At a time of accelerated global urbanisation and climate change, performance-oriented design has an increasingly important role to play. Here, Michael Hensel and Achim Menges describe their own ‘Morpho-Ecological’ approach to design that challenges some of the most deeply entrenched dogmas of architecture as a material practice, such as the notion of ‘efficiency’ in design and construction. It focuses specifically on the integral relationship between form generation, material behaviour and capacity, manufacturing and assembly, environmental modulation and a type of spatial conditioning which is set to deliver a richly heterogeneous space.
Architecture as a material practice operates through the articulation of spatial, material and energetic interventions within a specific context. Enhanced context-sensitivity of an integral design approach lies at the base of the approach introduced here, entitled ‘Morpho-Ecologies’. This approach commences from the unfolding of performative capacities inherent in material systems in relation to the specific environment they are embedded within, as well as an intensively empirical mode based on physical and computational form-generation and analysis methods. Compared with current practice it presents a radically different take on the relation between formal expression and performative capacity of the built environment, as well as a fundamental revision of prevailing approaches to sustainability.

An alternative understanding of performance, one that is based on multiparameter effectiveness rather than single-parameter optimisation and efficiency, must from the start of the design process include both the logics of how material constructions are made and the way they will interact with environmental conditions and stimuli. Computation, in analytical and generative modes, has a key role in both aspects. The underlying logics of computational processes, particularly in combination with computer-controlled manufacturing processes, provide a potential for a much higher level of design synthesis. Yet the current use of CAD-CAM technologies in architecture serves more often than not as the facilitative, and affordable, means to indulge in freeform architecture. Although this may occasionally lead to innovative structures and novel spatial qualities, it is important to recognise that the technology serves merely as an extension of well-rehearsed and established design processes.

Particularly emblematic is the underlying impoverished notion of form generation, which refers to various digitally driven processes resulting in shapes that remain detached from material and construction logics. In foregrounding the geometry of the eventual outcome as the key feature, these techniques are quintessentially not dissimilar to more conventional and long-established representational techniques for explicit scalar geometric descriptions. As these notational systems are insufficient in integrating means of materialisation, production and construction, they cannot support the evaluation of performative effects, and so these crucial aspects remain invariably pursued as top-down engineered material solutions.

Dae Song Lee, Differentiated Space Frames, Diploma Unit 4, Architectural Association, 2005-06

Through computer fluid dynamics modelling the aerodynamic performance of a local component of the Differentiated Space Frames project can be investigated. The recurrent analyses of system behaviour and performative capacity becomes an integral part of the system’s computational generation.
This suggests that the latent, but as yet unused, potential of computational design and manufacturing technology may unfold from an alternative approach to design, one that derives morphological complexity and performative capacity without differentiating between form-generation and materialisation processes. The logic of computation strongly suggests such an alternative, in which the geometric rigour and simulation capability of computational modelling can be deployed to integrate manufacturing constraints, assembly logics and material characteristics in the definition of material and construction systems. Furthermore, the development of versatile analysis tools for structure, thermodynamics, light and acoustics provides for integrating feedback loops in evaluating the system’s behaviour in interaction with a simulated environment, and can thus become generative drivers in the design process. Such computational models describe behaviour rather than mere shape. This enables the designer to conceive of material and construction systems as the synergetic result of computationally mediating and instrumentalising the system’s intrinsic logics and constraints of making, the system’s behaviour and interaction with external forces and environmental influences, as well as the performative effects resulting from these interactions. Thus the understanding of material effects extends beyond the visible effect towards the thermodynamic, acoustic and luminous modulation of the natural and built environment. As these modulations can now be anticipated as actual behaviour rather than textbook principles, the design of space, structure and climate becomes inseparable.

Realising the potential of computational design and computer-controlled fabrication therefore entails two aspects: first it enables a far more immediate relation between the processes of making and constructing by unfolding intrinsic material capacity and behaviour; and second, the utilisation of this capacity and behaviour as a means of creating spatial arrangements, microclimatic spatial conditioning and also structure.

While the latter may have a profound impact on our conception of spatial organisation, which can now be thought of as differentiated macro- and microclimatic conditions providing a heterogeneous habitat for human activities, the research of the former aspect will first require elaboration.

As this research seeks to develop and employ computational techniques and digital fabrication technologies to unfold intrinsic material capacity and specific performative capacities, it begins with extensive experiments and testing of what we define as material systems. Material systems are considered not so much as derivatives of standardised building systems and elements, but rather as generative drivers in the design process. Extending the concept of material systems by embedding their material characteristics, geometric behaviour, manufacturing constraints and assembly logics within an integral computational model promotes an understanding of form, material, structure and behaviour not as separate elements, but rather as complex interrelations. This initially requires disentangling a number of aspects that later form part of an integral computational set-up in which the system evolves.

