Material Computation

Neri Oxman

Neri Oxman is from an entirely new breed of architectural researcher, and is a rare individual looking at the profound implications of a wide spectrum of advanced process and material technologies. Her work investigates some of the most pioneering and far-reaching questions on what new openings technological evolution presents the designer. Her work is becoming extensively read and followed worldwide and in her words from elsewhere, 'It's been a long awaited dream of mine to see fabrication enter the very first stages of the design process. Fabrication is slowly shifting from a state of being simply a production protocol, a service station for the designer to gather knowledge, and moving to a point where it can have generative significance.'[1]

This essay proposes a new approach in design where processes of form-generation are directly informed by the combination of material properties and environmental constraints. Inspired by Nature's strategies where form generation is driven by maximal performance with minimal resources through local material property variation, this approach, entitled *Material Computation* is introduced as a set of computational strategies supporting the integration of form, material and structure by incorporating physical form-finding strategies with digital analysis and fabrication. In this approach, material precedes shape, and it is the structuring of material properties as a function of structural and environmental performance that generates design form. In proposing a unique approach to computationally enabled form-finding procedures, the essay investigates how such processes contribute to novel ways of creating, distributing and depositing material forms. Experimental designs employing theoretical and technical frameworks are presented, discussed and demonstrated. They support product customisation (architecture and furniture design), rapid augmentation (medical device design) and variable-property fabrication (FAB design). Developed as approximations of natural formation processes, these design experiments demonstrate the contribution and the potential future of a new design and research field.

Nature as Model

Natural structures possess high levels of seamless integration and precision with which they serve their functions. A key distinguishing trait of Nature's designs is the capability in the biological world to generate complex structures of organic, or inorganic, multifunctional composites such as shells, pearls, corals, teeth, wood, silk, horn, collagen and muscle fibres.[2] Combined with extracellular matrices, these structural biomaterials form microstructures engineered to adapt to prearranged external constraints introduced to them during growth and throughout their life span.[3] Such constraints generally include combinations of structural, environmental and corporeal performance criteria. The *shape of matter* is


Weighted material selection: a stochastic computational process assigns a stiffness ratio corresponding to structural performance. © Neri Oxman.

therefore directly linked to the influences of force acting upon it.[4] Material is concentrated in regions of high strength and dispersed in areas where stiffness is not required.

The implications of Nature's structural heterogeneity, achieved through the informed distribution of composites, holds significant implications from a design perspective. The control of material structure and orientation allows for an almost unlimited design space in terms of geometrical and topological variation. It promotes high levels of functional integration through the assignment of graduated properties; it supports the matching between material property distribution and continuous load paths; and, finally, it allows the designer to consider the possibility of adaptive response, and even real growth.

The Problem with CAD

The dominance of *geometrical* representations of design content has for centuries, prior to the use of computers, contributed to a *geometry-centric* approach in the design of products, buildings and cities. Accordingly, form must first be conceived in order to be constructed. Naturally, it is unfeasible (theoretically or technically) for processes of conception and construction to occur concurrently. Predictably, design has been driven by its many forms of expression defined and conveyed in geometrical terms. Material is consistently secondary in this milieu; and it is due to the priority of geometrical representation over physical material considerations, a phenomenon that has led to streamlining the design process: form first, material later. By methodological extension,
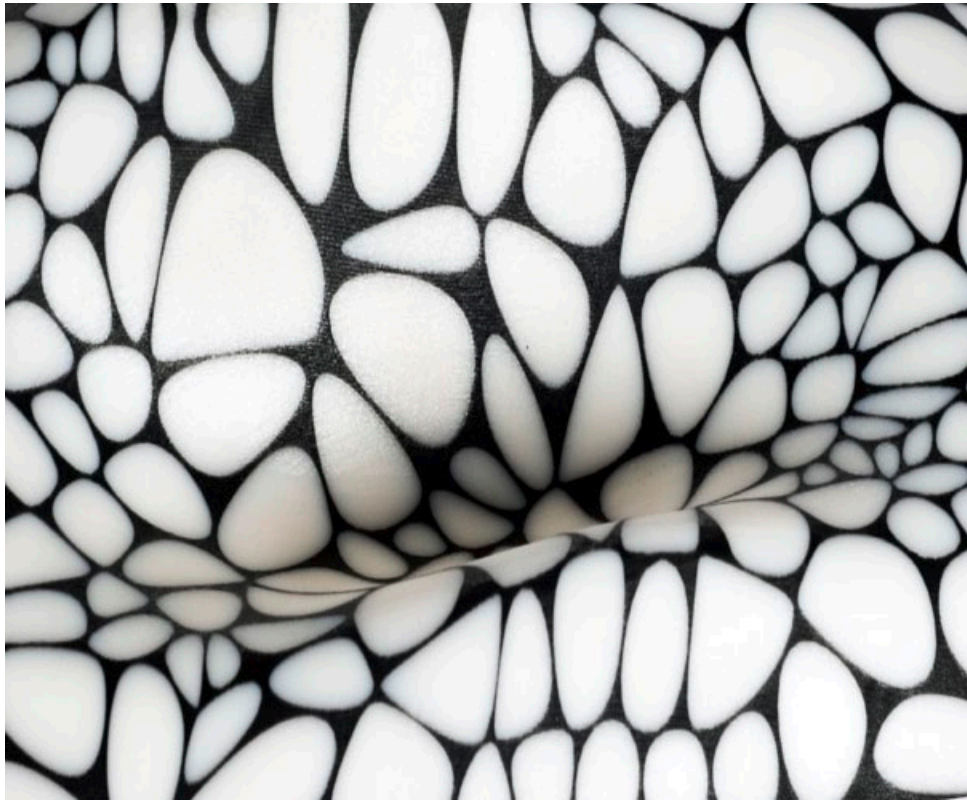
The distribution of shear-stress lines and surface pressure is embodied in the allocation and relative thickness of the stiff vein-like elements built into the skin (black) and the soft (white) cellular components between them. © Neri Oxman.

