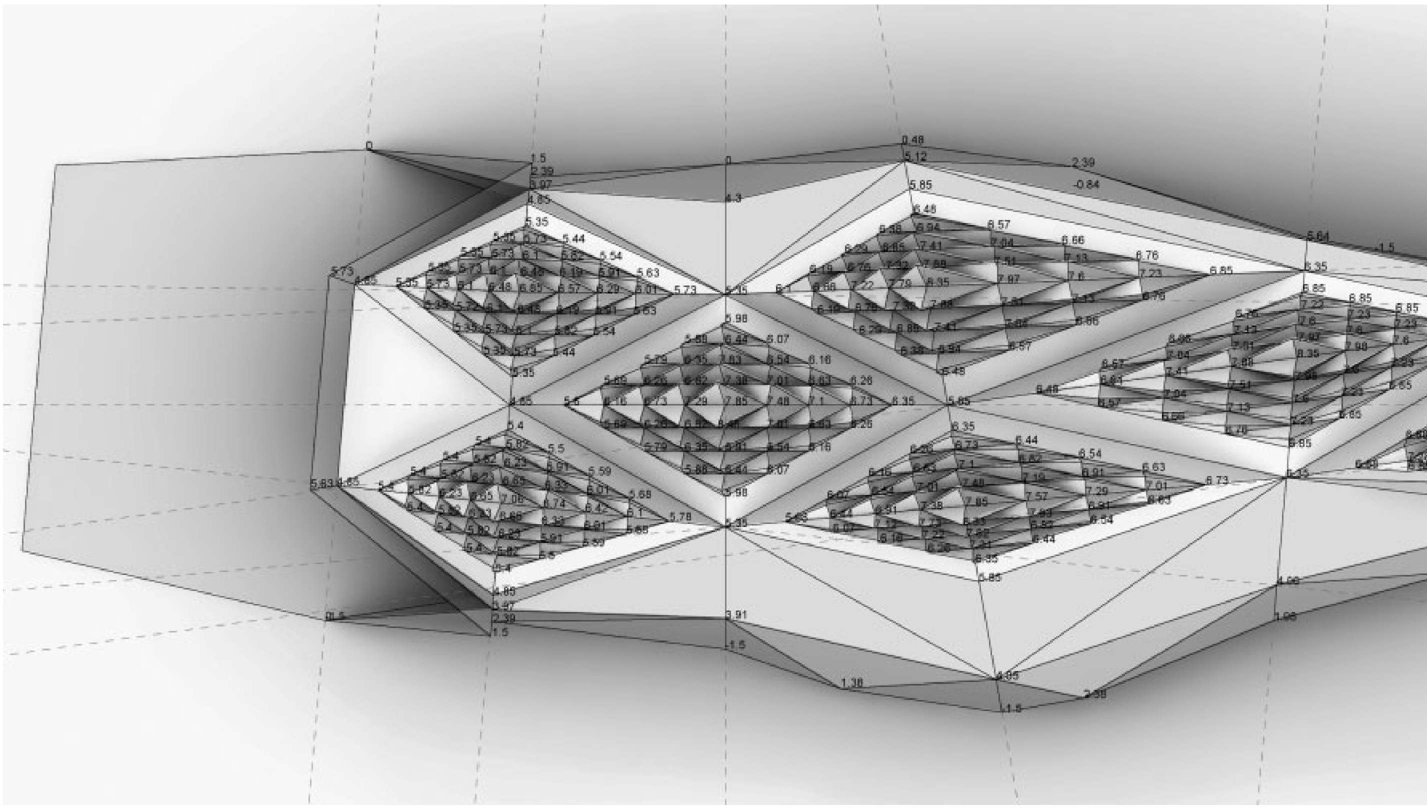
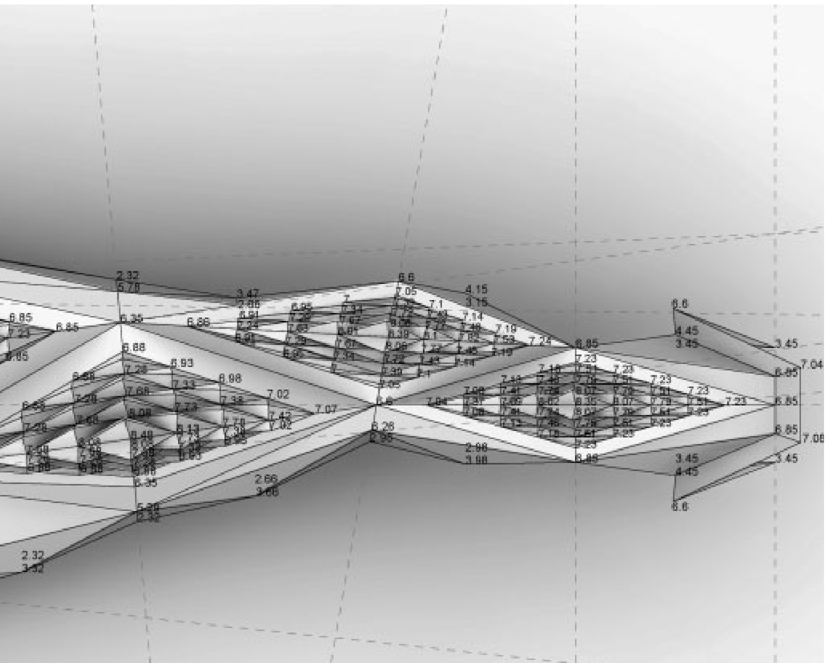
Material and Digital Design Synthesis

