transformation of mass customisation from a futuristic goal to a realistic approach. A diverse range of current and emergent digital-manufacturing processes, related facilitating expertise, enabling technology and construction strategies for the production task of complex building designs is currently being explored by world-leading companies. These processes do not only give an insight into what is possible to construct today, but help outline the potentialities inherent in advanced manufacturing and fabrication for future tectonic possibilities in architectural design.

Octatube Space Structures: Computer-Aided Composite Sandwich Manufacturing and Explosive Panel Forming

Octatube Space Structures, based in Delft in the Netherlands, has been exploring innovative means of digital production enabled and supported by advanced digital design and engineering approaches for more than a decade. Such innovation has been driven and consolidated by working on various prominent building projects, one of which is the Municipal Floriade Pavilion, called Hydra Pier, in Hoofddorp, a competition-winning design of Asymptote Architects.

Octatube was contracted for the construction of the pavilion’s curved-glass facade, a water-filled suspended frameless glass pond and the double-curved roof panels of the building. The curved-glass facade was constructed as a combination of hot-bent monolithic glass panels and cold-bent panels that achieve a camber of 80 millimetres (3 inches) over a 2-metre (6.5-foot) side length. The glass pond of 5 by 12 metres (16 x 39 feet) was articulated as suspended polygonal flat panels made from fully prestressed glass. However, the...
main challenge proved to be the manufacturing and assembly of the double-curved panels of the roof cladding.

With only one axis of symmetry in the freeform roof geometry, Octatube had to develop a process of fabricating a range of 3-D panels from aluminium sheets that are considerably different in size, curvature and depth. In order to achieve this variation in the double-curved geometry of the panels, the company developed a combined process of digital production and explosive forming. Explosive forming as such is not an entirely new method. It was first documented in 1888 for the engraving of iron plates and has been used in the aerospace industry for the manufacture of complex short-production-run components such as curved domes of missiles and rocket nose cones since the 1950s. Explosive forming entails the forcing of sheet metal into dies and moulds through the detonation of explosives under water. In a water tank the metal sheet to be formed is placed on top of the mould and sealed, and a vacuum in the mould cavity is produced. Due to the noncompressible nature of water, the pressure load of the detonating explosive located on top of the metal is relatively evenly distributed and forces the sheet into the mould. The vacuum ensures complete alignment of material and mould surface in the forming process.

Similar to many other fabrication processes of the aerospace industry, explosive forming proved to be too expensive for use in the building industry. However, Octatube, in collaboration with the Dutch company Exploform, has managed to adapt this process to an economically feasible production of cladding panels through the integration of advanced CAM. The required negative moulds were articulated by casting fibre-reinforced concrete into positive moulds, all of which were CNC milled from solid polystyrene blocks hardened with epoxy-resin glass. The necessary numeric data for the manufacturing of the geometry of each panel was extracted directly from the digital 3-D model of the pavilion roof.

Due to the strict government restrictions regarding the use of explosives, the actual forming process took place in water tanks at the premises of Exploform in Delft. The achieved geometric precision was demonstrated by the remarkable side effect that even the intricate tessellation of the original digital model, which is registered in the CAM process and thus expressed in the manufactured object, could still be recognised on the formed panels. The panels were then assembled on a wooden jig that had also been CNC cut using the data from the digital 3-D model. On this jig, digitally cut aluminium strips were welded onto the edges of the panels to allow for a watertight assembly using 10-millimetre (0.4-inch) gaskets at the seams between the panels. After spray painting, in order to achieve a durable and smooth surface finish, the complex 3-D aluminium panels were ready for assembly on the Floriade Pavilion roof.

In a subsequent project, Octatube explored an alternative way of constructing a smooth double-curved roof structure. The design of the Yitzak Rabin Center in Tel Aviv, Israel, by architect Moshe Safdie features five distinct double-curved roof surfaces over two building parts – the library and the great hall. Initially these roof surfaces were planned as steel structures with concrete cladding, but Octatube developed an alternative stressed-skin construction during the tender period. The concept challenged the original distinction of a load-bearing primary structure and cladding system by proposing a self-supporting polystyrene shell wrapped in glass-fibre-reinforced polyester layers. In this way, Octatube explored a different approach to constructing double-curved surfaces, namely by investigating the possibilities of deploying CNC-milled polystyrene as the load-bearing structure instead of using it as a mould, as in the Floriade Pavilion project. The proposed structures, not dissimilar to large surfboards, were approved by the client and architect, and Octatube was commissioned to engineer and build the five roofs.

