Material Computation

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Inspired by processes of form generation in nature, driven by maximal performance with minimal resources through local variation of material properties, this essay defines a set of computational strategies that support the integration of form, material and structure by incorporating physical form-finding processes into 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 digital form-finding, 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. Their applications include product customization (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 implications of a new research and design field.

Nature as Model

Material structures in nature possess high levels of precision and seamless integration of components with which they serve their functions. A key distinguishing trait of nature's designs is the capability to generate complex structures of multifunctional composites—organic and inorganic—such as shells, pearls, corals, teeth, wood, silk, horn, collagen, and muscle fibres[1]. Combined with extracellular matrices, these structural biomaterials form microstructures engineered to adapt to prearranged external constraints occurring during growth and throughout their life span[2]. Such constraints generally include combinations of structural, environmental and corporeal performance criteria. The shape of matter is therefore directly linked to the forces acting upon it[3]. Material is concentrated in regions of high strength and dispersed in areas where stiffness is not required.

Nature's structural heterogeneity resulting from the informed distribution of composites holds significant implications from a design perspective. The control of material structure and orientation allows for almost unlimited design opportunities 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

Prior to the use of computers, the historical dominance of *geometrical* representations of design content contributed to a *geometry-centric* approach in the design of products, buildings and cities. Under this view, form must first be conceived in order to be constructed. Naturally, it is unfeasible (theoretically and technically) for processes of conception and construction to occur concurrently—and predictably, design has been driven by forms of expression defined and

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[1] Benyus, J. M. Biomimicry: Innovation Inspired by Nature, Quill. New York (1997).
[2] Vincent, J. F. V. Structural biomaterials. London, Macmillan (1982).
[3] Vogel, S. Comparative biomechanics : life's physical world. Princeton, NJ, Princeton University Press (2003).

conveyed in geometrical terms. The priority of geometrical representation over physical material considerations has led to streamlining the design process—form first, material later. By methodological extension, 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, form is the result of the interaction 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 of its particular environmental template.

Compared with natural processes of shape formation, digital fabrication strategies apply homogeneous material properties to diverse building parts. Since the industrial age, the building industry developed discrete solutions for distinct functions[4]. A great example of such claims are building skins, where 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 customized. As far as material structuring is considered, in the artificial world—and 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 architecture and construction are rather limited in their ability to represent constructions of complicated heterogeneous composition, which guarantee desired material continuities in all the interfaces[5].

In cultivating design processes inspired by nature, Material Computation seeks to employ alternative computational processes that support 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 include material properties and behaviour protocols into CAD.

Material Computation: Definition

Material Computation supports the design of multi-functional products and building elements, in which variations in material properties and composition correspond to specific structural and environmental constraints. This approach to design, inspired by nature and supporting multi-functionality over discrete utility through the promotion of heterogeneity, seeks to advance and embrace strategies of material distribution over strategies of material assembly.

Material Computation comprises 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 material organizations 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

[4] Oxman, N. "Oublier Domino: On the Evolution of Architectural Theory from Spatial to Performance-based Programming." Proceedings of Critical Digital Conference: What Matters? Harvard Graduate School of Design, Harvard University, 2008; Cambridge, MA: 393-403.
[5] Shin, K. and D. Dutta. "Constructive representation of heterogeneous objects." Journal of computing and information science in engineering 1: 205. (2001)

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 customization), medical-device design (rapid augmentation) and fabrication design (variable-property fabrication), demonstrating some of the methods and principles behind Material Computation.

Material Computation: Adaptive Customization

Beast—a prototype for a chaise lounge—combines structural, environmental and corporeal performance by adapting its thickness, pattern density, stiffness, flexibility and translucency to load, skin pressure, and curvature. A single continuous surface acting both as structure and as skin is modulated to cater for structural support on the one hand, and corporeal performance on the other. Multiple algorithms are generated to coordinate these variables, mediating stability 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 surface-area-to-volume ratio in zones where the body potentially rests. A pressure mapping matches the softness and hardness of the cells to the cushion and support requirements of sensitive and high-pressured areas. By analyzing anatomical structures that cause concentrated pressures, *Beast* becomes soft 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 organized in areas of steeper curvature, whereas larger cells are found in areas of shallow curvature. *Beast's* natural relation between structural and sense datum is propagated in variable polymer composites that offer 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 then 3-D 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 deriving from the user and is 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 reinforcement members) and environmental requirements (assigned to the body pressure mappings). For the structural performance, a stochastic computational process is developed in which stiffer materials are assigned to vertical regions that 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 chaise's slope.

