Fabrication Information Modeling (FIM)

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ABSTRACT

This thesis discusses novel strategies to include physical media information at multiple dimensions and relating to diverse disciplines within traditional design tools. Specifically, it addresses challenges that arise when aiming at describing computational and manufacturing strategies for material-, time- and scale-dependent phenomena. Fabrication Information Modeling (FIM) develops design processes and exemplar projects able to operate across media, disciplines, and scales, incorporating concepts of multi-dimensionality, media-informed computation, and trans-disciplinary data integration.

Digital fabrication is today a rapidly evolving concept transitioning from traditional assembly of differentiated parts, to file-to-fabrication construction efforts, and even towards guidance of material synthesis on-the-fly and growth of biological agents into structures. Advances in the fields of materials engineering, robotic automation, artificial intelligence, and synthetic biology open up opportunities for incorporating new physical world information, from organism, material, machine, and environment, within and throughout digital design and manufacturing processes.

With FIM and FIM-driven projects I aim to contribute to the field of digital design and fabrication by enabling feedback workflows where (1) materials are designed rather than selected; where (2) the question of how information is passed across spatiotemporal scales is central to design generation itself; where (3) modeling at each level of resolution and representation relates traditionally-unlinked methods and is carried out by myriad media; and finally, where (4) virtual and physical considerations coexist as equals.

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FOREWORD AND STRUCTURE

1.2 Towards Integration

The making of architecture is evolving from an uni-disciplinary fragmented sequence of drafting, analysis, and construction, towards a multi-disciplinary parallel conception and development of design and production. Workflows able to, not only account for manufacturing parameters, but also model them, will allow design practice to incorporate crucial innovation in physical-world-focused disciplines such as biology, materials engineering, robotic automation, and artificial intelligence. These fields, open up opportunities to operate with information, from material, machine, and environment, within and throughout digital design and manufacturing processes. Design-to-manufacturing horizons can then expand to, for instance, seamless systems from a virtual design to an automated construction machine, or guidance of material synthesis on-the-fly, or even to control growth of matter by biological agents into structures.

1.3 Contents of the Thesis

This dissertation discusses impact and opportunities in design practice as digital fabrication becomes intelligent. Specifically, how current design-to-production workflows will be radically transformed by advances in design environments, by the integration of novel digital fabrication methods within design practice, and by an increased interest in interdisciplinary collaborations. The thesis foresees the following challenges and tackles their implementation; (1) design models that become aware of physical processes, (2) disciplines within and outside of design and architecture that tightly interconnect during the design process, (3) information flow between virtual and physical spaces that follows the laws of iterative feedback instead of instruction transfer, and finally (4) fabrication that acquires maximum intelligence within workflows.

1.3.1 Advancing and Expanding Digital Design and Fabrication

Chapter 2 elaborates on how the field of digital design and fabrication is today rapidly evolving. It reviews current developments in modeling and fabrication, as well as how the influence and integration of relevant disciplines is altering the definition of media and work scales of design. Environments have increased in representational dimensions, complexity, and analysis capabilities. Their fabrication counterparts have improved in degrees of freedom and materials available. New disciplines in the field of design and
architecture have pushed the definitions of; (1) materialization - form static to dynamic-, (2) dimensionality -from molecules to landscapes-, and (3) data - from physical phenomena rather than from geometry.

1.3.2 From MIF to FIM Workflows
The second part of Chapter 2 discusses how traditional workflows will need to be redefined. Current linear Modeling to Information to Fabrication workflows (MIF) favor intelligence within the virtual model, use information merely to transfer instructions to fabricating machines, and describe fabrication as a tool of maximum obedience. Challenges arise when faced with inclusion of physical media information at multiple dimensions and from diverse disciplines within traditional design tools. Specifically, when aiming at describing novel computational strategies for material-, time- and scale-dependent phenomena. Consequently, future workflows will have physically-aware models, provide tools and arenas for interconnected crossdisciplinarity work, implement information channels for iterative feedback rather than for unidirectional instruction transfer, and give fabrication maximum intelligence in the design-to-production process.

1.3.3 A Framework for Fabrication Information Modeling
Chapter 3 of this thesis elaborates on how Fabrication Information Modeling (FIM) addresses the transition outlined in Chapter 2 through the development of design processes and exemplar projects able to operate across media, disciplines, and scales, incorporating concepts of multi-dimensionality, media-informed computation, and trans-disciplinary data integration.

1.3.4 Case Studies in Fabrication Information Modeling
Chapter 4 presents and analyses case studies that exemplify FIM as a new mindset and methodology to materialize designs that require control beyond what can today be virtually conceived and computed, by deploying intelligent fabrication, feedback-based information, and physically-aware modeling. Methods presented include; parametric chemistry, robotically-tuned anisotropy, pressure-based smart folding, agent-based fabrication, biologically-driven fiber construction, and unit-base surface translation protocols.

1.3.5 Outlook and Thesis Contributions
Chapter 5 describes how FIM and FIM-driven projects aim to contribute to the field of digital design and fabrication by enabling feedback workflows where (1) materials are designed rather than selected; where (2) the question of how information is passed across spatiotemporal scales is central to design generation
itself; where (3) modeling at each level of resolution and representation is based on various methods and carried out by various media; and finally, where (4) virtual and physical considerations coexist as equals.

1. INTRODUCTION

2.1 Advances in Modeling and Fabrication

2.1.1 Digital Modeling

Computer-aided modeling environments have improved in the last ten years by including further operative dimensions, representation complexity, as well as virtual analysis means (Figure 1).

Dimensions

Models have augmented their representation capabilities from 2-dimensional drafting (pioneered with the Sketchpad in 1963 by Ivan Sutherland), to 3-dimensional geometric spaces (such as Autodesk’s AutoCAD® or McNeil’s Rhinoceros®), to 4-dimensional descriptions including objects with metadata (CATIA by Dessault Systems, or Maya® and Revit® also by Autodesk).

Representation

Complexity of objects represented has also increased from simple geometries of points lines and curves, to NURBS curves (developed in the 1950s as mathematically-precise representations of freeform), meshes and poly-surfaces (collections of vertices, edges and faces that defines the shape of a polyhedral object in 3D computer graphics and solid modeling) to describe 3-dimensional elements, genetic and informed shape derivation algorithms influenced by time, loading conditions, or multi-objective parameters [1], [2]. This allows for higher sophistication in geometric descriptions, but does not account for its performance in the physical world.

Analysis

In virtual analysis, shape and structure descriptions can today be inspected under diverse types of environmental performance data sets such as shading, rainfall, wind load etc. This is enabled by the integration of engineering analysis software in design and architecture practice (such as Ansys®, Abacus®, EnergyPlus® or Comsol®). In architecture and product design, already new capabilities allow embedding of data from related disciplines such as structural engineering, sustainable assessment or computer aided machining. Recent developments within explorative design-oriented environments enable integration of solver packages (such as Ladybug, Kangaroo, or Karamba3D within the 3-dimensional design environment
Rhinoceros® and its programming plug-in Grasshopper®. The widespread package AutoCAD® is also in the process of integrating material-driven design decision abilities in DreamCatcher®. However, it is still difficult to acquire, generate, or maintain different coexisting data types, describe novel virtual objects and entities, or virtually navigate and edit the many dimensions of physicality in order enrich and expand the digital design and fabrication field with those that work at other scales, or with physical matter and time-dependent media, such as materials science or biology.

![Digital design environments and their advanced capabilities in dimensions, form generation, and analysis.](image)

### 2.1.2 Digital Fabrication

In turn, fabrication means have fundamentally changed and improved in amount of work axis available, and in material choices. They have transitioned from traditional assembly of differentiated parts, to file-to-fabrication construction efforts, and even towards guidance of material synthesis on-the-fly and growth of biological agents into structures (Figure 2).

**Axis**

To achieve that, degrees of freedom have increased from 2 to 3-axis in Computer-Numeric-Control (CNC) systems for milling, etching, or extruding, and towards 6-axis robotic arm end-effectors borrowed from industrial assembly processes. Even eleven axis can be achieved in compound fabrication systems involving rails and wheels plus robotic arms [3], as well as quasi-infinite amount of axis in assembly via drone-based building [4].
Materials

Digital fabrication materials available have also augmented from limited stock choices such as wood, glass, and metal, to increasing diversity of polymers, clays, fibers and resins, or technical blends of selections on-the-fly in advanced 3-dimensional printing [5] such as fused-deposition or fast-curing liquid jetting. Moreover, invention of endless palettes of new digital fabrication materials can today be explored via biological printing of cells and their differentiation or via synthetically engineered living foundries [6].

Despite advances, current digital fabrication methods have key challenges preventing seamless integration with their modeling counterparts. For instance, design files and fabrication files are typically designed with different software and encoded in different languages, which promotes file translation interruptions and disables potential feedback loops that would allow iteration of design solutions based on materialization issues [7]. Once connection from model to machine would be established, monitoring manufacturing via automated sensing could provide a better understanding of fabrication failure and specify parameters needing editing within models.

2.2 Expanding the Frontiers of Digital Design and Fabrication

There is today an opportunity to further expand the frontiers of design and production, so that we can foster invention and imagination across media, disciplines and scales. Beyond advances in modeling and digital fabrication, emerging scientific and engineering fields open up opportunities for incorporating new physical
world information, from material, machine, and environment, within and throughout digital design and manufacturing processes.

Below I outline the key areas of study informing this research and their most relevant recent developments in (1) integrating disciplines, (2) redefining media, (3) broadening dimensions, and (4) intertwining data. Then, a theoretical translation from traditional MIF to future FIM workflows is defined.

2.2.1 Integrating Disciplines
Disciplines such as materials engineering, robotic automation, artificial intelligence, and synthetic biology are more and more relevant to the expanding field of digital design and fabrication [8]. They present designers with questions related to redefining the mission, limitations, and scope of contemporary practice. Particularly within these fields, parameters are not static but linked to time, evolution, and feedback; their modeling depends on very diverse scales of resolution from molecules to landscapes; and their data is formatted by different media such as matter, machine, or environment instead of by the laws of geometry within conventional design. Such complexity needs new strategies and environments to be integrated in design-to-production workflows.

2.2.2 Redefining Media
For digital fabrication to become intelligent, it must inform and be informed by the design model. The media of design becomes then iteratively re-evaluated by materialization feedback. Fabrication-aware digital environments can enable a higher level of explorative invention by monitoring and responding to materialization. They can display ‘system consciousness’ able to physically sense and virtually adapt, and even point towards artificial intelligence futures, where machines learn from the process of making in order to improve performance and quality of products.

Recent research in Engineering Living Materials focuses on synthetically modifying living cells to design or alter matter so that it is able to detect and respond to external signals [9]. For instance, advances in synthetic biology present genetically modified bacteria able to create protein networks where small particles can be attached [10] and act as chemical sensors so that these protein-based materials can track environmental cues. Moreover, the system can autonomously act upon the sensing by having the bacteria secrete chemicals in direct response to what is picked up by the particles [10]. Control of this revolutionary process presents ways to efficiently capture differentiated variables such as pH, temperature, or viscosity during manufacturing and respond with material-based adjustments to the design. A similar process programs cells embedded into soft substrates such as wearables so that fluorescence is induced by the presence of certain chemicals [10]. This is interesting because such cells are robust enough to perform their
function even under the deformations of garment, which promises to be also suitable for digital fabrication environments. However, challenges still exist to monitor biologic sensing. For instance, it is difficult to scale the system up and account for time delays in responses for both inducer and diffuser actions. Hardware such as imaging methods must be linked to the system, specific data acquisition must be programmed, and adequate responses must be ensured.

Another materialization process that can benefit from environmental or material-state feedback is biomaterials-based manufacturing, when distributing hydrogels in space, in order to monitor humidity and thereby control their evaporation-induced shrinkage [11]. This scenario, as well as other bio printing techniques to, for instance, pattern vasculature in tissue, could be dramatically improved by machine feedback to determine mass transport and proper hydration of structures as fabrication occurs [12].

In other exemplar research projects implementation of dynamic feedback could also be beneficial. For instance, in fiber-laying in cutting-edge boat sail manufacturing [13] it could sense and correct deposition pressure, resin impregnation, layer bonding, or fiber alignment. In a multi-robot cooperative construction setup, production awareness could contribute to real-time adjustments in the multiple agent’s rule-based behavior while building [14]. When fabricating with clay a camera and a pressure sensor can be mounted on a robotic arm as direct feedback aids to shape products [15]. The camera captures shape change and feeds it to a virtual model, then the designer commands the next pressure point for the robot to undertake, and the process restarts in a loop for interactive digital-material feedback [15]. These explorative design environments are in early development and lack resolution, time prediction, and data evaluation, but present very promising horizons. By similar means, such as 3D-scanning and thermal imaging, structural stability and material properties could be monitored and fed back into structural models in progress. In other types of robot-enabled autonomous building systems, such as long-distance fabrication or extreme environment habitat construction, feedback could help remotely correct structural deflection or guide exploration of new shape due to changes in environmental conditions.

In sum, some specific challenges to incorporate feedback from the new media of design include; (a) matching resolution of sensing data to model information needs, (b) predicting duration of (semi-) autonomous tasks during materialization, (c) evaluating effects of material property tuning during digital fabrication, (d) reducing the scale and complexity of scientific sensing equipment for easy integration in fabrication platforms, and (e) programming complex sensing devices for fast and specific data acquisition. New workflows should; (1) include hardware and parameters related to interactive fabrication, (2) account for composition and distribution of matter during manufacturing, and (3) sense and respond to changes in planned materialization with living or mechanical means (Figure 3).
2.2.3 Broadening Dimensions

Physically-aware models require design at multiple scales of resolution and representation. Recent research aiming at multiscale design has outlined the various challenges of designing bottom-up from the atomistic configuration of materials [16]. ‘Materiomics’ is an interdisciplinary framework to derive holistic multiscale material models and their interactions [17]. It merges engineering, materials science, experimental and computational biology, physics and chemistry, and looks at, for instance, the effects of nano-scale chemical design in macro-scale structural performance [18]. As identified by Materiomics researchers, issues arise when implementing linked models that address multiscale, combinatorial, and temporal problems, or when developing nano-to-macro modeling strategies applicable to different materialization processes, both living and synthetic[18].

In a practical example fracture mechanics of biological protein materials are inspected under the lenses of multiscale modeling. We could imagine, for instance, molecular design going from chemical building blocks, to proteins, to structural material, to beams, to trusses to the Eiffel Tower [19]. This would elucidate how macroscopic mechanical material behavior is controlled by the interplay of atomic properties throughout various scales. Such example, evidences the importance of integrating interdisciplinary constraints (material, structural, aesthetic etc.) throughout linked models for nano-to-macro design.

Figure 3: Challenges in Redefining Media.
In another example aiming at material design within digital design to fabrication workflows, nanoscale anisotropy in wood is studied to shape macro-scale plywood architectural components [20]. Local direction of fibers in plywood is used to provide regional curvature, then, each bent shape can interface with neighbor components at different curvatures in a free-form global structure. Challenges arise when designing for multiple functions, at different scales, within the same virtual design environment [20]. Workflows, call for not only taking advantage of the structure of a material, but also designing its performance at the molecular level in a sort of fabrication-driven chemical templating.

Difficulties for broadening dimensions within models arise to (a) implement linked models that address multi-scale, combinatorial, and temporal problems, (b) develop nano-to-macro modeling strategies applicable to different materialization processes, both living and synthetic, and (c) relate molecular processes to larger scale phenomena. It is crucial to; (1) develop holistic and flexible design algorithms and work models, (2) implement digital design strategies across varying resolution and representation, and (3) transmit and translate multi-dimensional data (Figure 4).

CHALLENGES

• Implementing linked models that address multi-scale, combinatorial, and temporal problems.

• Developing nano-to-macro modeling strategies applicable to different materialization processes, both living and synthetic.

• Relating molecular processes to larger scale phenomena.

• Designing for multiple functions within the same environment.

Figure 4: Challenges in Broadening Dimensions.

2.2.4 Intertwining Data

Workflow data from design to production and vice versa will carry diverse types of information such as machine, form, environment, material etc. In the last decade, pioneer design research has aimed at
incorporating material performance to inform shape at the very beginning of workflows, reversing the traditional sequence of shape design, then material choice[21], [22]. In ‘Material-based Design Computation’ generative design processes are based on material properties and behavior responding to specific multi-performance criteria integrating form and its material constituents throughout virtual workflows [22]. Furthermore, ‘Material Ecology’ calls for environmentally informed digital design and fabrication [23] so that material behavior can be designed within virtual models. In an early implementation of such endeavor, a novel design and technological approach for biologically-inspired layered fabrication entitled Bitmap Printing is defined so that human wearables can be additively manufactured with technical polymers enhancing protection, promoting flexibility, providing for comfort, or exploring some functional behavior combinations accommodating for multiple functions in helmets, corsets, hip splints etc. [23]. This application finds challenges in transitioning from material selection to material design within virtual models and in embedding models with interdisciplinary data such as biometrics or environmental energies.

Research on smart materials, aims at designing changes in, for instance, physical, chemical, or optical properties within objects or parts. Specifically, shape shifting materials can be designed by encapsulating hydrophobic matter within joints of bar structures and activating its expansion under water [24]. Transformations in the physical realm can only be predicted to certain degree within the virtual model. This is due to a lack of material property data formats able to be integrated within geometry-based design environments. Consequently, challenges of this type of research are modeling the effects of fabrication processes on product performance, as well finding appropriate templating strategies within a virtual model able to account for changes in material properties during smart activation [24].

Non-standard fabrication scenarios present, for instance, structural analysis data used to directly inform fabrication [25]. In a robotic printing implementation, material deposition can be modeled so that it follows stress lines in structurally-analyzed domes. This can allow for oriented material deposition enhancing load distribution performance [25]. Data here from the structural model is key to determine digital fabrication toolpaths, but data from the fabrication implementation, could also be a crucial asset to determine if material deposition – in terms of thickness and final shape of curd matter, for instance - is effectively providing the envisioned structural performance. To do so, sensing or 3d-scanning during fabrication could be of vital importance to guide re-iteration of fabrication design.

Challenges in all of these efforts arise when designing for multiple functions, derived from different disciplinary data sets, within the same computational environment. Specifically, it is difficult to (a) to embed material design data to design matter within virtual models, (b) manage and link interdisciplinary
data such as biometrics or environmental energies, and (c) acquire data to model the effects of digital fabrication processes on product performance. Future implementations need to include: (1) awareness of real-world performance within models, (2) inclusion of manufacturing constraints and properties, and (3) virtual modification of material properties (Figure 5).

CHALLENGES

- Transitioning from material selection to material design within virtual models.
- Embedding models with interdisciplinary data such as biometrics or environmental energies.
- Modeling the effects of fabrication processes on product performance.
- Templating strategies in the virtual model to change material properties during fabrication.
- Introducing sensing during fabrication.
- Adapting virtual models on-the-fly to accommodate materialization information.

Figure 5: Challenges in Intertwining Data.

2.2.5 From MIF to FIM

Given the challenges presented by the above current developments in integrating disciplines, redefining media, broadening dimensionality, and intertwining data, traditional workflows will need to be redefined. Current workflows (MIF) are generally based on models with geometric descriptions that are normally constrained by strict kernel definitions running in the software backbones [2], [7], [26], [27] (Figure 6). This makes integration of physical world awareness a near impossible task. Moreover, MIFs progress linearly from (1) virtual modeling of shapes - typically Computer-Aided-Design for drafting and Computer-Aided-Engineering for analysis-, to (2) generation of information descriptions for manufacturing - typically Computer-Aided-Machining-, then to (3) the execution of digital fabrication [28]. Such process favors high degrees of intelligence within the virtual model, uses information merely to transfer instructions to fabricating machines, and describes fabrication as a tool of maximum obedience. New challenges will arise when aiming at describing strategies to design based on material-, time- and scale-dependent phenomena, or when trying to gather fabrication-based feedback from the materialization process.
Consequently, future workflows (FIM) should have physically-aware models, provide tools and arenas to maintain interconnected crossdisciplinarity work at the beginning and throughout the design process, implement information channels for iterative feedback rather than for unidirectional instruction transfer, and give fabrication maximum intelligence in the design-to-production process (Figure 7).

**Figure 6: Traditional FIM workflows.**

**Figure 7: Future FIM workflows.**

With Fabrication Information Modeling (FIM) a cohesive way to think about and execute digital designs is presented. Designs are informed by multi-dimensionality, media-informed feedback, and trans-disciplinary data integration. FIM proposes total blending between transdisciplinary modeling and fabrication in explorative design-to-production workflows [29]. Its novelty lays on seamless integration of physical world phenomena within virtual design processes that operate at different levels of resolution and representation. To achieve such physical-to-virtual integration, on-the-fly monitoring and adaptation during materialization is key at each step of design.
2. FRAMEWORK

Figure 8: Fabrication Information Modeling (FIM) wants to expand the frontiers of the field of digital design and fabrication, proposing total integration between transdisciplinary modeling, information transfer, and digital fabrication in explorative design-to-production workflows.
3.1 FIM: Fabrication Information Modeling

A Practical FIM Diagram

A diagram for FIM (Figure 8) will accompany the rest of this dissertation and adapt to depict each case study implementation described in Chapter 3. It is understood as both, a cognitive representation of FIM and a tool to design specific FIM workflows bringing together physical apparatus (F), interdisciplinary agents and multiscale dimensions (I), and computational virtual models (M). The diagram is circular to demonstrate integration and parallel orchestration, unlike traditional design processes where workflows are linear and operated in steps [7], [30]. However, the diagram can also be unfolded to navigate design decisions in a visually-traditional way (Figure 12).

Fabrication comes first. Importantly, in the outer ring of the circular diagram and in the first section of its unfolded version, Fabrication is planned (Figure 9). This thesis postulates that future progress in design-to-production workflows will allocate complexity observed today in virtual models, into the digital fabrication realm. Higher degrees of intelligence will be conferred to manufacturing, providing it with a multiplicity of ‘inner models’ able to respond to feedback cues from the physical world; namely via living or non-living sensors, actuators, correction routines, environmental modification etc. Information in FIM moves in any and all directions. It can be understood as a multivariable, multiscale, multimedia, orchestration for materialization in design. Similar to biological systems [31], where the process of feedback governs how we grow, respond to stresses, or regulate vital factors, at every level from molecules, to cells, to organisms, or ecosystems [32]. The models of FIM will carry less and less complexity, serving as arenas for multidisciplinary integration and migrating their intelligence in support of materialization in material-aware, physical feedback systems.

Specifically, considerations of physical world behavior manage a multiplicity of disciplinary data sets translated within and related throughout design-to-fabrication virtual models, so that we can, not only inform design with the internal structure of a material, but also design at the molecular level, in, for instance, a sort of fabrication-driven chemical-templating to induce preferred orientation for desired performance in nano-scale material domains. A FIM design workflow, enables features such as the integration of structure-property relationships during modeling, material state feedback during digital fabrication, design with dynamic entities such as organisms or chemistries, or means to rethink an object or a building as a multi-scale strategy depending on both design of macroscale geometry and design of nanoscale material.
**Fabrication**

In the 'FIM' acronym, 'F' refers to physical world devices and processes that inform and enable fabrication. Namely, traditional digitally controlled manufacturing environments, end effector implementations in robotic arms, digital cameras and other physical monitoring means connected to the workflow, fabrication materials and their multiple blends, as well as environmental control chambers and apparatus (Figure 9).

*Figure 9: F in FIM.*
Information

"I" establishes four types of information flow: (1) virtual-to-virtual information links datasets and considerations between different disciplines within the model, (2) virtual-to-physical information is passed from the model to the digital fabrication devices in the form of instructions, (3) physical-to-virtual data collection is transferred from physical fabrication and monitoring devices to the model during iterative computation to provide new materialization decisions, and (4) physical-to-physical data is passed among physical devices and computed via preestablished or autonomous routines to respond to, for instance, environmental control variations or material distribution needs (Figure 10).

Figure 10: I in FIM.
Modeling

'M' refers to virtual model, where design algorithms integrate trans-disciplinary data sets and design decisions to handle instructions to and from the physical fabrication and monitoring world.

Over the course of this thesis and through its case studies, models will become less relevant and less intelligence-heavy, in favor of a deeper focus on materialization events and on fabrication-to-fabrication information implementations (Figure 11).
Figure 12: Fabrication Information Modeling (FIM) unfolding progression and unfolded diagram depicting an exemplar case of fabrication-informed modeling.
3.2 Research Fields for FIM

Based on the described disciplinary advances and opportunities, FIM research defines and addresses the following novel fields (Figure 13). **Trans-Disciplinary Data Design and Fabrication** is key to question new ways to manufacture designs informed by materialization processes across scales, media and disciplines. **Integrated Multi-Dimensional Design Workflows** within design-to-fabrication tools are inquired to devise how to operate at the varied dimensions of the physical world. Real-time modification of design solutions by collecting feedback during materialization will become very relevant in bridging the physical-to-virtual gap in digital design and fabrication. Strategies to incorporate material and machine **Media-Informed Feedback within Digital Design** are inspected through, for example, machine-environment awareness, multi-machine collaboration, or biological and mechanical material-based sensing during advanced robotic fabrication processes.

**Trans-Disciplinary Data Integration**
Incorporating data sets from diverse disciplines - material, machine, organism, and environment - and relate them within the virtual model

**Multi-Dimensionality**
Managing scales of time and space, from microseconds to decades and from atoms to landscapes

**Media-Informed Feedback**
Achieving real-time modification of design solutions by collecting feedback during materialization

![Diagram](image)

*Figure 13: Research fields for FIM.*

3.2.1 Trans-Disciplinary Data in Design and Fabrication

It is crucial to incorporate material, machine, and environment awareness in digital design models that account for different scales of work according to a rich interplay of disciplines, which work with very diverse media from molecules, to mechanisms, to organisms. This poses the question of: **What Needs to Change Within Design Models to Integrate Interdependent Trans-Disciplinary Data Considerations?** To address such challenges, design workflows could (1) include pre-compiled morphometric[33], mechanic, pneumatic[11], or structure-property[34] data as design drivers or as modeling inputs at any step of the
process (initial steps described in the Biomimetic Skins and Parametric Chemistry case studies), (2) modify shape-generation parameters by efficiently linking, for instance, protection to 3D geometry constraints[33], or anisotropic folding to 2.5D tool pathing sequences[35] (addressed in the Biomimetic Skins, and WBDF case studies), and (3) efficiently embed physical-world manufacturing constraints at play such as gantry size and weaving pathways[36], motion planning and collision avoidance[37], pressure, speed, or nozzle diameter[38] (addressed in the Silk Pavilion, Bots of Babel, and WBDF case studies).