The complex geometry, the considerable span of up to 30 x 20 metres (98 x 66 feet) and the 8-metre (26-foot) long cantilevering wing tips prone to fatigue due to changing wind conditions demanded a unique solution. The following pages will provide a detailed account of the innovative processes and techniques employed in the construction of the Yitzak Rabin Center roof, highlighting the collaboration between Octatube and other key players in the project.
loads presented a major technical challenge. Nonetheless, Octatube managed to stay relatively close to its initial concept in the eventual realisation of the project. The roof geometry was divided into 2.5-metre (8-foot) wide strips and digitally produced from Octatube’s 3-D model. Complot BV in Delft, which had already cooperated with Octatube in the Floriade project, machined polystyrene blocks into the required mould shapes by CNC milling. The moulds were delivered to another company, Holland Composites, where they were then covered with a special foil. A thick layer of coating and glass-fibre mats was applied on the negative moulds, and the glass fibre was impregnated with polyester resin using vacuum injection. After this layer had hardened, fire-resistant PIR polyurethane blocks were sawn, applied and covered with another layer of glass-fibre mats. The resulting roof segments are 30 millimetres (1.2 inches) thick and wrapped in 7-millimetre (0.3-inch) thick glass-fibre-reinforced vinylester resin. Internal GRP stringers reinforce the shell structure and cope with the forces introduced by the supporting columns as well as preventing the top and bottom GRP layers from delaminating.

The integrated working methods of Octatube allowed the utilisation of a digital master model to facilitate all engineering tasks and subsequent ‘file-to-factory’ production. The 3-D model also provided the relevant data to plan the efficient transport of the roof segments, which were nested in special containers and shipped from the Netherlands to Israel. Onsite in Tel Aviv, the five load-bearing stressed-skin sandwich shells were then assembled, glued together by additional seam reinforcements and wrapped in a final GRP layer.

Octatube’s developments for the Floriade Pavilion and Rabin Center roof structures indicate how an integrated approach to computer-aided design and manufacturing enables the fabrication and construction of geometrically complex building surfaces. In addition to this, digital production has also opened up new possibilities for the manufacturing of building systems that may consist of several thousand geometrically different components, as demonstrated by Covertex’s pneumatic cladding system for the Allianz Arena in Munich.

Covertex and Skyspan: Digitally Driven Membrane Engineering and Fabrication

In 2003, Covertex, a German company specialising in membrane constructions, was commissioned to realise the pneumatic roof and facade system of Herzog & de Meuron’s competition-winning proposal for a new soccer stadium, the Allianz Arena, in Munich. This entailed the planning and construction of approximately 26,000 square metres (280,000 square feet) of facade area and 38,000 square metres (409,000 square feet) of roof area consisting of 2816 individual rhomboid double-layered air-filled cushions, all of which needed to be defined and the related cutting patterns generated. Each cushion is manufactured from ethylene-tetrafluorethylene (ETFE), either transparent, or with gradient translucent print patterns, attached to the supporting transom steel structure, individually inflated and equipped with a drainage pipe penetrating the upper cushion surface to avoid heavy water accumulation in the case of accidental deflation.

The different cushion geometries meant that the gradient print patterns and the drainage hole, to be situated at the lowest point after an eventual collapse, also needed to be individually specified for each element. In addition, all cushion surfaces, with a diagonal length of up to 16 metres (52 feet), needed to be welded together from 1.5-metre (5-foot) wide ETFE rolls. The resulting complexity involved in the design, logistics and manufacturing compelled Covertex to use advanced CAD/CAM techniques and technologies for the form-finding and production process of the membrane structures. The architect’s digital model, which defined just the construction lines, served as a base for Covertex’s subsequent engineering process. A custom-made software tool allowed automated tracing of all relevant coordinate points in the architect’s model and notating them in spreadsheets. Additional programmed routines generated the precise offset of supporting frames and defined the associated attachment points of each cushion. These points then enabled the digital form-finding of the inflated state of each cushion and the subsequent generation of each cutting pattern, including the relevant coordinate...
information, the position of the cut lines and overlapping welding seams, the related orientation of the gradient print pattern and the location of the air supply and drainage holes.

The resulting datasets permitted the direct cutting and labelling of all ETFE elements by a digitally controlled cutting and marking machine at KfM in Germany. Subsequently, a digitally controlled welder connected the foil strips of each cushion, producing more than 250 kilometres (155 miles) of weld lines in the process. The limits of this technology became apparent due to the necessity of manually detailing the corner points of each cushion. However, the extensive use of integrated CAD/CAM enabled Covertex to realise the entire 64,000 square metres (689,000 square feet) of pneumatic cladding system, including all partial tasks such as calculation of the cutting patterns of the cushions, cushion manufacturing, production of fixation profiles, sealing, ventilation and air supply systems within a period of just 15 months.

