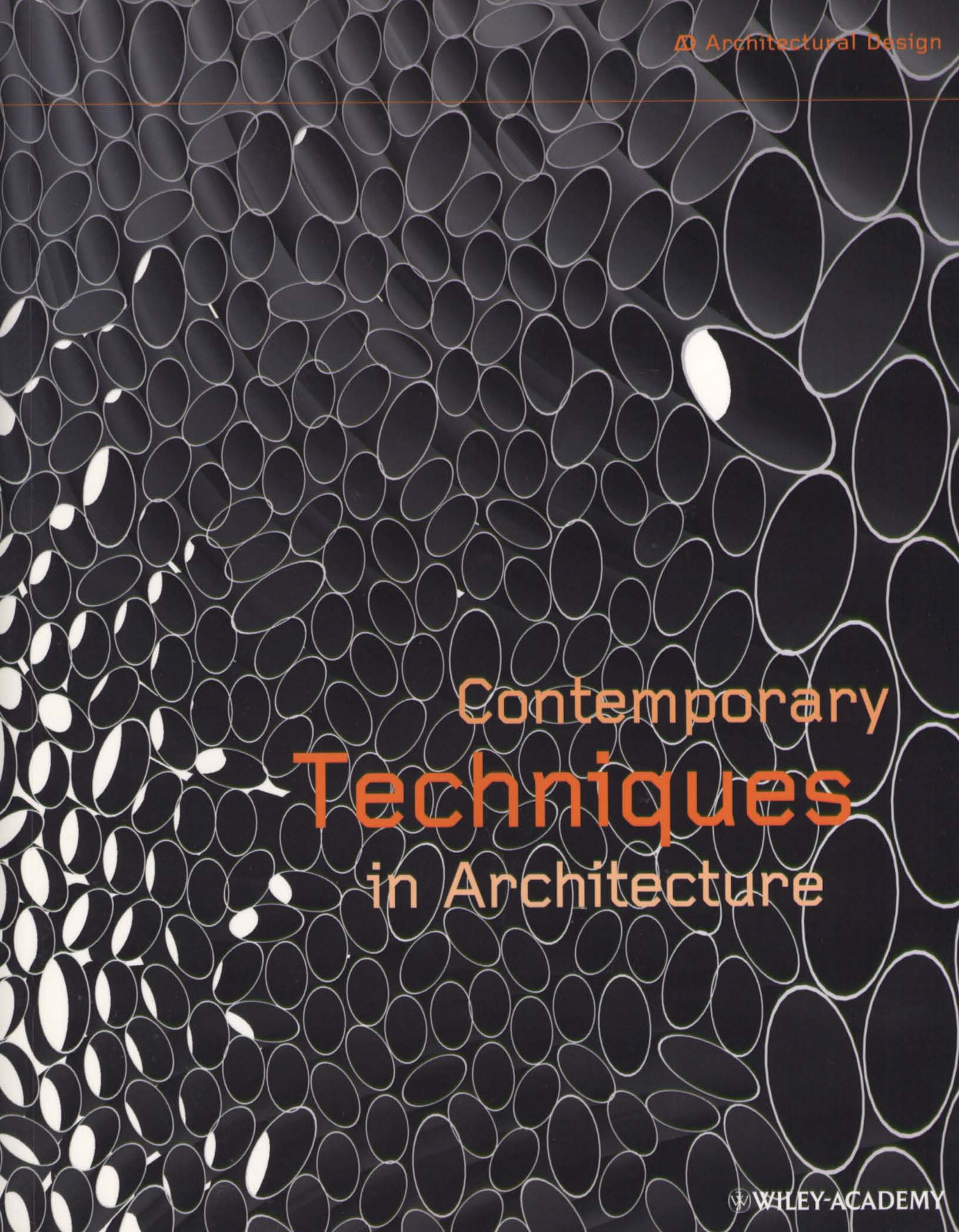
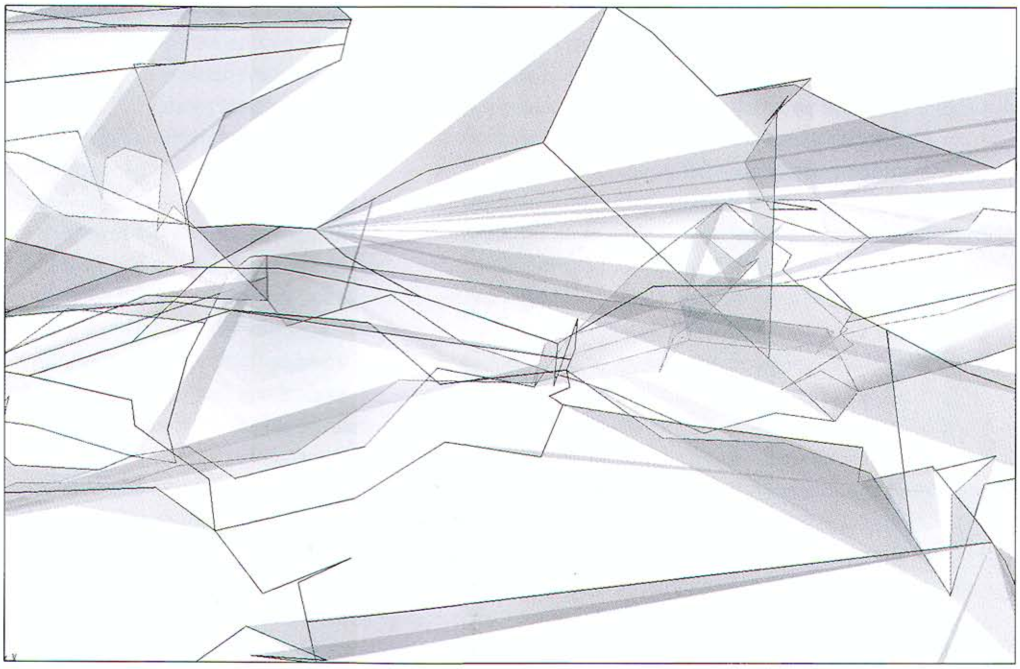