3.2.2 Integrated Multi-Dimensional Design Workflows

Foundation work to integrate nano-to-macro computational workflows in digital design requires multiscale design models and multiscale transfer of data. How can we apply Multiscale Modeling Strategies to Explorative Design Environments? Successful workflows to this complex need may (1) include holistic, flexible, adaptive, and hierarchical design algorithms and work models, (2) implement digital design strategies across varying resolution and representation within the same model, such as unit scale with geometric-level detailed features, differential functional-level regions of scales, and global shape with overall scale system-level fitting[33] (addressed in the Biomimetic Skins case study), and (3) transmit and translate multi-dimension data from virtual to physical environments, such as linear toolpaths embedding meta nodes of pressure and speed[38] (addressed in the WBDF case study).

3.2.3 Media-Informed Feedback within Digital Design

Strategies and methods to transform digital fabrication workflows accounting for environmental feedback can challenge the traditional linear progression from design to production, and towards real-time modification of design solutions according to on-the-fly gathered information at multiple physical scales. Specifically, in; dynamic feedback for machine-machine interaction in synchronized digital fabrication, machine-matter interaction for material property monitoring, or in machine-organism interaction to biosense changes in growth or in properties during design with living materials. What are New Possibilities in Feedback Systems for Fabrication? Perhaps to (1) gather real-time positioning and trajectory planning data for collision avoidance during multi-nodal construction (implemented in the Bots of Babel case study), (2) assess composition and distribution of matter during manufacturing, and sense changes in growth or in properties during design with living materials (both will be addressed in the Wet Lab on a Bot case study).

These fields will help define and implement a shift from MIF traditional workflows to FIM workflows where challenges of physical awareness and fabrication intelligence are addressed.
3. FIM CASE STUDIES

From elaborate models negotiating disciplines and scales, to parallel and retroactive information flows, and towards intelligent fabrication with physically-aware models, six case studies and resulting constructs explain the development of FIM (Figure 14, Figure 15).

Figure 14: Six case studies of FIM.

First, Biomimetic Skins, embodies a geometry-based model conferring complexity to virtual computation. The effort is put in translating interdisciplinary data from material system structure-property correlations and morphometric analysis into geometric relationships. It derives a powerful tool to design fabricable scale-based surfaces of all kinds, but does not provide efficient interaction with the physical world.

The second case study, Bots of Babel, is a demonstration of planned intelligence for fabrication, where the model is a rule-based recipe activated when receiving feedback from mechanical devices. The system tracks a set of swarming builder bots. Here, physical computation of fabrication events is achieved.
In the Silk Pavilion Research, a constraint-based model sets the stage for dynamic materialization. It blends organism physiology parameters, environmental datasets, and machinery limitations to scaffold a pre-structure. Then, **templated negotiation is conferred to bio-fabrication events** using silkworms.

The **WBDF** platform and its workflows are this thesis' forth case study and the first instance of physical-world computation. Material properties are directly mapped onto information flows to induce anisotropy, and consequent 2D-to-3D self-folding of structures, through the very process of fabrication. Building on the WBDF research, **Parametric Chemistry** derives as a fifth comprehensive case study showing **direct chemical design for optical, mechanical, and structural performance**. It results in structures embodying transparency and chromatic negotiation, or graded structural load distribution via molecular interaction in the design and synthesis of material blends.

The last case study, the **Wet Lab on a Bot**, points towards the virtual and the physical merging to allow for **maximum intelligence in fabrication**. Here, materialization information, its monitoring, and adaptation to changes, will autonomously occur, transferring the model’s intelligence to living cells and to hardware devices.

![Figure 15: Six case studies of FIM and their FIM diagrams.](image)
4.1 Biomimetic Skins: Prehistory for Biomechanics

4.1.1 Research Summary

This research is driven by a need to inspire, inform, and perform designs at different scales of resolution and representation. This relates to achieving multiscale design within the same environment including: decisions pertaining to chemical properties of specific materials (at the nano-scale), mechanical performance of assemblies (at the micro-scale), fabricability of parts (at the meso-scale), or real-world endurance of structures (at the macro-scale). Natural systems are a great example of material-geometry interplay at all scales providing functional gradients of properties by employing very simple building blocks. This is because design and assembly in nature is driven by hierarchy, and multiscale considerations and operations are inherent to its existence.

Specifically, here a hierarchical computational model aims at adapting a segmented scale armor of a prehistoric fish to fit biomechanically-complex host surfaces such as the human body. It responds to the computational difficulty in translating naturally occurring segmented and articulated armors to other surfaces. The model operates in three levels of resolution: (1) locally— to construct unit geometries based on shape parameters of scales as identified and characterized in a prehistoric fish exoskeleton via scientific morphometric analysis, (2) regionally— to encode articulated connection guides that adapt units with their neighbors according to directional schema in the computational mesh, and (3) globally— to generatively extend the unit assembly over arbitrarily curved surfaces through global mesh optimization using a functional coefficient gradient. Simulation results provide the basis for further physiological and kinetic development.

This work efficiently merges material science and computational geometry tools and workflows to provide a methodology for the generation of biomimetic protective surfaces using segmented, articulated components that maintain mobility alongside full body coverage.

4.1.2 A Context for Biomimetic Skins

Structure-property in Nature
Natural material systems achieve diverse functions (e.g. toughness, flexibility, strength) through spatial variation in materials and morphometry across organizational hierarchies with precise interfacial control [39]. Such systems often exhibit emergent behavior as a result of the interactivity of their constituents, such as non-additive tunable properties, or behavior and function that emerge from fundamental constituents beyond simple rules of mixtures [40].

The advent of new digital fabrication technologies such as additive manufacturing enables the design and fabrication of novel multifunctional structures inspired by their natural counterparts. Here, a computational design methodology combines scientific analytical methods [41]–[44] and computational form finding [45] for the design of a bio-inspired surface composed of articulating segmented units that is both protective and flexible. The goal is to computationally create a generative design framework for functionally-graded designs with tunable local performance that adapts to a host mesh surface by emulating design principles observed in natural armor systems.

The biological model is the exoskeleton of an ancient fish *Polypterus senegalus* (family Polypteridae). Its scale jacket (shown in Figure 16) contains mineralized components as a protective medium from external, environmental threats while the articulated squamation allows a high degree of biomechanical flexibility in motion [44], [46]–[50]. The combination of two seemingly contradictory functions – uniform coverage and mobility – can serve as a model for many applications in various fields such as transportation (e.g. ground, air, water, or space), architecture (e.g. building skins or canopies), sports and military (e.g. personal protection), and consumer products (e.g. packaging) [49]. However, theoretical and technical challenges still exist in beyond capturing the complexity of this biological system [51].

Structure-property in Modeling
Biologically inspired engineering, or the translation of design principles in nature, being chemical, physical, genetic, or in this case, geometric, into a new man-made system, requires complex models. The model for the translation of the *P. senegalus* exoskeleton must be able to synthetize natural morphology and provide multi-functionality through the gradual variation of interrelated parameters of shape. Prior work enabled the first steps toward understanding of the *P. senegalus* integument and established that geometric design rules underpin the functional framework. One model built a parametric definition of a single scale geometry and an associative model to generate an array of homogeneous scales using computer-
aided design (CAD) software for multi-material 3D printing of a flexible, flat surface [42]. Another model attempted to morph scale-based geometries along a sequence to determine dimensional parameters that can be varied while maintaining connectivity in one direction.

Figure 16: (top) Mineralized exoskeleton of Polypterus senegalus, Senegal Bichir. (bottom) Reconstructed µCT images of individual scales from different locations in the exoskeleton [51].

Here is addressed the challenge of computationally translating a biological integument to human synthetic wearables. The work distills the geometric design rules underlying the P. senegalus exoskeleton across
multiple length scales (local, regional, and global). Then the MetaMesh model translates these design rules hierarchically to a synthetic system using an efficient framework linking experimental analytical methods (X-ray micro-computed tomography and morphometric analysis) with advanced computational geometry techniques (custom data structures for polygon mesh processing and component adaptation). This hierarchical model uses information at local, regional and global length scales to ensure unit connectivity while using multi-functional gradients to conform to a complex hosting surface. Unlike component-based parametric techniques that focus on the packed placement of self-similar units over surfaces [45], MetaMesh incorporates complex connectivity and overlap of the units to enable articulation with neighbors. The MetaMesh model’s potential is demonstrated with its application to a human body mesh surface and further discuss the model’s advantages and limitations [51].

4.1.3 Interdisciplinary Data towards Biomimetic Skins

**X-ray micro-computed tomography (μCT)**
Eleven scales were excised from a deceased *P. senegalus* specimen (every 10th scale across a row on the left side of the body) and scanned via x-ray micro-computed tomography (μCT; Viva CT40, Scanco Medical AG, Switzerland) operated at 45kV and 177μA. The microtomographic data was reconstructed using bilinear and interplane interpolation algorithms into polygonal meshes with an interactive medical imaging software (MIMICS 14.1, Materialise, Belgium) to generate digital 3D objects of the scales in stereolithography (STL) format. Further processing was done in Rhino3D (RHINOCEROS®, Robert McNeel and Associates, USA) to remove noise and internal porosity [51].

**Morphometric Analysis**
The coordinates of anatomical loci on the scales were extracted from the 3D STL objects using a custom VB script in Rhino3D. These landmark coordinates were subjected to translation, rotation, and scaling relative to the centroid. Relative geometric parameters, presented, were calculated based on the coordinates. The volume of the scale was measured from the STL file in Rhino3D [51].

**Computational Modeling**
The computational framework defining the MetaMesh data structure (local scale geometric definition, regional directionality patterns, and global functional gradient application) was implemented in C# on top of the design platform Rhino3D (RHINOCEROS®, Robert McNeel and Associates, USA). The mesh
optimization process was scripted in Java (Eclipse IDE, © 2013 The Eclipse Foundation) and deployed in a customized applet [51].

**Multi-material 3D Printing**

The closed-surface multi-material prototypes were designed using parametric CAD software (SOLIDWORKS®, Dassault Systèmes SolidWorks Corp., France) as described previously by Reichert et al. for a flat surface [5]. The components of the prototype were exported as separate STL files per material component, and fabricated using multi-material 3D printing (OBJET Connex500™) with 30 µm resolution in the digital mode. The rigid components were printed with Vero White Plus (Objet Full Cure 835) and compliant components were printed in Tango Plus (Objet Full Cure 930) [51].

### 4.1.4 Biological Design Rules

The geometric design rules in the *P. senegalus* exoskeleton can be separated into: (i) local, (ii) regional, and (iii) global. The individual scales vary in shape spatially, are articulated with each other to allow for flexibility alongside full body coverage, and are organized in a long-range surface over the entire fish body. While all components are formed during the organism’s growth, and thus are inseparable, we can distinguish amongst these levels of resolution for ease of their computational association [51].

**Local Scale**

The local level of exoskeleton organization relates to a single scale, its anatomy, and its geometric variation. The scales are highly mineralized and display a multilayered internal composite structure [44], [49], and the material composition of scales is constant throughout the exoskeleton. The scales also possess complex geometrical features: an axial ridge, which connects the scale to the underlying dermis; peg and socket that defines an articulated joint within a column of scales (paraserially) that constrains the relative motion of scales; and anterior process, a rhomboid extension that overlaps with scales in the next column (interserially) and enables neighboring scales to slide relative to each other [51].

The scale geometry varies by position in the exoskeleton as shown in Figure 17 by a subset of 11 scales lying in the same row in the scale jacket. Changes in scale shape occur gradually and result in functional differences across the exoskeleton [46]. Variation of scale geometry was quantified by defining parameters in Figure 17a based on the coordinates of anatomical loci placed on the digitally-reconstructed 3D objects generated from µCT. These parameters include the relative length of the peg to the scale (PSL), the shape aspect ratio (SR), bounding box size (E), interserial overlap (IO), paraserial overlap (PO), relative edge
degrees (ANG), anterior process length (APL), and volume (V). Values for these parameters are presented for each scale in the series and plotted in Figure 17b [51].

The posterior variant of the scale shape is small with reduced features compared to anterior scales. Both E and V decrease toward the tail region. The most apparent trend is the reduction in the PSL and IO. The PSL diminishes gradually but significantly anteroposteriorly from 0.22 to 0.03. In the anterior region, the peg-and-socket plays a functional role in stiffening the dorsal-ventral column, while in the tail, the lack of peg-and-socket allows paraserial scales to move freely relative to each other. The connective overlap in the interserial direction (IO) also decreases from 0.28 to 0.13, thus compromising the relative sliding between columns is compromised. These features relate to inter-scale connectivity.

**Regional Connectivity**

The regional level of exoskeleton organization describes the connectivity of adjacent scales to each other, and the correlation between local shape variation and the regional functionality of the exoskeleton. The scales in the exoskeleton are connected by two joints in different directions: down a column (paraserially) by the peg-and-socket joint, and between columns (interserially) through scale-to-scale overlap, shown in Figure 18. Shape variation determines the regional function of the exoskeleton armor. Figure 19 demonstrates the difference in ranges of motion between two shape variants: an anterior lateral scale and posterior lateral scale. The anterior scale is bigger and possesses more pronounced shape features relative to the posterior scale. Paraserially, it has a well pronounced peg and socket plus additional overlap to limit rotational motion of neighboring scales. Interserially, the large anterior process overlaps with the neighboring scale; relative sliding of scales during fish motion results in significant changes in overlap (42-140% [46]) and allows the exoskeleton to bend to extreme curvatures. In comparison, the posterior scale is small and has simpler rhomboid shape with diminished features. This enables greater freedom of movement between scales for rapid motion of the tail during swimming.

The orientation of scales within the assembly exoskeleton further contributes the location and direction-dependent flexibility of the armor. The scale columns (rings, shown in Figure 20) and the fibrous tissues underneath them have oblique orientation to the main axis of the trunk, which changes from 60°-45° anteroposteriorly [10] as shown in Figure 21. The 60° orientation in the anterior is an optimum angle to enable extreme curvatures in helical arrangement, as shown in eel and worms [52], while the rigid peg-and-socket joint sustains the helical component of the torsional strain [46]. The 45° at the posterior end is optimized to prevent torsion [53]. Furthermore, the angle between the edges of the scale (ANG) also decreases gradually from 87°-60° anteroposteriorly, showing that the directionality of the rigid paraserial axis and flexible interserial axis are highly adapted to the kinetic motion of the fish. Shown later are initial attempts to reconstruct this directionality schema and adapt it to a new surface (e.g. the human body).
Figure 17: Geometric analysis of scale shape variation along the fish in the head-to-tail direction. (a) Key geometrical features of a typical scale: P—peg, S—socket, AP—anterior process, AR—axial ridge. (b) (top) Table summarizing parameter definition and calculation.
the morphometric parameters of 11 scales (C1–C50) normalized by maximum value, and (bottom) plot of the normalized scale parameters [51].

Figure 18: (a) Schematic and axonometric view of unit connections within the exoskeleton assembly: u-direction peg-and-socket (paraserial) and v-direction overlap (interserial) connections, stratum compactum (orange) attaching units to the organism, and Sharpey’s fibers (blue) attaching units to each other. (b) Schematic of allowable ranges of motion of the unit joints: bending in overlapping joint (upper left), twisting of overlapping joint (upper right), bending...
in peg-and-socket joint (bottom left), twisting in peg-and-socket joint (bottom right). (c) Schematics of the location in plan and section of the Stratum compactum (orange) and Sharpey's fibers (blue) [51].

Figure 19: Allowable motions between adjacent scales in head region and tail region scale variants. Head region scales: (a) rotation around the u-axis, (b) translation along the u-axis, (c) rotation around the n-axis, and (d) translation along the v-axis. Tail region scales: (e) rotation around the u-axis, (f) translation along the u-axis, (g) rotation around the n-axis and (h) translation along the v-axis [51].

Figure 20: Lines of symmetry on the top and bottom of fish trunk. (a) Identification of specialized (orange) and standard (blue) lines of units on the fish. (b) 3D-printed prototype mimicking the arrayed rings in the P. senegalus exoskeleton and the midlines of double-peg and double-socket specialized units. (c) 3D rendering of unit arrangement within two overlapping rings of standard units. (d) Section through peg and socket joints showing adaptation to the curved surface. (e) 3D-printed prototype showing the location of standard units (blue) and specialized units (orange) [51].
Figure 21: The global organization diagram: (a) spatial functional differentiation color map of unit shape ranging from maximum protection (blue) to maximum flexibility (red). (b) Functional differentiation is adapted to the varying radii of curvature (blue dashed line) during the swimming motion of the fish [51].

**Global Plan**

The global level of exoskeleton organization relates to the overall body shape. The assembly of scales into a long-range structure defines both the protective performance and mobility of the fish exoskeleton. The scales are assembled into mirrored semi-helical rings that are stacked into a tube anteroposteriorly to cover the entire length of the fish body, illustrated in Figure 20a-d. Furthermore, dorsal and ventral midlines are composed of specially shaped scales with double pegs or double sockets that receive the symmetrical semi-helical columns from each side (Figure 20e-f). These lines are defined as lines of fulcral scales by Gemballa and Bartsch [46]. The interserial and paraserial axes, which run between the dorsal and ventral midlines,
are both situated oblique to the main axis of the trunk. The oblique orientation and directionality of these lines of connections define the kinetic schema and flexibility of the armor [51]. Local scale geometry contributes to the global functional schema of the armor. A functional mapping coefficient (FC) was calculated by the average value of geometric parameters PSL, IO, PI, and AP and ranges from 0 to 1 for maximum protection to maximum flexibility. In Figure 21b, the FC is color mapped from anterior to posterior along the exoskeleton. Together, the functional gradient and the directionality schema of connections allow simultaneous protection and mobility to the fish [51].

**4.1.5 Computational Design Rules**

This section unpacks the organism-specific functional system to apply the design principles in a generative way to a new hosting surface while tailoring functional specification to fit the new host. The hierarchical computational model, MetaMesh, was developed to create and maintain consistent neighborhood relationships between the articulating surface units using a quadrilateral polygonal mesh. The data structure used in the model needed to meet specific topological, algorithmic, and data access requirements:

The topology of the structure is a high-resolution polygonal regular mesh of quads with boundaries. The three components of a polygon mesh (vertices, edges, or faces) determine the connectivity between the mesh elements [54]. To ensure smooth connectivity between component features, each vertex holds one scale and each face shares the information of four scale geometries. Meshes with boundaries, defined by edges incident to only one face [55] are needed to include neckline and sleeve openings. The interserial and paraserial axes in the fish exoskeleton must be translated onto the two principal directions of the parametric surface subdivision [51].

Algorithmic requirements operate on scale unit orientation and connectivity along the principal directions, as well as scale unit geometry by specifying vertex positions through mesh optimization. The model desires optimization for functional gradients of protection and flexibility mapped on the human body. Additionally, mesh optimization methods must associate extra geometry to the vertices, edges, and faces of the mesh to share unit shape characteristics with neighboring elements. To do this the model uses a finite set (V) of vertex indices, a table of 3D vertex coordinates $X = \{x_i : i \in V\}$ indexed by a vertex index, and a set $F$ of polygon faces, in which a face $f = (i_1, \ldots, i_n)$ is a sequence of nonrepeating vertex indices [56] [51].

There were further imposed access requirements to the sets of data included in the model. The data sets for vertices, edges, and faces are accessible by enumeration of all elements and the oriented transversal of face edges. Given an edge, we must be able to access its starting and end vertices. Finally, given a vertex, at least one attached face or edge must be accessible while all other elements in the neighborhood of the vertex (i.e. incident faces, edges, or neighboring vertices) can be enumerated [57] [51].
MetaMesh, was developed to meet these requirements at three organizational levels following the geometric rules of assembly. An overview of the stages of the model are shown in Figure 22, starting from a (i) local quadrilateral polygonal mesh, (ii) regional application of directionality and functional gradients, and (iii) global optimization of the scale mesh [51].

**Local Unit**

The local level of organization captures the scale unity as a building block by considering the features of its neighbors and of the underlying host mesh. Each scale unit geometry was centered on top of the mesh vertices and simplified to a set of controllable parameters (Figure 23a). Since each vertex has an associated unit, its geometry can absorb the host surface curvature. The local set of data per mesh face contains a shared contact surface between four units, which must consider the features of neighboring scales (Figure 8b). Each vertex stores the information of four parameters that will affect its associated unit shape in two different directions. Along the principal direction (u, paraserial), unit geometry is influenced by the PSL, PO, and APL parameters. Along the secondary direction (v, interserial), the unit geometry and lateral scale superposition are influences by IO [51].

Specific unit lengths were calculated to determine unit features and their placement on the quad. This unites the features of the underlying mesh with the geometrical parameters and functional requirements of the host. A particular vertex in question is defined as V0(i,j), and its four neighbor vertices are defined as V1(u+1,v), V2(u-1,v), V3(u,v+1), V4(u,v-1) as in Figure 23a. The midpoints of their edges are then defined as m4-0, m0-1, m0-3, m2-0. The unit lengths were calculated as follows, then mapped onto the mesh quads (Figure 23c) using bilinear interpolation [58]:

- **Scale Width** $L_8 = m_4 - m_0 - 3$
- **AP Length** $L_6 = m_2 - m_0 - 1$
- **PO Length** $L_7 = APL / L_6$
- **Overall Length** $L_2 = L_1 + L_5 + L_6$, where $L_1 = L_2 \times PSL$ and $L_5 = L_2 \times PO = L_6 / (1-(PSL+PO))$
- **Overall Width** $L_3 = L_8 + L_4$, where $L_4 = L_3 \times IO = L_8 / (1-IO)$

The principal and secondary directions act as guides for the construction of the peg-socket and overlap feature geometries in a unit. Each side of a quad can host either a secondary or primary direction, so any connectivity is allowed. For instance, the fulcral scales in the dorsal and ventral midlines were defined as variations from the standard scale through the encoded principal and secondary directions (Figure 23d).

This method of polygonal mesh connectivity is similar to the stitch mesh developed by Yuksel et al. for yarn patterns in 2.5D, where course and wale edges have an extra layer of information to define the connectivity of the yarn elements at the mesh edges [59] [51].
Figure 22: MetaMesh local unit construction. (a) Vertex-centric VO unit placement on top of the underlying mesh and identification of u-(peg-socket) and v-(overlap) directions in the model. (b) Unit construction from four connecting surfaces (blue) and a cross-shaped contact surface (orange). (c) Arrangement of 4 standard units in the model and in the organism and calculation of the unit features from geometrical analysis parameters (L). (d) Different specialized
unit types identified by the u- and v-directions present in the organism (D, E) or defined by the directionality pattern of the new host (A, B, C) [51].

Figure 23: MetaMesh regional directionality pattern. (a) Definition of the peg-and-socket u-direction (blue arrows) and the overlap v-direction (black arrows). (b) Identification of the directionality pattern on the human body and emergence of new specialized unit types (orange). (c) u- and v-directions on the idealized tube-shaped body of P. senegalus and location of the organism’s specialized units (orange) [51].
Regional Orientation

The regional level of organization encapsulates the orientation of mesh regions against the hosting surfaces. A mesh is defined as orientable if all faces are oriented towards the same side; in other words, normal vectors for all polygons, must point consistently to the same side of the mesh. The information encoded in
principal and secondary directions does not affect the orientability of the mesh, but tailors edge directionality as extra regional data in the data structure (Figure 24). While scales can slide relative to each other in the interserial axis, the peg-and-socket joint articulation impedes the translation and rotation of scales in the paraserial axis, thus forming the foundation of directions of non-extension on the surface [46], akin to Iberall’s “lines of non-extension” (LNE) [60] which serves as a basis for translational design of a space suit [61]. Identifying the LNE on the fish serves as a method to translate the orientation of scales on the fish body along the LNE of the human body to better adapt the armor logic over the minimal human skin strain directions and comply with human kinematics. The model places the principal direction encoded on the mesh edges along the LNE of the human shoulder, while the secondary direction is placed along lines of maximal movement, as shown in Figure 24.

![Figure 25: MetaMesh global iterative steps for regularizing the host mesh Tangential Laplacian Smoothing through 50 iterations. The quality of the quad ranges from distorted (red) to regular (blue) [51].](image)

**Global Host**

The global level of organization optimizes the mesh of unit geometries to the underlying hosting surface. The FC was calculated as a gradient that indicates relative local contribution of coverage versus flexibility.
for each mesh vertex. As shown in Figure 25, the FC was then encoded in every mesh vertex to modulate the unit geometry toward a protective variation of heavily articulated features (red) or more flexible with reduced features (blue) (Figure 25). In combination with the neighborhood relationships, this enables transition between functional characteristics across the mesh. Figure 26a illustrates this variation on the human shoulder mesh.

An overall mesh relaxation algorithm, Tangential Laplacian Smoothing, was applied to reposition the mesh vertices according to the geometries dictated by the FC without distorting the overall shape of the mesh, as demonstrated in Figure 26b. This algorithm maximizes the homogeneity across all of the quads in the mesh by replacing each vertex coordinate with a weighted average of itself and its first order neighbors [58]. In this model, a vertex displacement vector $\Delta x_i$ was calculated for each vertex $x_i$:

$$\Delta x_i = \frac{1}{n_i} \sum_{j \in v(i)} (x_j - x_i)$$

Vertex displacements were then applied to the vertex coordinates, $x'_i = x_i + \lambda \Delta x_i$, where $\lambda$ is a fixed-scale parameter in the range $0 < \lambda < 1$. Finally, the model replaces the original vertex coordinates $X$ with the new vertex coordinates $X'$ [56]. These three steps are repeated until quad area homogeneity criterion for minimum unit distortion is met. Here, it was important to preserve the shape of the mesh as new vertex positions were applied; we avoid mesh shrinkage by limiting vertex translation as only tangential to the mesh surface.

