PHYSICAL FEEDBACK IN FABRICATION INFORMATION MODELING (FIM): Analysis and Discussion of Exemplar Cases across Media, Disciplines and Scales

Jorge Duro Royo[a,b], Laia Mogas Soldevila[a,c] and Neri Oxman[a,d]
[a]Massachusetts Institute of Technology, Dept. of Architecture and Urban Planning
75 Amherst St., E14-333c, Media Lab, Mediated Matter Group.
First co-authors: [b]j_duro@mit.edu, [c]dumo@mit.edu
[d]Corresponding author: neri@mit.edu

ABSTRACT

Novel digital fabrication platforms enable the design and construction of materially sophisticated structures with high spatial resolution in manufacturing. However, virtual-to-physical workflows and their associated software environments are yet to incorporate such capabilities. Our research sets the stage for seamless physical feedback workflows across media, disciplines and scales. We have coined the term Fabrication Information Modeling (FIM) to describe this approach. As preliminary methods we have developed four computational strategies for the design and digital construction of custom systems. These methods are presented in the context of specific design challenges and include a biologically driven fiber construction algorithm; an anatomically driven shell-to-wearable translation protocol; an environmentally-driven swarm printing system; and a manufacturing-driven hierarchical fabrication platform. We discuss and analyze these four challenges in terms of their capabilities to integrate design across media, disciplines and scales through concepts such as multi-dimensionality, media-informed computation and trans-disciplinary data.

Keywords
Digital Design, Design Workflows, Direct Digital Manufacturing (DDM), Integrated Design, Multi-Scale Data, Trans-Disciplinary Data, Computational Design, Fabrication Information Modeling (FIM)