In addition to air-inflated cushion systems, another versatile membrane construction for covering large and geometrically complex roof structures is mechanically pretensioned foil and fabric systems, as demonstrated in Skyspan’s stadium roof in Frankfurt. The design of the new Commerzbank Arena by Gerkan Mark & Partner features the world’s largest retractable PVC cover, at 9600 square metres (103,000 square feet), and an 18,000-square-metre (194,000-square-foot) large membrane roof made from PTFE fibreglass fabric. While ETFE is a homogeneous foil, PTFE is a fibreglass fabric with anisotropic behaviour in warp and weft direction and with irregularities resulting from the weaving process. For this reason, Skyspan, a German specialist in membrane constructions, tests patches of each fabric production run on a digital biaxial measuring machine. After several test cycles the measurement data is fed back to the engineer to inform the digital form-finding process of the particular project geometry.

During this process, a fundamental understanding of the material behaviour and characteristics is as important as comprehensive digital tools. Once the pretensioned shape of the membrane construction had been form-found, the subsequent digital pattern generation was informed by the material anisotropy and took the necessary oversize for welding seams into account. After checking and marking local irregularities on the PTFE fabric on a light table, the generated patterns were nested on the material roll and cut into segments by a digitally controlled plotter. High-temperature welding was used to
connect the PTFE segments. The final pretensioning of the outer PTFE roof took place during the assembly process.

The inner retractable stadium roof, made from PVC/PES-coated PVC fabric, required a substantial belt system to withstand rain and wind loads. A new self-driving sewing machine was developed for the differential pretensioning of the belts during the process of stitching them together. This new manufacturing method, combined with digital simulations and exact calculations of the belts’ and PVC’s prestress, ensured that the retractable roof could be built and is now working.

**Seele: Integrated CAD/CAM Steel and Glass Facade Construction**

Due to the inherent flexibility of membranes, the main challenge for advanced foil and fabric constructions lies within the enhanced integration of digital design, form-finding and pattern generation and computer-aided processes of analysing, cutting and welding the material. In comparison, the fabrication and construction of building skins made from more rigid materials such as metal and glass require a greater range of digital forming and fabrication processes. Seele, a leading company in the design, engineering and construction of bespoke glass facade systems, employs a wide range of different CAD/CAM processes.

At its main manufacturing facility, situated right next to its engineering offices in southern Germany, Seele utilises computer-controlled machines for most cladding production tasks. Metal and aluminium profiles are cut by a numerically controlled saw permitting the rapid production of different length workpieces. A special CNC drilling and welding unit facilitates the preparation of holes and the fixation of stud poles according to digitally defined distance and angle protocols. Sheet material is automatically allocated, prepared, cut and marked by a digitally controlled laser. The laser is a powerful and controllable source of thermal energy that enables the cutting and marking of sheet material to any shape within the constraints of the machine. At Seele’s factory, the laser is combined with a digitally controlled shelving system that automatically selects, prepares and positions the material on the laser bed to increase workflow efficiency. Another machine facilitates the CNC bending and folding of sheet metal materials.
Finnforest Merk 3-D curved timber tracks. Basic gluelam arches (left) prepared for subsequent robotic milling (centre); finished 3-D curved timber tracks installed on a wooden rollercoaster in Soltau, Germany (right).

Finnforest Merk 3-D curved timber tracks. Basic gluelam arches (left) prepared for subsequent robotic milling (centre); finished 3-D curved timber tracks installed on a wooden rollercoaster in Soltau, Germany (right).

These CAM facilities, combined with sophisticated solid modelling CAD applications, allow for consistent engineering and fabrication datasets that have enabled Seele to contribute to the production of highly complex buildings such as the Seattle Central Library designed by OMA. In this project, Seele was responsible for the cladding preconstruction services, the production and installation of the 11,900 square metres (128,000 square feet) of exterior cladding comprising more than 6500 glass panels and 30,000 anodised aluminium profiles. The building’s faceted skin geometry required extensive 3-D engineering as the facade surfaces of aluminium extrusions, silicone gaskets, triple-glazing panels, pressure plates, gutters and closing panels join in up to five different angles at particular node points. A comprehensive digital 3-D solid model of the entire facade provided the manufacturing data for all prefabricated elements as well as the related labelling information, packing lists and transportation schedules.