**Universal Translation**

To validate the MetaMesh model, it was applied to populate the simplified *P. senegalus* scale geometry over a regular quad mesh of the human body (Figure 27). First, a regular polygonal mesh of quads with boundaries was constructed. Next, a set of raw polylines corresponding to the skin LNE was fitted to the surface and smoothed as control-point curves. A regional directionality pattern was applied over these lines to inform the construction of scale connectivity. The functional gradient was then determined, and the mesh was optimized for quad area homogeneity with the geometric parameters defining the scale shape. Finally, the segmented units were adapted to the smoothed geometry through integration of neighborhood parameters encoded into the mesh vertices for each scale. The association of the local unit parameters to its neighbors in addition to the underlying mesh information (FC, regional directionality), allows unit shape adaptation to the host geometry while preserving working articulating connections between the units (Figure 22).
4.1.6 Relevance of the Research

The MetaMesh model is a generative computational design framework for translating design principles observed in the flexible fish exoskeleton of \textit{P. senegalus} into functionally graded structures adapted to a new host surface, e.g. a human body. Figure 26 summarizes the main steps in translational process from analysis of the biological armor into generative computation through local shape construction, regional connectivity pattern, and global optimization and adaptation to overall geometry. MetaMesh attempts to solve many challenges heretofore unaddressed in architectural geometric design and flexible protective structures by developing bioinspired functional designs with components operating at multiple length scales.

Parametric Component Population (PCP) is a common method to adapt discrete geometrical components to large-scale complex shapes. The host surface is normally structured as a polygonal mesh of quadrilateral
faces or as a NURBS surface subdivided into u, v directions. The component’s geometry is described through a parametric model and then repetitively embedded as discretized shapes on the host surface in two steps: component enclosure in an axis-aligned bounding box, and translation of the bottom-face vertex to every vertex of the mesh face in order to parametrically fill the space of the host mesh. Despite its fast distribution of volumetric units over 3D surfaces, PCP restricts the footprint of the volumetric component to the boundaries of the host quadrilaterals, which does not support certain surface contacts or tangent connections of neighboring geometries. Hence, connectivity between component features along the surface is not assured. In the *P. senegalus* exoskeleton, the peg and socket joint and overlap joint articulations are key connectivity features of the system that must be preserved when translating to a new host environment. MetaMesh solves this challenge by including neighborhood relationships between the units, which PCP fails to do.

The originality of MetaMesh lies in its efficient framework linking experimental analytical methods (μCT and morphometric analysis) with advanced computational geometry techniques (custom data structures for polygon mesh processing and component adaptation). The results propose a novel strategy for the multifunctional adaptation of highly elaborate components to complex surfaces with tailored directionality, emergence of new unit types, and the conservation of their interconnectivity patterns.

### 4.1.7 FIM Aspects in Biomimetic Skins

Interdisciplinary INFORMATION was effectively included and related in the MODEL. This helped to understand biological design principles to translate to biomimetic devices. In turn, scientific analysis of the exoskeleton better informed the designer in devising computational methods to translate principles to a new hosting surface and hint at new ways to FABRICATE a functional bio-inspired system.

**MODELING in Biomimetic Skins**

This model is effective in translating multifunctional design principles of natural growth. The system can vary LOCAL unit features according to functional needs, and ensure REGIONAL neighborhood connectivity so that it can adapt to GLOBAL hosting surfaces (Figure 27).
**INFORMATION Structure in Biomimetic Skins**

Drawing from experimental biology, materials science and engineering, mechanical engineering, and architecture, workflows like this one challenge traditional design techniques by incorporating multiple layers of information, such as physiological features and kinetic dimensions, at any level of the hierarchical computational data structure. However, no information is passed to digital fabrication devices or feedback is collected from them, instead, manufacturing was achieved by traditional file-to-fabrication techniques using CAM file formats and 3D-printers (Figure 27).

*Figure 27: MODEL and INFORMATION in Biomimetic Skins.*
This work lacks continuity between computational construction and digital fabrication. The model preserves articulation and relation amongst units, but does not accommodate material negotiation strategies such as; layered microstructures for crack resistance, graded material interfaces for differential loading, or internal porosity for breathability. For instance, we could think of designing material gradients within units, related to loading performance needs, to be 3D-printed. Then further biomechanically tested, for subsequent material iterations. The system, however, provides an interdisciplinary platform and a work mindset for design of matter organization principles at the local, regional, and global levels of resolution (Figure 28).
4.2 Bots of Babel: All for One and One for All

4.2.1 Research Summary

This research is driven by a need to fabricate using distributed systems that share and collect intelligence from the physical world. This relates to achieving constant feedback between modeling and digital fabrication nodes through information describing; navigation, material state, and material deposition. Unlike the previous case study on Biomimetic Skins -where a computationally-heavy model managed multiple disciplinary and dimensional data structures to inform complex geometries-, here the model is simplified and in charge of setting behavioral rules for swarm-like construction with small robots building bigger than themselves. Fabrication, however, is here emergent and harnesses the power of a centralized and decentralized system. This bottom-up setup becomes more efficient than pre-computing top-down thousands of singularities when managing node-based systems building complex shapes. Specifically, centralized computation, within the virtual model, manages collision-avoidance, storage of material curing time clocks, and correspondence of design evolution and planning. Decentralized computation, on board of fabrication agents, operates spatial search without pre-defined pathways and effectuates deposition of pastes in layers when possible.

Distributed forms of construction in the biological world are characterized by the ability to generate complex adaptable large-scale structures with tunable properties. In contrast, state-of-the-art digital construction platforms in design lack such abilities. This is mainly due to limitations associated with fixed and inflexible gantry sizes as well as challenges associated with achieving additively manufacturing constructs that are at once structurally sound and materially tunable. This section reports on a successful first deployment of Bots of Babel, a system that demonstrates novel features characteristic of fabrication-information modelling such as multi-nodal cooperation, material-based flow and deposition, and environmentally informed digital construction. The work points towards long distance digital fabrication and autonomous construction based on simple starting design needs or global directions. Better control of additive material integrity could be provided by on-the-fly feedback-enabled evaluation and correction of environmental parameters such as humidity and temperature.

4.2.2 A Context for Autonomous Builders

**Biological Distributed Construction**

Distributed construction in the biological world enables what is currently lacking in digital design and fabrication: large scale, geometrically complex, materially variable and behaviorally responsive digital fabrication [62]. In nature, such features are enabled by an organism's ability to respond to environmental cues and adapt to the availability of matter [63], [64]. For instance, wasp nests and termite mounts are considered canonical examples for animal architectures that are coordinated and erected through distributed construction. These insects utilize simple communication via sensing stimuli to construct large-scale, highly sophisticated, multi-functional structures that are orders of magnitude larger than themselves. In contrast to its biological counterpart, man-made agent-based assembly is generally based on discrete processes, making it challenging to achieve high levels of complexity in agent-to-agent ("node-to-node") communication and material sophistication [4], [62], [65]. Higher overlap between material processes, environmental conditioning and fabrication constraints aims to tackle these challenges by increasing the dimensionality of the design space through multifunctional materials, high spatial resolution in manufacturing and sophisticated computational algorithms [37].

**Man-Made Distributed Construction**

The majority of current research efforts in distributed construction focus on the assembly of discrete components (e.g. blocks or beams) held together in ways that are not readily scalable (e.g. magnetism or friction) [66], [67]. These systems are typically developed around specific modular or prefabricated components, which limit the range of possible geometries and applications of the resulting structure [66], [67]. From a design perspective, such efforts focus either on duplicating existing rectilinear forms as made by conventional construction methods, or on simulation models that fail to be reproduced in physical environments. Few recent projects, such as the one presented here, explore distributed deposition of large-scale structures with tunable material properties [65] [37].

**Additive Manufacturing**

Current additive fabrication approaches for digital construction are generally limited by 3 major constraints: (1) the typical use of non-structural materials with homogeneous properties; (2) the dependency of product size in the gantry size, and; (3) the typical need for support material throughout the layered deposition process [37]. A distributed approach to manufacturing carries potential to radically transform digital
construction by (1) digitally fabricating structural materials with heterogeneous properties; (2) generating products and objects larger than their gantry size; and (3) supporting non-layered construction by offering novel fabrication processes such as free-form printing and robotic weaving. Here is presented a distributed multi-robot approach to additive construction at architectural scales.

4.2.3 Behavioral Model for a Cable-Suspended Robotic Construction System

Physical Implementation Strategy

Machine control firmware was developed in C and C++ language using micro controller boards (Arduino Mega 2560). The boards distribute serial signals to stepper motors (Gecko 6723-400-4) via the Probotix Bi-polar 7.8A drivers. The motors are NEMA 23 in size and are rated for a holding torque of 2.83 newton-meter. The drivers permit a maximum current of 7.8A and are powered separately from the electronic controls with a 48V power supply. Constant force spring motor assemblies (Stock Drive Products/Sterling Instruments, ML 2918) are used to spool up excess cable as well to keep tension on the pulleys. The micro controller receives feedback data from incremental rotary encoders (Yumo, A6B2-CWZ3E-1024, 1024 P/R Quadrature) and custom made zero switches comprised of copper contact and a connecting copper element attached to the cable at the right length. Each agent is suspended via four straight center stainless steel cables which are encased in a helically wound nylon/polyurethane sleeve (Stock Drive Products/Sterling Instruments, Synchromesh, 1.6mm outer diam.). Each custom-built extrusion head assembly is composed of a stepper motor with a rubber seal and a custom extrusion screw. Lead weights are applied for stabilization of the extruder head; cable fixtures are attached to four incoming cables with machined plastic housing and a material supply inlet Figure 29. The material feed for each head is composed of a pressure pot containing paste-like material fed to the extrusion heads by narrowing the flexible tubing diameter towards the extrusion head Figure 29.

Virtual System Details

The distributed system is implemented in a Java language customized applet enabling real-time 3D representation of the agents’ behavior. There are two sets of functionalities in the applet relating to two modes, the setup mode and the building mode. The setup mode takes as input data each agent’s envelope dimensions and base. The envelope dimensions of each agent are measured in 3D physical space, where the top corners of each envelope are placed parallel to the construction base plane. The agent’s base is an origin point measured in space where the “robot
"builder" is at rest. With this information at hand the system is able to determine initial cable lengths and to reset motor encoders as a starting point for subsequent construction behavior. Figure 31 shows the setup interface where initial data is read from motor encoders, and then used to position extruder head as well as to test the extrusion stepper motors.

The building mode function calculates the trajectories and temporal positions of each agent employing linear trajectories and constant velocity. The model uses a 3D modification of the Bresenham algorithm [68] to move and track the agents in space via shortening or lengthening one of the four cables that are assigned per agent. The system computes discrete close approximations to linear trajectories from any 3D origin to any 3D target in the agent's envelope. Trajectory corrections are applied to avoid collision although agent envelopes may overlap, allowing for co-construction in specific and designated areas.

![Design Control Diagram](image)

Figure 29: Flowchart and applet setup mode interface capture of the virtual implementation of a large-scale distributed cable-suspended additive construction platform.
Interesting design opportunities emerge when more than a single material deposition node shares a construction space. The implications of robotic collaboration are vast and must relate to challenges such as agent awareness to boundary condition, envelope sharing across agents, real time multi-agent 3D positioning protocols, means for collision avoidance, and distributed preservation of the mechanical cable-suspended system as well as the material deposition feed.

**4.2.4 Behavioral Model Rules and Adaptation**
Main Rule Sets

The main computational rule set encodes five key system functions. Those include three centralized operations - avoidance, storing and linking, and two decentralized operations - search and deposition. The avoidance function (1) keeps track of each robot’s position in space in order to avoid cable hyperextension when agent navigation occurs outside the determined envelope. It also supports collision avoidance either by pausing one of the agents or by modifying its trajectory. The storing function (2) saves the position and deposition time of each drop of matter placed onto the structure. The linking function (3) ties the emergent structure with design intent rules such that the designer can steer the robots towards building in certain areas and avoiding others. This is achieved by operating the virtual tool through a representation of the physical structure as it is being collaboratively built Figure 31. Included in the decentralized operations, is the search function (4) designed to enable the agents to explore their envelope spaces and determine an adequate deposition location. During search mode, the robots navigate in 3D by employing bouncing trajectories from their maximum envelope until a z-axis threshold is trespassed; then, the agents verify the possibility of depositing material with the central system. Given a 3D position for additional material - if the relative height of the neighboring structure and the curing time of the underlying drops are adequate - a new drop will be deposited. During the construction phase, the z-axis threshold is modified in order to adapt to the current height of the construction. Finally, the depositing function (5) consists simply of depositing a material droplet in a specific position as well as relaying time and coordinates to the central system.

Adaptation to Material Conditions

Material deposition is informed by data embedded in the material itself. Each time a droplet of matter is deposited by a cable-robot agent in the physical environment, the virtual central system stores its data in a clock-based counter. The next agent attempting to deposit a new droplet on top of the stored one, receives information about the structural properties of the existing construct based on expected curing times. If the curing time is adequate, the agent will deposit a new droplet on top of the structure. Else the agent will enter search mode and determine an alternative spot to deposit the stored material. Preliminary results demonstrate small-scale proof-of-concept of structural organization of droplets and proper discrete material bonding. Figure 32(top) shows first construction results of a layer of ¼ inch diameter droplets by one of the cable-robot extruders performing rule-based search motion in between depositions. Different droplet-based typology configurations were tested by manually directing an extruder to pre-set positions namely; 4-faced vault, nave, discontinuous wall, and cantilevered continuous wall Figure 32 (bottom). The material system used is industrial soft putty filler paste composed of gypsum plaster from hydrated calcium sulphate and
glue. The virtual and physical systems are currently ready for the implementation of real-time feedback using humidity sensors or thermal cameras reporting to the central program.

Figure 31: Virtual simulation of a cable-suspended construction system. Robot envelopes are differently shaped and overlap with each other in order to collaboratively build a structure that is bigger than each individual machine's gantry.

**Adaptation to Design Intent**

The construction strategy presented here complies with global electro-mechanical constraints in a rule-based system for the generation of form, while maintaining an adaptation strategy for direct remote intervention. The designer sets up the system to build a structural typology (e.g. a dome, an arch, a column array etc.), and lets the behavioral model initiate its construction in a bottom-up manner. The cable-robots negotiate the construction space without top-down specifications for which agent will build what section of the structure. However, in case of local structural instability or in case of design iteration during the building sequence, the designer can steer the agents toward abandoning an area or focus on completing
another. This technique enables the emergence of form through robotic node-to-node communication by applying space negotiation rules for each drop deposition. Exploration of this feature is not possible with continuous layering of material employed in traditional 3D-printing extrusion technologies, such as fused deposition modelling (FDM).

Figure 32: Top: Initial results of robotic deposition of layered droplets performed by one cable-robot extruder. Bottom: Preliminary manual experiments in soft plaster deposition including a 4-faced vault, a nave, a discontinuous wall, and a cantilevered continuous wall.

4.2.5 Relevance of the Research

A partly centralized partly decentralized digital fabrication environment of cable-suspended robots was designed and built. This environment demonstrates the first steps towards the design and construction of a novel fabrication technology made up of multiple digital fabrication nodes that is designed to support cooperative construction of large-scale structures.

The research explores themes of asynchronous motion, multi-nodal digital fabrication, lightweight additive manufacturing and the emergence of form through fabrication. Importantly, the project points towards workflows directly informed through fabrication, material and environmental constraints. Although the mechanical hardware requires further development in order to achieve a fully functional large-scale
implementation, the computational workflow shows promising results in simulation. Indeed, the successful deployment of a small-scale prototype embodies the benefits of combining a top-down centralized approach to fabrication with a bottom-up decentralized approach. Small size proof-of-concept fabrication was achieved using the described computational workflow and hardware, demonstrating that such an approach and system are feasible.

Specifically, improvements to the mechanical system such as higher zero-switch reliability to avoid strain on the hardware at failure must be implemented. In terms of dynamic control, the choice of a 1.6mm outer diam. Synchromesh cable proved to be challenging in terms of precision and overall dynamic strength. In terms of material supply, continuous feed via a pressure pot could be replaced by a cartridge approach, potentially providing a more stable print head without any physical constraints or interference from the material feed.

4.2.6 FIM Aspects in Bots of Babel

Unlike the previous case study in Biomimetic Skins where a sophisticated virtual model was able to integrate diverse disciplines and scales within geometric-based shape-deriving algorithms, this workflow emphasizes intelligence in the physical realm. There is constant feedback in place between digital fabrication and modeling. The MODEL sets behavior rules and building targets for bots to move and deposit material in space. INFORMATION is fed back relating to each bot’s position, potential collisions are computed, and material curing times are stored. FABRICATION is executed unprescribed, and emerges from collaboration.
MODELING in Bots of Babel

The model sets a computational ‘seed’ that then dynamically evolves based on physical feedback. Structural design constraints, mechanical hardware parameters and material properties come into play to set the rules for autonomous digital fabrication. For a given 3D space, navigation in any direction produces motor motion instructions for the suspended cable system. Material specifications, such as compression strength, viscosity and hydration, inform potential shape targets. Importantly, time-scales take relevance during the very design of shapes, as the model must calculate trajectories and account for time delays in the curing of matter before next deposition is achieved (Figure 33).

Figure 33: MODELING in Bots of Babel.
**INFORMATION Loops in Bots of Babel**

In future implementations, sensor-based feedback can play a key role in the design and development of the agents' rule-based behavior. By means of 3D scanning and thermal imaging, structural stability and material behavior can be monitored and fed back into the model via parameters of: (a) temperature for material curing prediction, (b) 3D geometry for integrity correction, and (c) humidity for crack avoidance. Such real-time comparisons - of virtual and physical built volumes and materiality factors -, can contribute to closing the gap in physical-to-virtual design workflows (Figure 34).

![Diagram of INFORMATION Loops in Bots of Babel]

*Figure 34: INFORMATION Loops in Bots of Babel.*
The fabrication system is intelligent in; (a) being aware of each agent’s position and travel speed via built-in encoders within the mechanical implementation, and (b) anticipating curing times through the time-based storage of extrusion instances. This allows for the information flow to rapidly compute and correct multi-agent space negotiation as well as material deposition steps via the rule-based virtual model. However, higher degrees of intelligence would come into place by improving the range and capacity of feedback devices and correction routines as explained in the previous section (Figure 35).

Figure 35: FABRICATION in Bots of Babel.
**FIM Outlook in Bots of Babel**

The work logic opens up new and exciting opportunities for innovative long-distance fabrication environments where the designer provides input from afar. Also, systems such as the one outlined here can be deployed for large-scale construction by attaching a distributed digital fabrication system to existing objects in the built environment. Cables from each robot can be connected to stable high points, such as large trees or buildings. The arrangement can enable movement over large distances without the need for conventional linear guides. A cable suspended system is straightforward to set up for mobile projects and affords sufficient printing resolution and build volumes (Figure 36).

![Diagram of FIM Outlook in Bots of Babel](image)

*Figure 36: FIM Outlook in Bots of Babel.*
4.3 Silk Pavilion Research: On Templating Dynamics

4.3.1 Research Summary

This research is driven by an exploration on digitally-templated biological fabrication. This relates to patterning a digitally-manufactured thread scaffold for further biological spinning of a tensile dome structure made by silkworms. The system blends organism physiology parameters, environmental datasets, and machinery limitations within the pre-structure and throughout co-fabrication.

A Silk Pavilion dome is comprised of 26 silk-threaded polygonal panels laid down by a Computerized Numerical Control machine. Inspired by the silkworm’s ability to generate a 3D cocoon out of a single multi-property silk filament, the Pavilion’s overall geometry was created using an algorithm that assigns a single continuous thread across patches, providing functional density gradients informed by environmental constraints such as light and heat. Overall density variation was informed by deploying the Bombyx mori silkworm as a biological multi-axis multi-material 3D ‘printer’ in the creation of a secondary fiber structure. 6500 silkworms were positioned on the scaffold spinning flat non-woven silk patches to locally reinforce the CNC-deposited silk structure. As stated above, the design model deals with 3 sets of constraints: (1) physiological parameters related to the silkworm motion and spinning behavior, (2) environmental parameters related to heat and light onto the structure as templating strategies to distribute silkworms, and (3) machine gantry size and machine instruction constraints to segmentally weave a large fiber dome. The future of this work points towards, not only passively influencing the complex dynamics of biological construction, but also to futures for co-fabricating structures through actively steering organisms based on design needs by implementing feedback systems on-the-fly.

4.3.2 A Context for Templating Dynamics

**Form-generation and Optimization in Nature**

Biological systems can be characterized as entities that “compute” material organization according to external performance criteria. Bone tissue, for instance, alters between states of compact tissue and spongy tissue as a function of the applied structural load and the requirement for blood circulation [69]. Similarly, spider silk alters its mechanical properties as a function of its use: spiral silk is used for capturing prey while cocoon silk is used for protective egg sacs [70]. The range of variation in material distribution and physical properties is typically defined by the extreme set of external conditions acting as the “environment”. The system’s overall form and mechanical properties are derived from processes of shape and material optimization respectively, maximizing compatibility between the system’s innate material properties, its external environment and its desired performance criteria. As a result, natural systems typically exhibit high levels of integration between shape, structure and material making Nature’s designs highly efficient and effective forms of “computation” [71].

**Form-generation and Optimization in Digital Design**

Unlike the biological world in which there exist high levels of integration between shape and material distribution [72], digital design protocols are typically divided into processes of form generation and processes of performance-based optimization, the former being a precondition for the latter. Finite element methods for example, implemented in order to optimize shape, material properties and distribution, are applied only after the form has been generated. Another distinction between biological and digital optimization is the ability in the Natural world to produce combinations of property and morphological variation of isotropic structures [72]. In digital design, optimization processes are typically divorced from material organization since most fabrication materials are anisotropic in property [73]. Given the advantages of biological shape-generation and optimization protocols, this work asks the question of; can processes of biological optimization be used to inform and compute desired structural and environmental performance of man-made structures? [71].

Given almost any 3D entity, a broad suite of techniques in computational design exists that supports form-generation and optimization processes within parametric environments [74]. Examples of such techniques include particle systems, multi-agent systems, network analysis, and finite element methods [75]. Replacing such computational processes with biological ones allows informing shape-generation processes as well as spatial material organizations within a single (biological) system [71].
Biological Computation for Digital Design and Fabrication

Numerous forms in Nature achieve their shape and structure through local optima processes, as material organization and composition are informed by structural and environmental stimuli [76], [77]. Consider the optimal shape of tree branches or animal tissue morphology. These shapes and their material composition express an effective use of information as well as an efficient thermodynamic operation for an environment-inter-acting system. These processes can be used both as models by which to explain and predict other natural processes but also as computations in their own right [76]–[78]. Research into the use of biological processes as forms of computation the can inform design generation are found for example in the use of slime molds in order to model real-world infrastructural networks [79]. Here problems are described as instances of the distributed growth dynamics of the slime mold resulting in the encoding of a general linear programming (LP) language. Results prove that the model converges to the optimal solutions of the LP (Ibid.). Captured in a biologically inspired mathematical computation, this research can potentially guide network construction in other domains.

4.3.3 Experiments Towards an Architecture

Basic research experiments informed processes of modeling, analysis and fabrication. The work considers biological forms of computation for digital design modeling, analysis and fabrication. Specifically, the formation of non-woven fiber structures generated by the *Bombyx mori* silkworm as a computational schema for determining shape and material optimization of fiber-based surface structures [80]. This biological form of “computation” can potentially exclude the need for Finite Element methods [71].

Fiber-Based Structures

Fiber-based structures are ubiquitous in both architectural and biological systems. Robust structural performance involves the balancing of force-and- response in order to achieve material morphologies that are structurally efficient and environmentally effective [73]. Typically, this process involves a step-wise process including computational modeling, finite-element analysis and digital fabrication. Biological fiber-based structures such as the silkworm’s cocoon however may provide for the unification of these three media through the use of the silkworm’s path as an optimization “toolpath” and a fabrication “technology”.

The guiding assumption here is that the silkworm’s ability to generate fiber structures with varying degrees of density based on its environment has been perfected through evolutionary pressure. It is also assumed that the cocoon is an optimal structure which itself is based on the idea that optimization-seeking processes
are omnipresent in Nature. Having been developed without top-down control this case may represent a
scalable approach for fiber-based structural design based on optimization. The goal was to determine
whether these structures are likely to yield reasonably efficient solutions to combinatorial optimization
challenges such as load informed fiber-density distribution in membrane structure [71].

Figure 37: (top) A Bombyx mori silkworm completing the deposition of approximately 1km of flat-spun silk. The
research confirms that given the absence of a vertical axis the silkworm will spin a flat silk patch. (middle) Comparison
of two 1-dice configurations with a 3mm and a 21mm vertical axis illustrating the difference between flat spinning
(sufficiently short vertical axis) and a cocoon spinning (sufficiently long vertical axis). (bottom) Series of one-dice
platforms ranging in vertical axis height from 3mm to 27mm each with 3mm increments.
Setting up a Matrix of Spaces

The experimental set-up consisted of a series of surface patches measuring 80x80mm in surface area with varying sectional configurations. A live silkworm was positioned on top of the surface and left to spin, with the hypothesis that spinning configurations and fiber density distribution would vary according to the morphological features of the “hosting environment” [71].

4.3.4 Fiber-Density Variation in Flat-spun Silk

The first experiment consisted of a flat surface patch with no additional surface features. The silkworm appeared to have spun a flat silk patch instead of the anticipated 3-D cocoon structure. This was due to the lack of a physical vertical pole/axis against which the silkworm would otherwise construct its cocoon. The experiment confirmed that the *Bombyx mori* silkworm would spin silk as a flat patch in the absence of vertical surface features (Figure 37) [80] [71].

The Dice Series

Following, a central vertical axis of varying heights was introduced to determine (1) at which height point would the 3D cocoon structure emerge, and (2) how might fiber distribution be affected by the relative location of the vertical axis and its height. A family of tent-like structures consisting of a rectangular surface patch with a single vertical axis (“1-dice section” per Figure 37) was set up [71]. Varying axes heights of 3mm, 6mm, 9mm, 12mm, 15mm, 18mm, 21mm, 24mm, and 27mm were implemented (Figure 37). The experiments demonstrated the following: (1) a 3D cocoon structure emerged only at a sectional height of 21mm height below which a tent-like structure in the form of a rectangular pyramid was spun. Given the dimensions of the natural cocoon it was assumed that a minimum height of ~21mm accounting for the longitudinal axis of the cocoon must be provided in order for a 3D structure to emerge. In the absence of this height, a non-enclosed surface patch will be spun; (2) fiber density typically varied as a function of the distance from the central vertical pole to the surface boundary. This may point to a local optima condition requiring the least amount of energy for the construction of a strong stable structure within a given timeframe (Figure 38); (3) boundary contours were typically denser. It was assumed that this is due to the silkworm’s constant search for a vertical pole tall enough to allow for cocoon construction [71].