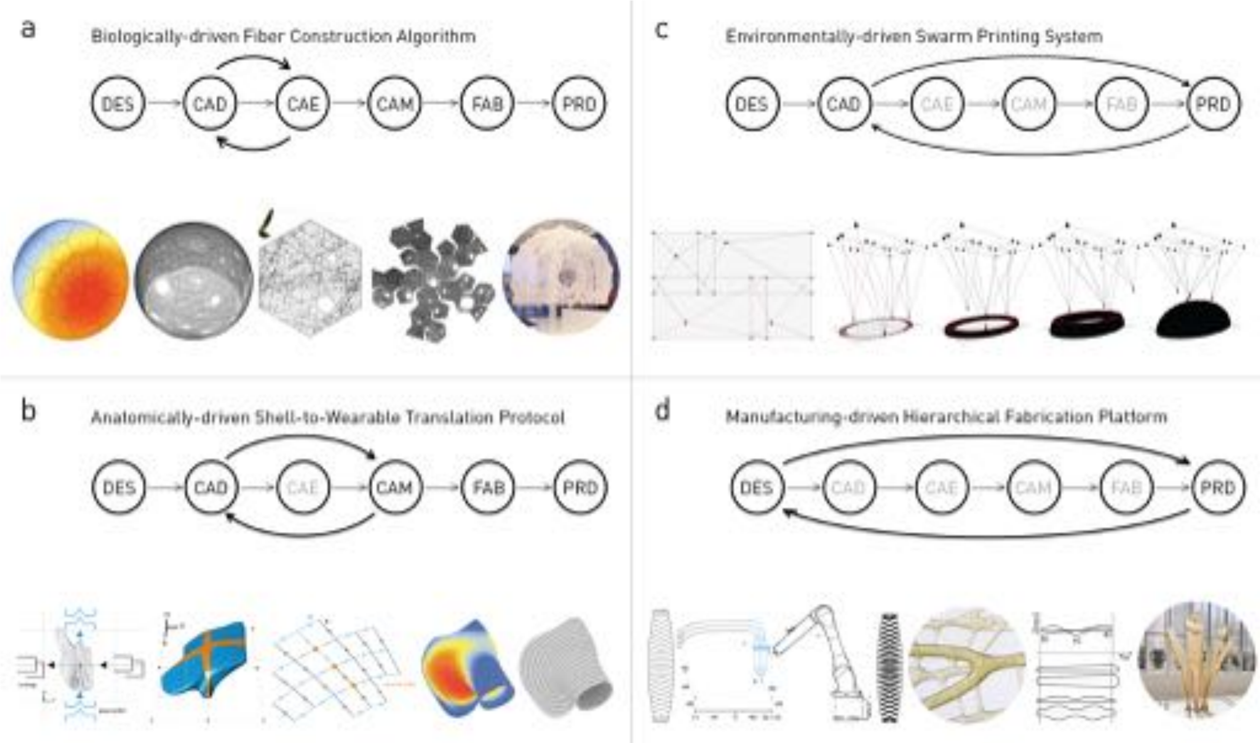

Figure 1: Four exemplar cases as steps towards a FIM methodology; (a) a biologically driven fiber construction algorithm (*FCA*); (b) an anatomically driven shell-to-wearable translation protocol (*STP*); (c) an environmentally driven swarm printing system (*SPS*); and (d) a manufacturing-driven hierarchical fabrication platform (*HFP*).

INTRODUCTION

Issues in Design of Physical Feedback Workflows

Recent advances in digital fabrication present an exciting opportunity to merge digital and physical tools and processes in the service of achieving high degrees of design customization across scales. However, the limitations associated with computational design tools for modeling geometrically complex and materially heterogeneous structures across scales frame and limit further progress (Oxman 2011; Duro et al. 2014a, Oxman et al. 2015). Specifically, the gap between virtual and physical platforms restricts integrated feedback across media, and limits invention and imagination of new designs and production processes (Duro et al. 2014b). Researchers in the fields of architectural design and advanced manufacturing are working towards the integration of material and fabrication constraints in the design process (Oosterhuis et al. 2007; Chiu and Yu 2008). Academic institutions and industry are rapidly developing complex multi-material manufacturing hardware able to incorporate material constraints, presenting software designers technical challenges in taking full advantage of novel hardware capabilities (Shapiro and Tsukanov 2004, 2011; Chiu and Yu 2008). Such challenges are due to the fact that conventional computer-aided design (CAD) tools can enable and support the manipulation of geometric and topologic virtual constructs; however, they generally lack the means to embed material data within virtual model constructs (Biswas and Shapiro 2004; Duro et al. 2015b) mostly since material homogeneity is typically assumed (Chiu and Yu 2008).

CAD tools, techniques and technologies are typically representation-oriented. As a result, digital design practices are generally governed by form generation prioritizing geometrical constraints over materially informed and fabrication-driven parameters (Sola-Morales 2000; Mitchell 2009). Combined with a shape-centric process, each CAD kernel - the software's core functionalities - is typically based on a strict set of low-level mathematical and geometrical definitions. These definitions provide a certain "style" to the software package that can be easily identified and traced in its design outcomes (Mitchell 2009;

Burry et al. 2011; Mogas 2013). For instance, due to embedded mathematical descriptions of software solutions, mesh-based CAD users are more likely to generate free-form designs with high degrees of agility (e.g. in Maya-Autodesk®). NURBS-based CAD users, however, are more likely to generate smooth curve and surface designs like the ones that typically describe the surfaces of automobiles or water vessels (e.g. Rhino-McNeel®). We claim that such stylistic underpinnings may actually limit the user's ability to conceive new design approaches. More importantly, CAD models, even if inhabiting a dimensionless virtual space, are scale-dependent due to representation tolerances embedded in their base package (Beckett 2014). It is true though that mainstream CAD software packages, such as Autocad-Autodesk® or Rhino-McNeel®, allow virtual direct export and manipulation of engineering analysis (CAE) and machine instruction generation (CAM) information via scripting or parametric design plug-ins such as Dynamo® or Grasshopper®, respectively. However, despite the overall successful integration of parametric design workflows in practice, as can be seen in façade construction, environmental benchmarking or structural optimization; parametric design for truly buildable projects remains labor-intensive, slow, and rather manual. Furthermore, such digital workflows become particularly challenging to author and to manage when dealing with more than fifty to a hundred variables (Andia and Spiegelhalter 2014). Consequently, it becomes extremely challenging to navigate, control, adjust and compare between parameters within a single model - and even within the same software package. This is due to the design process engaging multiple dimensions including those that are directly informed by fabrication and material parameters and those that span across scales or functional domains. If new capabilities for embedding multiple dimensions of and across media, disciplines and scales were in place, designers would be able to tailor material properties to environmental constraints in close association with the digital fabrication platform. Consider, for example, the ability supported by this approach to tune microfiber arrangements within architectural wood columns; or the ability to concurrently shape products at scales relevant to human ergonomics, body shape and tissue composition, spanning functional and fabrication scales – environment to body to voxel.

