A MULTI-SCALE WORKFLOW FOR DESIGNING WITH NEW MATERIALS IN ARCHITECTURE: CASE STUDIES ACROSS MATERIALS AND SCALES

Case studies across materials and scales

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Abstract. In this paper, we present a workflow developed for designing with and scaling-up new materials in architecture through an iterative cycle of materialization and testing. The framework establishes a connection between design requirements and form, taking advantage of different scales in new materials known as micro, meso, and macroscale in the process of design/manufacture. Different scales when dealing with material systems-especially in those that possess some level of uncertainty in their behavior from the formation process-make it challenging to deal with the different material variables controlled at each scale. This paper presents a brief review of existing design workflows centered on material properties. We then discuss case studies and argue for a multi-scale approach for design. Finally, we present the workflow. By implementing the workflow on two case studies, we answer how we can include material scales and their embedded properties as the central part of the design/manufacture process to aid in implementing new materials in architecture. The case studies are a responsive skin system and a free-standing tensile structure incorporating 3D printed wood filament and knitted yarn as the primary material.

Keywords. Material computation; material-based design; wood 3D printing; knitting; multi-scale workflow.

1. Introduction

With the development of new materials in textile design, material science, and related disciplines, architects have become increasingly interested in a material-centered research approach for incorporating new materials at an architectural scale. Researchers argue that the advent of digital design and fabrication has enabled the integration of structure, material properties, and form in novel computationally enhanced processes (Vazquez and Duarte, 2019). Nevertheless, incorporating new architectural design materials and scaling them up to the building scale is not without its challenges.

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One of the challenges is transferring material knowledge from other fields into architectural design. The challenge comes from the fact that different material scales exist: micro-, meso, and macroscale that have corresponding material behavior. The translation becomes even more challenging when designing with materials that possess some level of uncertainty in their behavior derived from material formation processes. Furthermore, the area of expertise of these different disciplines also varies in scale. While material scientists are usually concerned with the configuration of materials at a microscopic scale, architects are used to dealing with measurements from millimeters and up. This paper forms part of a broader research agenda concerned with leveraging material knowledge from other fields and successfully translating them into architectural design. From the micro-scale of material making to the macroscale of architectural elements, there must be a coherent material logic to take advantage of new materials' embedded material properties. This paper formulates a multi-scale workflow for designing and scaling-up new architectural design materials through an iterative making cycle of materialization and testing, considering the making process an informative asset of designing with new materials. The workflow is derived from a review of the theoretical approaches of material-centered design in the literature and the critical examination of existing research in textiles and additive manufacturing that identifies strategies and multi-scale approaches.

The first section of the paper describes the theoretical design models that argue for a material-centered approach that favors the emergence of forms from the material properties. We then identify design and manufacturing strategies in the literature on textiles and additive manufacturing, where we argue for the need of a multi-scale approach. In the following section, we present a workflow for incorporating and scaling up new architectural design materials. Finally, we examine two case studies incorporating the previous section's workflow. The first case study is developing a responsive skin system by 3d printing a wood-based composite material. The second case study aims to create a free-standing tensile structure using a knitting technique and fibers. In the case studies, the starting points are a filament for 3d printing and a yarn. By comparing the iterative development cycles of both case studies, this paper describes a workflow in which the material's characteristics across the scales are used to articulate fabrication, design, and functional material properties.

2. Background Studies

2.1. MATERIAL-CENTERED DESIGN

This section reviews theoretical approaches of material-centered design to set the foundation for a workflow centered around material properties across scales. (Oxman, 2010) introduces a theoretical approach called Material-based Design Computation, where the form results from material properties and their structuring according to performance requirement. The design methodology that emerges from this theoretical foundation is called the Variable Property Design environment (VPD). This methodology is associated with the modeling, simulation, and fabrication of the materials corresponding to the variable functional constraints. The model presented by the author is abstract enough that researchers can apply it to design with materials at different scales and with other requirements. The author presents a generalizable approach where the form results from several interrelated material variables.

Similarly, (Ahlquist et al., 2013) introduce a framework for design and computational thinking for complex material systems. Their framework, shown in Figure 1, illustrates how computational rules and material logics are generated through the physical prototyping and discrete experimentation of practical methods and simulations. In the framework, one can identify two levels that appear to refer to different scales, the left-hand side that contemplates discrete experiments at a smaller scale and the right-hand side that prototypes at a larger scale. On the left-hand side, the framework considers that combining experimental methods such as manufacturing and simulation studies allows researchers to understand material behavior. At the right-hand side, the framework describes prototyping at a larger scale by developing spatial material systems. The authors consider the approach to be iterative, where material systems are developed in increasing complexity levels, as new material parameters and rules are established.