Additional experiments followed exploring in-depth relations between topographical surface features and fiber density. These include the Rectangular FEM-Dice Series, the Pentagonal FEM-Dice Series, the Thrust Vault Series, and the Maltese-cross series. Their descriptions are given below.
Figure 38: (top) 18mm one-dice platforms illustrating higher density deposition along the shortest distances from the geometrical center to the surface boundary contour. (bottom) Series of (15) rectangular FEM-dice platforms ranging from 10mm to 15mm in pole heights.

The Rectangular FEM-Dice Series

The series included a set of 15 flat 80x80mm surface patches in different dice-face configurations. Poles of 10-15mm height were used to define the planar configuration and the sectional height of the patch (Figure 39). A live silkworm was then positioned in each patch to spin a typical 1km long filament. The assumption was that the variation in fiber density and organization would reflect the morphological constrains given by the “environment” (i.e. the surface patch). FEM representations were computed as hypothetical static-force studies for anticipated fiber variation in a membrane tent-like structure accommodating the environment given by the patch. Linear Elastic Isotropic 101 Nylon with an elastic modulus of 1000000000 N/M^2 was used to represent the membrane material. The results of the study confirm general correlation between anticipated Stress-Strain calculations (computed using the SolidWroks environment) and the resulting fiber-structure as spun by Bombyx mori silkworm Figure 39 [71].
The Polygonal FEM-Dice Series

This series is analogous to the previous one (FEM-Dice Series) containing four models based on a polygonal patch as the base environment. The results of the study confirm general correlation between anticipated Stress-Strain calculations (using the SolidWorks environment) and the resulting fiber-structure as spun by *Bombyx mori* silkworm [71].

![Figure 39: 4-Dice face configurations. Left to Right: Digital representation of anticipated stress for membrane structure based on 4 poles calculated within SolidWorks; physical model with digital representation as base. The silkworm is shown to the right; physical model juxtaposed with silk fiber by the Bombyx mori silkworm. Denser fibers appear between poles along boundaries as anticipated by the FEM model.](image)

The Thrust Vault Series

Unlike the two previous series, the Thrust Vault Series is comprised of non-flat 80x80mm patches varying in topographical features. Sectional height varies across 5mm and 20mm with 5mm increments; each model is repeated twice to validate the consistency of the resulting morphology. Color annotations represent variation in curvature with the color green typically representing anticlastic curvature and blue representing synclastic curvature (Figure 40) [71]. The assumption was that the variation in fiber density and organization would reflect the morphological constraints given by the environment. Indeed, results confirm this correlation below 20mm height (above this height the 3D cocoon appeared): a typical model demonstrates increased fiber density along the boundaries. In addition, a circular patch appears at the center.
of the patch marking the silkworm’s attempt to form a 3D cocoon between the two planes that make up the section (Figure 40) [71].

Figure 40: (top) Series of three-dimensional thrust vault spinning platforms. (middle) 20mm tall thrust vault spinning platform demonstrating the silkworm’s spinning behavior. (bottom) Series of three-dimensional Maltese-cross spinning platforms.

**The Maltese-cross Series**

The final series introduces variations in both plan and sectional configurations. The plan configuration in this series is no longer constraint to a completely flat rectangular, polygonal or circular surface patch but
rather it is oriented in a Maltese-cross configuration. The variation in section height introduces spatial ‘gaps’ to the silkworm’s movement as it spins silk in circular motion. Sectional height varies between 5mm and 20mm with 5mm increments; each model is repeated twice to validate the consistency of the resulting morphology. Color annotations represent variation in curvature with the color green typically representing anticlastic curvature and blue representing synclastic curvature (Figure 40). As anticipated, the results reflect the correlation between fiber density and surface features demonstrating a combination between the flat-dice-series and the thrust-vault series [71].

**The Relevance of Bio-Computation**

The silkworm *Bombyx mori* forms fibrous silk networks on flat patches. Fiber density distribution appears to be sufficiently similar to the anticipated fiber density variation that was computationally generated for a prescribed membrane structure of the same mass and surface area. It can be concluded that the *Bombyx mori* silkworm itself may be used as a biological “tool” with which to “compute” fiber distribution within small-scale 1:1 structures, or as scaled representations of larger architectural structures constructed with fibrous materials [71].

The core mechanisms required for fibrous network formation could be further captured within a biologically inspired mathematical model that may be useful for anticipating fiber density and organizational variation in fibrous membrane structures exposed to well defined local loading conditions [71].

By collecting qualitative and quantitative data from live silkworms spinning on top of pre-fabricated flat patches a correlation between the nature of material distribution and the geometrical characteristics of the patch was successfully predicted. These results, have significant implications for structural analysis protocols of fiber-based systems. Additionally, this work may also carry implications for biologically inspired digital design and fabrication. Here, the relationship between the global, top-down design of a constricting “environment” designed artificially by the designer informs its local, bottom-up material manifestation as portrayed by the biological organism (the silkworm). Finally, the *Bombyx mori* silkworm may be considered as an autonomous agent in processes of design optimization. As this initial research has shown, this project opens up new possibilities for the use of biological processes as forms of computation.

**4.3.5 The Silk Pavilion**

Inspired by optimization processes in Nature, the Silk Pavilion is an architectural structure fabricated by digital technologies combined with the deployment of live silkworms. It explores the relationship between digital and biological fabrication on architectural scales. The primary structure is created of 26 polygonal panels made of silk threads laid down by a CNC (Computer- Numerically Controlled) machine. Inspired
by the silkworm's ability to generate a 3D cocoon out of a single multi-property silk thread (1 km in length),
the overall geometry of the pavilion is created using an algorithm that assigns a single continuous thread
across patches providing various degrees of density. Overall density variation is informed by the silkworm
itself deployed as a biological "printer" in the creation of the secondary structure. A swarm of 6500
silkworms were positioned at the bottom rim of the scaffold spinning flat non-woven silk patches as they
fill the gaps across the CNC deposited silk fibers. Following their pupation stage, the silkworms are
removed. Resulting moths can produce 1.5 million eggs with the potential of constructing up to 250
additional pavilions (Figure 41) [71].

Affected by spatial and environmental conditions such as geometrical density and variation in natural light
and heat the silkworms were found to migrate to denser and darker areas. Desired light effects informed
variations in material organization across the surface area of the structure. A season-specific sun path
diagram mapping solar trajectories in the space dictated the location, size and density of apertures within
the structure in order to lock in rays of natural light entering the pavilion from South and East elevations.
The central oculus is located against the East elevation and may be used as a sun-clock [71].
**Fiber-based Construction**

Digital fabrication processes such as layered manufacturing typically involve the layered deposition of materials with constant and homogeneous physical properties. Yet most natural and biological materials are made of fibrous structures locally aligned and spatially organized to optimize structural and environmental performance [71], [72], [81], [82]. Within the fields of product and architectural design – specifically the automotive and avionic industries - fiber-based digital fabrication has typically been confined to the development and application of high-performance composites [13]. These materials and their related processes are typically toxic and harmful to the environment [36].

Construction processes found in Nature such as woven spider nets or aggregate bird’s nests are characterized by the animal’s ability to generate, distribute, orient, densify and assemble fiber-based composite materials. Spiders for example can generate fibers with varying properties based on a particular need or function. These fibers are optimized for a wide range of different conditions including but not limited to mechanical properties such as strength and toughness [83]. In addition to many existing types of silks, the silk itself may be rapidly adapted to different parameters during the silk spinning process. The final webs consider a delicate balance of function, environmental conditions and material efficiency as limited by the energy resources of the spider. Similarly, the silkworm can control the ratios of fibers and matrix to generate a wide array of mechanical properties ranging across tensile and compressive structures [84], [85], [36].

**Basic Research into Fiber-based Cocoon Construction of Silkworms**

**Anatomy, Behaviors & Methods**

The Bombyx mori silkworm is an arthropod with a body of approximately two to three inches in length. A break in the legs around the mid portion of the body allows the worm to bend freely from side to side in its typical figure-eight motion. The silkworm’s spinneret is located near its head allowing the organism to extrude upwards of one-kilometer raw silk fiber. It traditionally spins silk in its fifth instar after one to two months of feeding on mulberry leaves as it matures into a silk-producing caterpillar. When prepared to spin, the silkworm typically triangulates a three-dimensional space or corner forming a tensile structure within which forms the cocoon [83]. Silk production typically involves the harvesting and soaking of completed cocoons in a soapy water bath. The edge of an individual fiber is then pulled out of the bath and spun onto a spool for silk thread production. This production method requires the spinning of a full cocoon and a shortened life cycle for the silkworm eliminating the opportunity for reproduction [86].
Advanced Imaging Techniques and Quantitative Analysis of Silk Cocoons

Basic research was conducted to further observe, understand and predict the motion and material deposition behavior of the silkworm implementing the following tools, techniques and technologies:

1. Dynamic tracking was achieved by the application of magnetometer motion sensing to motion-capture a silkworm over the course of a 3-day cocoon construction period during which time the silkworm was tracked by attaching a miniature magnet to its head. The organism was placed within a boxed space fitted with three magnetometers capturing the worm’s movement in 3-D space. Data collected was converted into a visual representation of a point cloud (Figure 42).

2. Wide-angle high resolution MicroCT and SEM imaging techniques were developed and implemented to analyze the organizational properties of silk textures across various length-scales and species (Figure 43). SEM imaging techniques enabled micro scale analysis of material property variation across the transversal and longitudinal sections of the cocoon.

3. (As explained in the previous sections, with templated fiber-spinning experiments it was observed that when spinning on a relatively flat environment the silkworm will generate a flat non-woven silk patch [71]) Building on this observation, coupled with previous research, a suite of environments with varying morphological features was developed in order to explore the relation between surface features and fiber organization.

Experimental results determined the following: (1) a 3D cocoon structure emerged only at a sectional height of 21mm height below which a tent-like structure in the form of a rectangular pyramid was spun. In the absence of this height, a non-enclosed surface patch was spun; (2) fiber density typically varied as a function of the distance from the central vertical pole to surface boundary. This may point to a local optima condition.
requiring the least amount of energy for the construction of a strong stable structure within a given timeframe; (3) boundary contours were typically denser. This can be due to the silkworm’s constant search for a vertical pole tall enough to allow for cocoon construction [36].

Figure 43: Biological analysis (L to R): 2300x mag. polychromatic micrograph of Bombyx mori silk scaffold cocoon; 25x mag. overview micrograph of a Bombyx mori cocoon; 300x mag. polychromatic micrograph of the external surface of a Bombyx mori cocoon color coded to reflect surface typography; 40x mag. isometric view micrograph of an equatorially bisected Bombyx mori cocoon; 2500x mag. Polychromatic micrograph of the external surface of a Bombyx mori cocoon; 230x mag. plan view micrograph of an equatorially bisected Bombyx mori cocoon. Scanning electron micrographs in collaboration with James Weaver, Wyss Institute, Harvard University.

**Computation and Digital Fabrication**

**Computation**

The pavilion was designed and constructed in two phases: the first phase consisted of digitally fabricating a scaffolding envelope made of silk fibers and the second phase consisted of deploying a swarm of silkworms that spin a secondary silk envelope. A set of apertures built into the initial envelope capture light and heat thus controlling the distribution of silkworms on the structure.

Overcoming current limitations of existing computer aided design (CAD) tools; a parametric environment was developed that facilitates the design and fabrication phases of the project enabling continuous iteration
between digital form finding and physical fabrication processes. As such this computational tool also served to mediate between environmental input, material properties and organization as well as biological fabrication constraints. In addition, the tool enabled real-time evaluation of multiple design solutions.

Figure 44: (left) Computational projection of paneled dome - solar mapping. (right) Computational projection of paneled dome - aperture distribution mapping.

Figure 45: (left) Computational generation logic of single aperture. (right) Final computational of global aperture distribution.
The main goal was to develop a holistic computational design environment able to simultaneously capture and process multiple sets of complex constraints in real-time. Most of these constraints are difficult or impossible to capture using current CAD tools. Amongst them is the ability to automatically determine for every digitally woven silk fiber what is the conformal distance or space within which the silkworm can spin, enabling the convergence between the digitally laid fibers and the biologically spun filaments.

A subsequent goal was to computationally embody the geometrical complexity and scalability of the Pavilion, as well as the scaffolding resolution and the range of fabrication tools implemented. The tool developed informs the designer about overall material organization as well as the effects of the biological parameters (such as silkworm motion range) on the final design.

![Figure 46](image)

*Figure 46: (left) Computational silkworm spinning range calculation. (right) Computational unfolded panel and tool path diagram.*

The generative environment includes a new library designed on top of the RhinoCommon build that runs on the Grasshopper plug-in (within McNeel Rhinoceros 3d Modeler). The library is comprised of a set of routines that enable the shaping of a lightweight fibrous environment. The following data sets informed the algorithm for scaffolding thread geometry: the first set is comprised of the fabrication constraints captured by the algorithm. These constraints are informed by the robotic manufacturing platform along with its prescribed gantry size and tool reach. This set generated the need for spherical structure of the pavilion to be subdivided into a set of sub-structural patches. The patches conformed a truncated icosahedron whose faces fit the robotic manufacturing bed. The second set of constraints originated in two data maps; the first encoded the specific on-site solar trajectory and the second provided an opening radius multiplier to generate organizational fiber variation. Combined, these two maps informed the position and size of the pavilion apertures (Figure 44). The third set of constraints is linked to the silkworm's biological characteristics with the goal of providing maximum silk deposit reach.
For each aperture – the position and size of which is informed by the site’s light conditions - the computational protocol identifies a continuous tangent circle on the spherical geometry (Figure 45). Subsequently it is then converted into tangent line segments represented in 2D matching the patch fabrication representation. For each such circle a parameter was assigned controlling the resolution of the tangents relative to its geometry. This parameter determines the ratio between local fiber gradients to overall fiber distribution and organization. The algorithm then checks for each aperture if it is contained within a prescribed patch, multiple patches or none, and classifies this information as data lists. For each patch containing a full or partial aperture the algorithm computes the following:

- Aperture formation in relation to the overall image of a continuous thread (Figure 45).
- Thread redistribution across apertures providing balance between aperture distribution and continued thread allocation across the surface area of the overall volume.
- Contour attachments for local continuous threads.
- Scaffolding thread spacing conformation to biological parameters of the silkworm weaving pattern (Figure 46).
- Robotic tool path fabrication (Figure 46).
A final overall visualization of the pavilion, aluminum frame profiles for water jet manufacturing of the patches (visualized as the polygonal line segments), and unfolded of tool paths for CNC weaving are then generated as output (Figure 47) [36].

**Digital Fabrication**

Based on the analytical protocols developed and reviewed above a digital fabrication approach was developed that supported the findings with regards to the worm’s possible range of motion and deposition behavior enabling the merging between digital fabrication tools and biological construction. Initial tool path development was tested with a three-axis CNC (Computer Numerically Controlled) machine. Initial computational paths were explored and implemented as traditional milling tool-paths without using the machine’s spindle activation. These tests were originally developed as a drawing method prior to the development of the thread deposition tool (Figure 48).

Continued development of the CNC tool path output (from the digital model to the machine) enabled the development of a basic tool that allowed for the deposition of thread as a spool or roll based material. The gantry of the three-axis machine carried the rolls to be replaced as required based upon the panel to be fabricated. A tool tip was developed that could be affixed into the normal collet design of the cutting head; the spindle would remain off and in a locked position. The spooled material could then be fed down through the tool tip inside a low friction HDPE tube. The tube ends in a custom-made press fit bearing attached to a rotating shaft with a spring-loaded foot where the string could exit smoothly and in accordance with the direction of machine travel. The deposition of a lightweight material on to a temporary aluminum frame allowed the machine to run at higher velocities than normal cutting operations aiding the speed of the fabrication process.

![Figure 48: (left) Spring steel CNC threading tool and silk thread. (middle) 3-axis CNC machine adapted as CNC deposition tool. Custom threading tool, temporary aluminum scaffolding and MDF jig. (right) Vertex connections of non-woven silk patches on temporary aluminum scaffolding structure.](image)

The perimeter of the unfolded 2D dimensional panels making up the overall form of the structure was designed as perimeter scaffolding structures. They were water jet cut from aluminum in order to maintain
the deposited silk fibers during the fabrication process. The choice of a component-based assembly was
dictated by the relatively large size of the overall structure and the limitations given by the gantry size of
the CNC spinning tool. Designed as temporary support these panels could be reassembled after weaving to
maintain the overall geometry of the system while installing it into a tensioned state within the atrium space
(Figure 48).
The frames were developed with small hook elements to allow for the laying down of fiber. A release
mechanism enabled the extraction of the frames once the panels were joined together and the structure was
positioned in space. Between joining edges of each frame was a small rubber coated frame of music wire
to which the vertex nodes of the structure were affixed. The vertex nodes would be used in attaching the
tensile structure to its surrounding environment and the piano wire was the medium around which the edge
of each panel was affixed (Figure 48).
Once the truncated icosahedron panels were assembled and knotted edge to edge, the overall structure was
raised to its proper height and location. Following, a series of tension lines were deployed. Each of the lines
was affixed to a custom designed acrylic clip; each point location was calculated as part of the digital model
of the vertex normal intersection within the space. Tension cable lengths were measured, located and
labeled. Once the structure was in place the entire vertex and centroid tension lines were installed and
tensioned to their marked lengths suspending the metal frame and the structure in space. At this point the
frames were removed starting from the top of the structure and working down in circular fashion. Following
the removal of the frame some tension was lost that was recovered after the centroid suspension lines were
tensioned. The bottom of the structure was affixed to a 1” thick MDF floor structure with a white vinyl
covering [36].

**Biological Fabrication**
Parallel to the digital fabrication of the primary structure 6,500 silkworms were raised through the
remainder of their fifth instar feeding on a diet of mulberry leaves prior to the silk spinning phase (Figure
49). Reared in a light-, and temperature-controlled room at the MIT Media Lab the silkworms were fed and
monitored over the course of several weeks. As the worms began spinning they were transferred onto the
tensioned silk structure with a protective fence and drop cloth in place.
Over a ten-day period, all silkworms were positioned on the scaffolding structure, typically initiating
spinning from the bottom rim upwards (Figure 49).
Most silkworms were found to settle into a single space over the surface area of the structure spinning flat
patches in circular motion. In addition, most silkworms were found to migrate to the highest surface patch
of the structure possibly due to a combination of high temperature, low lighting conditions and decreased
metabolic cost that is the result of horizontal movement (Figure 49).
Following 2-3 spinning days the silkworms were released from the structure and collected on a drop cloth at the bottom of the dome. The silkworms were able to continue their cycle of metamorphosis into a silk-moth including egg laying and reproduction [36].

**Figure 49:** (left) Approximately 1000 *Bombyx mori* silkworms upon arrival within their 5th instar. (middle) View through pavilion apertures as the silkworms skin the structure. (right) Top view of the Silk Pavilion as approximately 1,500 silkworms construct the fibrous composite.

**Figure 50:** Side by side comparison of the completed scaffolding (left) and the final silk composite structure after spinning (right).

**Potential for Re-Applications**

The Silk Pavilion explores the duality of digitally and biologically fabricated structures by proposing a templated construction approach to Fiber-based Digital Fabrication (Figure 50). In this approach digital tools are implemented to deliver a highly differentiated scaffold on top of which a biological system is deployed. The two systems are complimentary: while one provides for the load bearing paths of the structure the other strengthens these trajectories and acts as skin. Moreover, the biologically deposited silk embodies qualities associated with its scale that could not have been achieved using current digital fabrication tools. The silkworm-spun nonwoven fibroin adheres to and wraps around the digitally deposited silk fibers and provides for a fibrous “infill” due to the interaction between the two chemical agents.
deposited by the silkworm: the fibroin that acts as fiber and the sericin that acts as glue or connective tissue. The templated construction approach can be implemented using other types of digital fabrication tools and biological systems [36]. In this respect, the computational FIM environment developed for this project is a generative one: it can address other similar problems across a range of scales and across an array of fabrication methods, environments and biological systems of choice.

4.3.6 The Relevance of FIM in the Silk Pavilion Research

From a FIM perspective this project is positioned half way between the two previous case studies, Biomimetic Skins and Bots of Babel. As in Biomimetic Skins, the virtual model here is able to effectively include and seamlessly manage parameters coming from diverse disciplines, such as architecture via traditional environmental mapping for buildings, biology by computing the worm’s motion capabilities, and engineering through embedding limitations and constraints from the cnc gantry fabrication process. It also implements a templated autonomous fabrication – namely deploying spinning silkworms onto a fiber scaffold - similar to the Bots of Babel’s rule-based bottom-up distribution of matter.
MODELING in the Silk Pavilion

This work embodies a hybrid machine-organism FIM workflow where the physical outcome does not result from a virtual model setup, but from biological computation instead. The model computes and templates a scaffold for the silkworm’s dynamic fabrication. It integrates the disciplines of architecture, mechanical engineering, biology, and environmental design, fusing; worm body size and its spin behavior, design constraints of sunlight and shading, and the flow of heat for steering deposition density. It also includes machine gantry size constraints to ensure fabricability of a dome bigger than the machine that makes it. It is interesting to note that here the scales of design are extended; the model must compute worm-scale physiology as well as a human-scale comfort within a construct (Figure 51).
**INFORMATION Dynamics in the Silk Pavilion**

Information in the silk pavilion is passed from a constraint-heavy model onto a digital weaving platform that executes a weave toolpath in 26 panels composing a dome scaffold. Then, biological fabrication begins based on the embedded "instructions" in every thread. Distance between threads, size of apertures, light and heat incidence, flatness coefficient, and gravity, **passively template** silkworm's fibrous construction.

In order to actively influence, monitor, and correct deposition, real-time feedback control could be implemented (here in gray) through cameras to track worm distribution, sensors to assess tensile strength being achieved, and actuators to steer organisms towards hotter areas to re-distribute spinning density. With this, the system would point towards effective biological-technological fabrication coexistence. This co-fabrication could even occur simultaneously, for robotic weaving and biological spinning to inform each other over time (Figure 52).

![Figure 52: INFORMATION Dynamics in the Silk Pavilion.](image-url)
FABRICATION in the Silk Pavilion

A CNC-weaver and thousands of silkworms made the Silk Pavilion passively influencing one another. If full feedback was implemented, the fabrication-side intelligence would be superior to the model's, and move away from traditional obeisance of file-to-fabrication platforms. A tension sensor would assess and compare tensile strength against a target structural tension. A camera and vision algorithm would count worm distribution onto the structure. Then they would directly inform a steer mechanism, such as heat or light -depending on the organism's sensitivity-, to summon the creatures spatially over the structure. Importantly, this would bypass the need for a model-based re-computation of designs. Spinning, or other bioconstruction types, would be re-localized and monitoring loop would be ready to start over (Figure 53).
**FIM Outlook for the Silk Pavilion**

Further research could explore aforementioned and other techniques for templating biological fabrication in order to generate highly controlled and tunable functional gradients of material properties. New types of high-performance textile composites may be designed in this way - not unlike the composites observed on the pavilion - which combine internal and external natural-silk wrapping of the synthetic threads. In addition, direct silk fiber deposition onto a scaffolding structure not only eliminates the processing of silk cocoons into thread and textile, but also promotes a more sustainable silk harvesting cycle. Finally, with regards to decentralized swarm-like construction processes similar to the ones viewed in Nature, future development into the potential of collaborative construction behavior can be explored [36] (Figure 54).
4.4 Water-Based Digital Fabrication: From Wings to Beams

4.4.1 Research Summary

This research is driven by the possibility to hierarchically control biological materials to produce highly sustainable architectural parts and objects. It invents a Water-Based Digital Fabrication (WBDF) platform to scale-up biomaterial manufacturing and digitally-tune all its parameters. It offers a new perspective on water-based manufacturing to form constructs that utilize graded properties for hydration-guided self-assembly.

Structural hierarchy and material organization in design is traditionally achieved by combining discrete homogeneous parts into functional assemblies where the shape or surface is the determining factor in achieving function. In contrast, biological structures express higher levels of functionality on a finer scale through volumetric cellular constructs that are heterogeneous and complex. Despite recent advancements in additive manufacturing of functionally graded materials, the limitations associated with computational design and digital fabrication of heterogeneous materials and structures frame and limit further progress. Conventional computer-aided design tools typically contain geometric and topologic data of virtual constructs, but lack robust means to integrate material composition properties within virtual models.

Here, a robotically controlled multi-chamber extrusion system is designed to deposit composites with functional, mechanical and optical gradients across length scales. The research derived the Ocean Pavilion, where components are form-found through evaporation patterns informed by the geometrical arrangement of structural members and the hierarchical distribution of material properties. Each component is designed to take shape upon contact with air and dissolve upon contact with water. Results show a wide range of structural behaviors that represent a novel approach to material-informed biodegradable structure formation by design and hold great promise for the future of sustainable manufacturing.

4.4.2 Context in Water-Based Digital Fabrication

**Designing Hierarchy**

Structures found in Nature are known to display heterogeneous hierarchical materials at high strains [69]. Such functional gradients can accommodate multi-functionality through spatial and temporal variation of material organization across length scales [69], [87], [88]. Complex physical behavior is achieved through shape-, and material-based feature and property variation of physical constituents. The advent of new digital fabrication technologies such as additive manufacturing (AM), coupled with the development of computational methods for the generation and evaluation of functionally graded materials (FGM) is contributing to advanced digital fabrication of novel multifunctional structures inspired by their natural counterparts [22], [51], [89]. The design and advanced manufacturing of heterogeneous materials and anisotropic structures spans scales and application domains from geophysical to biomedical [90], resulting in the design and manufacturing of products and systems with increased stiffness, reduced weight, wear resistance and even embedded sensing [90].

