IASS 2018 BOSTON, JULY 16-20
CREATIVITY IN STRUCTURAL DESIGN

Proceedings of the IASS Symposium 2018
Creativity in Structural Design
July 16-20, 2018, MIT, Boston, USA
Caitlin Mueller, Sigrid Adriaenssens (eds.)

Designing a Tree: Fabrication Informed Digital Design and Fabrication of Hierarchical Structures

Jorge Duro-Royo[1], Josh Van Zak[1], Andrea Ling[1], Yen-Ju Tai[1], Nicolas Hogan, Barrak Darweesh, and Neri Oxman*

*Corresponding Author
Mediated Matter Group, MIT Media Lab, Department of Architecture and Urban Planning, Massachusetts Institute of Technology
neri@mit.edu

[1]First co-authors
j_duro@mit.edu, jvanzak@mit.edu, asling@mit.edu, yjtai@mit.edu

Abstract

Aiming at tight integration between material formation, digital fabrication, and physical behavior we propose a large-scale hybrid structure encompassing *Fabrication Information Modeling* as framework by which the designer can control the composition, structure, and properties of matter within robotic manufacturing. *The Aguahoja Pavilion* is a multi-material shell combining biodegradable members and a tunable biocomposite skin. Material combinations are controlled through local-to-global function-dependent deposition. Flexible-to-rigid, dense-to-sparse, thin-to-thick, neutral-to-oxidized, transparent-to-opaque, and permanent-to-disassociated property maps are implemented as inputs for computational design and digital fabrication, thereby promoting full integration between robotic fabrication platforms, atomistic material modeling, and form generation. In particular, information is embedded within robotic toolpaths where each meta-node compiles geometric pattern density, nozzle deposition thickness, tonal composition, and chemically tuned decay. At the nanoscale, biomolecules are chosen to maximize desired basic-to-acidic and hydrophobic-to-hydrophilic transitions. At the mesoscale, crystallite orientation is controlled to affect flexible-to-rigid behavior, while hierarchical printing determines thin-to-thick gradients. Finally, at the macroscale, dense-to-sparse geometry is designed and permanent-to-disassociated decay maps are assigned in correlation to environmental factors. This work points towards a future where the grown and the manufactured unite. *Aguahoja* embodies the *Material Ecology* design approach to material formation and decay; it is a realization of the ancient biblical verse "From Earth to Earth"— from water to water.

Keywords: Fabrication information modeling, parametric chemistry, hybrid structure, biomaterials, multiscale design, structural creativity, material ecology.

1. Introduction:

1.1. Context of the Research

Since the Industrial Revolution, a drive for mass-produced commodities discretizes structures and objects into assemblies of parts made of materials such as metal alloys, rubbers, fuel-based plastics or technical ceramics. These materials are homogeneous, provide a single function, and typically require resource-depleting extraction (World Commission [1]).

In contrast, basic natural building blocks assemble into adaptive continua to generate living materials that sense, respond, and adapt to environmental conditions. Their biodegradation continue resource cycles that facilitate new synthesis. Moreover, the mechanical properties of certain biomaterials frequently exceed those of their synthetic analogues due to optimization providing subtle functions gradually negotiated along a structure (Vincent [2]).

1.2. Aims of the Research

We aim at designing a tree. Our work derives material- and machine-aware digital design and fabrication methods through *Fabrication Information Modeling* (Duro-Royo [3]), implementing strategies such as *Parametric Chemistry* (Van Zack and Duro-Royo [4]), to re-engineer manufacturing processes and their constructs into adaptive multi-functional continua and subvert wasteful material cycles. We point towards the ability of living systems to construct chemically-attuned, hierarchically-designed, environmentally-responsive structures.

Here, by manipulating multiple scales of material synthesis and digital fabrication from molecules to large-scale robotic 3-dimensional printing, we control the composition, structure, and properties of matter. *The Aguahoja Pavilion* is a biomaterial composite structure with constructs that dynamically fluctuate between rigid 'shell' and flexible 'skin' in response to heat and humidity (Figure 1). Using highly abundant ecosystemic by-products, we approach closed-cycle fabrication where material is temporarily diverted from an ecosystem, implemented in manufacturing, and in the end-of-life, is reintroduced via biodegradation to fuel growth and reproduction.