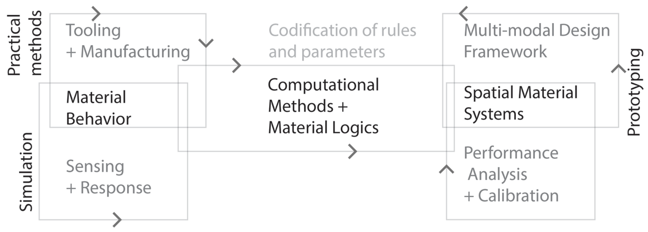

Figure 1. A material-based framework. Redrawn from (Ahlquist et al., 2013).

2.2. DESIGN FOR MANUFACTURING

Additionally, several design methodologies developed for additive manufacturing (AM) could inform design approaches for new materials in architectural design. Design for additive manufacturing is a well-consolidated field of research that seeks to take advantage of this novel manufacturing system. In this context, the structures are designed considering the possibilities and constraints of additive manufacturing methods, informed by the process and material properties. An example of an AM design methodology is proposed by (Yang and Zhao, 2015), summarized in Figure 2. The authors present a design workflow that considers the correlation between functional requirements, manufacturing constraints, and physical attributes, incorporating process knowledge and structural optimization into the design for better performance and functionality. One drawback of the proposed model is that it does not consider the design feedback loops at different design stages. Nevertheless, the workflow presents insights into designing a new manufacturing process, designing for this novel material process. A similar approach could be implemented when designing a novel material, where some comparable steps and constraints can shape the process.

Thus far, we have discussed three theoretical approaches that provide insights on a methodology for designing with new materials in architecture. Oxman (2010) sets the basis for a material-based design, where material properties and functional requirements are a priori of any shape or form. Ahlquist et al., (2013) present a methodology for a complex material system, identifying two scales of action and an iterative process. Finally, we discussed how design methodologies for a novel manufacturing process such as AM provide design requirements to take advantage of the material process's opportunities. One aspect of designing with novel materials that we want to address in this research is the existence of different scales that designers and researchers must consider to take full advantage of the new material.

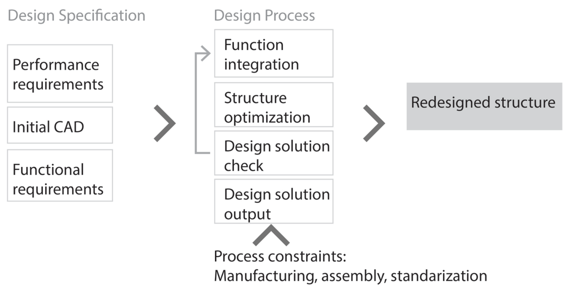

Figure 2. A design-based AM methodology- Redrawn from (Yang and Zhao, 2015).

2.3. CASE STUDIES: IDENTIFYING STRATEGIES AND MULTI-SCALE APPROACHES

In this section, we explore some strategies applied for integrating new materials at different scales related to AM and knitted material in the industrial, textile, and architectural fields. By analyzing the existing research on these two materials, we intend to extract common strategies for introducing new materials at an architectural scale.

Knitted textile material has been a dominant material in the garment industry for many years; however, knitted textile and the knitting technique are new material and processes in architecture. One of the advantages of knitted materials is that the knit's unique structure allows integrating other new materials into their structure and offers many architectural application opportunities. Additive manufacturing processes have also started to permeate architectural practice in recent years; the process allows for the generation of unique complex shapes and the introduction of new materials to architecture. Architects can utilize novel materials in building construction with the various AM technologies such as thermal processes and material extrusion.

There are three interconnected scales associated with AM materials and knitted textiles, namely micro, meso, and macroscale. In most studies, explorations on the material's behavior and characteristics are restricted to the mesoscale due to the manufacturing, simulation capabilities, and cost limitations. Manufacturing limitations refer to the size and volume restrictions that the machines themselves have. At the same time, computational capabilities limit the accuracy of digital studies that can simulate material behavior.