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, for instance, acts simultaneously as a structural membrane 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 optimized for their function, physical pain can also be mapped for the design and production of medical assistive devices such as pain reducing splints.

Carpal Skin is a prototype for a protective glove against carpal tunnel syndrome—a condition in which the median nerve is compressed at the wrist, leading to numbness, muscle atrophy and weakness in the hand. Nighttime wrist splinting is the recommended treatment for most patients before going into carpal tunnel release surgery.

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

Pain is very difficult to define, its experience is different for each individual, and it is poorly understood by Western medical sciences. *Carpal Skin* is the result of a process that maps the pain-profile of a particular patient—its intensity and duration—and distributes hard and soft materials to limit movement in a customized fashion, fitting his or her anatomical and physiological requirements. 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[6]. In this context, the reaction-diffusion algorithm dictates the distribution of material properties, allowing—beyond the scope of traditional systems—for an anisotropic and spatially non-uniform diffusion of material properties as a function of anticipated pressure on the surface area of the wrist[7].

In this particular prototype, stiff materials constrain the lateral bending motion at the wrist, whereas soft materials allow for ergonomic wrist support and comfort through movement. This distribution can be identified by the oblique trajectory of dark and stiff materials. The local thickness changes correspond to strategic zones across the surface area of the wrist, so as to cushion and protect the wrist from hard surfaces or to allow for a comfortable grip. These thickened bumps also increase flexibility and enhance circulation and relief pressure on the median nerve, acting as a soft tissue reshaping mechanism. The custom-fit property distribution built into the glove allows for passive but consistent pulling and stretching simultaneously.

[6] Witkin, A. and M. Kass (1991). "Reaction-diffusion textures." ACM SIGGRAPH Computer Graphics 25(4): 299-308.
[7] Oxman, N. Material-based Design Computation, Doctoral Thesis. Massachusetts Institute of Technology (2010).

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 handle graduated material properties[8]. Their basic strategy is typically to assign a material property to pre-shaped building components, such as steel beam profiles or glass panels[9]. Within the design process, this translates into assigning a material property to a predefined solid or closed surface polygon. Both computer-aided design (CAD) tools and industrial fabrication processes are thus not set up to allow for 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[10]. 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 specialized 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[11].

This phenomenon is clearly affecting the way goods are prototyped and fabricated[12,13]. Additive manufacturing platforms such as 3D printers, speed up product design by facilitating visualization, physical production and testing of prototypes[14]. 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[15]. Moreover, varied mechanical properties are currently achieved mostly by injection moulding—a highly costly process that presents time and size constraints[16].

Variable Property Fabrication (VPF) is a new methodological technological platform by which to model, simulate and fabricate material assemblies with gradient properties designed to

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[8] Oxman, N. "Structuring Materiality: Variable Property Fabrication of Heterogeneous Materials " Architectural Design: THE NEW STRUCTURALISM: DESIGN, ENGINEERING AND ARCHITECTURAL TECHNOLOGIES 80(4): pp78-85 (2010)

[9] Oxman, N. "Oublier Domino: On the Evolution of Architectural Theory from Spatial to Performance-based Programming." Proceedings of Critical Digital Conference: What Matters? Harvard Graduate School of Design, Harvard University, 2008; Cambridge, MA: 393-403.

[10] ibid

[11] ibid footnote 8.

[12] Ibid

[13] Oxman, N. "Variable Property Rapid Prototyping (VPRP)." United States Patent Pending US 61/248,555. (2009)

[14] Sachs, E., M. Cima, et al. (1993). "Three-dimensional printing: the physics and implications of additive manufacturing." CIRP Annals-Manufacturing Technology 42(1): 257-260.

[15] Chang, C. (2004). "Rapid prototyping fabricated by UV resin spray nozzles." Rapid Prototyping Journal 10(2): 136-145.

[16] German, R. (1998). "Powder injection moulding." ASM Handbook 7: 355-364.

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 provides the value of any property at any point (high or low conductivity, stiff or soft materiality) in order to structure the correct material composition and guarantee 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 with pre-assigned forms, structures and materials (i.e. the separation between structure and façade 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 using replicated modules. Despite its obvious advantages, the application of the modular logic of building holds some fundamental limitations when considering requirements driven by site-specific functionality and customization.

Alternatively, design based upon material properties and environmental conditions promotes customization 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 a shift in 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 elements across various scales, architectural components such as structure and façade 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 by modulating thickness, transparency, porosity and thermal absorption according to assigned functions or desired conditions of stability (structure) and comfort (environmental conditions). Here is to a new design revolution.