RESEARCH AIMS

Integrated Design across Media, Scales and Disciplines

We have coined the term Fabrication Information Modeling (FIM) to define the materialization of geometrically complex designs that span different media, scales, and disciplines. Three main characteristics underline designs based on the FIM approach: (1) they incorporate variables associated with design and construction media such as physical feedback sensing, fabrication and material parameters; (2) they operate across multiple dimensions; and, (3) they integrate and manage trans-disciplinary data - parameters, constraints, or data sets from multiple disciplines. With FIM, we aim to design and build physical feedback workflows where materials are *designed* rather than being selected; where the question of how information is passed across spatiotemporal scales is central to the design generation process itself; where modeling at each level of resolution and representation is based on various (and often complimenting) methods, and performed by different agents within a single environment; and finally, where virtual and physical considerations coexist as equals.

RELATED WORK

Towards Multi-dimensional, Media-informed, and Trans-disciplinary Design Workflows

Multi-scalar design is an emerging field of research in the disciplines of Materials Science and Engineering, Civil Engineering, and Synthetic Biology. Consider, for example, research into the mechanics of deformation and failure of biological materials. Such research integrates computational modeling of material properties from atomic scale to meter scale by examining fundamental links between processes, structures, properties and functions (Cranford and Buehler 2012). Other efforts aim to bridge the gap between modeling and simulation of products involving multiple physical processes interacting at multiple spatial and temporal scales such as research associated with the design and construction of fan blades, turbo-engines, or car chassis (Fish 2013). Furthermore, novel initiatives in computational biotechnology seek to examine living systems, considering dimensions of multi-scale data, to advance our understanding of how human bodies function (Kidd et al. 2014).

In the pursuit of incorporating fabrication constraints into the design process, File-to-Factory approaches aim to merge CAD (Computer-aided Design) and Computer-aided Manufacturing (CAM) into a seamless process (Oosterhuis 2004, 2007; Afify and Elghaffar 2007; Scheurer 2010). This is commonly achieved by exporting the virtual design into a specific machine file format (Chang 2004; Sass and Oxman 2006; Sheil 2013). Following, materials and tool paths are set within the machine's software with limited possibility for iterations; as well as incompatibilities between the original CAD environment and the machine logic that are lost in translation. Such discrete processes are all but seamless, constraining and directing the workflow of designs that are complex in shape and in material composition (Oxman 2011; Duro et al. 2015b).

Current efforts in the area of structural design, that focus on achieving material-informed architectural design processes, aim at better understanding the performance of existing material systems and incorporating it into shape-generating parametric models (Fleischmann et al. 2011, Schleicher et al. 2013). This is typically done by experimentally studying functional-morphological dependencies of systems such as plywood or fiber-based composites in abstract load simulation setups. Following, approximated models are built and evaluated via virtual structural analysis tools (Schleicher et al. 2013). Such digital chains depend on simulation methods that are difficult to implement with precision, and that generally respond to a narrow set of framing conditions. Moreover, the relevance of these workflows to the quality of the product lies at the structural scale, rather than the scale of material property. In the area of additive manufacturing, researchers combining software logic and digital fabrication claim that soon it will be possible to use multi-material printers and nanotechnology to design completely new materials whose behavior can be programmed (Andia and Spiegelhalter 2014). Despite all these efforts, fully integrated, material-driven digital models are yet to be implemented in off-the-shelf software to enable design processes that are fully informed by material behavior (Schleicher et al. 2013; Tamke et al. 2014).