Integrating material self-organisation, digital morphogenesis, associative parametric modelling and computer-aided manufacturing



The advanced material and morphogenetic digital design techniques and technologies presented in this journal call for a higher level methodological integration, which poses a major challenge for the next generation of multidisciplinary architectural research and projects. This collaborative task encompasses the striving for an integrated set of design methods, generative and analytical tools and enabling technologies that facilitate and instrumentalise evolutionary design, and evaluation of differentiated material systems towards a highly performative and sustainable built environment. Michael Hensel and Achim Menges describe recent progress towards a higher-level design synthesis of material self-organisation, digital morphogenesis, associative parametric modelling and computer-aided manufacturing (CAM) on the basis of two works produced within the context of the Emergent Technologies and Design Masters programme at the Architectural Association in London, and a recent competition entry by Scheffler + Partner Architects and Achim Menges.



Scheffler + Partner Architects and Achim Menges, Hercules Monument Visitor Centre competition entry, 2005
Micro-/macro-folded structure of visitor centre that parametrically responds to external influences such as sun path and sight lines.

Today, a paradigm shift can emerge from multiple discrete innovations that when brought together achieve a significant shift in operativity and design production. In this issue of AD, numerous morphogenetic design methods, techniques and technologies have been introduced, but eventually the question arises as to what all this amounts to, and what would happen if these processes were synthesised into a coherent toolset.

Imagine, firstly, digital associative parametric modelling that is informed by physical form-finding experiments, with self-organisational characteristics of materials and material systems rigorously encoded in a series of geometric relations and dependencies, so that these characteristics are retained across all system instances resulting from changes to parametric variables of the digital model.

Imagine, secondly, that the geometric relations and dependencies that characterise the setup and constituents of the associative digital model are, in addition, informed by computer-aided manufacturing (CAM) constraints of the material components so that each digitally defined system can be directly manufactured and assembled.

Imagine, thirdly, that the digital components that are geometrically characterised by material behaviour and materialisation processes populate evolving geometric host environments, such as surfaces or branch-like geometric structures, to form larger assemblies. Imagine that these base geometries are evolved by means of growth or evolutionary algorithms, so that many individuals and various generations of the system can be evolved in response to the increasing level of articulation of the input geometry.

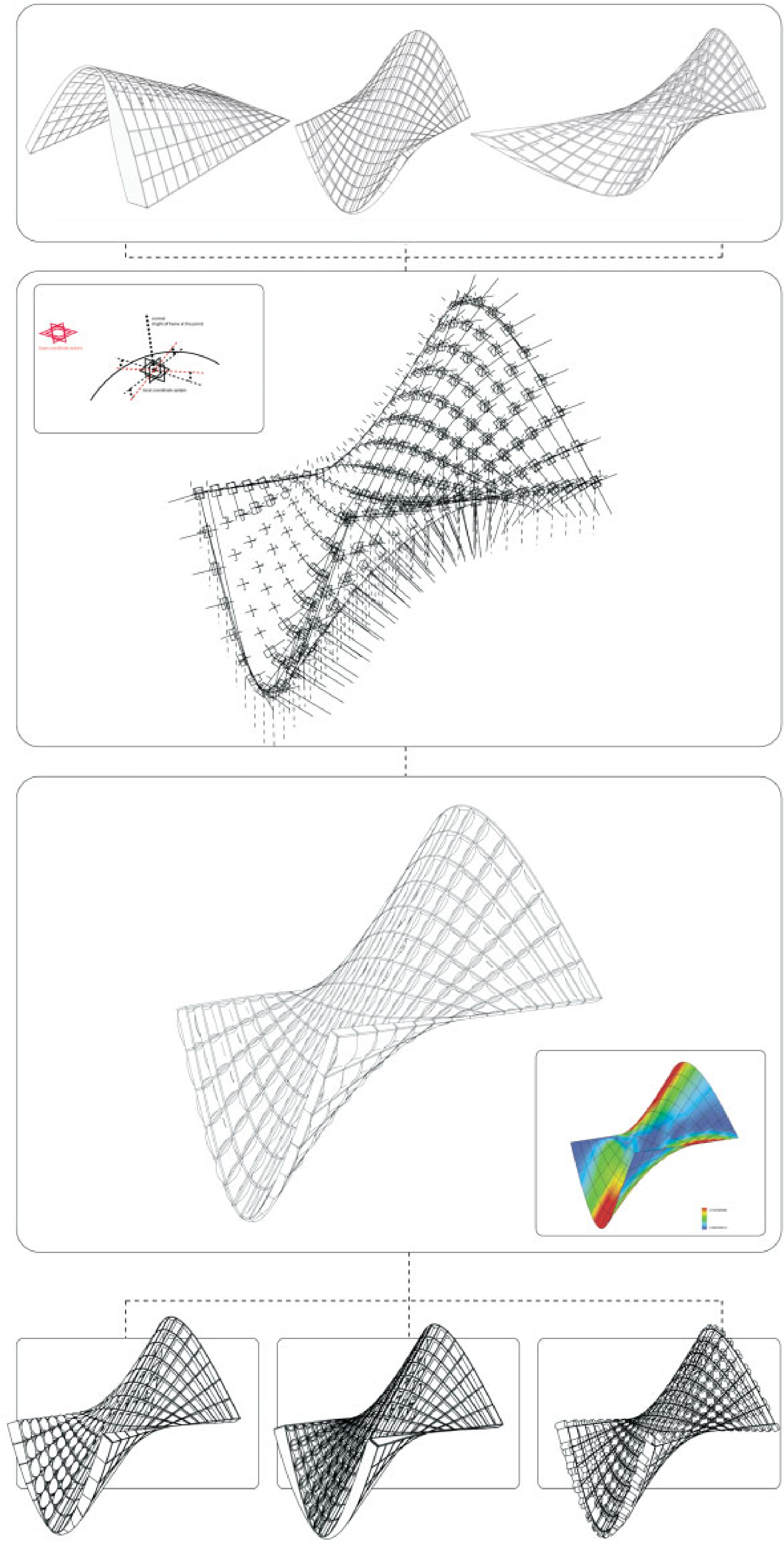
Then imagine that the growth or evolution of component assemblies can be informed on various scales of the system by multiple extrinsic influences, such as exposure to sunlight, prevailing wind directions, and so on. Negotiating between different and probably conflicting system-intrinsic criteria like manufacturing and construction constraints embedded in the underlying parametric setup, and multiple environmental influences, the system would unfold levels of increasingly complex articulation that could be ranked according to their ability to satisfy multiple goals and performance objectives. In exchange with appropriate analysis and evaluation techniques, this could even lead to a co-evolution of the driving criteria enabling an integral yet environmentally sensitive design process.