design conception is to be followed by analysis, simulation and fabrication. Indeed, how can the fabrication of form be manifest without form's conception?

We have seen that Nature's way is uniquely different. In nature, forms are the result of the matching between material parameters and their corresponding environmental constraints. Shape is then merely a by-product, a derivative of natural behavioural formation. It emerges as an effect exclusive to its particular environmental template. In nature, we have established, form's geometry is predominantly determined by the interaction between material and environment.

Compared with natural processes of shape formation, digital fabrication strategies assume the design and fabrication of building parts with homogeneous material properties. Since the industrial age, the building industry has been dependent on discrete solutions for distinct functions.[5] Building skins are a great example of such claims. Steel and glass possess significantly different structural and environmental properties that relate to a uniquely different set of performance requirements. Diversity is achieved by sizing, rather than by substance variation, and it is typically mass produced, rather than mass customised. As far as

material structuring is considered, in the artificial world, especially in the design of building components, one property fits all. This is partly due to the fact that current modelling and fabrication tools within the disciplines of architectural design and construction, are rather limited in their ability to represent constructions of complicated heterogeneous composition, which guarantee desired material continuities in all the interfaces.[6]

In cultivating design processes inspired by nature Material Computation seeks to employ alternative computational processes supporting the generation of form based on the interaction between material and environment. This entails a shift from computationally assistive processes to processes of a generative and performative nature that allow the designer to incorporate material properties and behaviour protocols into CAD.

Material Computation

Material Computation supports the design of multifunctional products and building elements. It is in the multifunctional condition that variations of material properties and composition correspond directly to specific structural and environmental constraints. This approach to design, supporting multifunctionality over discrete utility through the promotion of heterogeneity over homogeneity, seeks to advance and embrace strategies of material distribution over strategies of material assembly, inspired by nature.

This design approach is proposed as the set of processes enabling the distribution of materials and their properties in the design of a product or a building component. These processes are informed by functional, structural and environmental constraints. *Material Computation* is therefore a design approach, a methodology and a technical framework, by which to model, simulate and fabricate functional material organisations with varying properties designed to correspond to multiple and continuously varying functional constraints. Such framework includes processes of modelling, analysis and fabrication. Within each process, certain methods have been identified which carry the potential to rethink design not as form-driven, but rather as a behavioural-driven paradigm.

Following are three explorations into product design (adaptive customisation), medical-device design (rapid augmentation) and fabrication (variable-property fabrication) design, demonstrating some of the methods and principles behind *Material Computation*.

Material Computation: Adaptive Customisation

Beast – a prototype for a Chaise Longue – combines structural, environmental and corporeal performance by adapting its thickness, pattern density, stiffness, flexibility and translucency to load, curvature and skin-pressured areas respectively. A single continuous surface acting both as structure and as skin is locally modulated to cater for structural support on the one hand, and corporeal performance, on the other. Multiple algorithms were generated that correspond to these variables such that stability is mediated with corporeal and structural integrity.