First of all, the geometric description of material systems, or rather the notation of particular features of the system’s morphology, needs to be established. The designer needs to facilitate the set-up of a computational model not as a particular gestalt specified through a number of coordinates, but rather as a framework of possible formations affording further differentiation that remains coherent with the behaviour observed and extracted from physical experiments and explorations of the relevant system and to inform the dataset in addition to specific spatial characteristics, organisations and constraints. This computational framework, which essentially constitutes an open model but will be referred to as a ‘framework’ here due to the ambiguous notion of ‘model’ in a design context, is then step by step informed by a series of additional parameters, restrictions and characteristics inferred from material, fabrication and assembly logics and constraints. Principally this includes the
specific material and geometric behaviour in formative processes, the size and shape constraints of involved machinery, the procedural logistics of assembly and the sequences of construction. Here, the far-reaching potential of computer-aided manufacturing (CAM) technologies is evident once they turn into one of the defining factors of a design approach seeking the synthesis of form-generation and materialisation processes. At this point the highly specific restrictions and possibilities of manufacturing hardware and controlling software can become generative drivers embedded in the set-up and development of the computational framework.

Generally it can be said that the inclusion of what may be referred to as system-intrinsic characteristics and constraints comprises the first crucial constituent of the computational set-up, defined through a series of relevant parameters. The definition of the range within which these parameters can be operated, while remaining coherent with the material, fabrication and construction constraints, is the critical task for the designer at this stage.

**Analysis plays a critical role during the entire morphogenetic process, not only in establishing and assessing fitness criteria related to structural and environmental capacity, but also in revealing the system’s material and geometric behavioural tendencies.**

If effectiveness is defined as the extent to which actual performance compares with targeted performance, the inherent need for analysis and diverse and versatile analytical methods becomes immediately clear. The second crucial constituent of the generative computational framework are therefore recurring evaluation cycles that expose the system to embedded analysis tools. Analysis plays a critical role during the entire morphogenetic process, not only in establishing and assessing fitness criteria related to structural and environmental capacity, but also in revealing the system’s material and geometric behavioural tendencies. The conditioning relation between constraint and capacity in concert with the feedback between stimuli and response are consequently operative elements within the computational framework. In this way evaluation protocols serve to track both the coherency of the generative process with the aforementioned system-intrinsic constraints, and the system’s interaction with a simulated environment. Depending on the system’s intended environmental modulation capacity, the morphogenetic development process needs to recurrently interface with appropriate analysis applications, for example, multi-physics computer fluid dynamics (CFD) for the investigation of thermodynamic relations or light and acoustic analysis. However, it is important to note that CFD does always only provide a partial insight of the thermodynamic complexity of the actual environment, which is far greater than any computational model can handle at this moment in time. Nonetheless, as the main objective here lies not solely in the prediction of precise data, but mainly in the recognition of behavioural tendencies and patterns, the instrumental contributions of such tools are significant.

In parallel to the environmental factors, continual structural evaluation informs the development process. However, it is imperative to recognise that the computational framework described here does not at all reproduce a technocratic attitude towards an understanding of efficiency based on a minimal material weight to structural capacity ratio. Nor does it embrace the rationale of what 20th-century engineers called ‘building correctly’. Structural behaviour here rather becomes one agent within the multifaceted integration process. Overall this necessitates a shift in conceptualising multi-criteria evaluation rather than an efficiency model. Biologists, for example, refer to effectiveness as the result of a developmental process comprising a wide range of criteria. Accordingly the robustness of the resulting systems is as much due to the persistent negotiating of divergent and conflicting requirements as their consequential redundancies.