The following projects have focused on different aspects of such a higher-level material and digital design integration, yet seen together they provide insights into a latent synthesis of various techniques and technologies in morphogenetic design that have all, individually, already begun to alter current perceptions and practice of architecture.

Giannis Douridas and Mattia Gambardella, AA Emergent Technologies and Design, Associative Component Structures, 2005

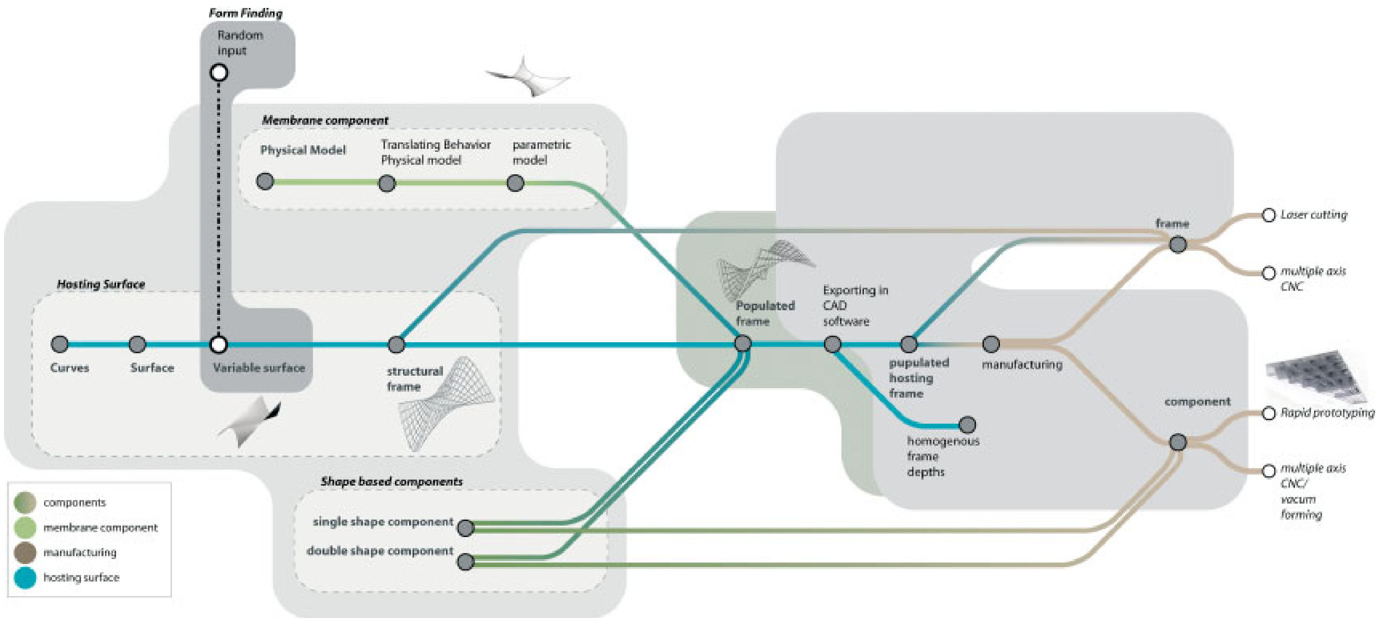
The research by Giannis Douridas and Mattia Gambardella, an AA EmTech team, aimed at setting up a geometric scaffold in an associative parametric modelling environment that consists of a subdivided host surface defined through two perimeter curves. The curves themselves are each defined by sets of three points, of which each central point's coordinates are iteratively altered by a function driven through a coefficient that calls pseudo-random numbers. Within a range defined through maximum and minimum allowed values, each numerical value generated results in a host geometry that provides the relevant U and V surface domain and normal vectors for the insertion of parametric components.

