MATTER, MATERIALIZATION, AND BIOMATERIAL FUTURES

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The material landscape of architecture is shifting. Architects are increasingly engaging in material systems design, no longer relying on mere specifications to address the materialization of architectural form. All the while, the climate crisis demands that the field develop new solutions to reduce energy consumption and forces us to reckon with the carbon footprint of the materials that make up our built environment. As a result, designers are often developing materials that are bio-based, utilize waste feedstocks, or water-based formulations to keep carbon costs to a minimum. By stepping away from industrialized materials, material behaviors, such as warping, shrinking, and curling, have re-entered the fabrication process and must be contended with. Furthermore, living materials disrupt any notion of determinism or "specification" and instead must be cared for and catered to guide the organisms towards desirable outcomes. New methods for robotic fabrication suggest ways that material realities may be fed back onto the design process, enabling new material expressions, and suggesting a shared design agency through adaptive construction methods. These developments defy the hylomorphic hierarchies of form and matter that have been present in architectural production since the Renaissance. Here, we will investigate how novel biomaterial systems are challenging existing practices of materialization and the nature of matter in architectural design.

Keywords: Biomaterials, bio-fabrication, robotic fabrication, cyber-physical systems, new materialism.

1. CLIMATE FUTURES AND BIO-MATERIALITY

The inescapable reality of the climate crisis is starting to materialize in our present moment, supplanting years of pessimistic projections and warnings that we should be doing more, but failing to communicate the consequences adequately. We can now watch through the media or our very eyes as landscapes burn, hurricanes batter and flood more frequently, coral reefs bleach, and heat and drought begin to displace vulnerable populations from increasingly unlivable regions. Architecture and the built environment play an outsized role in this drama – up to 40% of global carbon emissions may be attributed to the built environment (Abergel et al. 2019). While reducing energy consumption has been the topic of much research for the last 20 years, the UN Environment Programme recently published a report finding that 11% of global carbon emission can be linked to the extraction, manufacturing, and transportation of construction materials (Abergel et al. 2019). This embodied carbon energy constitutes a significant portion of the total carbon costs of the built environment. Even when replacing an older single-family home with a new, more energy-efficient one, it takes an average of 50 years of energy savings to repay the carbon costs associated with its construction (Frey, Dunn, and Cochran 2011). This predicament has led some architects, in what can only be understood as a sort of professional suicide, to reconsider whether we should build at all (Idenburg 2011; Malterre-Barthes 2022). However, the demand for new housing alone is set to rise in the next 30 years, as the population will reach 10 billion by 2050, and the global household size is trending downward. As a profession, we need to interrogate how we build and the materials we build with to reduce the embodied carbon footprint of our built environment.

While the 2000s saw a surge of interest in sustainability in architecture, that interest waned throughout the 2010s but is finally starting to see a resurgence. An example of this new generation of climate-focused researchers is Phillipe Block of ETH Zurich's eponymous Block Research Group. One of Block's research agendas as a structural engineer focuses on reducing the amount of concrete used in multi-story constructions by re-engineering the concrete floor slab to save weight and material. Compared to a typical floor slab, the BRG slab saves up to 70% of the material, close to one-third of the building's entire structural mass (Block et al. 2020). Block's critical insight is that, while it is much maligned for its high total carbon footprint, the problem with concrete is not so much with the material but the way we use it. Measured by weight, concrete has quite a low carbon footprint. However, to save on the financial (and, to an extent, environmental) cost of formwork, we design blocky, standardized slabs and beams with concrete containing excess weight and material, which drives up carbon costs.

While concrete's carbon footprint is only low compared with steel, plastics, and other industrialized materials, biomaterials are attractive because the original biological organisms that comprise them function as a carbon sink, absorbing carbon from the atmosphere naturally through photosynthesis. Some biomaterials even reach carbon negativity, sequestering more carbon during their lifespan than is required to produce the building material. However, the balance can be tenuous. Trees raised in responsibly managed forests have time to sequester enough carbon to make their wood products carbon negative. In contrast, wood from poorly managed forests is typically carbon positive, having its negative carbon balance overtaken by kiln drying and transportation costs (Law et al. 2018). In addition to the use of wood and other species as a dimensional material, scientists have made significant progress in replacing the petroleum-based compounds used for plastic production with bio-based feedstocks. Bioplastics can replace their petroleum-based counterparts in a 1:1 manner but feature a lower carbon footprint. They have even been used to manufacture high-performance applications, such as automotive parts (Mohanty et al. 2018). However, due to their extensive chemical processing, these bioplastics will never reach carbon parity, and many are not compostable or degradable.