In terms of scale, while textile designers mostly focus on the micro-and mesoscale properties of the knitted material, architects are typically concerned with applying the material at a macroscale. At the micro-and mesoscale, researchers usually investigate material properties from a small patch of the material. For example, the correlation between textile opacity and shape change of the material under the specific load is studied for a small textile piece by (McKnelly, 2015). In their study, a simplified mesh-based method is also introduced for the digital simulation of knitted textile material's overall shape. Similarly, (Çapunaman et al., 2017) illustrate scaled-up material properties at the mesoscale for a given general form using the crocheting method. The study explores the effect of a single material variation in the overall geometric result, touching upon the micro-scale (yarn thickness) and mesoscale (patch size). Along those lines, (Baranovskaya et al., 2016) explored the correlation between the material's local and global characteristics. The authors developed rules for top-down and bottom-up approaches to design pattern configurations. The study illustrates how researchers can utilize rules at different scales to transition from one scale to another.

Literature shows that two strategies have been implemented so far to study knitted textiles. The first is prototyping at the mesoscale by architect designers to learn about the behavior of the material. This approach also entails modeling the textile's exact shape and structure comprising the loops, their intersection, twist, and mechanical characteristics of the yarn and textile itself by textile designers to investigate the textile's structural performance. The second strategy is to incorporate digital simulations and substitute stitches with simple mesh geometries to implement the material in large-scale and complex architectural forms.

Similar issues of scale arise when designing AM processes for an architectural scale. For instance, (Hojati et al., 2018) discuss challenges in designing toolpath for concrete printing, considering the mixes' rheological aspects. Explorations at the toolpath level, which can be regarded as the meso or even micro-scale, are typical among concrete printing research. (Ashrafi et al., 2020) develop an experimental study at this scale to predict the deformation of material at different layers in concrete printing. The careful analysis and design of toolpaths for additive processes are at the core of current research in the area, which indicates the multitude of scales in introducing printed materials at the building scale.

Another research approach into additive manufacturing for architectural purposes consists of producing prototypes at the mesoscale, in a feedback loop that improves the manufacturing systems' accuracy. For instance, (Craveiro et al., 2020) present a method for printing functionally graded material and demonstrate their system by printing functionally graded parts. The research also delved into a different scale. While imaging analysis software analyzed cork particles' presence in the prototypes at the micro-scale, 3d scanners captured the printed geometries at the mesoscale to compare them with CAD models. Researchers have also recognized that different problems occur at different scales. Small-scale prototypes can provide insights for mesoscale toolpath design considerations, but full-scale constructions present their unique challenges (Ahmed et al., 2016).

The studies discussed in this section highlight the need to develop a framework that considers the different scales involved when introducing new materials to architectural design. New materials processes such as knitting and additive manufacturing entail thinking not only on the overall shape-but also on the mesoscale of the patterns or toolpaths and the micro-scale of the material. Knitted materials and AM processes are similar because the knitting pattern or the toolpath configuration determines the micro and meso scales. Also, the geometries at different scales that have their unique representation strategies: At the macroscale, geometries can be simplified into meshes, at a meso and micro-scale, lines and paths represent the manufacturing coordinates.

3. Proposed Workflow

This section proposes a design workflow that builds upon the available frameworks in material-based design systems while adopting a multi-scale approach. We emphasize the role of material properties at three micro, meso, and macro scales as the core part of the design-manufacturing process when dealing with new materials and their implementation in architecture. Therefore, the proposed framework establishes a connection between requirements (material performance, function, aesthetics, etc.), form, and scale. However, the non-linearity between architectural requirements and structural performance and the uncertainty of material behavior at different scales makes the implementation of the new materials more challenging. This is why the proposed framework reflects the non-linearity through feedback loops in the process.

The workflow comprises two main directional processes, design and manufacturing. In the design direction, the main concern is about applying the material at the macroscale for an overall shape and architectural scale. Designers are typically concerned with the application aspect of new materials; consequently, these applications require thinking about form and function at the architectural scale. Therefore, the direction of the design process is shown from the macro to the micro-scale. In the manufacturing direction, the focus is on the smallest units of the material, determining the material's properties at the other scales. This is why the manufacturing direction is shown from the micro-scale to the macroscale. The three scales of material characteristics known as micro, meso, and macroscale are interconnected and embedded elements at the center of the workflow. Digital simulation and physical modeling are also considered as strategies in the workflow. While these can be applied at different scales, physical modeling is a strategy that can inform initial explorations at the micro and mesoscale and increment in size with the iterative loops. Additionally, digital modeling and simulation can inform initial studies at the macroscale to speculate on different applications' full-scale appearance with the new materials. The correlation between the main elements of the proposed workflow is presented in Figure 3.