Within the specific UVN parameter space of each macro-geometric surface, two component types are to be populated. First, an array of local coordinate systems provides the surface normal vectors at variable intervals. At the same parameter coordinate position the curvature of the surface is analysed and, through a defined function, provides a specific offset distance for a rib structure of iso-parametric curves. As the curvature changes across all generated surface instances



Giannis Douridas and Mattia Gambardella, Associative Componenent Structures, 2005
Three surface instances of a parametrically defined geometric scaffold responding to pseudo-random numeric input (top); one surface populated with local coordinate systems in response to its specific UVN parameter space (middle); three different component types populating the local coordinate system array on the surface (bottom).

Giannis Douridas and Mattia Gambardella, Associative Component Structures, 2005
Flow chart of project investigations indicating operative interrelations of a synthesis of form generation, parametric modelling and computer-aided manufacturing.



and along each individual surface, the depth and orientation of the ribs changes accordingly. The second digital component reads the polygonal shape and its geometric features, such as edge length, angle, and so on, which is given through four local coordinate systems as input data. As various component types are capable of processing this input and adapting accordingly, the team chose a series of components defined by themselves, or by other EmTech and Diploma Unit 4 teams, to test and develop their scaffold. A variety of synclastic and anticlastic surface curvatures were evolved and tested.

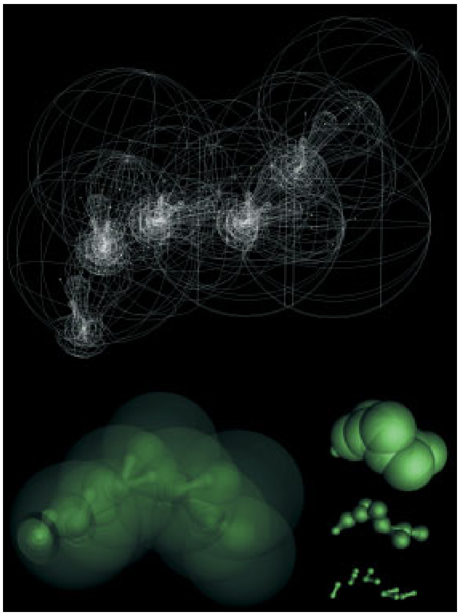
Since all tested components are informed by manufacturing and construction constraints, each specific component assembly within the evolving geometric scaffold can be manufactured immediately, although the question of tolerances relative to each specific component still needs to be addressed. In the following step, the pseudo-random numbers that generate the curves, which in turn generate the host surfaces providing the specific geometric data for each component-type instance, can be related to extrinsic influences: for example, the local surface vectors of each individual component of a larger population can be defined in relation to the sun path, and so on. In doing so it becomes possible to inform, for instance, the overall or regional articulation of a building envelope and to embed multiple-performance capacity in the system.

Pavel Hladík, AA Emergent Technologies and Design, Phyllotaxic Component Growth, 2005

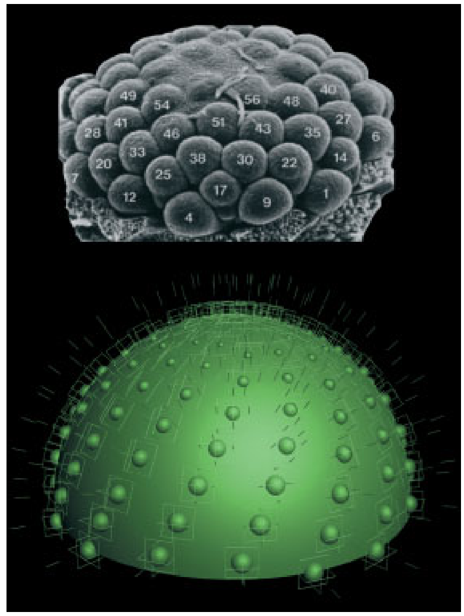
A second EmTech research project, by Pavel Hladík, aimed at implementing a growth algorithm and, more specifically, a Lindenmayer system (L-system) in an associative parametric modelling environment. The research commenced from form-finding experiments with an elastic net that wraps spherical solids fixed in a space, and was subsequently described as a series of geometric relations and dependencies that allowed the setting up of a generic parametric model. In a later step, a growth algorithm was implemented in the parametric modelling environment that enables the iterative rewriting of the underlying parametric definition. The application of L-systems provides the necessary rewriting and production rules for a digital growth process of a parametric component. The primary growth steps are parametrically defined through spherical and cylindrical coordinate systems. The secondary articulation follows a phyllotactic pattern and related mathematical models of plant growth. In botany, phyllotaxis describes the arrangement of the leaves, buds, thorns and so on of the plant. The regular arrangement of plant organs forms spirals or parastichies and can be alternate, opposite, whorled or in a spiral.