Evaluating a context-specific, differentiated material and spatial arrangement requires taxonomy on the basis of case-specific criteria, yet not inevitably type defined by gestalt. Each family of design solutions can evolve from a specific feedback between material system and environmental context without prejudiced pre-selection. It is therefore also of great interest to evaluate design solutions for unanticipated spatial arrangements and ultimately also the ensuing potentials for different modes of habitation. If effectiveness is defined as the ability to generate emergent effects, analysis therefore needs to be both quantititative and qualitative (although this artificial dichotomy often comes into the way of more integral modes of analysis), as well as open to questions not a priori defined on the onset of a design process. Morphogenesis driven by analysis thus requires creativity, intelligence and instrumentality in devising integral analytical methods. This necessitates both further research into the set-up and running of integral computational design processes and developing literacy in deploying these processes as well as gaining a new sensitivity of unfolding their inherent design potential. Architectures will always yield multivariated effects; the question is, however, how far designers are able to inform processes of form generation with desired and emergent effects and effectiveness.
CONTINUOUS LAMINAE

This research started with an interest in the anisotropy of wood, with its specific fibre-directionality and related response-range to environmental stimuli tested against the specific requirements of the context, a coastal sand dune conservation area in which the shifting of sand dunes is critical. Initially the basic elements were finite-length strips made from layers of laminated veneer; rotating the layers against one another allowed an investigation of different fibre-layouts. Shifting the layers of veneer made possible a continuous lamination process, so as to produce a large assembly without construction gaps. A correlated manufacturing strategy was developed, incorporating the possibility of rotating selected sub-locations along their long axis. Replacing the moulds with a nodal support system allowed the laminated components to be clamped at the endpoints and so made them self-organising; that is, able to find their form within the given constraints during the fabrication process.

Achieving a laminar flow by maintaining curvature continuity between the individual elements results in a continuous multiple load-path system that, together with the anisotropic characteristics of timber, helps to maintain the flexibility and integrity of the overall assembly. Furthermore, while the overall assembly consists of finite lengths of veneer strip, the continuous laminae arrangement does not yield a division into elements. The overall assembly becomes a single element, in which each local dimensional change produced by environmental stimuli affects the system at large.

Relating the systematic use of manufacturing-enabled form finding to extrinsic influences affects the articulation of the sub-locations and the overall system, and their orientation to the sun path and prevailing wind direction. The resulting surface curvatures and varied levels of system porosity can then be used to modulate airflow and related ranges of sand deposition, as well as exposure to sunlight. The overall flexibility of the system – a product of its material elasticity – enables a higher responsiveness to the fluctuations of the wind loads. Several dynamics are thus interrelated: airflow, system deflection and local terrain formation through modulated aggregation, as well as velocity of airflow, airborne sand and abrasion of the material assembly. Ultimately the main concern of this project is the strategic entwining of these time cycles.

In a larger laminated veneer assembly the insertion points of lamination geometrically vary for each local component. Due to the parametric definition of the component, which embeds the self-forming tendency of the veneer, a range of differentiated morphologies can be produced.
Three different rapid prototype models produced through selective laser-sintering (top) show the geometric adaptation of a multi-component system in response to particular parametric settings (centre) and the resulting performative capacity of the system interacting with a simulated luminous environment (bottom).

Full-scale prototype manufactured from multiple layers of veneer through processes of continuous lamination.
POROUS CAST

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This research was fostered by an interest in the formation process of diatoms and radiolaria. Diatoms are unicellular or colonial algae. The cell is encased by a characteristic and highly differentiated cell wall, which is impregnated with silica. Radiolaria belong to the order of marine planktonic protozoa and feature a central protoplasm comprising a chitinous capsule and siliceous spicules that are perforated by pores. The porous mass of the cell encasements of radiolaria and diatoms delivers an interesting model for differentiated cast walls in architecture that may feature a variety of specific performance capacities.

The initial phase of the material system development focused on producing a skeletal framework articulated through the interstitial spaces left between pressurised containers, so-called pneus. A first series of experiments explored ways of casting plaster between air-filled cushions to achieve the typical shape of the mineralised skeletons between pneus that occurs in nature. Based on different cushion arrangements four-, five- and six-armed configurations were produced and became the basic elements of the material system. Each of these elements is parametrically defined as the relation between pneu organisations and internal pressure by which aspects such as the volume, shape and thickness of each element can be varied. Based on this parametric set-up, a series of digital multi-element systems were derived from changing variable inputs. Secondary and tertiary levels of articulation were developed using a series of meso- and micro-pneus to further subdivide the interstitial space between macro-pneumatic cushions. Another series of experiments focused on how it might be possible to gain porosity in the cast form itself.

A list of casting materials that feature different thermal characteristics was established. Physical experiments and digital analysis served to establish the possible range of light and airflow modulation relative to morphological features such as the size and density of pores and other characteristics of the material system. Subsequently a range of manufacturing approaches were tested, resulting in the production of a full-scale prototypical portion of the material system that integrated computer-aided manufacturing processes and pneumatic form-finding as a construction method. A cast form was milled on a 5-axis CNC machine from high-density polystyrene blocks, from which first a fibreglass form and later a cast form from plaster were produced. Air-pressured cushions were distributed into the form and inflated to the defined pressure for each location, and then concrete and other materials were cast into the interstitial spaces between the pneumatic units and the mould.