The success of research developments reviewed above is highly dependent on efficient and timely incorporation of trans-disciplinary information. Design thinking is generally considered a non-linear process with multiple parameters; a process that incorporates diverse disciplinary knowledge such as, for instance: structural analysis via engineering of behavioral models (Silvetti 2012); complex performance evaluation via biologically inspired algorithms (Turrin et al. 2011); geometric function negotiation via morphometric analysis techniques (Duro et al. 2014a); structural property tailoring via materials engineering across scales (Cranford and Buehler 2012; Fish 2013); digital fabrication via form interpretation into machine code (Chang 2004); or even understanding innovation via techniques from social sciences (Nelson 2006). Workflows that seamlessly embed and operate with data from other disciplines are far more suitable to adapt and respond to contemporary issues, and to convert complex architectural design process into multi-agent discussions rather than tedious information translations.

METHOD

Exemplar Cases across Media, Disciplines, and Scales

We demonstrate the principles for the FIM methodology in four customized experimental methods: (1) a biologically driven fiber construction algorithm; (2) an anatomically driven shell-to-wearable translation protocol; (3) an environmentally driven swarm printing system; and, (4) a manufacturing-driven hierarchical fabrication platform. The methods are implemented combining custom applets in C++ and Java languages using the Eclipse IDE environment (The Eclipse Foundation 2004), as well as C# scripts using the RhinoCommon geometrical kernel (McNeel 2010). The resulting designs are fabricated with advanced additive manufacturing hardware using commercial and customized tools, techniques and technologies.

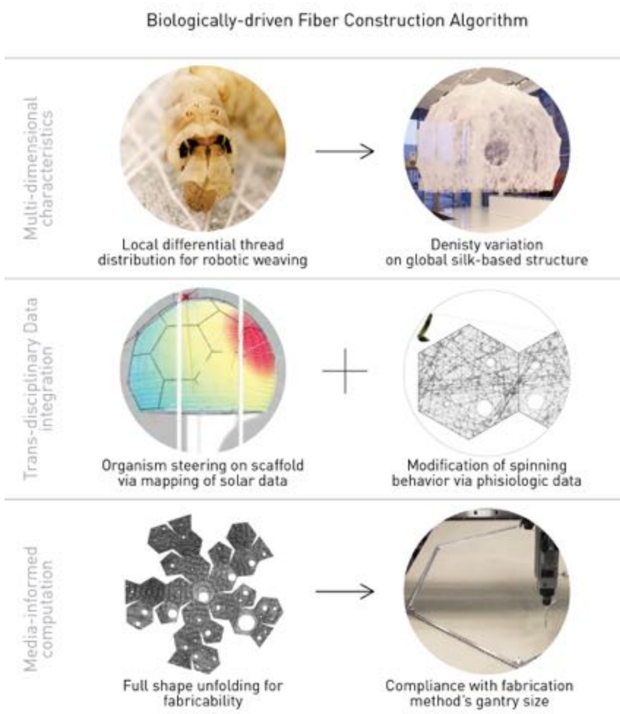

Figure 2: *Biologically-driven Fiber Construction Algorithm (FCA)* analyzed in terms of multi-dimensionality, trans-disciplinary data integration and media-informed computation.

Biologically-driven Fiber Construction Algorithm (*FCA*): The goal of the *FCA* model is to design and fabricate a fiber-based large-scale structure integrating three sets of constraints, namely: environmental parameters relating to solar radiation; physiological parameters relating to the silkworm spinning process; and manufacturing parameters relating to a computer-controlled fabrication machine. The model is designed to integrate biological spinning and robotic construction into a composite structure made of both natural and industrial silk (**Figure 1a**) (more information on the computational model can be found in Oxman et al. 2014).