In this research project, smaller system constituents are proliferated in the defined parameter space and provide potential subcomponent interfaces at situations where growing macro-components begin to intersect. Furthermore, the growth of the macro-components and the propagation of micro-components within the growing host geometries can be related to extrinsic influences, as is the case with phyllotaxis, by which plant elements are packed and/or oriented towards environmental influences. The parastichies inform the geometric definition of a scaffold made from laser-cut sheet material on which tubular rods can be formed and welded together and subcomponents can be attached to the helical body. In this way, it is possible to grow and construct a material system that can be informed by tropism, the turning or bending movement of an organism or a part towards or away from an external stimulus, such as light, heat or gravity,

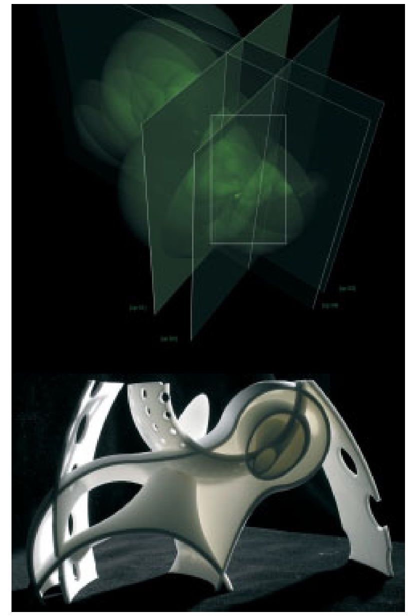
Pavel Hladík, Phyllotaxic Component Growth, 2005
Three growth steps of a population of digital components algorithmically derived through the implementation of L-systems in a parametric modelling application.



View of a component population cut by four sections planes for closer examination of the complex system intersections (top), and related rapid prototype manufactured through a selective laser sintering process (bottom).



Component population cut by four sections planes for closer examination of the complex system intersections (top), and a related rapid prototype manufactured through a selective laser sintering process (bottom).



and an optimised disposition of elements and subcomponents, for example photovoltaic panels, that are directly informed by the macro-articulation of the system due to tropism.

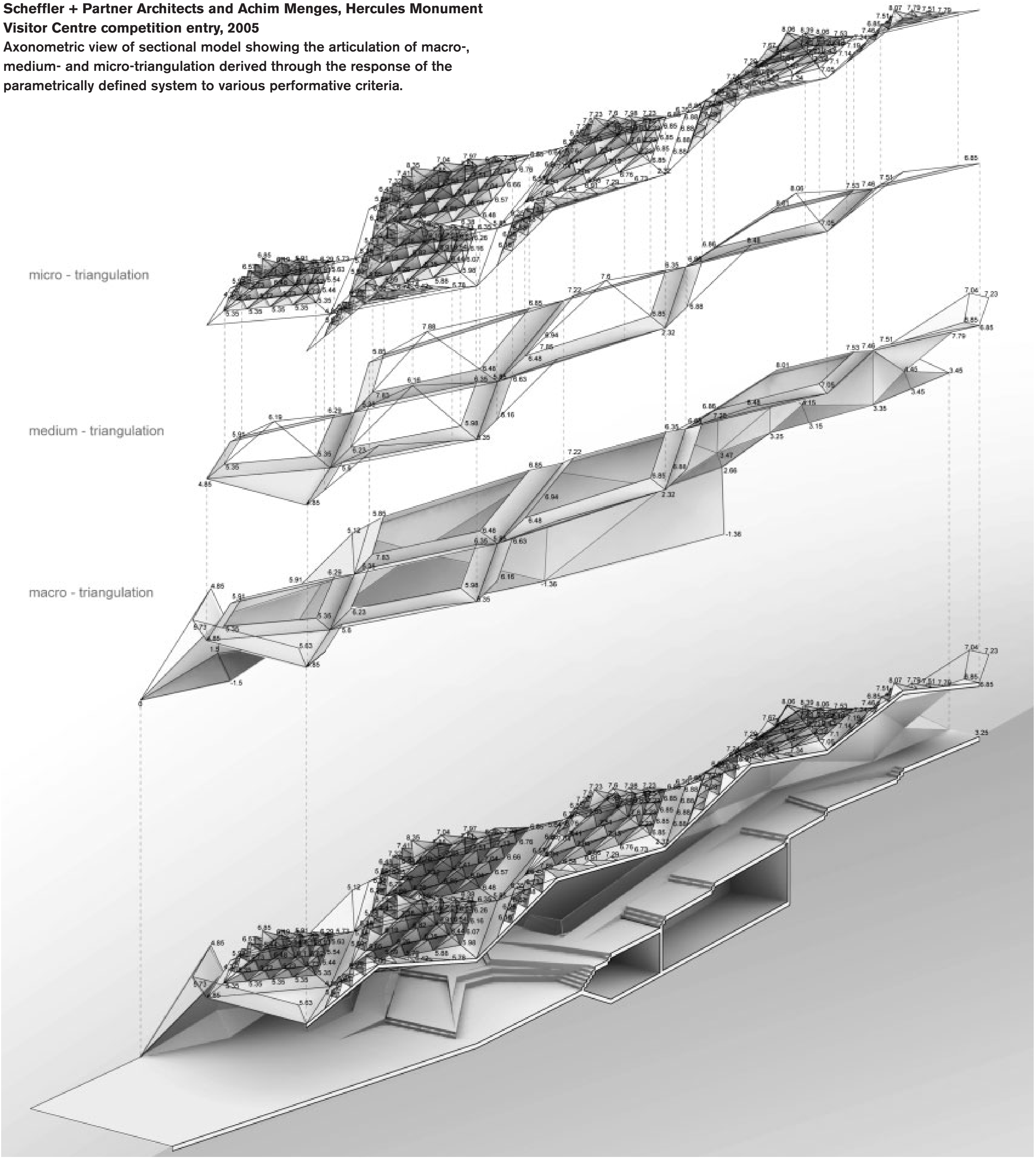
Scheffler + Partner Architects and Achim Menges, Hercules Monument Visitor Centre competition entry, 2005