Figure 1: Designing a tree - *The Aguahoja Pavilion* is a five-meter-tall, multi-material skin-shell system combining reusable scaffold members and a tunable biocomposite skin that can dynamically modulate its properties in response to heat and humidity and ultimately inform its own process of decay.

2. Discussion:

We propose *The Aguahoja Pavilion* as a multi-material skin-shell system combining a reusable scaffold and a tunable biocomposite skin. Material combinations are designed via environmental data maps and fabricated through robotic deposition. Given a five-meter tall truncated ovaloid skeleton

(Figure 2 left), a set of three interrelated data maps are developed including (1) structural self-load forces (Figure 2 gradient), (2) extrinsic environmental forces (Figure 3 gradient), and (3) intrinsic hydration forces (Figure 4 gradient).

2.1 Materials to Design a Tree

The ovaloid skeleton structure is additively manufactured via fused deposition of a reusable photopolymer with high strength and elastic modulus (Garlotta [5]). The structure comprises a vertical spine supporting horizontal ribs and a connected entry aperture. In between the ribs, a skin-shell system consists of 32 panels constructed via robotic deposition of functionally graded biocomposite blends. Complete details for this manufacturing system are described in Duro-Royo et al. [6], [7].

Biocomposites are composed of a flexible pectin substrate and a tunable mix of cellulose and chitosan, which exhibit a broad array of tunable mechanical properties and are biocompatible, biodegradable, and widely abundant in Nature. Many of these materials are produced in excess as forestry or fishing industry byproducts (Kennedy and Shimizu [8], Fernandez and Ingber [9]). Previous research on these biocomposites reports scale-specific performance enhancement as well as designable mechanical and optical properties. Specifically, proportional relationships between pH, surface roughness, and hydrophilicity of pectin and chitosan-cellulose skin-shell systems yield vastly different colors, which correlate to differential stiffness, strength, shape change, brittleness, and solubility product constant (k_d) across large-scale panels (Van Zak and Duro-Royo [4]).

2.2. Generative Maps for Embedded Information

The above-mentioned forces – structural, extrinsic, and intrinsic - drive six strategies of fabrication-informed structural behavior for the digital design of complex panels to be slotted within the ovaloid skeleton system shown in Figure 1. Specifically, (i) flexible-to-rigid, (ii) dense-to-sparse, (iii) thin-to-thick, (iv) hydrophilic-to-hydrophobic, (v) transparent-to-opaque, and (vi) temporal dissociation transitions are engineered to bridge chemical, geometric, and mechanical domains.

2.2.1. Structural Forces: Design for Flexibility and Thickness

Structural self-loading of panels slotted into the ovaloid skeleton informs their thickness and flexibility requirements. First, loads are distributed toward the central spine. Second, a bulging effect is designed into each panel. Third, the panels are configured to absorb deformation due to changes in heat and humidity. A global minimum of flexibility is defined along the rim that interfaces with the skeleton structure, while a global maximum of rigidity is defined across the center of mass of each cell (Figure 2). A gradient between the two maximizes gradients of functions in intermediate areas. This strategy allows the properties of each panel to be hierarchically organized within the existing global structure via a soft interface (Figure 1, right).

To obtain flexible-to-rigid transitions, material is distributed in 2.5-dimensions via hierarchical layering and differential extrusion pressure (Duro Royo et al. [7]). Each geometric toolpath within a panel is informed by kinetic speed and line thickness. The combination of these two parameters generates graded material patterns that will conform to-a three-dimensional shape when dry (Mogas et al. [10]) (Figure 2, right).

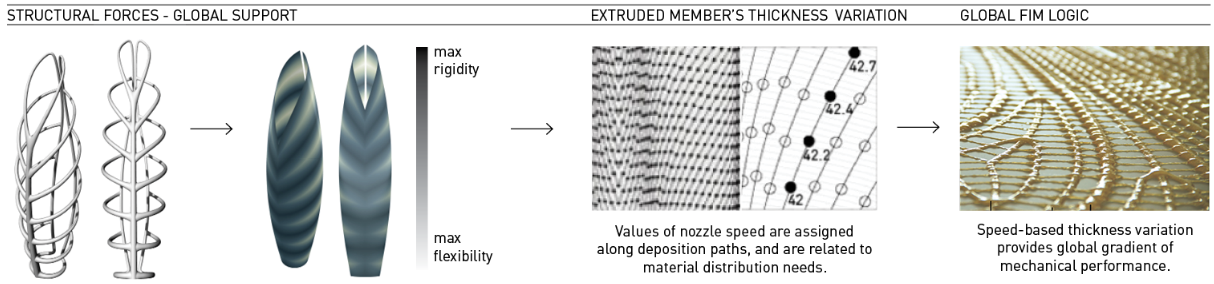

Figure 2: Structural self-loading of panels within a given global support informs their thickness and flexibility requirements. Material is then distributed via differential layering and extrusion pressure variation.