Researchers in academic institutions and industry are rapidly developing complex multi-material additive manufacturing (AM) hardware posing software designers technical challenges associated with taking full advantage of hardware capabilities [90], [91]. 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 [92] mostly since such tools typically assume material homogeneity. The field of Heterogeneous Object Modeling (HOM) addresses the growing demands for computational tools that embed material data and enable the design of functionally graded structures.

The **Water-Based Digital Fabrication** (WBDF) platform is a customized and integrated virtual-to-physical computational workflow for the design and direct digital fabrication of multi-scale variable property objects additively manufactured using a wide range of viscous water-based materials. Workflows derived can encode a diverse range of interrelated multi-domain meta-data belonging to various classes of flow linking the computational tool to its digital fabrication output. Flow classes include: the flow of numeric and binary data, the flow of motion, the flow of pressure, the flow of time and the flow of water. The approach is demonstrated by assigning a wide range of material properties and extrusion geometries to basic geometric primitives in order to additively deposit heterogeneous structured constructs.
**Direct Digital Manufacturing (DDM)**

Direct Digital Manufacturing is generally defined as the usage of additive technologies to fabricate end-use components by digital means. DDM enables the generation of 3-D physical objects out of 3-D digital models through the deposition of material in a layer-by-layer fashion, without machining, molding or casting. DDM bridges the gap between rapid prototyping and mass production, enabling the rapid manufacturing of non-standard functional and structural parts [89], [93]. Many considerations and requirements come into play when considering additive manufacturing of structural parts when transitioning from Digital Prototyping to Digital Manufacturing. As with the work presented here, many DDM applications take advantage of the ability of AM technologies to produce parts with geometrically complex customized designs that cannot be mass-produced with traditional manufacturing technologies.

**Graded Materials Additive Manufacturing**

Functionally Graded Materials (FGM) are man-made materials characterized by property variation as well as high levels of anisotropic control [94]. Manufacturing processes of FGMs typically include two stages: the first involves the creation of a spatial heterogeneous structure and the second involves its consolidation [94]. Spatial heterogeneous structures are obtained with constitutive, homogenizing, and segregating methods. The consolidation stage is obtained by drying, by sintering, or via solidification techniques [94]. Recent advances in automation are making both gradation and consolidation processes technologically and economically viable. Within the design fields, property gradation of single materials with multiple functions carries the potential to revolutionize how products and buildings are designed and fabricated [95]. Ultimately, such advances will lead the way towards the design of multi-functional material systems with variable properties reducing the need for complex assembly of multiple parts with homogeneous properties and discrete functionality.

WBDF research is inspired by the biological world where single material systems are known to vary their internal composition in order to accommodate a variety of structural and environmental requirements that are then manifested in different property gradients across the surface area and volume of the manufactured product.

**Heterogeneous Object Modeling (HOM)**

Recent advancements of multi-material additive manufacturing present pressing demands on software designers to generate CAD tools that can take full advantage of novel hardware capabilities. Heterogeneous object modeling (HOM) aims at accommodating multiple objective functions within a single material construct. A heterogeneous construct is defined as an object with spatially varying material
composition, as opposed to objects designed and manufactured out of a single material with constant properties. Relevant work within the field of HOM was previously demonstrated that aims to better represent such constructs [92], [96]. A range of mathematical models exists that achieve heterogeneous object representations. These representations are generally classified under one of three categories: evaluated models, unevaluated models and composite models. Strategies known to encode material distributions in such methods are: (1) discretization of the objects volume into simple parameterizable elements, (2) implement a simple parameterization whose domain does not coincide with the object’s boundaries, or; (3) construct a specific parameterization for the interior and boundary of each object.

The main issues with the virtual representations of material anisotropy are associated with the difficulty in parameterizing the interior of a given boundary representation of a solid model. Since typical 3-D printing software is designed to assign single materials per polygon meshes representing the object, any continuous gradation between multiple materials raises technical challenges. These challenges appear again when material properties and geometrical features are decoupled, and custom material definitions that are not embedded in the system are reused.

A workflow is presented here that associates heterogeneous material properties with simple geometric primitives enabling to compute meta-data instructions that are communicated to the digital fabrication platform. It addresses the design and representation limitations of heterogeneous objects by continuously controlling material organization and variable extrusion geometries through time-dependent flow functions, and by establishing an extendable calibrated material database with deposition-related parameters stored within the software. Continuous control is based on accurate synchronization of a positioning platform (e.g. a robotic arm) and a deposition platform (e.g. a multi-chamber pneumatic extruder attached to the arms end-effector). This synchronization enables controlled flow and speed variation along deposited paths. In addition, it enables sectional height and overall thickness variation of multi-material extruded geometries.

**Integrated Design-to-Fabrication Systems**

File-to-factory design approaches provide the ability to merge Computer-aided Design (CAD), Computer-aided Engineering (CAE) and Computer-aided Manufacturing (CAM) into a single seamless digital process [97]–[99]. It involves the transfer of data from 3D-modeling software environments to a CNC (Computer Numerical Control) subtractive or additive digital fabrication platform [100], [101]. In most cases the data transfer process implies the translation of the virtual design into the G programming language (known as “G-code”) for controlling automated machine tools defining optimized tool paths and operating speeds [102]. This is commonly achieved by exporting the virtual design using a specific file format and reopening this file using the CNC tool software environment installed by the manufacturer. Following, material dimensions and tool paths are assigned with limited possibility for further iterations as well as
incompatibilities between the original software environment and the G-code that are lost in translation. Such discrete and streamlined tool-based process is all but seamless, framing and limiting the workflow of designs that are complex in shape and heterogeneous in material composition.

Architectural and design firms with particular interest in direct digital manufacturing of non-standard building parts need workflows that fuse computational modeling environments with manufacturing platforms [103]. As a result, some establish common online databases that are accessible to the manufacturer, or that embed instructions in the fabrication file itself in order to secure the most appropriate method for realizing their parts [97]. Furthermore, relying on unprecedented degrees of machinic precision DDM designs in product and architectural scales are defined by zero tolerance between virtually defined features. In order to ensure accuracies of sub-millimeter length scales of products and architectural parts, new DDM tools and their respective software environments must strive towards high definition manufacturing as can be found in the automotive and aeronautic industries [101]. Large-scale high-definition (LSHD) fabrication requires the generation of irreducible representations across domains including geometrical features and material properties [101].

**Designing Alignment**

There is a growing interest within both design and engineering communities to develop large-scale self-organizing materials and structures displaying programmable folding, curling, or shaping phenomena[8], [104], [105]. Motivated by the opportunities and potential impact associated with this challenge a design and digital fabrication strategy is presented that attempts to associate architectural-scale 3-dimensional folding with the induction of anisotropy at the molecular scale. Utilizing this approach, direct relationships can be observed between the preferred orientation of polymer chains and their programmed extrusion in meter-scale 2.5-dimensional printing. These discoveries help lay the groundwork for the development of new approaches to control hierarchical assembly of complex structures, with the potential to exhibit versatile mechanical properties and environmental adaptability that matches biologically grown structures[69], [105], [106].

**Polymer Orientation**

The ability to precisely tune both organization and composition of polymeric materials can provide for a wide range of desirable properties and behaviors in product and architectural scales. For example, it has been well documented in the synthetic polymer manufacturing community that chain alignment and crystallinity can be leveraged for the tunability of mechanical properties or the induction of self-folding phenomena[107]-[112]. Similarly, the introduction of crystalline order within naturally derived biopolymers poses great opportunity to enhance material performance for the design and digital fabrication
of new classes of composite structures [113]. The main challenge associated with the induction of organizational order across spatial and temporal scales, however, is the relative lack of robust techniques for arranging biopolymer molecular building blocks into hierarchical structures, given a desired performance. To achieve this, researchers frequently employ both physically- and chemically-guided techniques that harness the self-assembling properties of biopolymers into ordered structures over dimensions spanning from the nanoscale to the microscale[113], [114]. Utilizing these approaches, researchers have been successful in ordering the internal structures of several biopolymers, including collagen gels, collagen-alginate blends, and regenerated silk fibroin[115]–[117]. Methods to achieve these results have included methanol treatment of films, direct or anisotropic aqueous straining of gels (i.e., compressing or stretching)[118], [119] and of crystalline mesophases[120], as well as the application of uniaxial extension[116] and external electric fields over biopolymer blends[121], [122], or electrospinning of nanofibers [123].

**Self-Folding in Natural Systems**

Form modulation occurs in the natural world when systems spontaneously respond to the environment in order to achieve a specific function[104], [124]. This process is made possible through the cooperative integration of shape, structure, and material—as well as through biologically-hardcoded processes operating *simultaneously* within organically grown tissues[69], [124], [125]. Bending, folding and other such self-shaping forms in biological systems often occur due to the presence of residual internal stresses rather than through the application of externally imposed mechanical stresses[105]. These pre-programmed biological strategies for achieving shape tunability include (1) the controlled orientation of material reinforcement, (2) the asymmetric distribution of material reinforcement, and (3) the breakdown and reorganization of material reinforcement[104]. Because the first two strategies include environmentally responsive materials that frequently don’t require the input of cellular energy (as described below), they provide fertile ground for research on programmable matter and active technical composites[126].

Inspired by this potential, there is an active search in the design and engineering sciences to create materials and structures with self-arranging capabilities in response to environmental stimuli, leveraging strategies observed in natural structures across scales[17], [110], [127]–[132]. For example, at the **nano scale**, DNA self-assembles into helices[105] using chiral twisting, and polypeptide chains fold to form proteins with different structures, properties, and functions. At the **micro scale**, helical self-shaping occurs in climbing plant tendrils and orchid tree seed pods using passive means in search for minimum energy configurations driven by material reinforcement within inner fiber architectures[104], [133]. Water also plays an important role in plant self-shaping[134], [135], with folding by shrinking and swelling of plant tissue in leaves, stems, and roots driven by a close interplay between internal water content and cell turgor pressure[135]. The
regulation and coupling of these processes, in turn drives the deformation of tissue at different levels of hierarchy using both microscale geometrical constraints and nanoscale polymer chemistry[126]. Without the use of metabolic energy, pre-programmed hygromorphs in the dying tissue of pinecones mechanically open due to local changes in water availability[104], [125], [136]. At the meso scale, nemertean and turbellarian worms achieve passive shape change using fibrous lattice rearrangements in their epidermal membranes[52], and, in direct response to chemical stimuli, echinoderms such as sea cucumbers are able to modify the interactions between their dermal collagen fibers in order to change their overall stiffness on the time scale of a few seconds[104]. At the macro scale, trees are able to tune their cellulose microfibril angle based on environmental cues such as gravity, wind, or damage, deriving heterogeneous internal architectures that regulate bending and overcome load stresses in branches[104].

Self-Folding in Synthetic Systems

Inspired by biological examples such as those described above, research on analogous synthetic systems that can morph or self-fold in a controllable manner points towards a wide range of applications across scales—from microscale biomedical devices, to macroscale aircraft components[137]. Current material and fabrication techniques for induced folding can be classified according to their relative scale and application domains. At the nano scale, DNA origami workflows have been developed for the precise and tailored folding of a single DNA strand into complex 3D geometries[138], echoing traditional origami techniques that enable the creation of complex shapes from a series of simple paper folds[139]. On the micro scale, precise micro engineering of intelligent materials via the self-folding of thin polymeric films into 3D geometries are enabled by utilizing specific stimuli such as light, heat, pH, electric fields, or chemical gradients[140]–[142]. As reviewed in [137], bio-inspired shape transformation in soft materials by modulating internal stresses include: programmed folding of bilayers, evolution of 3D configurations from non-equilibrium states, differential cross-linking, halftone lithography, small-scale modulation of stresses, iono-printing via electrochemical electrodes, electronically programmable 3D hydrogels, and inorganic nanomaterial composites to induce shaping[137]. On the meso scale, the production of functional robots via the induced folding of 2D plans into 3D shapes using joule heating actuation or through the design of complex pop-up-book-like mechanisms have been demonstrated[143].

Laser-engraved origami with actuated hinges or active spring elements have also been used for the production of meso-scale self-assemblies[124]. In addition, “four-dimensional” printing technologies have been developed that incorporate time-dependent shape-changing geometries and direct multi-material printing, or printing and casting for the production of active composites that can react to environmental stimuli [110], [111], [133], [144]. To achieve these effects, four-dimensional printing frequently uses
composite inks that inform elastic and swelling anisotropies; as well as dynamic materials such as thermo-responsive shape memory fibers or hydrophilic hinges within flexible matrixes [110], [130], [133], [144]. Balsa-wood inspired 3D printing of lightweight cellular composites, for example, is enabled by the high aspect ratio fiber reinforcement within the 3D printing inks. Here, orientation of meso-scale fibrils takes place at the printing nozzle under shear and extensional flow fields [145]. On the macro scale, based on the moisture-sensitive characteristics of wood, weather-responsive self-folding of macro-scale architectural components and assemblies can be designed from simple wood elements [146] or, by 3D-printing custom wood grain structures from single wood fibers or multi-material combinations [147]. Such hygroscopic actuation methods harness natural swelling and shrinking present in the cellular structure of wood, which provides a dimensional shape change of up to 10% perpendicular to the grain [148]. Recently, large-scale warping and morphing techniques have been used to control the surface of aircraft wings and adaptively change their chamber geometry during flight through the incorporation of actuated elastomeric materials [149]. These constant adjustment methods allow for increased flight efficiency at multiple altitudes, reduction of structural weight, and improved fuel economy, as well as decreased environmental and noise impacts [149], [150].

Despite these advances, additional research is required to better understand shape-change and self-folding driven by natural microstructural features, as man-made solutions remain less effective than their biological counterparts. For example, in bio-inspired self-shaping materials triggered by hydration, there are still many unknowns and possibilities regarding the directed optimization of energy efficiency, reversibility, and shaping accuracy [104], as well as the discovery of simple techniques for complex shape control.

Towards this goal, the WBDF platform can be employed to describe a digital design and fabrication method and its predictive material simulation model, using water-based biological materials, and inducing anisotropic self-folding within manufactured objects across multiple length scales [35]. This work is able to operate at the nano-scale (via molecular chain alignment), micro-scale (via directional extrusion design), meso-scale (via global stress line toolpaths), and macro-scale (via architectural design) demonstrating high degrees of opportunity to tune and control both material properties and global geometric shape [35].
4.4.3 Flow-Based Fabrication

The WBDF aims to integrate design and digital fabrication environments by way of calibrating metadata defining the flow of bits and atoms in a continuous fashion. Meta-data available to the system is comprised of product definitions such as geometric, topologic and material specifications, as well as process definitions relating to mechanical deposition and spatial positioning constraints. In order to access, compute, interpret and interrogate the vast quantity of data, multiple domain methods are implemented.

Described here is a generalized model, an enabling technology and a workflow sufficiently generalized to adapt to a wide range of materials and digital fabrication platforms [151]. The proposed workflow is designed to integrate the virtual modeling environment to the physical fabrication platform, achieving
multi-material multi-property constructs at the service of multi-functional objects. I propose that seamless computational workflows such as the one presented here, can be viewed as vehicles to encode multidisciplinary non-standard design constraints into generative frameworks (Figure 55). These frameworks can provide for methodological design tools that enable navigation between tightly related constraints typical of complex and heterogeneous designs.

Every flow layer included in the system is independently defined. Importantly, 3D constructs characterized by complex material organization will emerge, not by direct 3D modeling, but by the layering of meta-data informing the manufacturing process through variable motion speed, variable pressures and diverse water-based viscous material compositions available for deposition. These interrelated processes can be rationalized through domain-specific flow fields. Flow fields include the flow of data, the flow of bits, the flow of motion, the flow of pressure, the flow of time, and the flow of water [38].

![Diagram](image)

**Figure 56:** Data including materials (Ma, Ma'), positioning platform (Po), deposition platform (De) and geometrical designs (Ge), is introduced to and incorporated within the computational model. The processing of this data results in global constants (invariants) and design decision consequence parameters (variants). The model invariants compute the range of extrusion forces (EF), the height and thickness ranges of the extrusion geometries (EG), the extrusion delays and synchronization timings required (ET); and the correcteds speeds of the positioning platform (Sp'). The model variants compute the material and mixtures required flow-rates (FR), and the pattern of barrel refills over time (RP).
The Flow of Data

The flow of data is initiated by variant design parameters and invariant system constraints defined at the level of the system’s building blocks. These include: the materials to be extruded (Ma, Ma’), the positioning platform (Po), the deposition platform (De), and the geometrical designs (Ge) (Figure 55). The system is designed as general as possible by defining variant and invariant constraint parameters as independent and external to the hardware system in use. The goal is to enable its implementation using various DDM platforms. In Figure 1 a positioning platform (Po) is given as a 6-axis robotic arm, and a deposition platform (De) is given as a three-barrel pneumatic extruder [38].

Invariants

Invariant constraints serve to calculate the overall system specific parameters of the computation. Invariant constraints of the base materials (Ma) include: viscosity (Vi), shear rate (Sh) and material data identification (Id). Invariants constraints of the deposition platform (De) are: range of nozzle types (Nz), hardware response times (Rp), and material reservoirs capacity (Ca). Previous research into nozzle designs can be found in [17]. Finally, the invariant constraints of the positioning platform (Po) include: system repeatability (Re), envelope size (En), as well as minimum and maximum speeds (Sp). With the mentioned sets of invariants, the system can calculate the range of extrusion forces (EF) required for a given design, the range of extrusion 3D-shapes to be deposited (EG), the range of extrusion timings and delays, and the revised speeds (Sp’) of the positioning platform (Figure 55, Figure 56) [38].

Variants

Variant constraints serve to calculate substrate specific parameters of the computation. Variant constraints relate to materials (Ma’) including specific properties; concentrations (Co) can be chosen, and new material mixtures (Mx) can be created from the systems base materials (Ma) (Figure 56). A calibration capability can be used such that, in addition to the set of initial materials (Ma), an extendable database of material behavior is stored as different materials are calibrated by the system. Variant platform parameters available include: nozzle types (Nz’) e.g. to perform co-axial, parallel or mixed extrusions as well as time-dependent pressure maps (Pm) that determine the extrusion geometry. Continuous, discontinuous or discrete geometries, such as points (Po) or curves (Cv) can be assigned with the aforementioned material choices and time-dependent pressure maps. With the mentioned sets of invariants, the system can calculate the range of flow-rates (FR) required as patterns of reservoir refill over time (RP). The extrusion shape map is defined per material and includes the extruded volume per n map repetition along a given trajectory. As a result, each extrusion length map $Lt$ is compared to a control extrusion length $Lc$ associated with a typical
continuous extrusion. In order to determine the refill pattern of the material barrels (RP) compute: \( L_c < \) \( L_t \times cs \times ct \), where \( cs \) is an estimate security coefficient (0.75) and \( ct \) is the averaged type of extrusion map that the trajectory carries. It is assigned the value of 1.00 for continuous paths and 0.25 to 0.75 for discontinuous ones [38].

Instructions

Once the variant and invariant parameters are defined and computed into the model, local (Lo), regional (Re) and global (Gl) material heterogeneity can be processed in order to structure the geometrical construct. The instruction data to achieve such hierarchy is computed via Extensible Markup Language (XML) and transmitted to an instruction interface that will distribute it to both positioning and deposition platforms (Figure 3). The interface is designed to distribute instructions while considering constraints of both platforms in order to synchronize motion and extrusion for complex depositions [38].

![Diagram of virtual and physical interfaces](image)

**Figure 57:** The virtual model operates at three levels of resolution: local (Lo), regional (Re) and global (Gl) to fabricate heterogeneous structured objects. This hierarchical computation results in fabrication instructions fed to a distribution interface that coordinate both positioning (Po) and deposition (De) platforms. The physical construct is achieved by implementing pressure (v, c, r), electrical (m), extrusion (E0) and motion (M0, M1, S0, R0, T1, Tn) data flows that tightly link both platforms.
The Flow of Bits

The flow of bits is initiated within a design-modeling platform and transitions to the deposition platform via serial USB communication. The deposition system is located at the positioning system’s end-effector and is based on a multi-barrel head digitally actuated by pneumatic hardware and circuitry. Bits flow from a micro controller (m) into a set of relays that control a digital pressure regulator (r), and into a set of pneumatic valves connected to the different material reservoirs (Figure 57). The pressure regulator transforms the flow of bits into flow of pressure and receives variable impulses that determine different regional extrusion geometries with tunable heights and widths along the trajectory (Figure 59a). The regulator’s pressure response \( P \) is empirically calibrated when given input values from \( 0 \) to \( 4000 \) of type 16-bit unsigned integer, that correspond to \( 4 \) to \( 20\text{mA} \) of electrical current \( (I) \). A linear interpolation is then performed as follows; 
\[
I = 10 + (I_1 - 10) \times (P - P_0/P_1 - P_0),
\]
so that the flow of pressure is mapped onto the flow of bits [38].

Figure 58: Local-based control is achieved by associating and finely tuning mechanical property gradients \((b,c)\) and layered compositions \((a)\) of multi-material extrusions.
The Flow of Motion

Motion flow is transmitted from the instruction interface via an Ethernet UDP socket to the positioning platform every 0.012s. The positioning platform is instructed to follow complex paths made of points, lines, poly-lines or curves through different motion instructions, starting from a point in space called home (H). The motion types can be M0 (composed of multiple targets), M1 (composed of a single target), S0 (a static motion), and R0 (a reservoir refill motion) (Figure 57). The M0 motion spans the first trajectory target (T1), and carries the total length of the trajectory ensuring smooth positioning even if the trajectory is composed of multiple targets (Tn). A static motion S0 carries the amount of instruction cycles in order for the system to remain static. This avoids repetition of identical instructions to be sent, and therefore makes the allocation less computationally intensive, as the internal instruction file is substantially reduced in size. A refill motion R0 targets the same custom point in space and waits for user action indicating that the reservoir, or reservoirs, are refilled properly and further action can take place (Figure 57) [38].

The Flow of Pressure

Each extrusion path is designed such that it can define different extrusion shapes and material properties from base materials (Ma) or from new combinations of base materials (Ma'). This is due to the fact basic curve primitives (Figure 59b) are assigned material properties in the model as opposed to processes, which take as input polygonal meshes. The flow of motion and pressure can vary while following the primitives providing different speeds, extrusion forces, and material volumes from each reservoir. From a positive pressure source (air compressor, c) and a negative pressure source (vacuum pump, v) airflow is transmitted into the system’s valves in order to deposit materials in different levels of organization. At the local level, different materials in different concentrations, and diverse layering strategies can be assigned to distribute material along trajectories. Figure 58a demonstrates different layering deposition strategies providing structural hierarchy within the construct. A gradient of local stiffness given by material concentration (1% to 12% in aqueous solution) is depicted in Figure 58b and its instances identified in a dried construct. Regional levels of control are achieved by differentiating extrusion geometries in height and width through pressure and motion flow maps. The regional pressure flow is described by three main classes (Figure 59d): a data allocator is in charge of reading the motion and deposition instructions (At) at the beginning of each complex path, taking around 5ms. Then a regulator sets the initial pressure (Rt) pausing the program with a 1s delay, and any other required pressures are set (Tt) to fulfill multiple variant flow maps over a trajectory (Figure 59d, 5e). Air-flow control is achieved through a set of valves that set initial extrusion inertia (It), remain open through the extrusion time, finalize the extrusion accounting for material inertia (Ft), and perform negative pressure to stop the material flow (Vt) (Figure 59d). As a result, the air flow controller
The flow of time is tied to the flow of pressure. Graphs describing pressure distribution (PSI) and height distribution (Z) over time inform the height and width of regional extrusion geometries (Figure 59c). The minimum and maximum bound of the pressure axis is determined by the empirical material calibration data with each of the system’s nozzles. The graphs describe changes in the time it takes to complete each path trajectory. They are encoded in mathematical formulas where pressure P is dependent on time T; continuous
(P = a), incremental (P = a*T +b), exponential (P = T), sinusoidal (P = a*sin (b*T+c)), etc. that the customized firmware, loaded in the pneumatics micro controller, is able to interpret. The encoding is achieved through geometric 2D to 3D mapping. In this case, time and flow mapping transform simple curve primitives (Figure 59a) into 3D extrusion shapes with variable height and width along deposition trajectories (Figure 59e) [38].

![Image](image_url)

Figure 60: Global-based control is achieved by combining local and regional deposition strategies into global shapes in order to achieve heterogeneous organization of the material constructs. (a) Single material dried extrusions of identical global shapes defined by their boundaries, with different internal patterns achieve different global shapes due to varied material distributions; (b) Multi-material geometries combining various concentrations demonstrating 2 states varying in curvature as a result of water evaporation; (c) A multi-material construct combining high strength materials at the ribs and low strength materials as infill skin; (d) A highly complex large-scale self-supporting construct designed as a cantilevering structure. Overall curvature is defined by geometrical patterning of the internal structure, in addition to multi-material deposition informed by structural requirements.

The Flow of Water

Evaluated materials have viscosities ranging from 500cPs to 50,000cPs at room temperature such as hydrogels, gel-based composites, certain types of clays, organic pastes, resins, polyvinyl alcohols etc. These
materials are water-based and undergo slow curing from pastes to solids at room temperature [17]. Global levels of control are achieved by the effect of combined local and regional strategies. Global shapes are revealed in the constructs when the contents of water and solvents of the materials evaporate into the environment. Single material dried extrusions of the same contour shapes with different internal patterns achieve different global shapes due to varied material distributions (Figure 60a). Multi-material geometries where different wet concentrations are placed side-by-side in a longitudinal manner, achieve significant curvature changes after drying (Figure 60b). Multi-material constructs where structural members are assigned high strength materials and infill surfaces are assigned low strength materials achieve controlled degrees of curvature after drying (Figure 60c). In highly complex large-scale networks, overall curvature is informed by the boundary conditions and the geometrical patterning of internal structures, in addition to multi-material deposition informed by desired structural requirements. (Figure 60d) [38].

4.4.4 Designing with the WBDF Platform

The integrated file-to-fabrication workflow presented is initiated at the designer’s CAD software environment and finalized at the DDM technology’s operations control. It negotiates shape and material attributes with the DDM technology’s mechanical constraints within a single representation and computational environment. The workflow is bidirectional in the sense that it can be implemented for top-down or bottom-up control. Specifically, it can process constraints as inputs to generate performance-based fabrication outputs and at the same time it can process performance-based fabrication inputs to generate constraint outputs. When combined, this bidirectional workflow can enable powerful material and site-specific products. In addition, the workflow is designed to control the deposition of both continuous and discontinuous printing modes to support functional gradation. This is achieved through the deposition of materials with variable mechanical properties, through the deposition of single or multiple layers and, finally, through extrusion geometry specifications given by the nozzle shape at the tip.