AD Architectural Design

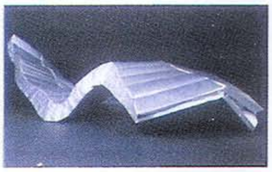
Contemporary Techniques in Architecture

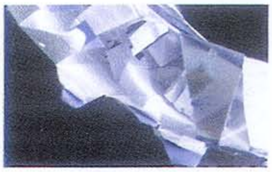
WILEY-ACADEMY

Emergent Structural Morphology



Peter Testa and **Devyn Weiser** develop 'theoretical frameworks and computational environments to relate computational thinking to the design process.' This trans-disciplinary approach incorporates and adapts the very latest programming techniques from artificial intelligence, computational geometry, advanced structural engineering, manufacturing and material science, to establish a generative process. Their work brings about a synthesis between space-oriented and structure-oriented models, thereby creating self-regulatory patterns in which potentialities are regulated by the developing structure itself, through a process of interlocution within its individual components. The link between form and technique that is initiated within these discontinuous yet consanguine parts is mutable, and integrates non-linear combinations of digital and analogic sequences, innovative algorithims and intensive 'deep' computing techniques. These techniques result in the simulation of stochastic, evolutionary and environment based three-dimensional structures and surfaces.





The development of new material and building systems is closely linked with end-to-end process redesign that includes the inventive application of computational tools across design and manufacturing. Computation has become the engine of experimentation and research in architecture and structural engineering. Advances in computing technology have made the technique of simulation as crucial to design and engineering today as theory and experiment were in the past. The trend is evident in computational geometry, advanced structural engineering, material science and manufacturing. Many of these advances are related to the availability of high-performance computing and new software tools that enable high-speed generation and analysis of formal systems and structures, as well as new algorithms for searching, matching and aligning information. Powerful deep-computing techniques have been used to develop analytical tools, and still more powerful techniques will be required to fulfil the promise of emergent structural morphology. Deep computing implies the use of powerful machines running sophisticated software and using innovative algorithms to solve complex problems. But there is another more accessible approach to building *ad hoc* design machines which, when creatively applied, can vastly expand the design space and formal potentials of architecture and advanced structural design. This approach involves the modification and augmentation of existing and readily available tools and techniques.