2.2.2. Extrinsic Forces: Design for Comfort and Opacity

In a simulation environment, the site-specific forces of radiation and sunlight is applied to the ovaloid over time in order to inform shading-cooling and lighting needs, as well as the aesthetic effects of backlighting. In order to provide shading, the translucency of pectin-chitosan blends can be tuned by incorporating calcium carbonate or altering the proportion of the two main copolymers (Van Zak and Duro-Royo [4]) (Figure 3). In order to incorporate both aesthetically interesting chromic effects and the mediation off reflection or absorption, pH-dependent molecular reactions and additives can be introduced to color dry constructs white, golden, or dark brown (Figure 3, right) (Van Zak and Duro-Royo [4]).

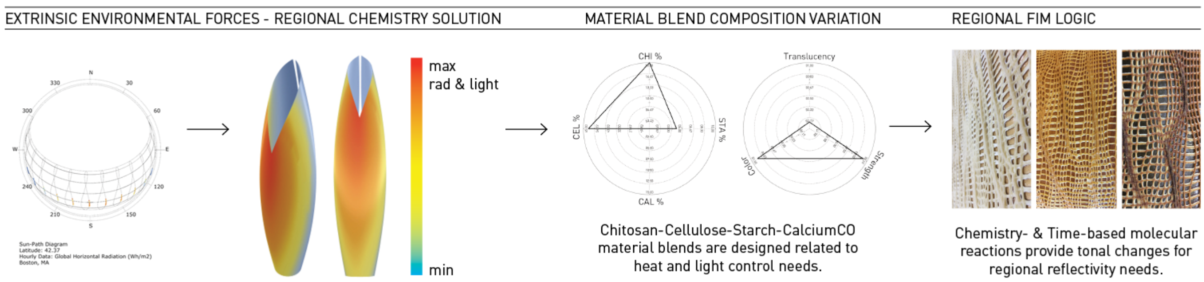

Figure 3: Extrinsic environmental forces acting on the panels inform material blends and opacity. Fabrication parameters are modulated to elicit degrees of transparency and oxidation and dehydration-dependent coloration.

2.2.3. Intrinsic Forces: Design for Density and Decay

Intrinsic forces acting on the skin are governed by relative hydrophilicity and equilibrium constants. In response to large changes in relative humidity, cellulose, pectin, and chitosan will swell and undergo mechanical deformations resulting in perceivable changes in shape. These can be harnessed to program subtle shape changes within the structure's skin. Specifically, bracing geometries with a high cellulose content will deform less than sparse geometries with low cellulose content, especially in proportion to pectin-chitosan content. Ultimately, extreme swelling will accelerate the panels' decay. Controlled decay can then be induced by designing geometric variations of open and closed cell line pattern densities across the paneling system (Figure 4, left).

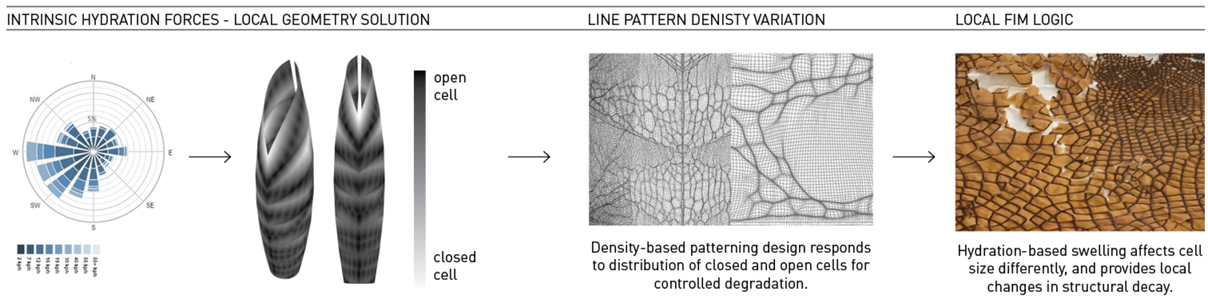

Figure 4: Intrinsic forces acting on the panels inform patterning for controlled decay. Geometric variations coupled with swell-ability and wettability are interfaced across the paneling system.