When generalized, the workflow can support DDM of a wide range of materials, deposition platforms and nozzle designs spanning various application domains characterized by optimal synchronization between the CNC platform and the extrusion system.

Design principles and methods underlying the general model and workflow are defined at the intersection of multiple research areas such as Digital Design, Computer Science, Mechanical Engineering and Materials Science and Engineering. This rich plexus of knowledge contributes to the generation of complex CAD tools, techniques and technologies tailored to provide LSHD for complex 3D designs [38].
**Multiscale Heterogeneous Constructs**

The integrated system and workflow can achieve a continuous and seamless multi-dimensional design-to-fabrication data flow (Figure 55). Based on system invariant constraints and decision-driven variant input sets (Figure 56), a hierarchical model is implemented operating at three levels of resolution defined as local, regional and global. Basic geometric primitives are associated with diverse materials and extrusion shapes where; local refers to the way material is deposited in gradients and layering patterns (Figure 58), regional refers to the 3D shapes in which material can be extruded (Figure 59), and global refers to the topologic effects of material organization, combining both local and regional strategies (Figure 60). Based on these domain definitions interrelated meta-data is encoded into transmission instructions that synchronize motion and deposition platforms (Figure 57) to produce heterogeneous structured objects with viscous water-based materials. It is important to note that 3D constructs and complex material organization will emerge, not by direct 3D modeling, but by meta-data informing the manufacturing process with its different motions, variable pressures and diverse material compositions to deposit (Figure 59, Figure 60).

A novel workflow for direct additive manufacturing of multifunctional heterogeneously structured objects enables the design and digital fabrication of structural parts made of water-based materials characterized by spatial and material complexity. At its core the workflow integrates virtual data with physical data enabling real time calibration of data and material flow. Through the implementation of this workflow is demonstrated the design and direct additive manufacturing of structurally patterned lightweight shells spanning overall distances of 10-feet, with a minimum amount of support, and thin cross-sections (Figure 60) [38].

**Towards an Architecture**

In terms of local structural controls, the system has the ability to additively manufacture 3D objects characterized by high levels of control over local, regional, and global structures at the meso and macro levels. Future research focus on enhancing material complexity at micro and nano scales combining micro layering of specific material structures and properties could lead to produce large-scale and high-resolution composites inspired by natural structures such as nacre or silk [93].

In particular research on the possibility of reversing the design workflow to enable formal iterations into the virtual model, can close the loop characteristic of the file-to-factory paradigm and will promote a factory-to-file methodology thereby further refining the workflow as feedback-enabled. Such feedback positive workflow can incorporate interrogative methods such as environment-specific and performance-based predictive modeling [101]. Furthermore, the effect of temperature, humidity, light or airflow can be modeled at the global level of resolution thereby informing both local and regional features. Global shape
outcomes could then be visualized in the virtual model for informed design decision-making prior to final fabrication. Such closed loop fabrication workflows, contribute not only to a substantial improvement of virtual-to-physical flow field computation, but will also offer insight into the way in which CAD platforms for HOM are designed and implemented [38].

![Perspective view of the Ocean Pavilion. Structural assembly and research exhibit focusing on water-based additive fabrication and biological design at the MIT Media Lab.](image)

**4.4.5 The Ocean Pavilion**

Driven by aqueous material formation, the *Ocean Pavilion* embodies a robotically controlled system to deposit natural water-based organic structures at ambient conditions, using mild chemicals and low amounts of energy. Components are form-found through evaporation patterns informed by the geometrical arrangement of structural members and the hierarchical distribution of material properties (Figure 61). Each component is designed to take shape upon contact with air and dissolve upon contact with water. The principles and method applied are a unique case demonstrating a FIM design approach through additive manufacturing of lightweight, biocompatible and materially heterogeneous structures.
Empirical studies involve the design and fabrication of functional patterns inspired by insect wing and leaf venation geometry, mimicking structure-and-skin graded architectures. In particular, dragonfly wings are passive lightweight structures supporting dynamic loading and employing high corrugation to increase stiffness and strength [152] (Figure 62a). It is interesting to note that the Young’s modulus of dragonfly wings can vary widely within the structure partly due to hydration patterns induced in the presence of chitin and proteins altering local properties [152], [153] and providing for both graded flexibility and graded tensile strength along the wing from the joint to the tip [154]. As insect wings, leaves are flat structures that maximize surface-to-volume ratios. Their venations are two-dimensional ramifying structures that tightly relate form and function performing both transportation of mass and energy, and distributing force fields across the surface area of the leaf structure [155], [156]. The highest mechanical stresses in leaves occur along their longitudinal axes; and transversal parallel veins contribute to stabilize bending forces (Figure 62a). Both longitudinal and transversal structural systems are lignin-based with a high elastic modulus,
which, when combined with hydration and turgor pressure within cells, provides support and allows for high flexibility to reconfigure or fold under mechanical loading [155], [156]. Such support and functional variation strategies, as well as the use of primary and secondary structural systems, are applicable to architectural structural cantilevers, shells and spatial structures.

Structural design patterns are synthetized combining strategies from both Voronoi-based insect wing patterns, and leaf ramifying venations in order to obtain functional and mechanical gradients. Functional gradients, spanning column-like behavior to surface-like behavior, are obtained by negotiating geometrical pattern density and hydration rates (Figure 62b bottom). Mechanical gradients are obtained by modulating stiffness, pressure, and layering strategies. Finally, optical gradients are obtained that are directly proportional to structural gradients and are a result of grading material concentration from 3% w/v - translucent- to 12% w/v - opaque - in deposited gels. The constructs are 1m to 70cm wide and range from 2.5 to 3m tall when dry (Figure 62b bottom). In this implementation, as in insect wings and many leaf types [155], [156], the size of the local diameter of load bearing members with respect to the global size of the structure is key to guaranty self-support and bending stability for cantilevered performance of the constructs.

**Templating Structure, Manufacturing, and Performance**

Design templates are defined as frameworks for data translation that inform and encode material and immaterial performance criteria. For example, an anticipated load map can be used as a template for structural component thickness; whereas a thermal map can be used to template surface thickness and porosity for ventilation purposes. Such templates accommodate property variation in the course of the design process, while ensuring the implementation of the main algorithm. The work tailors and integrates structural, manufacturing and environmental design templates relating to multi-scale feature resolution and global structure formation and performance. This is possible via a seamless computational process encoding virtual design and physical digital fabrication that relates to multi-dimensional, media and trans-disciplinary data informed design workflows. In other words, this is possible because of Fabrication Information Modeling (FIM). Variable flow rates, differentially distributed material properties, and environmental control inform self-folding by shrinkage of the constructs as water evaporates from the water-based deposited gels. Results display a range of structural behavior (Figure 62b) and represent a response to some of the planet’s distresses related to the construction industry’s unsustainable practices.
Structural Design Templating

In the *Ocean Pavilion*, structural template maps are designed based on hierarchical flow of loads encoded into principal and secondary structure streamlines. The principal structure is longitudinal to the global shape of the construct and provides for stiffness employing thicker diameter members and higher material concentrations as can be observed in leaf venation and insect wing structures. The secondary structure can be semi-parallel or semi-perpendicular to the principal structure and is composed of hierarchical networks of thinner member diameters and lower concentration materials. Parallel secondary structures allow for column-forming structures, and perpendicular secondary structures allow for wall-forming structures. Figure 63a shows principal and secondary streamlined structural pattern generation by interpolating 2D vector fields from 3D scalar fields. Desired 3D surfaces are modeled and their gradient of slope is mapped into 2D vector fields that represent local structural behavior. The vector fields are then computed into continuous principal and secondary directions of flow (Figure 63a).

Robotic Manufacturing Templating

Once the streamlines for principal and secondary directions are determined, hierarchical material distribution is implemented. There are three ways to determine differentiated material distribution to achieve selective structural capacity; pressure variation can be implemented along selected lines resulting in continuously varying material accumulation (Figure 63b); material concentration can be assigned to each trajectory resulting in stiffness gradients from lower to higher concentrations; and, finally, layering onto dry deposited material provides higher degree of reinforcement. Such strategies are encoded into position, speed, pressure, and material instructions that are sent in real-time to both positioning and deposition platforms (for further detail on manufacturing instruction generation see [38]).

Environmental Performance Templating

Hydrogel materials are deposited in geometrical and pressure patterns onto a flat substrate following instruction parameters. As water evaporates, shrinking forces accumulate across the networked gel and induce self-folding once the construct is removed from the substrate. In order to distribute hydration across large-scale depositions, a computerized evaporation control system can be easily implemented composed of 100 variable speed fans with differential control according to desired degrees of final hydration compared against thermal imaging of the deposition (Figure 63c). Hydration control allows for increased final folding in hydrated areas providing for structural interface joints as shown at the foot of the dry structure in Figure 63c. If uncoated, the structures will fully biodegrade providing nutrients as they decay in contact with the environment. Such materials can be fully recovered and reused if dissolved in water.
The Relevance of the Ocean Pavilion

Variable-property biomaterial-based components are printed at room temperature, using relatively little energy and mild chemicals. Applications of the design and manufacturing method range in scale and function form lightweight robotics such as flapping micro vehicles, cell growth promoting environments such as biocompatible wearable devices in contact with regenerating tissue, biofuel-producing bacterial culture supports, fully compostable consumables, ecosystem-enhancing constructs that replenish soils with nutrients as they decay, and temporary biodegradable architectural structures or building skins.

Future Work in Biological Templating

Chitosan is a naturally produced (Figure 64a) biocompatible material that is used in the medical industry as cell scaffold for tissue growth [157], [158]. Consequently, in future iterations of the manufacturing platform presented herein, biological microorganisms can be printed using the pneumatic extruder with fine pressure tunability. Bacterial biofuel production pockets will be designed and deposited along with water-
storing gels and embedded nutrient and collection devices. Figure 64 illustrates preliminary results of bacterial culture growth on top of deposited chitosan samples (Figure 64b). Biological-driven design will involve further integration of environmental parameters and biological phenomena such as solar and airflow exposure patterns, temperature gradients, photosynthetic rates, nutrient availability, etc. As in leaf venation patterns, multifunctional aspects of hydraulic transport and mechanical protection [156] can be integrated into hierarchical structures generating a true material-based ecosystem.

By deriving fabrication technologies, structural design, and environmental capacities from material-driven research, novel cross-disciplinary multi-functional properties are unveiled such as; optical gradation proportional to load-bearing capacity; merging of structure and skin functions within the same material system; energy and resources savings due to material environmental responsiveness; emergence of functionally-graded shape induced by time, air and water; or the possibility to flow biofuel-producing organisms within structural nerves. The Ocean Pavilion’s lightweight robotically fabricated biomaterial structures represent an ecological and economical approach to materially heterogeneous formation by design, and an innovative exploration into future biocompatible living spaces that can have a high impact in alleviating our planet’s resource and health issues.

**Figure 64:** (a) Top: Chitin is naturally produced within crustacean shells in combination with minerals and proteins. Bottom: X-ray transmission image of Ibacus sp and Enoplometopus sp. Image credit: Dr. James Weaver, Harvard Wyss Institute. (b) Top: Photosynthetic cyanobacteria growing within two layers of chitosan. Colorimetric assay quantifying sucrose production in bacterial co-culture (12-24-72h). Image credit: S. Hays, T. Ferrandt and Prof P. Silver, Harvard Medical. Bottom: Synthetically engineered Escherichia coli colony (1 um length) strain forming biofilm. Synthetically engineered Escherichia coli (1 um length) with protein fibrils attaching gold nanoparticles. TEM images. Image credit: Eléonore Tham, Lu Lab, MIT.
4.4.6 Fabrication-induced Material Modification

Multiscale Hierarchical Structures

A novel additive manufacturing process, the Water-Based Digital Fabrication Platform (WDFP) [38], was implemented for the production of large-scale hierarchical structures informed by natural systems. In this approach, biological materials such as chitosan, a chemically modified form of chitin which is Nature's second most abundant biopolymer, are deposited along structural paths that describe major load bearing stress lines. Deposition can be performed longitudinal, transverse, or oblique to geometric paths so that different macro-scale structural motifs can be integrated into the final form. When fully cured, the resulting constructs (Figure 65) frequently exhibit non-intuitive curling behaviors. As such, one of the major goals of the present study was to explore the potential mechanisms responsible for the production of these resulting 3D geometries from simple 2D tool paths.

To address these questions, the approach was multifaceted. First, the effects of concentration-dependent crystallization were investigated (Figure 66) as well as induction of preferred orientation of polymer chains (Figure 67) within structural paths at the nano-scale using synchrotron x-ray scattering, followed by the development of a finite element-based model for exploring the effects of this resulting structural anisotropy on the induction of directional folding (Figure 68) [35].

Figure 65 depicts the bio-inspired design, fabrication, and resulting cured construct of a 3m-long chitosan-based additively manufactured and self-folded column inspired by dragonfly wing and leaf venation patterns (Figure 65a). The WDFP characteristics implemented here consist of a highly precise 6-axis robotic arm positioner, with a multi-nozzle pressure-based extruder as its end-effector, carrying diverse chitosan concentration hydrogels ranging from 2% to 12% w/v in 4% aqueous solution of acetic acid (AA) (Figure 65b). Pressure and speed maps are tailored to achieve 2.5D differential extrusion shapes along toolpaths defining final global shape and anisotropic material behavior. At room temperature, and through water evaporation, the structure is cured, displaying a large-scale hierarchically structured symmetrically-folded column (Figure 65c). Note that since the samples are printed on a rough gripping surface, only the height of the samples change during evaporation, not the in-plane size. Upon removing the samples from the surface, they self-fold to their final curved state in a matter of minutes[35].
Figure 65: Overview of the Water-Based Digital Fabrication Platform (WDFP) a) INSPIRATION Biomimetic digital design process for 2.5D toolpath generation based on dragonfly wing and leaf venation patterns of a 3cm-long dragonfly wing specimen and a 10cm-long dried leaf specimen. a-right) VIRTUAL 3m-long digitally generated toolpath with hierarchical geometric patterning within regional and local extrusion areas. b) PHYSICAL Fabrication platform characteristics: robotic arm positioning system with 1m reach and 10kg payload and multi-nozzle pressure deposition system carrying diverse chitosan concentration hydrogels from 3% to 10% w/v in 4% acetic acid. c) RESULTS 3m-long self-folded column cured at ambient conditions and close-up of structural folding along toolpaths induced by fabrication. From [35].

**Nano-Scale Anisotropy Analysis**

To better understand the material behavior at the molecular level, printed samples were analyzed using synchrotron-based x-ray diffraction (Figure 66, Figure 67). Powder diffraction measurements performed on printed samples ranging from 2% to 12% chitosan concentration demonstrated a clear link between chitosan concentration and the degree of crystallinity (Figure 66). Samples at and above a 4% chitosan concentration exhibited sharp diffraction peaks, while those with lower concentrations did not, suggesting that this variability could be potentially leveraged during fabrication for the creation of macroscopic...
samples with programmed structural anisotropy. To test this hypothesis, a sample was excised from a large printed construct (Figure 67a) and micro-diffraction patterns were acquired from series of positions along two ribs running at 90-degree angles to one another (Figure 67b, at regions labeled C and D). Diffraction patterns from the two ribs are shown in Figure 67c and Figure 67d, and in the main intense ring, greater diffraction intensity is observed along an axis indicated by the green dashed lines. The maxima are more easily seen in the corresponding “unrolled” plots of Figure 67e and Figure 67f, and the integrated peak intensity shown as a function of azimuthal angle chi in Figure 67g and Figure 67h. These results demonstrate that the diffracting planes in the polymer crystallites exhibit preferred orientation parallel to the direction of the rib. This is the case for both ribs despite the fact that the ribs run along directions at 90 degrees to each other in the macroscale construct.

Figure 66: Powder X-Ray Diffraction (XRD) analysis of extruded dried acetic acid-solubilized chitosan films demonstrating a clear correlation between polymer concentration and the induction of crystallinity. The background diffraction pattern obtained from the kapton sample holder is highlighted in gray. From [35].

In order to gain additional insight into the factors driving the often-non-intuitive large-scale deformations in 3D printed constructs, a finite element model was developed to investigate the effects of these processes across a wide range of different printing parameters. The inputs for this model were derived from real-time
drying behavior of 3D printed constructs, as follows. After 3D printing of the acetic acid-solubilized chitosan, the material begins to dry while still anchored to the aluminum substrate. Since the top surface of the 3D printed chitosan is exposed to the surrounding atmosphere, it dries at a much faster rate than the underlying material, which is in contact with the aluminum. This resulting partially constrained drying mode results in a bilayer-like design, consisting of a fully cured and rigid top surface and a hydrated underlayer. Once this bilayer-like form is removed from the underlying substrate, the more hydrated underlayer begins to rapidly shrink, resulting in the induction of curling within the structure.

**Micro-Scale Elemental Simulation**

In simulations, the forms were similarly modeled as a bilayer architecture using the finite element analysis software package, Abaqus. Preliminary experiments of printed square samples of chitosan demonstrated a distinct dependency of the printing direction on the induced direction of folding, which then was modeled using orthotropic shrinking properties of the bottom layer.
Figure 68 shows the simulation results investigating the effects of structural anisotropy on the induction of predictable curling behavior in a bilayer construct. In the absence of structural anisotropy, the bilayer constructs exhibit an induced curling along either one of the short axes and never along the diagonal, with minute (and largely uncontrollable) differences driving this unpredictability in folding direction. In contrast, it is observed that for a high level of anisotropy in shrinkage (i.e. the material shrinks mostly in the direction parallel to the printing direction), there is a nearly linear relation between folding direction and printing direction. More specific, when the shrinkage ratio is $\frac{y-x}{l} > \frac{\sqrt{2}}{2}$, there is a sudden transition at $\theta = \frac{\pi}{4}$, such that when shrinkage becomes more uniform, only the two folded states along the short axes of the square are observed. These results demonstrate that for a square, a small imperfection can be amplified to fold the sheet towards one of two possible states, an observation which is in accordance with existing literature[159], [160]. In fact, possible folding directions can be tuned depending on the shape of the printed sample[159]. Comparing simulation (Figure 68 top) with experimental results (Figure 68 bottom), square samples fold along the diagonal, demonstrating that the difference in shrinkage in the directions parallel and orthogonal to the printing direction are $\frac{y-x}{l} < \frac{\sqrt{2}}{2}$, so that the difference is relatively large. Therefore, the direction of curling behavior in the samples can be directly specified by the printing direction, suggesting that the manufacturing process is responsible for induced anisotropic behavior at the macroscale. While in the printed samples there are some macroscopic features remaining (i.e. the surface curves slightly orthogonal to the printing direction), it is expected that additional anisotropy exist at the nano/microscale to account for this large dependency on printing direction [35].

Nano-to-Macro Design Control

Consequently, nano-scale order induced by residual stresses during material extrusion in conjunction with the local and regional geometric design of tool-pathing logic could be leveraged to induce the observed large-scale folding patterns (Figure 69), essentially decoupling global geometric design from induced material behavior[35]. As a result, for the same design, different material responses could be programmed, such that global line paths could contain local and regional tool paths within principal, secondary, or other directions determining material alignment which could then direct folding [35].

Characterization

Printed samples analyzed were extruded using hardware and software described above. The sample in Figure 67 was fabricated by printing high concentration chitosan (12% w/v chitosan in 4% w/v acetic acid) parallel to the rib direction (dark brown) and by casting low concentration (3% w/v chitosan in 4% w/v acetic acid) chitosan in the skin pockets (light brown). Rectangular samples shown in Figure 66 were printed
using 2, 4, 9, 10 and 12% w/v chitosan in 4% w/v acetic acid respectively with tool paths parallel to the rectangle length. Square samples shown in Figure 68 had tool-paths parallel and diagonal to the side respectively. All constructs were fabricated and handled at ambient conditions, left to dry overnight, then mechanically removed from the substrate, and allowed to freely self-fold.

Powder X-Ray Diffraction (XRD) analyses of dried acetic acid-solubilized chitosan samples at different concentrations (Figure 66) were performed by from cast thin films. The resulting material was ground under liquid nitrogen, placed into kapton capillaries, and analyzed at the 11BM beamline at the Argonne Advanced Photon Source (with an electron energy of 7 GeV with a critical photon energy of 19.5 keV). The samples were scanned from 0.5-50 degrees 2-theta and were calibrated using a mixture of ca. 70 wt% Si (SRM 640d) and ca. 30 wt% Al2O3 (SRM 676). Corrections are applied for detector sensitivity, 20 offset, small differences in wavelength between detectors, and the source intensity, as noted by the ion chamber before merging the data into a single set of intensities evenly spaced in 20.

For the 3D printed samples, synchrotron X-ray data were collected at Beamline X6B at the National Synchrotron Light Source, Brookhaven National Laboratory, using 19 keV X-rays (λ = 0.65 Å) and a beam spot focused to ca. 100 μm × 100 μm. 3D printed chitosan samples were mounted onto the beamline sample holder in transmission geometry. Transmitted X-ray intensity was recorded using a photodiode detector fixed beyond the sample at the beam stop and normalized by incident intensity measured with an upstream ion chamber to produce the density contours shown in Figure 67b. Diffraction data were acquired with a Princeton Instruments CCD detector approximately 15 cm beyond the sample. The detector pixel positions were calibrated to momentum transfer Q using a sintered corundum standard, per the JCPDS data card, and the software package Datasqueeze. The diffraction data are shown as raw detector images in Figure 67c, Figure 67d; corrected for spatial distortions within the detector optical taper and “unrolled” along the chi axis using MatLab for Figure 67e, Figure 67f; and the intensity was integrated around the main diffraction ring in the Q interval 1.15-1.35 Å⁻¹ using Datasqueeze for Figure 67g and Figure 67h.

Finite Element Development

Numerical nonlinear implicit folding simulations were performed using the Finite Element Analysis code Abaqus (v6.12-1) (Figure 68). The square sheets were modeled as a bi-layer with a thickness to length ratio of t/L=0.005, in which both layers had the same thickness. The layers were meshed using one layer of linear 3D solid wedge elements (C3D6). Each layer was modeled using linear elastic material properties with Young’s modulus E (simulation is independent of absolute value), and a Poisson’s ratio of ν=0.3. Shrinkage of the top layer was effectively induced by giving the material orthotropic heat expansion coefficients and reducing the temperature. In the simulations, rigid body translation and rotation were constraint, while gravity was not considered.
Figure 68: Numerical simulations and experiments of fabrication-induced folding as a function of structural anisotropy. **Top**) Contour plot showing the dependency of the folding behavior on the direction of anisotropy $\theta$ and the size of anisotropy introduced by varying the swelling ratio parallel and orthogonal to $\theta$, $\frac{s_{||\theta}}{s_{\perp\theta}}$. The folding direction is characterized by the absolute change in distance between the outer points lying on the short axis of the square. **Bottom**) Experimental verification of the numerical model, showing a relatively high level of anisotropy (i.e. $\frac{y-x}{L} > \frac{y_z}{L_z}$). From [35].
4.4.7 Relevance of the WBDF Research

The present study demonstrates the production of large-scale structures with nano-to-macro anisotropic folding behavior induced within large-scale manufacturing, using a single biopolymer in an aqueous form, at different concentrations, and at ambient conditions. It is additionally shown that by imposing thicker regions with macro scale orientations, such as structural ribs, in an otherwise uniform deposition process, crystallinity with preferred orientation is induced, and it affect the material properties of those regions. If we compare the work's application space to other modern manufacturing processes inducing material anisotropy [8], [147], [161], the system could be potentially useful when implemented at large-scale, within difficult to monitor environments, and with limitations for use of simple or single materials. Other work on inducing orientation via 3D-printing has focused on the use of magnets and magnetic additives within inks [134], or on folding of shaped hydrogels within water baths [133], or in integration of fibrous fillers within blends [145] for the production of small-scale prototypes. Several of these processes are difficult and potentially expensive to robustly scale up [35].

4.5.8 FIM aspects in WBDF

Within the workflows described above, the MODEL includes material property data to directly edit physical fabrication constraints. The INFORMATION embeds the flow of bits, motion, pressure, time, and hydration dependencies, and the FABRICATION apparatus directly informs the emergence of anisotropy and shape.
**MODELING** in **WBDF**

In this implementation the model **negotiates physics and structure** performance. The disciplines of architecture, structural engineering, mechanical engineering, and materials science come to play. For a global bio-inspired geometry, cross section distribution is negotiated by load dependencies, and directly informs the shear stress to be applied to extrude a certain material that complies with the section needed. Blend type and its viscosity, tune the flow-rate at the fabrication extruder. Within a geometrical streamline map with an associated local shape and thickness target, pressure, speed, and time delays are specified in each node in order to inform digital fabrication equipment (Figure 70).

![Figure 70: MODELING in WBDF.](image-url)
**INFORMATION Flow in WBDF**

Data in this system is based on flow, as a metaphor for water, as well as a practical embodiment of **seamless physical-to-virtual integration**. It includes the differential flow of bits (activating and deactivating electronics within the system), the flow of motion (determining position, rotation and speed of a robotic arm), the flow of pressure (determining positive and negative airflow input as well as flow variation maps within a pneumatic extrusion system), the flow of time (ensuring that delays are tightly related to the energy required to start and stop flow of different material blends), and the flow of water (observed as a function of temperature through a thermal camera and directly influenced by a convection platform) (Figure 71).

![Diagram of Information Flow in WBDF](image-url)
**FABRICATION in WBDF**

The digital fabrication elements of this system - robotic arm, multi-material pneumatic extrusion end-effector, thermal camera and convectors - are able to interpret pressure maps that embed extrusion shape variations for informed folding in the dry construct. Importantly, **fabrication directly informs shape**: extrusion-based fabrication direction and custom geometric tool-pathing induce nano-scale alignment of the material. Feedback systems, such as humidity probe or real-time thermal camera feed interpretation - or even a sort of XRT beam analysis system on-the-fly -, could allow for better control of large-scale deposition of constructs where environmental conditions can vary across the print bed. Also, a nano-scale material design capability within the model could provide for better understanding of outcome folding solutions (Figure 72).