New advances at the intersection of material science and synthetic biology have recently unveiled new biocomposites that leverage synthetic chemistry and biology in collaborative ways. Scientists have begun to look to smaller and smaller biological units as their feedstock to construct new material systems from the bottom-up. As an example, researchers have constructed bulk materials by condensing individual tobacco cells into stock forms through compression molds (Roumeli et al. 2022). The new approaches of bio-fabrication and Engineered Living Materials look past the simple harvesting of biological feedstocks to begin to develop ways in which biological processes might form, assemble, or bind the material itself or deliver new functionalities (Nguyen et al. 2018). Mycelium is a classic example of this concept, as the living fungi are grown in place to bind together loose fragments of cellulose-rich plant material into a usable product. Researchers are also pursuing this work at the nano-to-micro scale by using micro-organisms. Bacteria have been introduced to grow self-reinforcing, nano-scale cellulose networks within a 3D printed material system (Schaffer et al., 2017). Furthermore, other biological organisms may be included in the material to impart novel, ongoing behaviors through their metabolic functions, such as the destruction of Volatile Organic Compounds (VOCs) in the air.

Many architects and designers have started to engage in the process of bio-material design, exploring new material systems with low-to-negative carbon footprints. However, fabricating with biomaterials—or in the case of bio-fabrication, living materials, such as mycelium—presents unique technical challenges and forces us to question many long-standing notions of the relation between matter, design, craft, and materialization. Many biomaterials express unique characteristics from individual to individual, have variations in mechanical properties based on their growing conditions, or are acutely sensitive to environmental conditions at the time of fabrication. Living materials disrupt any notion of determinism or "specification" and instead must be cared for and catered to guide the organisms towards desirable outcomes. From a technical standpoint, these materials' behaviors must be accounted for in the fabrication process in ways that are difficult to predict or simulate. In this way, living and biomaterials undermine the Aristotelian notion of inert matter that has largely underpinned architectural discourse for centuries and instead hews closer to a Ruskinian material dynamism that supports his ideals of craft-based construction.

Next, we will show how these biocomposite materials, which represent an important tool to combat the climate crisis, give us a clear opening to reconsider materiality in the built environment. The issues of craft and materialization in the digital era will be investigated through the lens of active materials.

2. ON CRAFT, MATTER AND MAKING

2.1. MATERIALIZATION, REPRESENTATION, AND ERROR

The first aspect of design and construction that a heightened mode of material dynamism disrupts is the materialization of design. Since Leon Batista Alberti developed our current model of architectural authorship based on drawing, the materialization of those drawings—our construction and fabrication processes—has been siloed from the design process (Carpo 2011). Alberti's distinction between building and design had far-reaching implications, first and foremost, that construction processes relied on information to be encoded and decoded through the form of orthographic notation. For Alberti, the design of the building found on paper and the physical building itself are notationally identical to bestow the authorship of that building onto the architect. Alberti renders the architect as someone who can "project whole forms in mind without any recourse to the material" (as cited in Ingold 2013). Thus, from Alberti forward, design is transformed into an immaterial act.

The immateriality of design is reinforced by the nature of the notation system that the architect hands to the builders. The orthographic drawing set features only geometric information. Achim Menges argues that building based on geometric notation alone has two effects—it renders the material as a passive recipient of form and understands construction as merely the materialization of a wholly pre-designed product (2015). Tim Ingold's interpretation of this paradigm is that "The architect, then, conceives the lineaments of the structure, while the builder's task is to unite the structure with the material." (2013). This separation raises the question, what is lost when an architect is not forced to contend with the dynamism of the material world?

Francesca Hughes sees the distance that architects keep from the materiality and building processes as the critical driver for their obsession with precision, and its opposite, error. For Hughes, dimensioning a brick wall to six decimal places when the workers are bound to be wearing heavy gloves to assemble it speaks to a desire for a level of precision or control that was never possible (2014). When the assemblies inevitably fail to meet this level of precision, the error is assumed to be from the material. This reinforces an Aristotelian view of the form-matter divide, where a pure form is to be comprised of a subservient material. The advent of digital technologies and CAD/CAM processes only reinforces this hierarchy as CNC machines offer extreme levels of precision to the designer. However, the precision of the machine does not equate to the precision of the part. Materials expand and contract with heat and humidity, often in dramatic ways. The material may also deform during the fabrication process—wood may chip or splinter during milling, or material may sag during 3D printing. The assumption that the level of precision offered by the software and by the machine will be perfectly translated to the material is a false one. As the High-Definition issue of AD explored through LiDAR 3D-scanning, the as-built conditions of our digitally fabricated assemblies always deviate from their idealized digital form (Sheil 2014). Even with industrialized materials, material behavior and the stubborn pull of gravity are forces to reckon with.