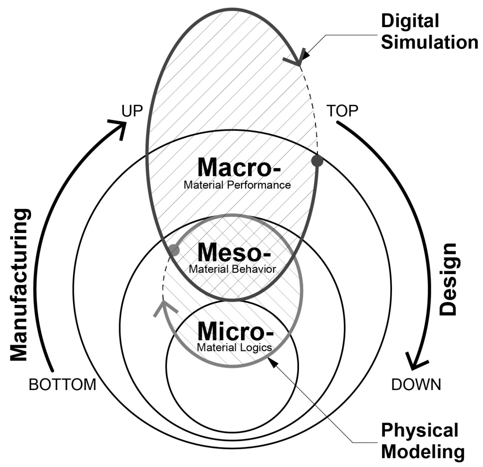

Figure 3. Proposed multi-scale workflow for design and manufacture with new materials in architecture.

The starting point for researchers can be at any of the three scales. One option starts from the mesoscale, which is placed between design and manufacturing. At this scale, one can identify material rules getting informed from other scales. Here a top-down approach will entail thinking about the full-scale form. At the same time, a bottom-up study will explore the material logic and material behavior at the micro and mesoscale and build up from there. At this step, the making process is a principal tool of discovering and characterizing material properties. The emergent shapes, forms, and material behaviors through the making process help categorize the rules that satisfy the macroscale requirements.

4. Case Studies

This section shows how we implemented the multi-scale approach in two case studies. The two case studies are a responsive skin system and a free-standing tensile structure that incorporate 3D printed wood filament and knitted yarn as the main material. Table 1 shows the details related to the 3D printed wood filament and knitted textile characteristics and structure. It also shows material/design/manufacture variables related to the material properties and material formation that can be controlled at different scales. For a more detailed discussion of the case studies themselves, readers can refer to previous studies on hydro-active skin systems (Vazquez et al., 2020)

As illustrated in Figure 4, by having the first imagination about the overall form, one can experiment with the mesoscale's material behavior (step one). Explorations at the mesoscale will be informed by performance analysis results and design requirements at the macroscale (step two). To satisfy the macroscale requirements, we change and manipulate the micro-scale's material variables to develop a new material configuration with specific characteristics at the mesoscale (step three).

Table 1. Variables of Material/Design/Manufacturing for case stidies.

	Microscale	Mesoscale	Macroscale
Characteristics			
Knitted Textile Structure (Outdoor Hypar Canopy)	- One loop/ Stitch	- Combination of loops for a piece of fabric/ pattern generation	- Combination of knitted pieces in a specific pattern to construct overall Hypar form
3D Printed Shading (Responsive skin system)	-Toolpath design for a single layer	-Combining layers of toolpath design within kirigami geometry	-Repeating unit in a specific pattern to construct a skin system
Variables			
Knitted Textile Structure	Materials: Yarn type (thickness, elasticity, strength) Design: Type of stitch Fabrication: Tension, speed	Design: Adjacency of stitch types (Patterns), looseness and stiffness, the distance between stitches	Materials: Connection between pieces (with joint or seamless) Design: Sequence of knitting, boundary shapes, and size
3D Printed Shading	Materials: filament type Design: bead distance, toolpath geometry Fabrication: printing settings (temperature, speed)	Design: Layer count, layer distance, geometry type.	Materials: connections and frame materials. Design: Number of units, gradients between units, connections, attachments, frames.

For example, in a free-standing tensile structure, we understand that we need to control the knitted textile's strength at the edges and around the support points against the strain from the form-found and structural analysis models. Additionally, displacement of the structure under the load requires to have a material that resists unusual displacements. Having this structural information from the overall form's critical analysis, we examine the material's behavior at the mesoscale for different pattern types and different knitting directions. There are multiple possibilities of developing patterns when choosing stitch types at the micro-scale and manipulating their adjacencies at the mesoscale. However, we systematically narrow our design space to the options aligned with the overall design and manufacturing requirements. In addition to the structural performance, other architectural requirements must be met as well. The process can be iterated multiple times to develop various patterns with determined characteristics that satisfy multiple requirements. The macroscale product could be a seamless knitted structure with different patterns, opacities, and direction of knitting at different structure sections.