2.2.4. Fabrication Information

Here, flexible-to-rigid, dense-to-sparse, thin-to-thick, hydrophilic-to-hydrophobic, transparent-to-opaque, and temporal dissociation transitions are highly interdependent. This is due to the multifunctional nature of the biocomposite skin-shell system and the parallel constraint management within Fabrication Information Modeling (Duro-Royo [11]). In this framework, information is embedded into generative design and fabrication toolpaths, whereby each meta-node compiles heterogeneous, multiscale data. In *The Aguahoja Pavilion*, each node carries data relating to geometric pattern density, nozzle deposition thickness, tonal composition, and chemically tuned decay (Figure 5). This implementation demonstrates material- and machine-aware digital design, working toward bridging the gap between virtual and physical realms.

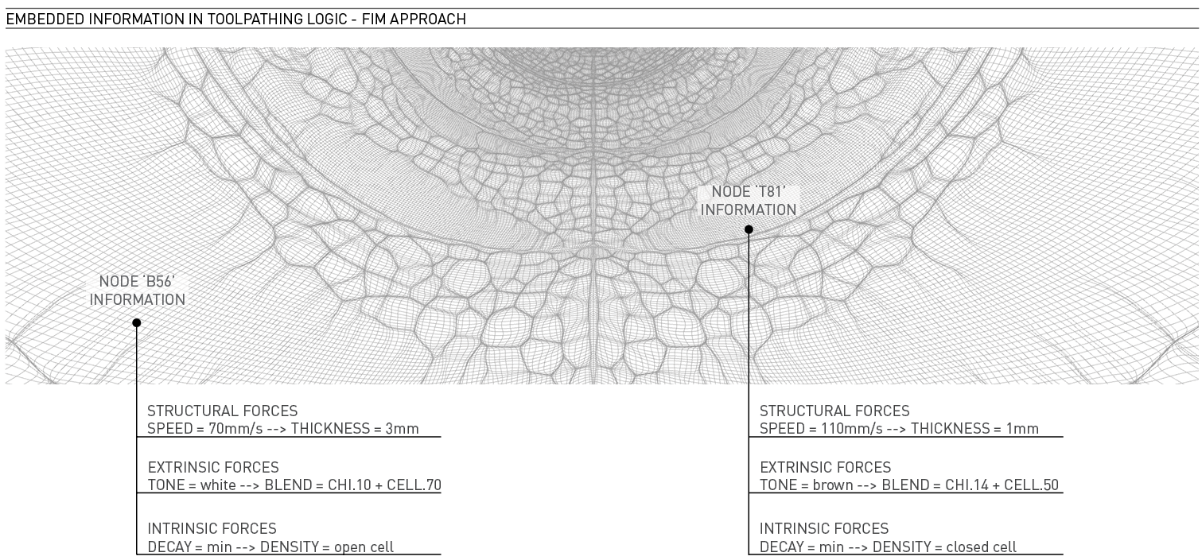

Figure 5: FIM is embedded within fabrication toolpaths, whereby each meta-node compiles heterogeneous, multiscale data values, demonstrating material- and machine-aware design.