2.2. DIGITAL CRAFT

Thus, the notion of digital craft is currently rife with contradictions. While digital fabrication specialists often speak of their work in terms of craft, the reality of their methods represents a limited portion of the Ruskinian notions of craft. Ruskin believes that craft, as both a moral and aesthetic imperative, is in touch with and speaks to the dynamism of the natural world. An artisan takes cues from the materials they are presented and works through the material's particularities and tendencies, like the grain of marble or the tendency of wood to swell and curl when soaked. Lars Spuybroek, writing along the lines of Ruskin, insists that "we only have to sympathize with the technological tendencies present in matter itself" to reestablish both craft and a matter-oriented theory of ornament (2016). While Richard Sennett argues that nearly anything may be considered craft, he still states that craft is anchored in a tangible reality and is linked to the "intimate connection between the hand and the head." (2008).

On the other hand, there is almost no influence from the material on a traditional CAD/CAM process. For a standard CNC milling operation, the digital model is set into a generic solid that represents the stock material. As most CAD software platforms rely on the NURBS modeling paradigm, which simplifies all solids to only their boundary representation (more commonly referred to as a BRep), it is impossible to represent the material's interior structure in the software. Toolpaths are then generated over this homogeneous stock volume with minimal input about what kind of material is to be milled. Finally, the machine carries out these instructions in a pre-defined manner without any process feedback. The machine has no way to slow down as it approaches a knot in the wood, it cannot surmise if a part of the object is unstable and will flake off during the routing, and perhaps most damningly, the machine does not even know if it is contacting the material that it is attempting to mill. 3D printing operations can be similarly fraught, with no feedback to know whether the print is warping, sagging, or deforming as it is being constructed. As it stands, we have almost no off-the-shelf tools to incorporate material realities into a digital design or digital fabrication process. This digital fabrication model is a one-way process incapable of responding to the material condition and only projects pure forms onto it. Thus, our current digital fabrication workflows are designed exclusively for an abstract version of materiality—a materiality of generic sameness that is personified by the industrialized, homogeneous materials kept in stock at digital fabrication labs. Therefore, the notions of digital craft are the same pursuits of ever-higher levels of precision inherited from modernism, but with nostalgic overtones. Alberti's quote about architects projecting whole forms without recourse to the material is as true today as when it was written.

3. TO BIOMATERIAL FUTURES

3.1. WHEN MATTER IS NOT INERT

This lack of feedback from the real world into the fabrication process severely limits how we might fabricate with living and biomaterials. Many biomaterials being used in large-scale applications are water-based formulations, as they carry much lower carbon footprints than other bio-based materials, which are chemically cross-linked or encapsulated in a synthetic polymer matrix. Water-based biomaterials are mixed into a wet or slurry state and then condensed and dried into a structural material. These materials are especially popular as they can be easily amended to work in direct ink write (DIW) or liquid deposition modeling (LDM) additive manufacturing processes. During the fabrication process, the biomaterial will shrink as it loses water, but at rates dependent on the atmospheric humidity, the geometry of the part, and the biochemistry of the original organism. This shrinkage is problematic for any additive manufacturing process as the lower layers of the print will begin to shrink mid-print, potentially causing alignment issues with the upper layers. Additionally, differential shrinkage across the part can lead to cracking or misalignment with other parts in the assembly. Due to the competing factors and differences between material batches, it is incredibly challenging to build a model to predict how the biomaterial will behave during the fabrication process. Machine learning would be well-equipped to handle this challenge. However, machine learning models are only effective when they have been trained on thousands of samples, making the data collection process onerous.

Living materials are even more indeterminant in their bio-fabrication processes. Their growth is reliant on environmental conditions such as temperature and humidity, the availability of nutrients, and competition with other micro-organisms in the environment. While measures can be taken to assure constant atmospheric conditions and nutrient availability, gauging the health of the starter colony or the presence of other microbes is challenging in large-scale bio-fabrication. As a result, there is wide variability in the growth rates of living materials, which affects performance metrics down the line. Furthermore, bio-fabrication processes extend the threshold of what is typically considered the fabrication process. Monitoring and caring for living organisms are just as important as the forming process and knowing when a material is ready for harvest or has stopped growing can be a difficult judgment call as well.