Anatomically driven Shell-to-Wearable Translation Protocol (*STP*): The goal of the *STP* model is to design an armored system composed of overlapping and interlocking units that can adapt to any surface. Data is obtained by analyzing the scales of a prehistoric fish exoskeleton. In the fish scale system differentiated geometric features and varying material properties achieve a dual function of flexibility and protection. Observed levels of sophistication are quantified and incorporated into a mesh data structure adapted to the human chest that can generate a new scale system from geometric metadata embedded in its vertices (**Figure 1b**) (more information on the computational model can be found in Duro et al. 2014a).

Environmentally driven Swarm Printing System (*SPS*): In the *SPS* model we design a workflow for a distributed approach to construction of larger-than-gantry size structures. We develop a multi agent system composed of cable-driven robots ("cable-bots") able to deposit material drops in a layered manner. Material curing times are computed in the system along with swarm-like motion behavior rules of space exploration. We achieve structural emergence with only punctual designer's input opening up approaches for long distance fabrication (**Figure 1c**) (more information on the computational model can be found in Duro et al. 2015a).

Manufacturing-driven Hierarchical Fabrication Platform (*HFP*): In the *HFP* model our goal is to design and fabricate large-scale biomaterial structures. We implement a customized computational workflow integrating multi-scale material distribution. The material micro-to-macro distributions respond to deposition of hydro-gels with variable mechanical properties in single or multiple layers. The final designs demonstrate emergent geometries and are fabricated with a customized material deposition platform (a portable customized multi-nozzle deposition tool attached to an industrial Kuka KR robotic arm) (**Figure 1d**) (more information on the computational model can be found in Duro et al. 2015b).

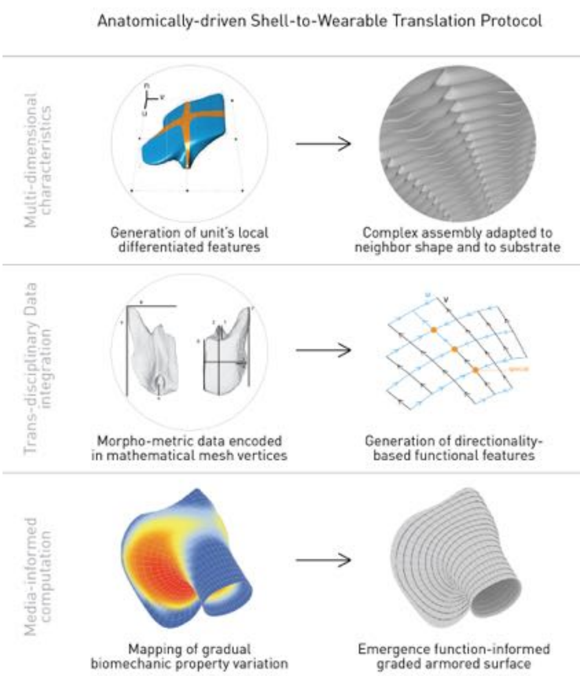

Figure 3: *Anatomically-driven Shell-to-Wearable Translation Protocol (STP)* analyzed in terms of multi-dimensionality, trans-disciplinary data integration and media-informed computation.

DISCUSSION

Analysis of Exemplar Cases towards a FIM Methodology

Below we analyze and integrate key strategies employed in each of the models. We relate to the three main principles of FIM: (1) multidimensionality, (2) trans disciplinary data integration and, (3) material-informed computation.