A second approach focused on strategising a mould that would respond to the casting process and therefore deploy an element of material self-organisation. After several experiments with fabric moulds a rigid frame with an equally rigid back panel was made. The back panel supports an inflatable formwork, with pneus placed between two layers of rubber sheet. The concrete was then cast between the two layers of rubber sheet to fill the space between the pneus. An acrylic inlay in the frame allowed visual control of the casting process and the proper filling of the space between the pneus. The resulting cast is characterised by double-curvature, controlled porosity, and density and mass of the poured material. It can absorb thermal energy and release it to the airflow enabled by the porosity, and the double-curvature can be utilised for thermal exposure or self-shading. Moreover, the artificial dichotomy between mass and lightness are brought into an interesting performative synergy.
The Porous Cast project is based on manipulation components constituted by the interaction of various pneumatic bodies within a cast system. Through processes of component proliferation and associative adaptation to a mould’s shape and curvature, a specific morphology with varying degrees of porosity can be achieved.

Driven by context-specific information the parametric definition of the system enables an integral set up of the context-specific articulation responding to a range of performance criteria that include structural, environmental and spatial parameters.

The system’s performative capacity to modulate airflow through regional (top) and local (bottom) porosity gradation was analysed through computer fluid dynamics modelling.
DIFFERENTIATED SPACE FRAMES
Dae Song Lee, Diploma Unit 4 (Michael Hensel and Achim Menges), Architectural Association, 2005–06

This project examined strategies and methods to incrementally change an assembly from a vector-active to a surface-active structural system. The system has four distinct characteristics: triangular faces of tetrahedrons varied with respect to their porosity, tetrahedral elements that vary in size, hexagonal elements varied in cross-sectional profile thickness relative to structural necessity, or alternatively the multiplication of element layers.

The transition from space-frame to surface morphology offers a range of performative capacities through related changes of porosity. Finite element analysis and computer fluid dynamics analysis were used in order to establish the complex interrelation between the morphology of the system and its structural behaviour and environmental modulation. This process began with basic digital studies that simulated airflow around differently articulated single elements, varying the angles of the faces of the tetrahedrons and the size of aperture in each face, as well as the range of sizes within each element. Configurations consisting of a greater number of differentiated elements were then analysed and the performative capacity of the system documented and notated in a digital protocol. This directly informed subsequent generations of the system in response to a specific climatic and luminous context.

The investigation of geometric-topological articulation and performative capacity was paralleled by an investigation of manufacturing options. Various approaches to unfolding assemblies into flat-sheet patterns for laser cutting were examined and tested in a series of scaled physical models. As a specific cutting technique, an industrial origami method was chosen that allows the flat sheets to be scored from one side only, while folding is possible in both directions. The associative modelling set-up was developed so that each assembly was automatically unfolded and laid out for laser- or CNC-cutting. With this manufacturing approach, each profile is hollow unless another material is cast into it in order to increase the self-weight or thermal mass of the element or charge subassemblies differentially across the entire system.

Once the issue of cutting and folding had been resolved, the project pursued a second complementary manufacturing strategy in which space-frame-like slender profiles that make up a tetrahedron can be cut as three pieces for each face. This was done to achieve increased self-weight and thermal mass in one production step. Initially elements were cut from Styrofoam and assembled to ensure that the correct cutting angles were defined. Subsequently elements were cut from MDF to produce models for load testing. Physical load tests went hand in hand with digital tests based on the finite element method.

The design was informed by extensive measuring and mapping of thermal, luminous and aeolic conditions across a specific test site. Environmental measurements taken for different times of the day are listed on a data spreadsheet and directly fed into the parametric model.

The particular parametric specification of the system is informed by extensive measuring and mapping of thermal, luminous and aeolic conditions across a specific test site. Environmental measurements taken for different times of the day are listed on a data spreadsheet and directly fed into the parametric model.
In combination with the analysis of the local component in terms of airflow velocity (top), directional turbulences (centre) and the differential distribution of pressure zones (bottom), a comprehensive dataset for further evolutionary steps of the system can be established.

The regional and global articulation (top) is derived through the aerodynamic behaviour of the system tested in computer fluid dynamics. The overall shape emerges according to the particular modulation of high- and low-pressure zones in relation to prevailing wind directions (centre and bottom).