The digital model also allowed for adjusting the production and installation of the facade system to tolerances in the primary steelwork of up to 2.5 centimetres (1 inch) occurring after the actual erection. For these adjustments a digital scanning process notates clusters of measure points of the already built primary structure in relation to fixed reference points. The resulting 3-D point cloud allows for digitally overlapping the primary system as built with the digital model of the facade as designed. The identified deviations can then be compensated for in the manufacturing and installation of the cladding elements on site.

Finnforest Merk: Robotic Timber Manufacturing

Most of the CAM processes described thus far require specialised machines that can perform specific manufacturing tasks such as milling, cutting, welding and so on. However, in a few cases the more versatile machines used, for instance, in the automotive industry are beginning to be employed in the building industry. An interesting example of this development is the use of a robotic manufacturing unit by German timber construction company Finnforest Merk. Equipped with different tool heads and driven by the appropriate software, such a basic manufacturing robot can execute diverse manufacturing processes ranging from welding of sheet metal to cutting and sewing of composite reinforcement. Furthermore, such robots can automatically identify the position and type of workpiece to be machined, perform an entire sequence of fabrication steps by automatically changing tool heads, and later on check the result for accuracy and tolerances.

Equipping such a basic robotic unit for timber manufacturing has enabled Finnforest Merk to produce both complex single building elements and geometrically complex constructions made from a large number of different components. A typical case for the fabrication of complex building elements is the 3-D curved timber tracks Merk produced for a wooden rollercoaster located in Soltau in Germany. For this project, Merk combined its long-established expertise in producing gluelam arches with the machining potential of its five-axis robot equipped with a milling tool and the ability of its CAD/CAM engineers to translate the relevant data into machine-readable manufacturing protocols. The high strength required by cars travelling at 120 kilometres (75 miles) per hour and forces of up to 4g, as well as the complex curvature of the tracks, was achieved by robotically machining gluelam arches curved in one plane into 3-D curved beams.

In another project, the 2005 Serpentine Pavilion designed by Álvaro Siza and Eduardo Souto de Moura together with Cecil Balmond of Arup and Partners, the main challenge for Merk has been the construction of a complex structure from a large number of unique components. The pavilion’s 17-metre (56-foot) clear spanning curved roof and walls are articulated as an undulating offset grid of laminated timber. The lattice elements are arranged in mutually supporting patterns and joined by mortice-and-tenon connections. The unique
geometry of each element was digitally defined by Arup’s Advanced Geometry Unit and mapped out in a format that could directly communicate with Finnforest Merk’s CAD/CAM engineers. Using robot technology the required 427 unique timber beams could be manufactured within two weeks. Starting at one corner and radiating out to the opposite sides, the subsequent assembly process of the lattice also required a specific protocol defining the only possible erection sequence for the unique interlocking beams.

Today, with digital production and continuous datasets comprising a practical approach rather than an idealised aim, the production of geometrically complex buildings and building systems from differentiated components appears a tangible, as well as feasible, proposition. Overall, the most relevant consideration for now is the relation between existing skills and tools and emerging techniques and technologies. The work of the leading manufacturing companies suggests that the transfer and integration of CAM in the field of construction requires the development of new production approaches in parallel with an understanding of traditional means and skills. In fact, CAD/CAM technology may become a mechanism through which the potential of existing expertise and methods is fully realised. The projects and processes that have been presented here indicate that the critical moment of integrating existing and emerging manufacturing techniques and technologies provides the inroad into an understanding of the yet uncovered potential of new means of digital production. This moment of synthesis and synergy will be the vehicle for rethinking in the necessary and latent redefinition of the construction process itself.

This article is based on an indepth research into the current possibilities and future perspectives of fully integrated computer-aided design and manufacturing. As part of this exploration, Achim Menges and Michael Hensel visited specialist manufacturing companies and their facilities in Germany to investigate and discuss the latest computer-controlled fabrication processes. Following this field trip, the Emergence and Design Group organised the symposium entitled ‘Manufacturing Diversity’ with representatives of the key companies at the Architectural Association in February 2005. The article reports on the work and projects presented by Dirk Emmer (Skyspan, Germany), Benoit Fauchon (Covertex, Germany), Michael Keller (Finnforest Merk, Germany), Thomas Spitzer (Seele, Germany) and Dr Karel Vollers representing Professor Mick Eekhout (Octatube, the Netherlands).
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 also in educational processes. Over the last five years I have pursued related differentiating between formation and materialisation performative capacity from material constituents without design entails unfolding morphological complexity and tectonic elements.

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 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 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. 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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
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
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

Component differentiation and proliferation
Physical test models of paper-strip system derived through a parametric process embedding the material characteristics, manufacturing constraints and assembly logics observed in physical tests.

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).

Physical test model of a population of 90 paper-strip components and related strip-cut patterns.
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 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 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.
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.