Multi-dimensional Characteristics: In the *FCA* model, we create a scaffold with local differenced thread distributions using robotic weaving techniques. The weaving patterns and distances between threads are informed by typical physiological spinning ranges observed in live silkworms. Six thousand five hundred ready-to-spin silkworms are deployed onto the scaffold and produce a silken dome with throughout density variations steered by local changes in woven structure (**Figure 2 top**). A similar local-to-global strategy is implemented in the *STP* model. In this case, unit-level geometric features are dependent on, and negotiated within, higher-level assemblies; so that interlocks and overlaps are preserved keeping the whole construct functional and flexible (**Figure 3 top**). In the *SPS* model, a virtual a-dimensional rule-based behavioral system generates local rules for global coordination of agents. This results in agents achieving construction of a whole structure without top-down control (**Figure 4 top**). The *HFP* model is the one that spans most dimensions in disciplines and scales. We design and modulate the chemical makeup of polymers at the nano-scale, use their material properties to allow for full bonding across printed sections, and then control global structural emergence of shape via hydration patterns at the architectural scale (**Figure 5 top**).

Trans-disciplinary Data Integration: Efficient and timely integration of trans-disciplinary information is fundamental to the development of workflows that integrate media-informed designs across complex dimensions. In the *FCA* model, two main data sets are integrated into the design applet. The first one considers solar radiation for a given period of time relative to the surface of a dome scaffold, and the second one encodes the typical physiological ranges of silkworm spinning as explained above. The combination of both environmental and biological data sets allows the design to seamlessly combine environmental and biological considerations (**Figure 2 middle**). In the case of the *STP* model, morphometric data from a material science driven study of the scales of a prehistoric fish is parameterized and categorized to respond to geometrical features. Principal and secondary directions for the emergence of interlock and overlap features are then linked to functional requirements in new synthetic designs (**Figure 3 middle**). Both in *SPS* and *HFP*, structural design data is integrated in the models. In *SPS*, rules for structural design intent are introduced as typological "steering forces" affecting the swarm-based printing system (**Figure 4 middle)**. In *HFP*, the principal load distributions of simple structural typologies, such as cantilevers or post-and-beams, are combined and encoded into streamline gradients that produce structural support gradients in the final manufactured objects (**Figure 5 middle**).

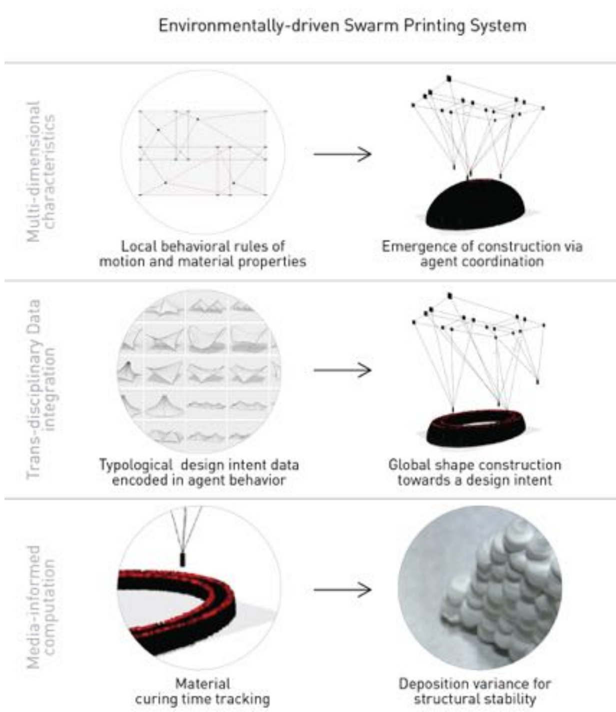

Figure 4: *Environmentally-driven Swarm Printing System (SPS)* analyzed in terms of multi-dimensionality, trans-disciplinary data integration and media-informed computation.