While the two Emtech research projects focus on exploring and assessing a higher level of material and design synthesis through a primarily bottom-up design methodology, the following project investigates ways of instrumentalising integral form-generation techniques for a competition project for a historical site. In 2005, Achim Menges and Scheffler + Partner Architects (Professor Ernst Ulrich Scheffler and Eva Scheffler), in collaboration with Professor Dr Klaus Bollinger (Bollinger + Grohmann Consulting Engineers) and Claudius Grothe (Freiraum Landscape Architecture) developed a competition design for a visitor centre for the Hercules monument in Bergpark Wilhelmshöhe, Germany, which is on the list of prospective world heritage sites. Situated at the 515-metre (1690-foot) high peak of a major Baroque sight axis of Kassel Wilhelmshöhe Palace and a 250-metre (820-foot) long water cascade, the 71 metres (233 feet) tall Hercules monument was designed by Francesco Guerniero and completed in 1717.

Due to the complex historical situation, the proposal for the visitor centre suggests an infolding of the park to articulate an interior landscape submerged underground that intensifies the transition from the natural surrounding of Habichtswald to the Baroque park and monument. Thus, rather than relating the competition brief to specific spatial entities that aim at directly answering the programmatic and volumetric requirements, the project's spatial strategy is based on providing an interior environment made up of different micro-milieus. These offer a range of luminous conditions, surface articulations and views along each visitor's path to the Hercules monument through strategic penetrations of the exterior park by which the structure is covered. Thus the western approach to Wilhelmshöhe through the visitor centre is articulated as a series of terrains that allow each visitor to choose individual itineraries and sojourns as a personal response to daily and seasonal changes of light intensities, different vistas, programmatic provisions and duration of visit. By means of synthesising digital form-generation and associative modelling techniques, a system of self-similar triangulated faces across multiple scales of articulation and performativity became instrumental in the development of the design proposal.

The biomimetic principle of self-similarity underlies the setup of a parametrically defined and constrained triangulated system with four interdependent scales of articulation: central to the performative strategy are arrays of triangular micro-folds nested on the faces of quadrilateral pyramids which themselves are parts of the macro-folds that articulate the overall geometry of the system. Each scale of resolution shares the basic parametric setup defined through triangular geometry, but responds to different input parameters in the iterative development process of the system. These underlying geometric associations are informed by the constraints of manufacturing and construction, ranging from computer numerically controlled (CNC) cut planar formwork for the in-situ concrete of the triangulated structural main body, to the folded-glass and steel plates of the micro-tessellation. The strategic negotiation of geometric control parameters of independent and interdependent system constituents enables an increasing level of complexity through nonlinear responses to the system-intrinsic constraints, performative criteria and surrounding environment during the generation of system variants. This synthesis of generative digital design tools and

Scheffler + Partner Architects and Achim Menges, Hercules Monument Visitor Centre competition entry, 2005
Axonometric view of sectional model showing the articulation of macro-, medium- and micro-triangulation derived through the response of the parametrically defined system to various performative criteria.



long-chain parametric dependencies assures coherence with a series of defined criteria, while at the same time allowing for novel and undetermined performative capacities to emerge through the negotiation of a top-down and bottom-up approach.

The setup of such an operative interrelation of system constraints, definition and capacity to achieve a differentiated landscape, 'lightscape' and 'viewscape' is explained as follows. The Baroque central axis and sight line provides the notional spine of the parametric control rig of the visitor centre's overall geometry, which adapts to the circulatory and volumetric requirements and coheres with the structural needs of an underground, tunnel-like building. As a response to the specific vertical and horizontal forces resulting from self-weight, earth thrust and live loads interacting with the overall geometry, the main body is further articulated through a series of macro-folds. For example, a framework of V-shaped trusses with sufficient structural depth carries the dead and live loads of the park and micro-fold articulations