In the responsive skin system, the mesoscale's starting point is to characterize the shape change of the hydro-active material to satisfy a daylight requirement at the macroscale. By conducting a series of experimental studies at the mesoscale, one can determine the effect certain variables have on the shape-changing behavior and study the use of different geometries to design the skins. These variables at the micro-scale, such as bead distance in the toolpath design, significantly affect the hydro-active response. Therefore, we can systematically study the effect these variables have in samples constructed at the mesoscale to select which of these variables can be optimized. Moreover, the experiments conducted at the mesoscale studied kirigami geometries' potentials in amplifying the shape morph of the prototypes. Simultaneously, daylight analysis informed the mesoscale's explorations by providing performance information on how the shape change should be. Table 1 summarizes the material, design, and manufacturing variables for both case studies at the three scales.

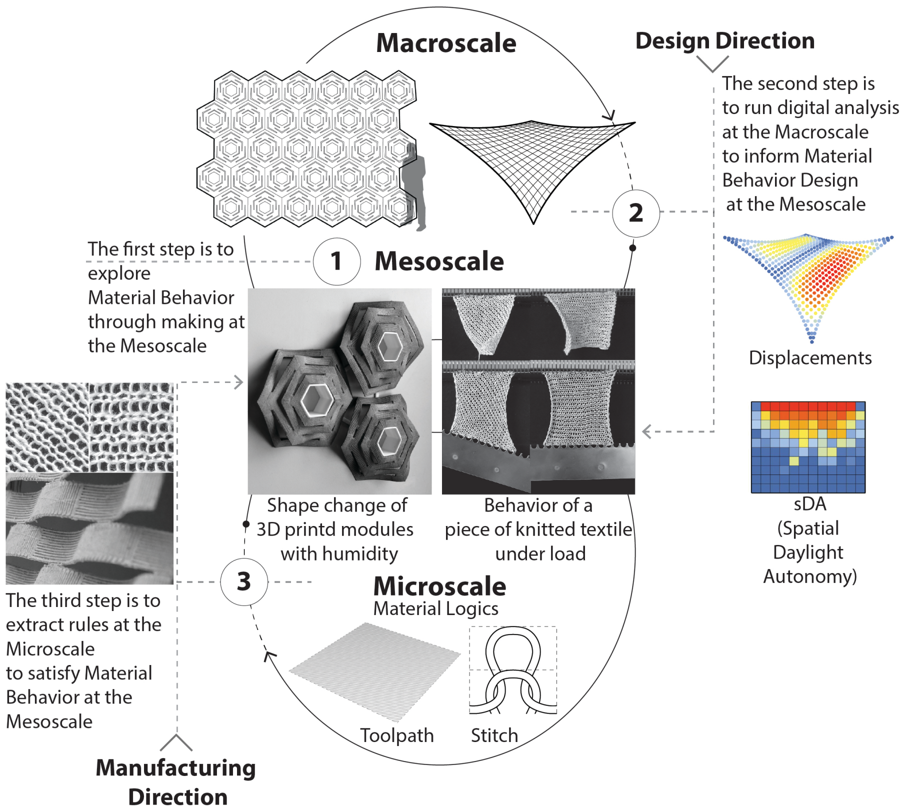

Figure 4. Case studies: 3D printed shading system and knitted Hypar tensile structure.

5. Conclusion

The application of new materials in architecture comprises the integrated design process with the new materials and design of material behavior itself. However, uncertainty in the behavior of new materials at different scales makes it difficult and unpredictable when we apply them in developing architectural forms. In this research, we introduced a multi-scale workflow to enhance the integration of new materials in architecture. The main elements of the proposed workflow are: design/manufacturing requirements, form, and scale. The three material scales are known as micro-, meso-, macro, which sit at the center of the workflow. We showed how we can systematically control and introduce new materials to the architectural scale through an iterative process of manipulating, making, and simulating within two case studies. The process entails the manipulation and creation of new material logics at the micro-scale, the emergence of the new material behavior during the formation process at the mesoscale, and the translation of that behavior into a digital environment at the macroscale. The framework developed in this research is general enough to be incorporated at the first steps of design and manufacturing with other new materials that possess uncertainty in their behavior for developing architectural forms. However, it should be mentioned that there is no restriction in categorizing the three scales of new material as we did for knitted tensile structures and wood 3D printed responsive skin. Even in case studies introduced here, a mesoscale in one project can be macroscale in another project. The important point is to take advantage of the three scales in a way that helps designers control mesoscale behavior by manipulating microscale characteristics of the material for a macroscale performance.

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