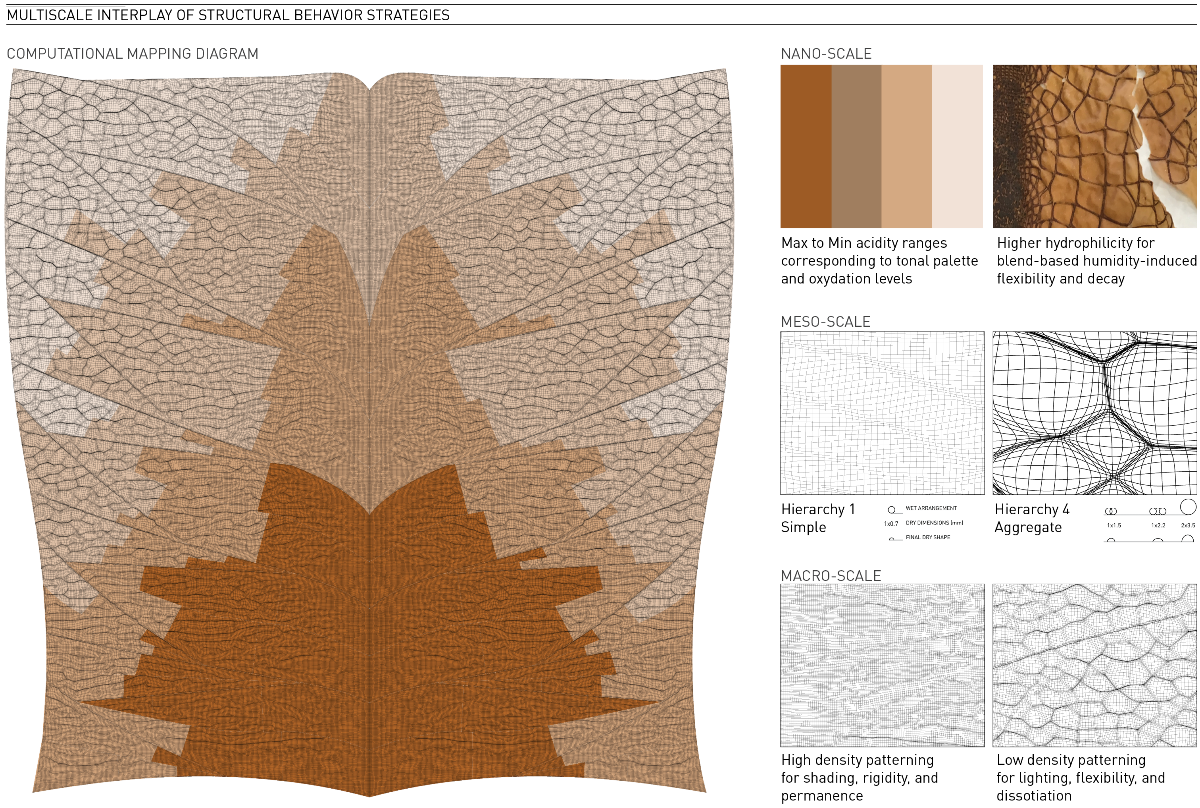

Figure 6: Multiscale interplay of strategies for fabrication-informed performative behavior.

2.3. Fabrication Informed Performative Behavior Across Scales

The Aguahoja Pavilion is conceived as an integrated system of functional behavior maps that impact both skin and skeletal members (Figure 6). However, to ensure the stability of a five-meter tall experimental material construct, an ovaloid skeleton was printed separately and bound to the biopolymer panels (see *Section 2.1* for further detail). In future implementations, thick support members with maximal strength can be designed by further optimizing cellulose-chitosan blends.

Below, we summarize our multiscale approach to performative functional design. Mapping strategies mentioned in *Section 2.2*, are implemented across scales of resolution and performance. At the *micro*scale, biomolecules are chosen to maximize desired basic-to-acidic and hydrophobic-to-hydrophilic transitions; at the *meso*scale, printing orientation is controlled to affect flexible-to-rigid behavior, while hierarchical printing determines thin-to-thick gradients; and finally, at the *macro*scale, dense-to-sparse geometry is designed and temporal decay maps are assigned in relation to site-specific environmental factors.

2.3.1. Microscale: pH and Hydrophilicity

In order to dynamically interface strength, controlled decay, and opacity, biomolecule composition can be tuned. Basic-to-acidic gradients can be designed within different pectin blends to create flexible skins (Figure 6 top). For instance, pectin with acetic acid yields a low pH hydrogel that can pull water from the chitosan-cellulose pattern layered on top of it, allowing the shell material to be oxidized and colored brown. In turn, the dry solids become less flexible over time, resulting in a rigid, but brittle, construct that can be rehydrated in the presence of humidity to recover some of its lost flexibility and take on a different geometric conformation. In this vein, hydrophobic-to-hydrophilic gradients allow for controlled decomposition and aligned layering during the printing process. By depositing higher amounts of pectin within blends, specific areas will rapidly swell and dissociate from the inside-out, in the presence of elevated humidity (Figure 4, right) (for further detail on *Parametric Chemistry* strategies, refer to Van Zak and Duro-Royo [4]).

2.3.2. Mesoscale: Anisotropy and Hierarchy

Tuned anisotropy can be achieved within our biocomposite blends. Hierarchical layering of geometric toolpaths determines thin-to-thick gradients and direction of printing induces flexible-to-rigid transitions (Figure 2, right; Figure 6, center). These strategies contribute to geometric tuning of structural behavior at the mesoscale, and can inform further development of large-scale constructs. In doing so, we can design materials that embody the mechanical performance of fibrous trees.