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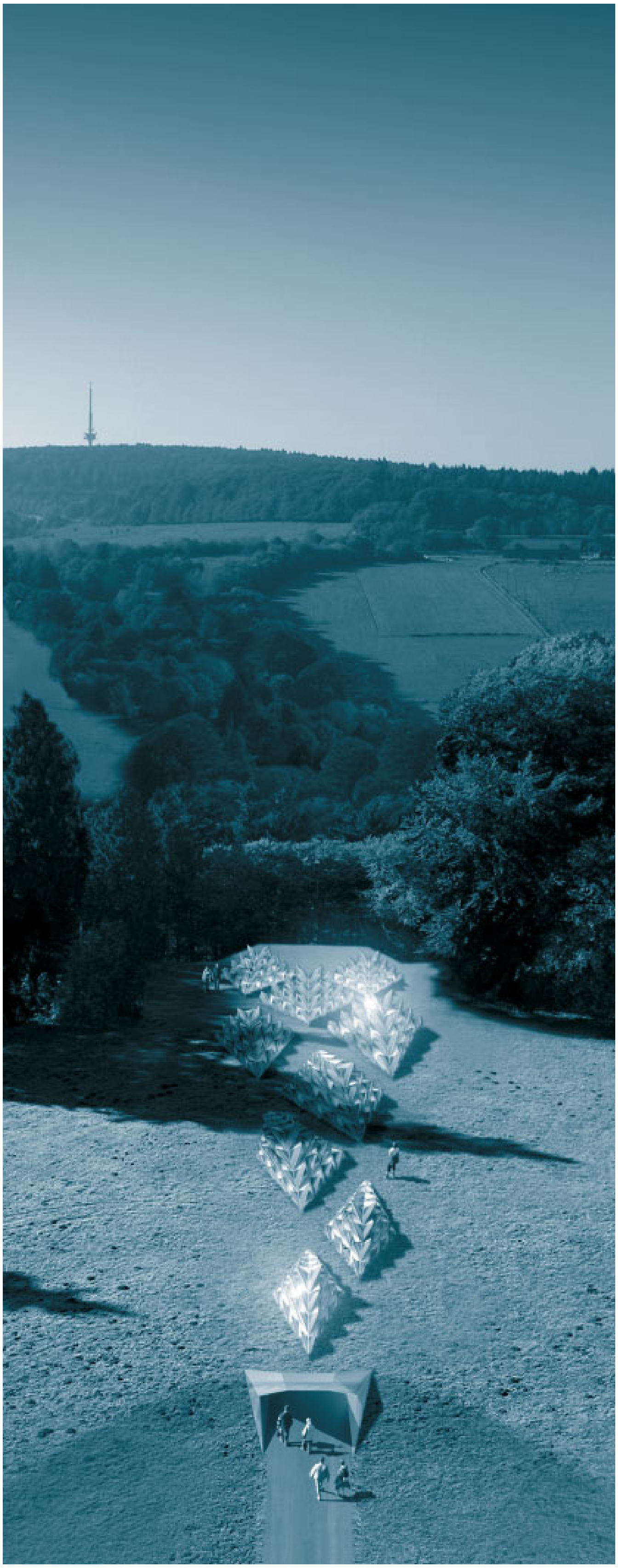
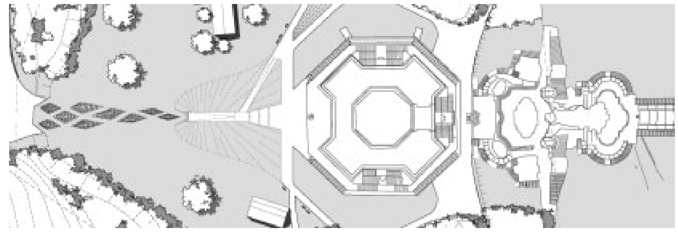
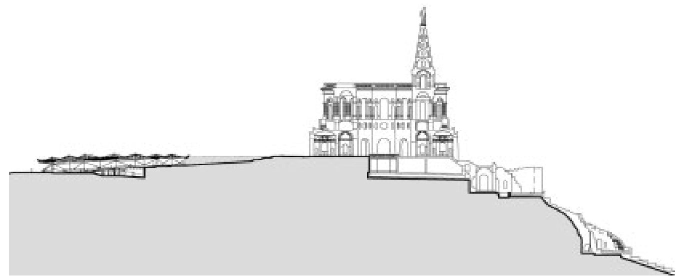
External view of the underground visitor centre with micro-folded skylight structures seen from the Hercules monument visitor platform.



Site plan (top) and section (bottom) of the historical Hercules monument and the proposed visitor centre.





above, while the triangulated walls counteract the earth thrust and transfer the loads into the sole plate and medium-triangulation of the structure. The orientation and inclination of the faces of the medium-triangulation distributes the forces resulting from the glass-and-steel micro-triangulated system. The adaptation to the specific forces is constantly negotiated with the notional parametric constraint envelope of the interior landscape given, for example, through clear heights, surface inclinations, maximum slopes, areas and volumes. Furthermore, the orientation of the medium fold-lines, the related edge vectors and surface normals are set up in relation to the sun path and transmittance and reflection of light. At the same time they define the main fields of view and sight lines. These become further differentiated through the nested micro-triangulation of self-supporting folded glass and stainless-steel plates.