The traditional chaise is transformed here to promote lounging of a different kind. The cellular pattern applied to its entirety is designed to increase the ratio of surface area to volume in occupied areas where the body potentially rests. A pressure map study

was conducted that matches the softness and hardness of the cells to cushion and support sensitive and high-pressured areas. By analysing anatomical structures that cause concentrated pressures, Beast becomes softer and flexible where pressure needs to be relieved. The relative volume of each cellular cushion is locally informed by pressure data averaged with values representing structural support and flexibility. Its density is informed by global and local mean curvature values such that denser, smaller cells are organised in areas of steeper curvature whereas larger cells are found in areas of shallow curvature. Beast's natural relation of structural and sense datum is propagated in variable polymer composites offering a wide range of physical properties. Through these algorithms force conditions naturally propagate functionality. Stiffer materials are positioned in surface areas under compression and softer, more flexible materials are placed in surface areas under tension. State of the art technologies are applied here for the first time to cater for a large range of physical properties and behaviours. The surface patches are 3D printed using a new multi-jet matrix technology that simultaneously deposits materials of different properties corresponding to structural and skin-pressure mappings.

During the initial stages of the design, the texture inherits the geometrical features of the design as defined by the user. Such geometrical features are, in the case of Beast, costumed to fit body curvature criteria. The initial distribution of cells corresponds to the type and degree of curvature: smaller and denser cells are located in regions of higher curvature, and larger, sparser cells are located in regions of smoother curvature. Material properties correspond to both structural requirements (self stability with no additional enforcement members) and environmental requirements (assigned to the body pressure mappings). For the structural performance, a stochastic computational process was developed in which stiffer materials are assigned to vertical regions, which work for buckling, and softer materials are assigned to horizontal regions that work for bending. The probability of a material being stiffer or smoother depends on the angle defining the level of horizontality in the chaise.

Material Computation: Rapid Augmentation

Nature's engineering expertise matches material properties to environmental pressures, be it the formation of stiff materials for load-bearing functions, or insulating materials as protection from extreme temperature gradients. The human skin is designed in the same fashion and acts simultaneously as a structural and an environmental filter and barrier. In the very same way that load or temperature can be mapped in order to design structures that are highly optimised for their function, physical pain can also be mapped in the design and production of medical assistive devices such as pain-reducing splints.

Since the experience of pain is a very personal one, it is different for each individual. Pain is very difficult to define, and it is one of those conditions that are poorly understood by the Western medical sciences. Carpal Skin is a prototype for a protective glove against carpal tunnel syndrome. The syndrome is a condition in which the median nerve is compressed at the wrist, leading to numbness, muscle atrophy and weakness in the hand. Night-time wrist splinting is the recommended treatment for most patients before going into carpal tunnel release surgery.

Beast. Prototype for a Chaise Longue, Boston Museum of Science, 2008. The chaise combines structural, environmental and corporeal performance by adapting its thickness, pattern density, stiffness, flexibility and translucency to load, curvature and skin-pressured areas respectively. It is patterned with five different materials colour-coded by elastic moduli. Stiff (darker coloured) and soft (lighter coloured) materials are distributed according to the user's structural load distribution; soft silicone 'bumps' are located in regions of higher pressure. © Neri Oxman.

Carpal Skin. Prototype for a Carpel Tunnel Syndrome Splint,
Boston Museum of Science, 2008. © Neri Oxman.

The main problem behind immobilised braces is that as they are mass produced they are often too big, too small or too constricting in terms of mobilisation. In this case, as is the case with most muscular and nerve-related syndromes, product mass customisation – as opposed to mass production – is crucial.

Carpal Skin is a process by which to map the pain-profile of a particular patient – its intensity and duration – and distribute hard and soft materials to fit his or her anatomical and physiological requirements limiting movement in a customised fashion. The formation process involves case-by-case pain registration and material property assignment. The 3D scan of the patient's hand, including its pain registration, is mapped to a 2D representation on which the distribution of stiff and soft materials is applied. This pain-map is then folded back to its 3D form and 3D printed using photopolymer composites.