2.3.3. Macroscale: Patterning and Dissociation

At the macroscale, dense-to-sparse geometry is designed from a primary regular grid with centimeter-scale cell size. This grid is modified from an open-cell, decimeter-sized schema to a millimeter-scale closed cell one (Figure 6, bottom). Dense-to-sparse interplays allow for rigid-to-flexible behavior, temporal dissociation gradients, and translucent-to-opaque chromaticity, which are dictated by desired comfort levels and performative factors of self-loading, light, and humidity.

3. Conclusion:

The Aguahoja Pavilion demonstrates the fabrication-informed design of performative behavior by tightly integrating material formation, digital fabrication, and physical behavior within a large-scale hybrid structure. We aim at a future where growth and manufacturing converge. *Aguahoja* embodies the *Material Ecology* design approach (Oxman [12]) to material formation and decay by design; it is a realization of the ancient biblical verse "From Earth to Earth"— from water to water.

Acknowledgements

This research was primarily sponsored by The Mediated Matter Group at the MIT Media Lab. Ideas, methods, products and techniques included herein were developed to support an ongoing project and research platform focusing on large-scale biodegradable additive manufacturing, originally commissioned by the TBA-21 Academy (Thyssen-Bornemisza Art Contemporary). Research and scientific exploration related to this project was partly sponsored by GETTYLAB. We thank the Autodesk Build team at the Boston Design Center for facilitating this project and providing workspace and use of equipment.

References

[1] World Commission on Environment and Development, “Our Common Future - Report of the World Commission on Environment and Development (The Brundtland Report),” *Med. Confl. Surviv.*, vol. 4, no. 1, p. 300, 1987.

[2] J. Vincent, *Structural biomaterials*. Princeton University Press, 2012.

[3] J. Duro-Royo, “Towards Fabrication Information Modeling (FIM) : workflow and methods for multi-scale trans-disciplinary informed design,” Massachusetts Institute of Technology, 2015.

[4] J. Van Zack, J. Duro-Royo, Y. T. Tai, A. S. Ling, C. Bader, and N. Oxman, “Parametric Chemistry: Reverse Engineering Biomaterial Composites for Robotic Manufacturing of Bio-Cement Structures across Scales,” in *Architectural Robotics*, 2017.

[5] D. Garlotta, “A Literature Review of Poly(Lactic Acid),” *J. Polym. Environ.*, vol. 9, no. 2, pp. 63–84, 2001.

[6] J. Duro-Royo, L. Mogas-Soldevila, and N. Oxman, “Methods and Apparatus for Integrated Large Scale Robotic Fabrication of Functionally Graded Materials and Structures,” M.I.T. Case No. 17388T, 2014.

[7] J. Duro-Royo, L. Mogas-Soldevila, and N. Oxman, "Flow-Based Fabrication: An Integrated Computational Workflow for Digital Design and Additive Manufacturing of Multifunctional Heterogeneously Structured Objects," *Comput. Des. J.*, 2015.

[8] J. F. Kennedy and J. Shimizu, *Cellulosic polymers—blends and composites*, vol. 37, no. 1. Munich: Hanser Publishers, 1994.

[9] J. G. Fernandez and D. E. Ingber, "Unexpected strength and toughness in chitosan-fibroin laminates inspired by insect cuticle," *Adv. Mater.*, vol. 24, no. 4, pp. 480–484, 2012.

[10] L. Mogas-Soldevila, J. Duro-Royo, and N. Oxman, "FORM FOLLOWS FLOW: A Material-driven Computational Workflow For Digital Fabrication of Large-Scale Hierarchically Structured Objects," in *Computational Ecologies: Design in the Anthropocene Proceedings of the 35th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, 2015.

[11] J. Duro-Royo, L. Mogas-Soldevila, and N. Oxman, "Physical Feedback Workflows in Fabrication Information Modeling (FIM): Analysis and Discussion of Exemplar Cases Across Media, Disciplines and Scales," in *Real Time Proceedings of the 33rd eCAADe Conference*, 2015, vol. 53, pp. 1–9.

[12] N. Oxman, C. Ortiz, F. Gramazio, and M. Kohler, "Material ecology," *Comput. Des. J.*, vol. 60, pp. 1–2, Mar. 2015.