Within the main viewing fields organised by the medium fold-lines and dimensions, the micro-triangulation differentiates the vistas towards the Hercules monument and surrounding landscape. From different viewpoints within the interior landscape, the monument is exposed, framed, partially visible or entirely hidden. Along the individual path of each visitor, the views experienced change from obstructed, framed and open vistas that culminate in the direct exposure of the enormous monument when transiting from the infolded interior landscape to the Baroque park. In addition, the micro-folds' geometric differentiation of face sizes, heights and orientations also modulates the transmission and reflection of luminous flow during the daily and annual changes of the sun path. As a result, dynamic fields of differential light intensity and solar gain emerge in correlation with different fields of view, providing dynamic micro-environmental zones and programmatic opportunities. Not dissimilar to the partial transmittance of light through leaves in the adjacent forest, the micro-shades resulting from this articulation allow the inhabitants to choose from a wide range of luminous

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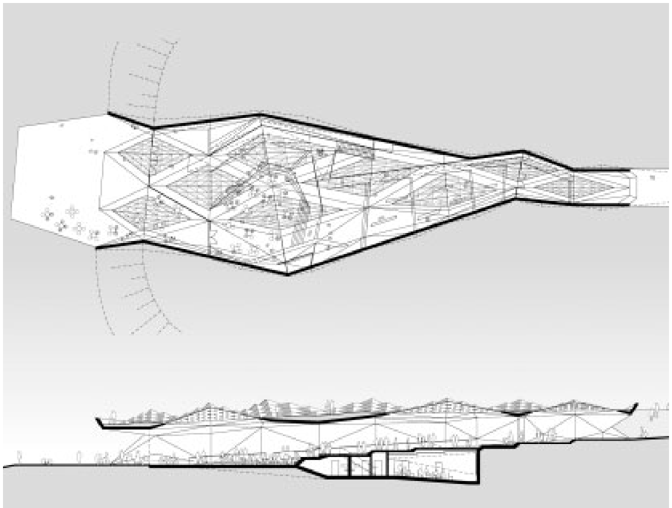
Plan (top) and sectional (bottom) articulation of the interior landscape, 'lightscape' and 'viewscape' of the proposed visitor centre.



Interior view of the visitor centre indicating the visitor's differentiated field of obstructed, framed and open views towards the Hercules monument.

intensities in the café, lounge, waiting and information areas. At the same time, the high number of differently orientated faces reflects the light of the polished stainless-steel and glass surfaces to extend the Baroque concept of the adjacent water cascades through a cascade of reflected and refracted light.

The generative drivers and system-intrinsic and -extrinsic control parameters can be strategically altered in various design iterations within the editable and nonlinear design history of the project. Through this synthesis of form generation and associative parametric modelling, which embeds the geometric constraints of the related fabrication and construction processes, a greater degree of coherency and/or strategic incongruence can be achieved. This setup then yields complex, unpredictable and undetermined performative effects through which alternative spatial strategies can be implemented and explored. Although the digital setup, as well as the material/structural systems, is organised hierarchically, the integral nature of this design process enables each scale of definition to implicitly address a whole series of defined criteria and performative aspects. Through the continuous negotiation of these constraints and the resulting defined, anticipated and novel performative effects, the integral capacity of the system emerges. The investigation and evaluation of these emergent capacities then allows for the redefinition of the driving criteria, and thereby provides an inroad for a critical and innovative approach to architectural design.

Besides the work undertaken by Michael Hensel, Achim Menges, Michael Weinstock and Nikolaos Stathopoulos in the Emergence and Design Group and at the Architectural Association, there are a number of contexts in which related important work is currently being undertaken. Three related lines of research critical to a higher level of material and design integration are currently under way: 1) a rigorous and instrumental analysis of living nature leading to major advances in designing composite materials with higher functionality as pursued, for example, at the Centre for Biomimetic Engineering at the University of Reading led by Professor George Jeronimidis; 2) research into advanced adaptable structures and alternative approaches to environmentally modulating building envelopes, such as that conducted by Professor Werner Sobek and his team at the Institute for Lightweight Design and Construction (ILEK – the former IL Institute for Lightweight Structures of Frei Otto); 3) new ways of understanding and designing morphologies, as investigated by Professor Mark Burry at the technical office of the Temple Sagrada Familía, RMIT University in Melbourne and UPC University of Catalunya. These lines of research promise very interesting results that can feed into a rigorous and instrumental higher-level methodological integration as described in this article, out of which a higher-level functionality and performance-oriented design paradigm might arise.

Overall, the argument and instrumental toolset that begins to emerge operates largely on gradient threshold conditions and effects and their experiential value. In the next stage of development, it would be interesting and necessary to re-engage a discourse of spatial arrangement and social formation that operates on the combination of the hard material thresholds and the environmental gradient threshold. Topological alterations of each evolved design instance may thus yield alternative and novel spatial arrangements together with the social formation pattern that these spaces can provide for. On the whole, the possibility for this renewed discourse is perhaps the most significant indicator of a paradigm shift in architectural design and a relevant topic for a future issue of AD. AD

Project credits
Hercules Monument Visitor Centre competition entry, 2005
Architects: Scheffler + Partner Architects (Professor Ernst Ulrich Scheffler and Eva Scheffler) in collaboration with Professor Achim Menges.
Structural engineers: Bollinger + Grohmann Consulting Engineers (Professor Klaus Bollinger and Mark Fahlbusch).
Landscape Architect: Freiraum (Claudius Grothe).