In 1997, we founded the Emergent Design Group (EDG) at MIT to pioneer this new transdisciplinary design approach located at the intersection of architecture, artificial intelligence and material science. Our research develops theoretical frameworks and computational environments to relate computational thinking to the design process. Some of the themes we study are structural morphology, generative modelling of architectural form and building assemblies. While our projects find support in advanced computational techniques, they are also motivated by ongoing developments in material science. Today we are in the position not to simply specify material assemblies from catalogues, but to design materials adapted to specific aesthetic and tectonic objectives. This opens up radical new possibilities for architectural form but also demands new skills and insights from the designer.

Design Machines

Our research team has designed and implemented a series of tools that apply cutting-edge programming techniques from the domain of artificial intelligence and artificial life. The work is significant in inventing algorithms for environment-based, stochastic and evolutionary simulations of three-dimensional surfaces and structures.

The source code of our design machines, that is, the basic structure of how information works inside them, is a mutable link between form and technique that results from discontinuous yet related processes. We design our tools to deal with an interlocking or interaction of digital and analogic steps, as alternating processes instead of a linear series of steps that are all alike. To use computation creatively we have found that there must always be a generative process whereby the classes are created before they can be named. Evolutionary computation provides a readily available set of techniques and control models to generatively model the development of pattern, form and structure in architecture.

Various models of morphogenesis exist that use computer graphics to visualise the results of simulations. Przemyslaw Prusinkiewicz has succinctly characterised these models in two classes.[1] Space-oriented models capture the flow of information but have only limited capability to describe the structure embedded in the medium and its expansion, as growth is limited to the boundary. Structure-oriented models can simulate the expansion of the whole structure, but they do not inherently capture information flow through the medium. Our work represents a synthesis of both approaches with the goal of initiating self-regulatory patterns whereby growth is potentially controlled by the whole developing structure, using communication via the existing components of this structure.

Two of the software systems we have developed – Morphogenetic Surface Structure (MoSS) and Generative Form Modelling and Manufacturing (GENR8) – explore developmental mechanics and demonstrate aspects of the flow of control information during the development of multicellular structures. MoSS and GENR8 use programming languages to further architectural exploration, and assist in the development of a contemporary design approach that incorporates knowledge and awareness of structural forms and material qualities along with aesthetics and computational processes. Our tools enable the designer to envision structures, the potential in new forms and the possibilities of generating other forms, and to experiment with changeable forms through metamorphosis. As a result, spontaneity is a constant in this process as forms pass from one to the other.

Both tools are written in C++ as plug-ins to Alias|Wavefront Studio and Maya platforms. They are fully integrated with the Alias|Wavefront API and can be used in a manner similar to, and in conjunction with, the powerful modelling and simulation environment. The plug-in aspect implies the potential for these tools to be

Previous page
GENR8 is an innovative design tool that fuses an expressively powerful universe of growth languages with evolutionary search. The software combines 3D map Lindenmayer systems that are extended to an abstract physical environment with Grammatical Evolution. Plug-in to Alias|Wavefront Maya.

Above
Aluminium prototype of MoSS three-dimensional truss system. Models fabricated by Ben Piper/MIT.

integrated with existing tools and conceptualised as part of a larger design process that includes simulation, evaluation and manufacturing.