*Figure 72: FABRICATION in WBDF.*
**FIM Outlook for WBDF**

The implementation of predictive computational folding could facilitate a production of extrusion-based structures with non-intuitive 3D outcomes. Contributions could ultimately be adapted in other polymer-based applications that require simple and robust solutions for the production of large-scale complex forms. The potential for more widespread implementation is due to the fact that the results are obtained from extrusion-based fabrication along with designed 2.5D tool path directionality[35]. The combination of these two simple methodologies induces nano-scale alignment and macro-scale folding without the need of multiple materials and additives or complex material tuning devices during digital fabrication[115], [118], [119], [123], [162] (Figure 73).

![Diagram of FIM Outlook for WBDF](image)

*Figure 73: FIM Outlook for WBDF.*
4.5 Parametric Chemistry: Trees to Molecules and Molecules to Trees

4.5.1 Research Summary

This research is driven by the possibility to design with chemistry. It extends the WBDF platform’s workflow with further digital control of chemical properties in the design model mapping molecular composition to translucency, color and strength. Metadata of rigidity, and viscosity from each designed blend, inform digital fabrication parameters such as speed, pressure, nozzle diameter, and deposition height. Material contribution is studied to devise that, for instance, cellulose provides more mechanical strength, chitosan increases both strength and elasticity, calcium carbonate gives less weight with the same strength; whiter color and more translucency; faster drying time; and added stiffness, and finally, starch adds stiffness, whiter color and translucency.

This workflow sets the base for robot collaboration, more material design control, and for integration of feedback from biological sensing within the biomaterial blends. It derived the Aquahojia Pavilion, a multi-material shell combining biodegradable members and a tunable bio-composite skin. 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.

4.5.2 Context in Parametric Chemistry

Designing Chemistry

Living structures develop from cells that customize and tune their local physical and chemical properties—through growth and remodeling—as a function of genetic, intracellular, and environmental constraints. This research discusses a novel design approach and technology that enables tight integration between material synthesis, robotic fabrication, and physical behavior at scales that approach—and often match—those of Nature [34].

Parametric Chemistry is a method by which to control the composition, structure, properties, and alteration of matter across multiple length scales, using a customized multi-material, robotically actuated additive manufacturing platform, and its associated computational environments. As a proof-of-concept, a tunable bio-cement composite has been engineered via parametrically controlled deposition of organic and inorganic elements including chitosan, calcium carbonate, pectin, cornstarch, and cellulose. The chemical, mechanical, and optical properties of prototypical bio-composites were evaluated and implemented as inputs for computational design and digital fabrication, thereby facilitating a nearly full integration between robotic fabrication platforms, material modeling, and form generation. Toward this end, the work demonstrates a set of parametrically-tuned and chemically-altered surface-based structures exhibiting designed hierarchical behavior informed by geometry and material composition.

In order to utilize strategies that enable parametric tunability for digital fabrication, bio-composite is developed that can be digitally tuned and digitally fabricated using a previously developed Water-Based Digital Fabrication platform (WBDF) [38], [93], which has been configured to facilitate the digital design and fabrication of large-scale bio-composite architectures using multiple materials with varying properties [34] (Figure 74).

This study focuses on two natural biopolymers—chitosan and cellulose—which are widely abundant in Nature and exhibit extraordinary mechanical properties, especially when combined with organic and inorganic substances [69], [93], [163]. However; architects, and engineers have yet to establish the methods by which to reconfigure biopolymers into useful composites across functional length-scales that match—and even transcend—the properties and functionality of traditional building materials [34].

Designing Growth

Basic natural building blocks assemble into adaptive continua to generate living materials, such as trees, that sense, respond, and adapt to environmental conditions. Their biodegradation continues resource cycles that facilitate new synthesis [164]. This implementation of Parametric Chemistry aims at designing a tree,
by deriving material- and machine-aware digital design and fabrication methods through Fabrication Information Modeling to re-engineer manufacturing processes and their constructs into adaptive multi-functional continua and subvert wasteful material cycles. This points 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, the composition, structure, and properties of matter can be controlled. Composite structures, such as the Aguahojia Pavilion described later, can be designed to dynamically fluctuate between rigid ‘shell’ and flexible ‘skin’ in response to heat and humidity. Using highly abundant eco-systemic by-products, closed-cycle fabrication can be approached 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 [164].

![Figure 74: Parametric Chemistry correlations.](image)

**Designing Decay**

As described in [165], contemporary sustainable building practices are largely based on extraction of resources, where even green-labeled construction materials usually require high energy processes to be made usable and to be recycled for re-use. Materials such as concrete, glass, and steel are often assembled without consideration of either the lifespans of their assemblies or the long-term future of the components from which they are made. As the buildings become obsolete or when the structures fail, these constituent
parts are left behind in landfills and take centuries to degrade. With the use of biologically derived materials in additive manufacturing, an alternative model of material use can be designed, where both use and decay can be constructively programmed into the lifecycle of a structure [165]. Furthermore, although recent advances in additive manufacturing are challenging the way in which objects and structures are conceived and made, digital design processes are nevertheless largely confined to being an extension to mechanical tools developed in the Industrial Age, where artifacts are made to be materially and functionally homogeneous within single objects and typologies. In our research [165], water-based dissociation, as a precursor to decay, can be designed as a function of material density distribution, tuned, and graded across spatial and temporal scales; whereby a denser material distribution in a given spatial domain takes more time to dissociate in water. The distribution, in turn, can be templated according to various environmental or structural criteria [165].

4.5.3 Steps towards Scale

Building on WBDF

As discussed in the previous Case Study, the WBDF platform consists of a custom extrusion system attached to an existing robotic arm with programmed and integrated real-time instruction feed and feedback capabilities [29]. Designs are elaborated computationally to tailor speed and motion paths, nozzle sizes, air pressure, material selection, and distance from the substrate. Modulating these parameters enables to tune the weight and height of extruded material, down to sub-millimeter tolerances [29]. Specifically, the platform is configured to deposit water-based materials such as polysaccharide blends, clays and cements, as well as various colloids, in 2.5- and 3-dimensions. Using molds with extreme curvature and irregular geometry, the WBDF platform is able to engender purposeful three-dimensionality within large, panelized components (Figure 78b). Furthermore, taking advantage of multiple robots simultaneously extruding material facilitates quick and expansive experimentation and fabrication in this research (Figure 77b) [34].

Bio-blends Development

Natural biopolymers are abundant, biocompatible, biodegradable, and nontoxic, making them appealing as stock materials for use in additive manufacturing of sustainable products [166]. Bio-cement composites discussed in this research utilize a chitosan-cellulose backbone, with organic and inorganic additives. The synthesis of these structural biomaterials is a promising step toward large-scale digital manufacturing of economically viable, non-toxic, biocompatible, and biodegradable products and structures [34].
Specifically, various blends of cellulose, chitosan, cornstarch, pectin, and calcium carbonate are digitally designed and synthesized to elicit specific mechanical and optical properties by varying the proportional chemistry through novel fabrication strategies. In doing so, materials with precise and tunable properties perform differently at multiple scales, with locally-tailored characteristics for desired performance-based outcomes across length scales [34].

Chitosan is a natural biopolymer found in the shells of crustaceans such as shrimp and lobster. It is the second most abundant natural polysaccharide on the planet, after cellulose [167].

Cellulose is a natural biopolymer found predominantly in the plant kingdom, and is structured as a long chain of linked sugar molecules, which give wood its stiffness. It is also the main structural component of plant cell walls and a building block for textiles [168] (Figure 75) [34].

Calcium carbonate is widely used in the pharmaceutical, agricultural, construction, and paper industries. It comes mainly from powdered marble and limestone, but can also be found in mollusk shells and stony corals [169]. Importantly, calcium carbonate can endow a strong material with a high stiffness-to-weight ratio [170], which—in Nature—allows for the formation of lightweight, easy to carry shells. Applied on a larger scale, calcium carbonate can enable reductions in the mass of structures, which can allow for smaller

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**Figure 75:**

a) Ashby chart depicting material properties of the composite building blocks comparing their density and Young's modulus with that of other architectural materials.

b) Natural origin of materials of interest: cellulose pulp from housing insulation, chitosan from chitin in insect wings, starch from corn, and calcium carbonate from mining or quarrying.

c) Requirements in function and 'fabricability' selected for the integrated design of biomaterial-based large-scale structures.
and lighter supports, formal freedom, precise and purposeful geometric patterning, and low embodied energy [171].

**Pectin** is a carbohydrate in the skin and core of fruit that acts as structural ‘glue’ holding cell walls together. In solution, pectin can form a fibrous network that traps liquid and sets upon cooling. Combined with acid and sugar, pectin can form a hydrogel [172]. In layering bio-cement on top of pectin films—utilizing the WBDF platform—a mechanical bond counteracts the bio-cement’s propensity for contraction and curling. In a favorable proportion, its elasticity dominates the bio-cement’s rigidity and strength, thereby allowing for additional control, as well as relatively high levels of spatial tenability, over both the local and global shape of large bio-cement pieces. Furthermore, pectin’s natural translucency allows it to act as skin in patches.

**Cornstarch** is a powder made by pulverizing corn grains after soaking and removal of the embryo and outer covering [173]. Cornstarch is used here as a shear-thickening liquid, which gives the bio-cement, added rigidity and cohesion.

**Bio-blends Synthesis Methods**

A solution of 4-10% cornstarch (w/v) (VWR, Radnor, PA) is heated to 95°C for 20 minutes, while stirring vigorously. The temperature is then lowered to 78°C, at which point 8-18% chitosan (w/v) (85% deacetylated VWR, Radnor, PA) is added to the mixture. The temperature of the solution is then lowered to 37°C, and acetic acid is added in a ratio of 2 parts chitosan to 1-part acetic acid (v/v). At this point, 1-8% calcium carbonate (w/v) is stirred in while folding vigorously to avoid rapid expansion. Finally, 40-70% cellulose (v/v) is added in small amounts to acquire an extremely viscous hydrogel, which is then homogenized with a drill mixer [34].

**Bio-blends Fabrication Methods**

As seen in the previous Case Study, the WDF fabrication platform can integrate both the pneumatic extrusion of materials and the precise positioning of a nozzle in space via a custom virtual interface [38]. To smoothly deposit material structures, robotic interface distributes serial-based signals and valve response delays to inform the custom extrusion system. Simultaneously, an Ethernet-enabled data stream locates feedback for the existing robotic arm system [38].

Specifically, the flow of data is initiated through a combination of variant design parameters as well as invariant system constraints defined by the system’s building blocks (Figure 76). These include the materials to be extruded (Ma, Ma’), the positioning platform (Po), the deposition platform (De), and the geometric designs (Ge). Here, basic rules can include envelope size, global curvature, intersections of
members, etc., each of which can be reached by varying local properties and fabrication strategies, resulting in graded micro details that optimize materials for local environmental conditions and functions. In addition, the printing substrate can be manipulated in terms of temperature, morphology, electrical current, and magnetism for various fabrication typologies and material compositions [34].

Beginning as a wet, off-white, clay-like mass, biomaterials used here are packed into cartridges that are loaded into a holster within a rotating, multi-material end-effector. A nozzle diameter is then chosen in relation to the viscosity and cohesive forces within the material. Subsequently, air pressure, the distance of the nozzle from the substrate, and the speed of the robotic arm are set in the design code's variants. Each of these parameters is also informed by the resolution and turning radii of the tool path geometry. Following extrusion, the material is left to dry at room temperature [34].

![Diagram](image)

**Figure 76**: The WBDF platform's workflow diagram contains parameters associated with the robotic fabrication process, including nozzle positioning, robotic (arm) speed, air pressure, and time delays. These parameters are integrated and processed in a real-time fashion to construct databases that communicate instructions to hardware components, enabling feedback between software and hardware media on slice time (graphics extended and adapted from [38]).

Thus, the system is defined as general as possible according to variant and invariant constraints that are extrinsic to the hardware system in use with the goal of enabling it to be implemented using various DDM
platforms. In this implementation, a 6-axis robotic arm is used as a positioning platform (Po), and a multi-barrel pneumatic extruder is used as a deposition platform (De) [38]. Diverse large-scale curved molds can be placed in the print bed to deposit materials in 3D for enhanced shape-based structural inertia. The robotic arm can easily cover curved areas with specific wrist motions while conserving orthogonal positioning to the substrate [34].

4.5.4 Implications of Parametric Chemistry

This research integrates multiple disciplines to realize large-scale design and digital fabrication with biomaterials. Parametric Chemistry describes the method by which aspects of materials science, engineering, architecture, physics, biology, mathematical modeling, and chemistry are utilized to parametrically tune the chemical components and digital fabrication methods to design and digitally produce a wide range of bio-composites. Material blends are digitally-fabricated at various scales using the WBDF platform, which enables 2.5- and 3-dimension flat and molded deposition of water-based materials forming hierarchical structures. In this case, multiple materials are layered—oriented in a semi-parallel or semi-perpendicular configuration—to control local-to-global mechanical properties (Figure 74). Such geometric patterning has been configured to either enhance or compensate for the mechanical and optical properties of the bio-cement material blends described below. Parametric Chemistry has informed the fabrication of a biomaterial pavilion called Aguahoa, which highlights how a scalar gradient of data—from molecular to environmental—can drive design decisions, digital fabrication parameters, functional properties, and, finally, degradation [34].

Material Design Results

There is a direct relationship between the mechanical properties of the developed prototypical bio-cement structures and the relative proportions of cellulose, chitosan, calcium carbonate, and starch (Figure 77, Figure 74). By observing the controlled layering of organic and inorganic materials found in natural shells, material properties can be tailored as well as drying durations of constructs to local and global prerequisites through chemical interactions [34].
A high proportion of **cellulose** (40-70% v/v) provides the material with additional mechanical strength; likely due to the distributing of cellulose fibers contributing to an increase in anisotropy. Adding cellulose to the solution turns it into a more viscous, quick-drying hydrogel. Material tests of intricate geometry printed using this material show little-to-no spreading on the substrate. The hydrogel is squeezed through a ~1.0mm nozzle with 40-90 psi of air pressure, resulting in an ability to print at a higher resolution.

Increasing the amount of cellulose relative to the amount of chitosan results in a whiter, slightly translucent material. Conversely, the speed at which the robotic arm is programmed to move decreases with increasing amounts of cellulose; because the printed geometries stick together so well such that turning corners and making curves drag the material out of place [34].

A greater proportion of **chitosan** (8-22.5% w/v) results in a global increase in both strength and elasticity.

A high ratio of chitosan relative to cellulose and starch makes the material more golden brown in color and
opaque. However, this ratio also results in a more viscous hydrogel that does not keep its shape well when printed, thereby reducing the ability to print at high resolutions. Conversely, the robotic arm could move at a higher speed because the hydrogel does not stick together as well, nor does it dry as quickly [34].

Increasing the amount of calcium carbonate (1-10% w/v) yields a lighter weight material with the same, or an even better, mechanical strength; a whiter, more translucent color; faster drying time; and added stiffness. The hydrogel also becomes much lighter—likely due to chemical reactions with the acetic acid—and holds its shape very well. This allows for a high printing resolution (~1.0mm), but again necessitates a slower printing speed and more air pressure (40-90psi). Adding calcium carbonate also results in a higher pH (4-7.3), which may create a more hospitable environment for bacteria and other organisms [34].

Finally, increasing the amount of cornstarch (4-10% w/v) results in added stiffness as well as a whiter color and slightly more translucency. The use of pectin can dominate chitosan's mechanical properties and endow the material with more flexibility and translucency [34].

**Material Intelligence**

The material behavior of eight geometric lattices with varying chemical proportions has been analyzed (Figure 74). Geometric design, number of layers, and printing nozzle diameter are kept constant for every lattice, while pressure and speed are varied depending on the material’s shear stress and flow. Figure 74 illustrates material composition of each lattice, including its performance-based attributes in terms of color, translucency, and strength [34].

The concentration of calcium carbonate is a determining factor for both the strength and stiffness of the material (Figure 78, Figure 79). A higher ultimate tensile strength in materials with greater concentrations of chitosan; whereas, increased stiffness can be largely attributed to higher concentrations of starch. Alternatively, higher concentrations of cellulose added both strength and a higher elastic modulus to the composite; most likely due to its fibrous structure. It is important to note that—within the scope of this work—potential interactions between materials were not further analyzed [34].

It should also be noted that the bio-cement was cross-linked with acetic acid to form a hydrogel, which was left to dry at room temperature after being deposited in 2.5- and 3-dimensions via the WDF platform. Both heat and humidity led to embrittlement and large contractile deformations in the material, respectively. Further curing, crosslinking, and deprotonating experiments will be conducted. Regardless of material composition, a thicker line weight and an increase in layer count typically result in increased mechanical strength and rigidity. Similarly, more complex geometrical features could be used to compensate for the contractions of the material as it dries, as well as a strengthening agent. Printing successive layers in opposite orientations could endow the material with additional resistance to lateral forces. Some of these strategies were investigated in large constructs described in Figure 78, Figure 79.
Mechanical data—including data relating to properties such as strength, rigidity, and viscosity—has informed deposition parameters such as speed, air pressure, nozzle diameter, and height relative to the substrate [34].

Moving forward, multi-scale material properties could be further functionalized by using data-driven material mixing and deposition within a rotating extruder with coaxial mixing and extruding capabilities, using real-time intrinsic and extrinsic sensing of molecular and environmental dynamics, respectively. Such dynamic material transformations within a single tool-path can engender truly reactive—rather than prescribed—properties of materials and the structures that they form [34].

4.5.5 Large-scale Biomaterials Manufacturing Experiments

Two large proof-of-concept constructs were designed and manufactured with differentiated geometric and material distribution to respond to varied structural behavior along its construction. One construct was printed in 2.5D and 3D shape was found via local strengthening and shrinking forces due to differential material distribution. Another construct was directly printed in a 3D mold to ensure controlled shape. This can further drive structural inertia and enhance strengthening strategies tested in the first construct. In both cases, material deposition was achieved utilizing the WBDF in subsequent layers of cured multi-material colloids. Specifically, a base layer combining pectin (35% w/v) (BASE), acetic acid (15% v/v), and glycerin (2% v/v) was coarsely deposited and left to dry to accommodate subsequent hierarchical extrusions. A 1mm nozzle is used for all depositions. Differential extrusion thickness is achieved by incrementally varying air pressure from 40 to 80 PSI (Figure 78, Figure 79) [34].

Construct 1

The first lattice-like layer (L1) is composed of vertical and horizontal bio-cement extrusions. Vertical extrusions are performed with differential pressure to ensure a rigidity gradient with maximal material content toward the top and bottom of the construct. Doing so will—in the future—allow us to compose connections to the ground and the top of an architectural pavilion’s crowning. At the structure’s center, additional flexibility was achieved by layering less material amounts and higher polymer concentrations to allow the piece to accommodate an arch-like configuration (Figure 78b). The horizontal bio-cement extrusions in the first layer (L1) also follow a pressure gradient, with a maximum at the edges. The same strategy was applied in the final and external layer—layer five (L5)—to accommodate for deformation in the center of the construct (Figure 78a). In between, layers two (L2) and four (L4) carry vertical bio-cement depositions with varied pressure as in L1. They also contain added horizontal extrusions of pectin to ensure flexibility of cross ribs and provide longitudinal, arch-like behavior, as displayed in Figure 78b. Layer three
(L3) contains a combination of pectin and bio-cement in its horizontal lines. Pectin is placed at the center ribs, and bio-cement—at the lateral ribs. The center of the construct is expected to achieve maximal folding in longitudinal and transversal directions, so its material composition is kept as flexible as possible.

L3 also contains vertical bio-cement extrusions, with pressure gradients for differential rigidity from the extremes towards the center (Figure 78a) [34].

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### a) VIRTUAL FABRICATION PARAMETERS - layering strategy and composition:

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1 &amp; L5</td>
<td>H &amp; V grid</td>
<td>varied pressure</td>
</tr>
<tr>
<td>L2 &amp; L4</td>
<td>H</td>
<td>pectin</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>bio-cement</td>
</tr>
<tr>
<td>L3</td>
<td>H</td>
<td>pectin</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>bio-cement</td>
</tr>
</tbody>
</table>

### b) PHYSICAL EFFECTS ON STRUCTURAL BEHAVIOR of 2.5m long constructs:

Construct 1:

- **Maximum Rigidity**: base attachment to beam / roof
- **Medium Flexibility**: neighboring piece attachment means
- **Maximum Flexibility**: adaptation to global multi-part shape
- **Maximum Rigidity**: top attachment to beam / roof

**Figure 78:** a) Digital fabrication parameters and material composition data within a large-scale prototype. b) Experimental large-scale results of 2.5m long prototype depicting flexibility and rigidity property design. Local and global behavior is designed and expressed within a single physical construct.
Construct 2

The second construct uses a similar global shape and size, but is directly printed in a 3D single-curved mold. Layering strategy is here based on geometrical hierarchy and is shown in Figure 79a. On top of a pectin base, a lattice (L1) is deposited. It is selectively densified in subsequent layers L2 and further in L3. Depositions are achieved on top of a 3D mold by calculating angular robotic wrist motions to ensure orthogonal deposition to the substrate. Toolpath patterns are designed in a structural bracing fashion to preserve desired molded shape after curing and removal from substrate (Figure 79a). Resulting hierarchical dried construct satisfies shape conservation and behaves like a structural shell (Figure 79b).

Qualitative observations regarding the physical behavior of the fully cured, large-scale 3D prototypes displayed in Figure 78b and Figure 79b confirm the capacity for the tunability of flexibility / rigidity enabled
by the multi-material WDF system. Results shown here will drive future design of multi-functional structures for a full-scale biomaterial pavilion [34].

4.5.6 Towards an Architectural Scale

By parametrically reconfiguring the chemical properties and thereby informing the emergence of mechanical hierarchies (typical of shell structures) the ability to tune the properties and behavior of novel bio-cements is optimized using a customized additive manufacturing platform (WBDF). In doing so, the capacity to obtain geometrically complex constructs with tunable structural and environmental properties is demonstrated [34].

Coined Parametric Chemistry [34], a nano-to-macro control system for bio-material blends integrated with on-the-fly mechanical evaluations is conducted within a single computational environment [34]. This enables the local control of extrusion thickness and material distribution for precise structural requirements on a global scale. By differentially-configuring pressure, speed, and geometrical organization during fabrication, the system compensates for structural weaknesses identified in various bio-cements, enhancing desired properties—such as strength or flexibility—by design [34]. This has been demonstrated in the design and robotic fabrication of medium-to-large scale lattices exhibiting high strength to weight ratios. Moreover, the system implements control of shape formation vis-a-vis 3-dimensional folding of large-scale structures by implementing robotically informed 2.5- and 3-dimensional deposition thereby informing stiffness distribution while curing [34].

This research has enabled the design and digital fabrication of large-scale architectural structures that demonstrate: (1) differentiated optical qualities and mechanical behavior within a single material system; (2) high weight to surface area ratios, and; (3) complete biodegradability. Mechanical tests, utilizing a wide array of tunable bio-composites, demonstrate the ability to precisely control the shape and properties of 3D printed constructs. Using this approach, user-defined, small-scale and chemistry-based control of structure-function relationships can be leveraged on an architectural scale [34].

4.5.7 Making the Aguahoja Pavilion

The Aguahoja Pavilion is 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, a set of three interrelated data maps
are developed including (1) structural self-load forces, (2) extrinsic environmental forces, and (3) intrinsic hydration forces (Figure 80) [164].

**The Matter of a Tree**

An ovaloid skeleton structure is additively manufactured via fused deposition of a reusable photopolymer with high strength and elastic modulus [174]. 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 [164].

Biocomposites used here 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 [163], [175]. 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 [164].
The Mapping of a Tree

Structural, extrinsic, and intrinsic forces 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 81. 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 [164].

AGUAHOJA PAVILION - DESIGNING A TREE

Figure 81: Designing a tree - The Aguahoa 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.

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 82). 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 81, right). To obtain flexible-to-rigid transitions, material is distributed in 2.5-dimensions via hierarchical layering and differential extrusion pressure. 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. (Figure 82, right) [164].

**Figure 82: 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.**

**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 (Figure 83). 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 83, right) [164].

**Figure 83: 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.**
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 84, left) [164].

![Figure 84: 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.](image)

Notes on the Dynamics of Programmed Decay

Four 150 mm x 150 mm squares were printed on an anodized aluminum substrate. The squares consisted of a base film of 35% pectin (w/v), 2% chitosan (w/v) mix. Approximately 75 mL of the pectin colloid was deposited in each square, with toolpath lines set in parallel, 3mm apart. The squares were left to air dry for 24 hours at room temperature and ambient humidity, after which the chitosan-cellulose toolpaths were applied [165] (Figure 85).

Shown in Figure 85, sample toolpaths were based on the Euler path methodology, with mappings driven by the following sources for density distribution: a point source (4383 mm long), a line source (4459 mm long), a function source (in this case, a gyroid) (4489 mm long), and an image source (8526 mm long). The toolpaths were printed along one polyline, with an additional bounding box pass. Two layers of each polyline were printed at 40 PSI at 5m per minute [165].

All the samples were left to dry for 12 hours, before removal from the substrate. The panels were then set in shallow dishes of distilled water for 14 days, and the dissociation was monitored via time-lapse photography. The samples became saturated and expanded in volume, deforming with the expansion, after
which the samples began to dissociate. The pectin film dissociated quickly in relation to the more viscous chitosan-cellulose layers. Mold growth began on Day 5. Photos at $T_1=0$ hr 0 min and $T_2=2$ days 18 hr 18 min were analyzed to measure the amount of dissociation in relation to the material distribution. $m = \int |\nabla g| \, dA$ ($g$ is the greyscale value of the image) is used as a measure for how dissociated the pieces are in water. As $\min |\nabla g| \, dA$ implies $\nabla g = 0$ whose solution $g$ is a smooth as possible function subject to boundary conditions. $m$ indicates how blurred an image is - linked to dissociating. Thus, low values of $m$ indicate high dissociation and conversely, high values indicate low dissociation [165].