The mapping of required material properties and their assignment to the surface area of the wrist-splint is guided by a texture synthesis based on the simulation of local nonlinear interaction, called reaction-diffusion, which has been generally proposed as a model of biological pattern formation.[7] In this context, the reaction-diffusion algorithm dictates the desired distribution of material properties. In this design context, the traditional reaction-diffusion system has been extended to allow anisotropic and spatially non-uniform diffusion of material properties as a function of anticipated pressure on the surface area of the wrist.[8]

In this particular prototype, stiff materials constrain the lateral bending motion at the wrist, and can be identified by the oblique trajectory of dark and stiff materials. Soft materials allow for ergonomic wrist support and comfort through movement. The local

thickness changes correspond to strategic areas across the surface area of the wrist in cushioning and protecting the wrist from hard surfaces as well as allowing for a comfortable grip. These thickened bumps also increase flexibility and enhance circulation and relieve pressure on the median nerve as it acts as a soft tissue reshaping mechanism. The custom-fit property distribution built into the glove allows for passive but consistent pulling and stretching simultaneously.

Material Computation: Variable Property Fabrication
Current digital fabrication technologies designed for, and applied in the building industry, specifically additive manufacturing platforms, are limited in their capacity to represent graduated material properties.[9] Their basic strategy is typically to assign a material property to pre-shaped building components such as steel beam profiles or glass panels.[10] Within the design process, this translates into assigning a material property to a predefined solid or closed surface polygon. Neither computer-aided design (CAD) tools nor industrial fabrication processes are thus set up to represent graduation and variation of properties within solids such as varied density in steel or varied translucency in glass. As a result, the design process is constrained to the assignment of discrete and homogeneous material properties to a given shape.

Historically, the assumption that discrete solids are made from single homogeneous materials is deeply embedded in Modernist design thinking and generally unquestioned.[11] It is also enforced by the logic underlying the dynamics of industrial supply chains; at their lowest levels, supply chains support component manufacturing processes performed by highly specialised machines that operate on particular materials to produce prefabricated building modules. These low-level sub-assemblies are then put together to form higher-level hierarchical assemblies made of a range of properties corresponding to their respective range of required functions. It is safe to claim that this logic of component-based design fabrication has since the industrial revolution penetrated all stages of the design process from conception to fabrication, particularly in the building industry.[12]

This phenomenon is clearly affecting the way designed goods are being prototyped and fabricated.[13] [14] Additive manufacturing platforms, such as 3D printers, speed product design by facilitating visualisation, physical production and testing of prototypes.[15] However, such technologies are generally limited to using only one material at a time; even high-end 3D printers, which accommodate the deposition of multiple materials, operate discretely; or if they are able to deposit mixtures, they are often pre-mixed.[16] Moreover, varied mechanical properties are currently achieved mostly by injection moulding – a very costly process that presents time and size constraints.[17]

Variable Property Fabrication (VPF) is a new methodological technological platform by which to model, simulate and fabricate material assemblies with gradient properties designed to correspond with multiple and continuously varied functional constraints. Within the VPF environment, the program must translate desired model properties to material properties. The VPF environment gives the value of any property at any point (high or low conductivity/stiff or soft) in order to structure the correct material composition and

emulate both its structural and electrical performance. Currently, transition functions that compute gradient property distribution across one or multiple dimensions do not exist in CAD. The VPF environment is developed in order to cater for such requirements and present physical data and material composition by treating voxels as tensors (geometrical entities containing multiple physical parameters), or by computing transitions between multiple compositional phases as extrapolation functions.

Conclusion: The Material Shift

The Modernist tradition typically promoted the division of functions implicit in the architectural elements: their pre-assigned forms, structures and materials (ie, the separation between structure and facade and the assignment of steel columns and glass walls respectively to each function). Coupled with automation in construction, this logic gave birth to an architecture that is easily mass produced, assembled and built of replicated modules. Despite its obvious advantages, the application of the modular logic of building holds some fundamental limitations in considering requirements driven by site-specific functionality and customisation.

Alternatively, design based upon material properties and environmental conditions promotes customisation through formal, structural and material heterogeneity. Our ability to quantify a building's structural and environmental performance allows the designer to account for site-specific differences of use and behaviour.

Given such ability to predict and respond to performance criteria and desired effects, this research holds implications for shifting design practice from *homogeneous modular design* driven by the *logic of material assembly* to *heterogeneous differentiated design* driven by *material distribution*. In this approach, matter is distributed where needed responding to its structural, environmental or, indeed, social performance. In fostering material integration of architectural elements across various scales, architectural elements such as structure and facade are no longer divorced in function and/or behaviour, but rather negotiated through the informed distribution of matter. Perhaps the most significant consequence of design that is informed by matter is the incorporation of difference: gradients of structural and material effects emerge modulating their thickness, transparency, porosity and thermal absorption according to their assigned function or desired condition of stability (structure) and comfort (environmental conditions). Here is to a new design revolution.

Notes

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