Morphogenetic Surface Structures (MoSS)

MoSS uses a specialised implementation of 3D Lindenmayer systems (L-systems) that grow surfaces by applying rewrite rules to an axiom with an accompanying interpretation of movement and drawing in space. L-systems are based on recursive replacement of characters according to a set of grammar rules. The recursive replacement is limited by the number of generations specified for a run. In an L-system growth is controlled by a context-free or context-sensitive grammar. In MoSS the designer specifies the grammar and guides surface growth by defining shaping forces and boundary conditions. The environment in which a MoSS three-dimensional L-system operates ultimately decides the final geometry of a surface.

The interface includes control factors that establish grammar, limit generation and shape environment. For example, any number of attractors and repellors, points where growth is promoted or discouraged, can be added to create a complex growth environment with feedback. An attractor and repellor is defined as a point in 3D space. Around this point, movement and drawing are warped to force movement closer to the attractor or further from the repellor. The amount of warping depends on distance and force. This force is parameterised for the user to set. Attractors and repellors significantly alter the generated surface from its specification in axiom and production-rule terms. They can be used to represent various forces in the environment.

One example of a structural system that has emerged from the MoSS research programme is the free-form honeycomb truss. In this system, vertices of generated surfaces are joined to form an adaptive three-dimensional cellular structure. The structures may be produced with sheet materials or as a matrix to be filled with structural foam. We are exploring a cellular membrane, using advanced composite materials in which cell geometry, size, wall thickness and depth are simultaneously varied in response to stress and various loading conditions. The longer term goal is to develop tools for generating cellular structures and structural membranes. These constructs should exhibit local or microscopic behaviour in length and time scales related to their thickness, and macroscopic behaviour in length and time scales related to growth and movement perpendicular to their surface.

Generative Form Modelling and Manufacturing (GENR8)

In an effort to create a bridge between local and global simulation of cellular structures, we implemented GENR8, a software system for emergent simulations that uses Map L-systems. Map L-systems extend the expressive power of L-systems beyond branching structures to graphs with cycles – called maps – that represent cellular layers. GENR8 is a Map L-system with geometric interpretation that operates first by establishing the neighbourhood relations between the cells, then assigning geometric parameters to the resulting graph. Grammar-based rules specify a model's topology, which sequentially determines its geometry. GENR8 combines 3D Map L-systems, which are extended to an abstract physical environment, with Grammatical Evolution. An innovative aspect of this tool is that it fuses expressively powerful languages for simulating growth with evolutionary search.

GENR8 addresses key issues arising from exploiting evolutionary adaptation within an interactive design tool. Evolutionary Algorithms (EAs) typically adapt 'off line' but GENR8 is designed to accommodate iterative control exchange between user and tool during on-line evolutionary adaptation. It allows users to interrupt, intervene and then resume an EA tool. In addition to user-based interactive design evaluation it also offers the option of computationalised multicriteria evaluation to enable wider searches in shorter time spans. Constructing grammars by hand is tedious and difficult. To generate and evaluate the universe of possible grammars, we use Grammatical Evolution. GENR8 has two mapping processes, one that maps a genome to a grammar and another that interprets the grammar and constructs a surface (phenotype).

GENR8 has a powerful simulation environment that significantly influences growth. In the current instance, there are three types of forces: attractors, repellors and gravity. As in MoSS, attractors and repellors can be used to direct growth. The user situates them in space and their effect depends on the relative location of the surface being modelled. The user may also draw arbitrary surfaces and volumes that act as boundaries.

A key issue for EAs is the fitness evaluation. GENR8 allows the user to express preferences by setting the parameters of the fitness function. Five independent fitness criteria are implemented: size, smoothness, soft boundaries, subdivisions and symmetry. The different (independent) parameters can be used to express multilevel, nonlinear and possibly conflicting design criteria. Similarly, the weight and parameters of any criterion can be changed at any time during a run. The fitness function has several parameters (rewarding different features of the surface) and modifying these will alter the ranking of individuals. The user can guide evolution by setting fitness values by hand. The user

Note

1. Przemyslaw Prusinkiewicz, 'Visual models of morphogenesis' in C Langton (ed), *Artificial Life*, MIT Press (Cambridge MA), pp 61–74.

can also indirectly affect fitness by changing an individual and inserting those copies into the population. It is also possible to insert another population (previously saved to a file) into the existing population. This enables the user to insert new formants in a controlled way.