Results show that the grid with a higher density of chitosan takes more time to dissociate. Similarly, material distributions with dense areas retain their shape and diffuse less. Furthermore, a uniform material distribution in the grid patterns results in dissociation graphs that have varying, yet similar, rates of dissociation, shifted proportionally with material density; despite having almost twice as much material as 4, sample 3 shows a similar dissociation rate (Figure 85).

![Figure 85: A sequence of grids 3D printed at various spatial frequencies. From left to right: 1 mm, 5 mm, 15 mm, and 30 mm spacing. Areas with denser material distribution retain their shape and material concentration better; spatial distribution of material has effects on shape retention and degree of dissociation.](Image)

Regardless of the amount of material, it is primarily the density distribution that affects the dissociation rate of these samples; while amounts of material distributed affect the total time for dissociation. Patterns with larger areas of densely patterned materials retain their shapes better and dissociate at a slower rate; while
patterns with areas of sparse distribution that are not surrounded by denser regions exhibit larger deformation locally and faster global dissociation rates. By characterizing dissociation properties of these materials in relation to material density distributions, the design space allows to create objects with predefined dissociative behavior, guided by extrinsic and intrinsic constraints [165].

**Fabrication Information**

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. In the FIM framework, information is embedded into generative design and fabrication toolpaths, whereby each meta-node compiles heterogeneous, multiscale data. In the Aguahojaj Pavilion, each node carries data relating to geometric pattern density, nozzle deposition thickness, tonal composition, and chemically tuned decay (Figure 86). This implementation demonstrates material- and machine-aware digital design, working toward bridging the gap between virtual and physical realms [164].
4.5.8 Fabrication-Informed Multiscale Behavior

The Aguahoja Pavilion is conceived as an integrated system of functional behavior maps that impact both skin and skeletal members (Figure 87). However, to ensure the stability of a five-meter tall experimental material construct, an ovaloid skeleton was printed separately and bound to the biopolymer. In future implementations, thick support members with maximal strength can be designed by further optimizing cellulose-chitosan blends [164].

Below, summarized a multiscale approach for performative functional design. Mapping strategies are implemented across scales of resolution and performance. At the microscale, biomolecules are chosen to maximize desired basic-to-acidic and hydrophobic-to-hydrophilic transitions; at the mesoscale, printing orientation is controlled to affect flexible-to-rigid behavior, while hierarchical printing determines thin-to-thick gradients; and finally, at the macroscale, dense-to-sparse geometry is designed and temporal decay maps are assigned in relation to site-specific environmental factors [164].

Figure 87: Multiscale interplay of strategies for fabrication-informed performative behavior.
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 87 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 84, right) [164].

Mesoscale: Anisotropy and Hierarchy

Tuned anisotropy can be achieved within the biocomposite blends. Hierarchical layering of geometric toolpaths determines thin-to-thick gradients and direction of printing induces flexible-to-rigid transitions (Figure 82, right; Figure 87, 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 [164].

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 87, 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 [164].

4.5.9 FIM aspects in Parametric Chemistry

The Aguahoja Pavilion demonstrates fabrication-informed design of performative behavior by tightly integrating material formation, digital fabrication, and physical behavior within a large-scale hybrid structure [164]. Within the workflow, the MODEL negotiates chemical parameters of blends to derive design strategies obtaining optical, mechanical, and structural properties within constructs. The INFORMATION flow, maps blend considerations to fabricability variables, and the FABRICATION apparatus synchronizes machinery accordingly and, eventually, will be able to interpret feedback from the physical world.
MODELING in Parametric Chemistry

Interdisciplinary relationships between architecture, structural engineering, mechanical engineering, material science, and chemistry, interact in the model, to achieve **multiscale mapping** able to link chemical composition of blends to their effects on optical quality, mechanical properties, and structural behavior at the large-scale. Chitosan, calcium carbonate, cellulose and starch, are combined into different material blends. Relationships derived are, for instance; chemistry-level decision-making to account for structural loading, distribution of material opacity according to architectural shading needs, or tuning flow rate parameters to the constraints of certain blend types and their viscosity (Figure 88).
**INFORMATION Negotiation in Parametric Chemistry**

Information is computed by the model at each node within a toolpath. It carries; nozzle speed and extrusion thickness according to structural strength needs, blend type to be extruded according to color tone specified, or geometric density of lines related to decay degree. These data are passed to the digital fabrication hardware’s position, rotation, speed, pressure, flow map, or time delay parameters. To link the virtual and the physical even tighter, information from digital fabrication to model (here in gray) could account for feedback from materialization-monitoring devices such as thermal imaging, convection assistance for curing, or humidification systems. This would inform curing maps and iterate deposition for design fidelity and integrity of un-cured constructs (Figure 89).

![Diagram of INFORMATION Negotiation in Parametric Chemistry](image)

*Figure 89: INFORMATION Negotiation in Parametric Chemistry.*
**FABRICATION in Parametric Chemistry**

In this implementation, a six-axis robotic arm and a pneumatic extruder are tightly synchronized to deposit diverse materials. The platform is parallelized and flexible in accounting for design parameters translated to machinic variables. For instance, differentially-specified positioning and rotation of each of the six axis in space, variation of end-effector speed on print-bed to modify extrusion shape or to account for flow of matter, cartridge ID mapping to direct the system to the blend type specified in each node, extrusion thicknesses related to flow map and pressure, and time delays to account for shear thinning of each material in the database (Figure 90).

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**Figure 90: FABRICATION in Parametric Chemistry.**
**FIM Outlook for Parametric Chemistry**

Parametric Chemistry in FIM, opens up a new design space with *chemistry-informed decision-making* linked to structural, architectural, and mechanical considerations when completing materially-complex constructs. Improvements in the system could go, as mentioned above, towards providing material state feedback during digital fabrication by using thermal cameras, humidifiers, or convectors. They could also look into robot collaboration to complete larger structures by using camera control. In the virtual side, one could think of establishing a chemical design model to predict new time-dependent optical properties, or even reversing the logic of the current computational implementation to find an ideal material blend for a desired structural performance (Figure 91).

*Figure 91: FIM Outlook for Parametric Chemistry.*
4.6 Wet Lab on a Bot: On Extinction of the Protocol

4.6.1 Research Summary

This research is driven by full integration between physical and virtual domains, so that they operate in unison. It relates to the future of FIM on devising platforms where physical materialization directs both design and digital fabrication in an effective loop of decisions. It envisions tight relationships between - not one, but many - models inhabiting digital fabrication hardware - effectors and sensors -, and connecting geometries to data (like in Biomimetic Skins), with tunable chemistries relating to performance (like in WBDF and Parametric Chemistry), to the action of biological organisms, and to sensing and responses in feedback protocols.

A natural example of FIM is a cell or bacteria, where model, information and digital fabrication are inseparable and able to adapt and grow matter with resource simplicity and functional complexity yet to be attained by man-made platforms. The WLOB postulates that harnessing some of this intelligence can be done by directly employing living systems within digital fabrication environments.

Diverse stages of WLOB can be imagined. First, we can think of a centralized-decentralized system where a model embodies a loose road map with designed material deposition targets (as in Bots of Babel), as well as calls to action for living systems to react. Here living cells would be able to locally sense and locally make decisions, but always monitored and triggered by a central model.

In a second stage, a multiplicity of models can be embodied by living organisms that respond to a controlled environment (as in the Silk Pavilion Research), but here, the living can be engineered to sense and respond to the environment by detecting certain conditions in stiffness, humidity, porosity, etc. and responding with chemical expressions to mediate fabrication for a programmed outcome of, for instance, flexible nodes and strong beams.

Third, functional expressions could be designed and implemented on-the-fly for a future where cells can be engineered within digital fabrication systems during materialization, to output required properties on demand. For instance, making constructs locally transparent, or regionally porous, or even globally grading reinforcement based on asymmetric loads.
4.6.2 A Context for WLOB

Biological micro-organisms such as certain fungi and bacteria can radically transform digital fabrication via well-known metabolic processes [32] that continuously occur in the natural world, but that are difficult to achieve in man-made manufacturing systems. We can define four interesting bio-enabled fabrication processes for FIM; (1) environmental and material state sensing, (2) compound production, (3) new function templating, and (4) enhancing of constructs’ performance (Figure 92).

**Figure 92:** Strategies towards integrating useful biological systems in FIM workflows.

**Bio-Sensing**

Advances in Synthetic Biology make it possible today to design cell signaling responses via internal synthetic logic circuits [176], [177]. Genetically engineered cells can detect surrounding chemicals or levels of specific molecules such as nucleic acids or proteins [178], as well as variations in light, heat, pH, humidity, and other factors. Input signals can then be processed via designed internal circuits to make logic decisions, and output responses in the form of color or fluorescence [178], or even other chemicals or environmental factors. Many of these sensing capabilities would be very useful to deploy within structural materials – such as water-based biomaterial blends – while being deposited, cured, or layered in advanced fabrication systems. Such large-scale, non-destructive and distributed reporting, can provide digital fabrication efficiency and matter state insights difficult to achieve with electro-mechanical sensing equipment.
**Bio-Production**

Many micro-organisms such as yeasts, bacteria and micro-algae are used in bio-technological processes to produce interesting active chemicals for pharmaceutical, cosmetic, medical and food applications [179]. Types of outputs can be reporters, toxins, chemicals, electrons, cell motility or growth changes [177]. Specifically, production of useful chemicals such as biofuels or sugars is possible by using certain naturally photosynthetic or engineered strains of bacteria [179]-[181]. We can imagine using this bio-strategy in cells deployed throughout digital fabrication environments to output liquid, solid or gas compounds and correct material or environmental factors during manufacturing.

**Bio-Templating**

It is today possible to synthesize -via genetic editing-, pattern -via additive manufacturing-, and control -via sensing strategies-, **new function** in composite materials with engineered cells [182]-[185]. Bacteria can be programmed to produce living materials such as biofilms with self-healing and evolvable functionalities [186]. In one example, amyloids from *Bacillus subtilis* can be secreted and can assemble into diverse nano-architectures or gels with tunable physicochemical properties, such as viscoelasticity [185] [187]. Moreover, these cells can be flexibly configured in space allowing for 3D-printing [186]. Other cell types are able to assemble multifunctional and environmentally-responsive networks of living and non-living components. Specifically, recent research has shown that *Escherichia coli* curli protein production can be engineered to organize across multiple length scales, producing amyloid-based materials that are either externally controllable or undergo autonomous patterning. Importantly, fibrils can be interfaced with inorganic materials, such as gold nanoparticles and quantum dots to create conductive materials or materials that heat up with light [9]. All these strategies – viscoelastic, conductive, or temperature-changing fibrous domain secretions - are interesting because they provide constructs with on-the-fly tunability and introduction of local, regional or global new material properties during digital fabrication.

**Bio-Enhancing**

Certain types of bacterial colonies can structurally-enhance performance of designs during materialization [188], [189]. They could be locally-deployed within constructs’ highly stressed or loaded conditions - such as joints, undercuts, or supports, - to enhance material properties via functional gradients. For instance, bio-mineralization can lead to higher compressive strength [188], or bacterial output of cellulose fibrils can induce changes in tensile strength [10], [190]. Bacterial calcium carbonate precipitation is a common phenomenon in the bacterial kingdom occurring in soils, freshwaters, oceans and saline lakes which leads to precipitation of mineral carbonates. Importantly, it can be induced by specific environmental conditions [188], [191]. Bacterial cellulose films with different tensile properties can be induced by changes in porosity
and compression [192]. A digital fabrication system could be designed where specific physical cues or environmental conditions would trigger bio-production of these structurally-enhancing minerals.

**Biological Design of Fibrous Composites**

**Design of Bio-Function**

Desired new function can be production of **nano-cellulose fibrils** within printed materials to strengthen fiber-based composites. Different bacteria genuses perform this function in nature such as *Acetobacter, Agrobacterium, Sarcina, Bacterium, Azotobacter, Rhizobium, Pseudomonas, Salmonella, Achromobacter, Aerobacter,* or *Alcaligenis.* Microbial cellulose has been shown to be purer than plant cellulose, which may be related to its remarkable ability to retain water and increase hydrophilicity. It has been found to be beneficial in forming fibrous composites [193]. In particular, *Acetobacter* species *A. xylinum, A. pasteurianus,* a *A. hansenii,* are the most efficient producers of cellulose [194]. *A. xylinum BPR2001* (AXY) can be implemented here because it is a model well documented organism and a great start for research into nano-fibril reinforcement networks on top of natural fibers [190]. AXY survives in a relatively acidic environment (pH 3.5-6.5) and performs a well-known production pathway to synthesizes cellulose from glucose [195], which makes it suitable to enhance fiber adhesion within a bio-based composite digital fabrication platform.

**Design of Bio-Sensing**

Cellulose production can be monitored through (1) a binding assay to detect the presence of cellulose using, for instance a pigment such as Congo red, (2) a modified continuous enzymatic assay, or (3) detection of a precursor or byproduct selected from the biosynthetic pathway (indirect) [196]. The ideal output of these assays would be colorimetric or fluorometric (Figure 94), and would be imaged with the appropriate lighting system and a high-resolution camera. This could be done continuously over the surface of a large print, with the signal optimized for an easy readout.

**Design of Bio-Production**

Many known cellulose-producing bacteria have been extensively researched with their biosynthetic pathways elucidated. It is possible to design control of enzyme activity – and thereby spatiotemporally control production of cellulose – by introducing inducers and activators [197]. This would allow for a closed production control loop. For instance, a colorimetric assay could be used to detect cellulose; the image could be analyzed on-board the digital fabrication system; this would inform the printing of an activator and additional media, yielding more cellulose production in specific areas at precise times.

This would be a key demonstration of the regulation and automation available via FIM. Furthermore, the bacteria could be engineered in a variety of ways – to optimize cellulose production or insert reporter genes.
and relevant genes could potentially be under control of an inducible promoter, offering another production control strategy.

**4.6.2 Virtual and Physical Unite**

The overall aim of this implementation is to fully blend distinction between virtual and physical worlds in digital manufacturing. The ‘Wet Lab on a Bot’ is an enabling technology to fabricate structures with the aid of living cells able to monitor and alter material state during production. It addresses the challenges and benefits of designing at multiple scales of resolution and integrating multi-disciplinary data with fabrication-based feedback.

This can be achieved via an almost autonomous system able to: deposit material, sense its state, compute sensed data, generate new digital fabrication instructions, and respond with end-effector action. Working dimensions span nano-scale cell physiology, up to macro-scale pavilion-like structural design. It involves (1) a controlled environment chamber, (2) a 3-to-6-axis positioning system for (3) a multipurpose digitally-controlled input/output end-effector.

**Design of Intelligent Fabrication**

The design and development of this novel end effector with maximum intelligence features, is key to this implementation and able to: **Fabricate**: extrude material in hierarchies with single, dual, or coaxial systems, as well as have the means to cure these materials on-the-fly, or alter their hydration levels, thickness, porosity, or temperature via heating devices, actuated fans, etc. **Bio-interact**: distribute living cells within materials deposited, activate or deactivate cell function, and provide nutrients to maintain life. **Sense & Track**: collect material-state information via camera vision, temperature-sensitive lenses, on-board digital microscope, or humidity probe.

**Design of Multiscale Materials**

Multiscale biodegradable composites can be designed and fabricated within the ‘Wet Lab on a Bot’ implementation, and then monitored or enhanced using bio-enabled strategies. Namely: a biopolymer matrix - such as chitosan, starch etc.-, a fibrous filler - such as cellulose, sisal, hemp etc. -, a reinforcing agent – such as fiber adhesion-enhancing bacteria or bone formation cells, plus bio-reporting features to better assess material and living cell production states. The workflow could hierarchically distribute matter with attention to, for instance: global geometric structural integrity needs at the macroscale, regional
distribution of differential fiber concentration within blends to tune strength at the mesoscale, and local adhesion-enhancing properties at the nanoscale. Below I describe challenges and processes to derive such composites by combining strategies.

Modification of Material Reservoirs
Environmental parameters within material containment reservoirs need to be tuned to specific organism’s needs. Extrusion heads will need to ensure adequate conditions of pH (~5), temperature (~30°C), and oxygen levels. Environmental parameter monitoring probes can be implemented within material reservoirs to provide a first level of pre-printing material state feedback to the platform.

Modification of Printable Materials
In order to use matrixes, fillers, and enhancing organisms to fabricate bio-composites, we need to ensure compatibility of printed materials once they are laid on the print bed. For instance, broth of cells, polymer matrix such as silk fibroin, chitosan, cellulose acetate butyrate or poly-lactic acid, and fibrous filler such as 1cm long cellulose, hemp, or sisal fibers. In a scenario, matrix and un-enhanced filler will be contained in an extrusion reservoir, and cell cultures with nutrients and environment control in another. Importantly, ingredients need to coexist in the blend while providing adequate viscosity and shear-thinning properties. Once laid on the print, cells will perform action such as ferment fillers and promote adhesion to matrix. Different acids, such as acetic or gluconic [198], [199] can be produced as byproducts of the bacterial cellulose synthesis process. This can significantly decrease the pH of the printed material, and inhibit the activity of the bacteria themselves, which can be used to terminate organism activity once their adhesion-enhancement function is completed. Alternatively, a feedback response can be designed so that pH levels are rectified within prints through the introduction of buffers.

Automation Design for WLOB
Responsive Platform Prototyping
Once sensing data is collected, it must be integrated within a virtual model in order to track any relevant changes and tailor a response. Specific data mining software and evaluation metrics need to be developed here. For instance, a response to poor layer bonding can be to reapply adhesion-enhancing bacteria, or a response to low levels of nano-cellulose production can be to tune the available nutrients or the pH levels within the printing blend.

Large-scale Design-to-Fabrication Integration
Materials need to be test printed to evaluate survival or embedded living organisms during and after extrusion throughout simulated digital fabrication. Also, tools for collection of bio sensing data need to be adapted to fit an automated process. For instance, hardware needs to be scaled-down in weight and size to
be carried on board by a robotic arm for local or regional sensing, or it might need to be scaled-up across a large printing bed to collect global information at once.

**Experimental Methods for WLOB**

**Growth Media**

The growth media is selected based on the organism(s) being used, but would generally include a carbon source, nitrogen source, and potentially salts or other minerals or vitamins as coenzymes [200], such as glucose (50g/L), yeast extract (5g/L), peptone (5 g/L), Na2HPO4 (2.7g/L), and citric acid (1.15g/L) [190].

**Biological Testing**

Survival of organisms on drying prints at room temperature are tested with a Live/Dead viability assay. New bio-based function within materials can be assessed using the following equipment: (i) scanning electron microscopy to study changes in fiber surface morphology, (ii) atomic force microscopy or nano indentation to evaluate strength of bacterial cellulose fibrils, (iii) load cells to test single fiber pull-out for interfacial shear strength to determine adhesion [190], as well as traditional load cell methods to test printed composite performance under tensile, bending, or compression loads.

**Biological Sensing**

Bio sensing data can be collected by a lighting system and a high-resolution camera. It can be analyzed via image processing software such as ImageJ.

*Figure 93: The WLOB operates at all scales to output hierarchical constructs closer to those grown by nature.*
4.5.9 FIM aspects in WLOB

In essence, the WLOB transfers **intelligence to the digital fabrication realm**, and emphasizes the collection of feedback during materialization of designs. Feedback would be here achieved by combining living and non-living machinery able to sense, produce, template, and enhance matter. Interestingly, the FIM diagram of this research is understood not as a single one with a starting model where the designer operates, but as a set of diagrams, one in each living cell, one in each fabrication sensor, one in each digital fabrication end-effector. Here MODELS are connected, and each one is able to compute and transfer INFORMATION to effectively monitor, evaluate, and modify FABRICATION parameters and actions autonomously. Perhaps transcending the need of a process protocol, and surely challenging the traditional linear step-based flow of design-to-production implementations (Figure 94).

![FIM Diagram](image)

*Figure 94: FIM in WLOB.*

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MODELING in WLOB

Digital environments that are, not only aware of physical world constraints, but also able to design with physical world media, scales, and variables, can enable unforeseen levels of invention. Design can become hierarchical in essence, from genes and molecules, to matter and structures. Namely, a model within which material at different connected scales could perform; (a) gene editing in cells for useful reporting on or alteration of matter, (b) design of molecular production to change material properties, (c) induction of extra-cellular matrix tuning for further differentiation of cells into local needed functions, (d) description of chemical composites for regional needs of optical, mechanical and structural capacities, while (e) in parallel, it could introduce environmental maps specific to site informing distribution of properties, for (f) a global condition or shape, derived from (g) other shading, tension, compression, flexibility, decay, or porosity needs in a construct.

INFORMATION Feedback in WLOB

Feedback is key and can be implemented throughout scales in (1) monitoring integrity for macroscale structural design, or (2) informing layering or deposition for mesoscale hierarchical matter design, and (3) sensing and validating microscale bio-enabled new function design. In an implementation scenario, a dual robotic arm head could compose and extrude material blends via an on-board “MAT SCI LAB”, and bacterial cultures with nutrients and environment control could be deposited with an on-board “BIO LAB” (Figure 93).

FABRICATION in WLOB

Digital fabrication machines and devices in WLOB are able to sense, respond and inform their own models, so that new fabrication actions can be executed in response via inner routines and computation without a need for a centralized model. An example of bio-sensing enabled digital fabrication within a FIM workflow can gather material state feedback (Figure 1). Genetically engineered bacterial sensors can be embedded within extruded materials, and can sense a useful parameter to the presence of which they can respond with fluorescence (GFP). The wavelength change can be captured by an on-board UV light and camera and the collected data can inform the platform to alter fabrication parameters such as: layering, air pressure, speed, etc. (Figure 95)
FIM Outlook for WLOB

This project points towards a deeper approach of FIM where the virtual model is extended in dimensional representation and data integration by including synthetic biology. Information feedback will come from multiple levels of resolution, such as tracking the state of material with living cells as well as modifying environmental cues through electro-mechanics. Finally, the intelligence in digital fabrication will be increased by biological and technological co-manufacturing.
4. OUTLOOK AND CONTRIBUTIONS

This thesis is about broadening disciplines and seamlessly connecting virtual and physical domains in digital modeling and fabrication workflows. By doing so, the media and scales of design must transform to accommodate data sets, constraints, and parameters from biology, chemistry, physics, manufacturing, and engineering. The design-to-production environment becomes an integral microscope with many lenses to analyze and synthesize matter, unlocking transversal relationships through multiscale and multidiscipline information maps.

The work presented here confers digital Fabrication with renewed value by transferring intelligence to it at the forefront of the design process and not after geometries are derived. This has proven to, not only output more sustainable designs in terms of use of energy and resources, but also more multilayered proposals accounting for parallel constraints and paradoxically enabling higher freedom in FIM projects.

The dynamics of Information in case studies has powered scenarios in where design and digital fabrication have been driven by chemistry, agency, decay, biomechanics or anisotropy, deriving constructs with un-prescribed sophisticated aesthetics and performance. Even if results could be now re-produced by off-the-shelf systems available today, no platform integrates required features. Modeling tools would need to be hacked, customized, partly re-written, and forcefully connected to bypass stiff file formats, descriptive kernels, and backbone assumptions to establish a coherent flow of information and feedback among them.

For instance, computer-aided modeling environments are able to compute shapes that we cannot imagine, and even provide with optimized families of solutions for the designer to choose from, but no chemical or biological dimensions of design can be harnessed and operated upon.

The thesis contributes to today’s great room for improvement in digital design and fabrication. Involved production machines are still tools that obey modeled instructions. Instead, they could gain intelligence by, as a first step, collecting, learning from and suggesting parametric combinations for specific designs (in, for instance, geometric tolerances, air pressures, motion speeds, humidity and temperature levels, or nozzle and bid sizes). From there, little by little fabrication would participate in the design process, becoming responsible for a much-needed merger of all disciplines.

With FIM I aim to contribute to the field of digital design and fabrication by enabling feedback workflows where materials are designed rather than selected; where the question of how information is passed across spatiotemporal scales is central to design generation itself; where modeling at each level of resolution and representation is based on various methods and carried out by various media or agents within a single environment; and finally, where virtual and physical considerations coexist as equals.
FIM's Public Contributions
My dissertation research has contributed to the field of Digital Design and Fabrication with twenty peer-reviewed publications, two patents, three full-scale prototypes, six public exhibits, two research platforms and several grants.

Platforms:
“Water-based Fabrication Platform” as a design and manufacturing tool that bridges the gap between physical and virtual domains from concept to fabrication and back, rendering experimental design processes material- and machine-aware.

Full-scale Prototypes:

Public Exhibits:

Group Grants and Honors Awarded:
Grants: TBA-21 Academy, GETTYLAB, MIT Seed, QuestAI, MITSkoltech.
Honors: STARS Prize Honorable Mention for Water-based Fabrication, ArsElectronica Festival in 2016, Mediated Matter Emerging Voices Award as team member, The Architectural League of NY 2015, Design and Content Awards for Poster Presentation as team member (Ortiz Lab & Mediated Matter) – 1st Prize and 3rd Prize in 2014.

Patents:
2019 “Methods and Apparatus for Parametric Fabrication”, Application number 16260124, Josh Van Zak, Jorge Duro-Royo, Andrea Ling, Ye-Ju Tai, Nicolas Hogan and Neri Oxman.
Peer-reviewed Publications:

2019  Aguahoja 2: Functionally Graded Architectural Biocomposites
2019  Designing (for) Decay
2018  Fabrication-informed Multi-Functional Anisotropy across Length Scales
2018  Aguahoja 1: Designing a Tree, Fabrication Informed Structural Behavior
2017  Parametric Chemistry: Reverse Engineering Biomaterial Composites
2015  Towards Fabrication Information Modeling (FIM)
2015  Designing the Ocean Pavilion
2015  Form Follows Flow
2015  Modeling Behavior for Distributed Additive Manufacturing
2015  Physical Feedback in Fabrication Information Modeling (FIM)
2015  Towards Fabrication Information Modeling (FIM)
2015  Flow-based Fabrication
2014  Water-based Robotic Fabrication
2014  MetaMesh: A Hierarchical Computational Model for Biomimetic Armor Surfaces
2014  Towards Swarm Printing
2014  Hierarchical Computational Model for Biomimetic Armor Surfaces 2
2014  Silk Pavilion: A Case Study in Fiber-based Digital Fabrication
2013  Hierarchical Computational Model for Biomimetic Armor Surfaces 1
2013  Biological Computation for Digital Design & Fabrication
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