Media-informed Computation: In order to design and materialize complex projects such as natural silk domes, biopolymer cantilevers, or articulated armors, design models must incorporate material-, and fabrication-informed parameters into computational models. In the *FCA* model we implement a functionality that unfolds the structure and coordinates the robotic weaving of 26 frames composing a full-scale dome. The algorithm was made fully "aware" of machine gantry dimensions, speeds, and feeds (**Figure 2 bottom)**. In the *STP* case, functional maps inform computation of geometric negotiations within the scale-based system. The maps can encode bio-mechanic requirements of breathability, opacity, or flexibility and protection, on the surface of a human chest (**Figure 3 bottom).** Both *SPS* and *HFP* incorporate novel material-informed computation strategies. In *SPS* virtual clocks track material extrusion of drops in position and runtime in order to calculate estimated final curing times. The agents in the system are computed to obtain this data avoiding the deposition of new material drops on top of the uncured ones so that structural stability is guaranteed (**Figure 4 bottom**). In HFP, the levels of hydration of the deposited polymers are controlled by convection systems that target different areas of the structure. Such differential convection allows for shrinkage control of the polymers as they dry, so that final shaping can be induced in certain areas (**Figure 5 bottom**).

CONCLUSION

Fabrication Information Modeling (FIM) as a Novel Framework and Methodology for Materially Heterogeneous and Geometrically Complex Design

The challenges associated with the projects described and analyzed in this paper can be grouped into types of limitations associated with virtual design environments. The first set of limitations arises when attempting to integrate design variables from a wide array of disciplines such as material science, mechanical engineering, biology or structural design (e.g. in *FCA*, *SPS*, *STP* and *HFP* models); the second set of limitations arises from challenges associated with adapting shape-based parameters to digital fabrication and computer aided machining constraints (e.g. in *FCA, SPS* and *HFP* models); the third set of limitations arises when aiming to intervene at different scales of time, resolution and representation (e.g. in *SPS* and *STP* models). The challenges in achieving design synthesis across media, scales and disciplines are many and, typically, they are the result of following computer-aided design traditions that should be adapted to, or replaced by, novel ways to understand and implement physical feedback workflows. We propose Fabrication Information Modeling (FIM) as a methodology and framework to combine form generation, digital fabrication, and material computation in seamless processes. Initial results from our related work demonstrate functional integration, multi scale performance and novel aesthetic qualities. We anticipate that additional research in this area will point towards advancing the capabilities of computational design and digital fabrication workflows with real-time multi-scale trans-disciplinary data.

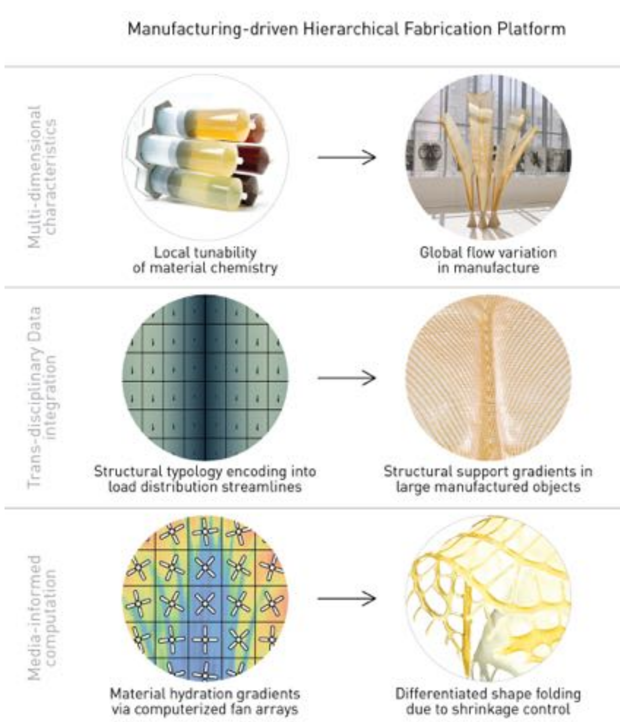

Figure 5: *Manufacturing-driven Hierarchical Fabrication Platform (HFP)* analyzed in terms of multi-dimensionality, trans-disciplinary data integration and media-informed computation.

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