Looking further ahead, there is a need to instantiate growth models with the capability to combine the atomic structure and mechanical properties of materials, and the macro behaviour of the structure as a whole operating in a dynamic environment. This would lead to different control models for different materials, and different grammars for the larger structure related to specific material properties. In this way tunable factors in the materials may be adapted through mutualist feedback with the emergent structural morphology as a whole. For example, atomistic simulation of materials using force-field parameters or methods based on high-capacity molecular dynamics may allow us to evolve highly tuned and sophisticated material forms and three-dimensional structures on all scales.

Carbon Tower Prototype

To further develop and apply our research in emergent structural morphology we have founded the Hyperarchitecture Research Center (HYPR) in the Department of Civil and Environmental Engineering at MIT. A primary research platform for this new centre is focused on developing an innovative tensile building system using advanced composite materials. We are currently developing a prototype of a 40–60-storey high-rise and have received a preliminary patent. All the developments described in the preceding EDG projects, from computational tools to materials and manufacturing and the goal of fusing surface and structure, are being incorporated in this new project.

The structures of the future require minimum materials and maximum performance. Advanced composite materials, primarily developed in aerospace, defence and other industries, are finding more applications in civil engineering and they emerge as attractive future construction materials. Structures made of these materials enjoy a host of benefits because they are stiff, strong, light and formable. However, their use in buildings and other structures is currently limited because of inherent design requirements.

In our system, compressive loads are carried by an array of vertical columns and cores, constructed on site using high-strength steel-reinforced concrete and composite reinforcing. In contrast to the traditional 'bottom-up' construction schemes, our approach is to construct the compression members (the cores) first, and then build the structural skeleton from the top to the bottom. A composite mesh formed of continuous pultruded sections is hung from this compressive structure. Operating in concert with Kevlar cables, this exterior meshwork supports the floor slabs. These are laminated resin slabs with a composite mesh continuous with the exterior tensile envelope. All connections between elements are made using high-strength adhesives. The resulting hybrid structure combines a flexible building envelope with a rigid core, yielding a structure that is earthquake resistant. The open interior plan is combined with a variable section as the floors are independent of the constrictions of frame and curtain-wall construction.

A key concept in this system is the use of a tensile mesh or woven structure suspended from the compressive cores. We are developing new pultrusion and robotic technology to weave the structural envelope on site. In the new enclosure system, transparent resins and silicone membranes allow for a spectral and smooth exchange from opaque, reflective, translucent to transparent, without sacrificing the structural properties of the enclosure. The layering of exterior skins can be developed as a series of plenums, supporting natural ventilation. In order to better design the system, we are coding different generative structural design and analysis tools. For example, we designed a tool to generate woven meshes called WEAVER. It allows the user to explore patterns that can either be used to generate the building morphology or be applied to a shape established by other parameters.

We address the potential integration of sensors and active materials within this structural system and material assemblies. The feedback is necessary as a means of monitoring the integrity of components during the construction process. Damage and failure in composite materials are exceedingly difficult to detect. Embedded sensors can also serve as an active component throughout the life of the structure, allowing for real-time adaptation to dynamic loading conditions and differential movements between highly stable composite materials and other material systems used in construction.

Application Oriented Basic Research

The digital revolution combined with the rapid development of new materials and prototyping technology has fundamentally changed the way buildings are designed and constructed. New tools and techniques are required to capture the emergent relations among evolving material properties, structural morphology, manufacturing technology and architectural form. Our work is foundational to this next step in design, which integrates the propensity of materials and manufacturing processes within generative computing. Δ

Above
WEAVER uses a grammar capable of describing and generating woven strands to a user-defined surface. The resulting weaves can be complex, and depend on both the description of the weave pattern and the topology of the surface on which the weave is applied. MEL script for Alias|Wavefront Maya.