However, these biomaterial systems can also be seen as only one example of active matter. The field of smart materials has been developing materials that act as either a sensor or an actuator in response to changing ambient conditions, as evidenced by the wealth of research investigating bi-layer materials that actively change shape. The dynamism of matter present in these materials calls for a new mode of materializing design.

Ultimately, we must recognize that the fault lies not with biomaterials or any other material that exhibits active, discernible behaviors but instead with our assumption that construction materials are comprised of inert matter. As anyone who has detailed an expansion joint will attest, this assumption has always been convenient but false. The prevalence of new biomaterials simply exposes the false assumptions that our fabrication systems are based on. This, however, is not an argument against digital technology nor a call for a return to handicrafts. Instead, we must find ways to translate material into information, such that the algorithms that drive digital fabrication technologies are not reliant on geometrical information alone. Through the transmutation of matter into information, we can develop advanced fabrication processes that upend the hylomorphic paradigm of form over matter.

3.2. NEW FORMS OF AWARENESS

Achim Menges laid the groundwork for a materially-aware computational construction model that he termed “cyber-physical systems.” (2015). Rather than the open-loop model wherein all machine instructions are pre-computed and followed unambiguously, the cyber-physical system creates a closed loop of information with a network of sensors. The sensors endeavor to give the fabrication process information on the workspace, materials, and progress of the assembly. This model uses information on the material to parametrically adjust process parameters, tool paths, and action sequences in response to the material realities. In this way, fabrication decisions are made based on the unique nature of the materials present in the workspace, and the process can account for divergences between the idealized assembly and the physical one. Menges also argues that the open-loop model avails the possibility of considering materialization as a generative part of the design process. In the cyber-physical model, the design can evolve as the process unfolds, holistically uniting design and materialization. This fabrication method is compared to Kostas Terzidis' distinction between computerization and computational design processes (2006). Computerization refers to the replication of manual tasks within a digital environment, while computational is the exploration of indeterminant processes.

One of the earliest examples of these closed-loop processes was by a team at the University of Stuttgart in their ICD/ITKE 2014/2015 Research Pavilion. The project robotically laid carbon-fiber tape on the interior of an inflated formwork until a rigid shell was formed and the formwork could be deflated and taken away. To compensate for inaccuracies and deflections in the inflated formwork, the team equipped the robotic end effector with a pressure sensor to know when they were in contact with the inflated surface and could start laying tape (Vasey et al. 2015). In this way, the robot has an awareness of the elements in the workspace, which it must be in contact with for a successful tape-laying procedure. Other research at Autodesk's Technology Centers explored how closed-loop robotic assembly processes might be brought to actual building construction practices by using computer vision to assist with the assembly of prefabricated facade panels. Equipping the robot with a 3D camera, it could locate the cladding elements for the façade in the workspace, select one of the available module sizes, and assemble the cladding into an unplanned façade pattern (Tish, King, and Cote 2020). While this project uses standardized materials, the process of materialization influences its final design.

New sensing regimes will need to be explored to transmit information about the biomaterial state to the fabrication process. 3D cameras can be used to monitor shrinkage or to check for material deformation during fabrication. Weight and moisture sensors are useful for monitoring water content during the process. Additionally, thermal cameras can be used to monitor drying as the surface temperature of an object will slowly rise from the dew point to the ambient temperature as water leaves the surface. New tools for monitoring living materials are yet to be developed. The timber industry uses technologies such as Near Infrared (NIR) spectroscopy, acoustic propagation, or even Computed Tomography (CT) scanning to nondestructively test wood elements or standing trees to estimate their internal density or modulus of elasticity (Schimleck et al. 2019). Similar techniques will need to be developed for living materials to test when growth networks of mycelium, for example, have reached their desired density or strength.

Adding living and minimally processed biomaterials further instrumentalizes the cyber-physical fabrication method by expanding the range of material behaviors to which the cyber-physical system may respond. Working with biological materials is not a determinant operation, but rather more a process of coaxing or guiding the materials into shape. A closed-loop process that can adapt and respond in real-time to the indeterminant nature of these biomaterials, to their whims and tendencies, is the only feasible way to fabricate with these materials. In future research, when other organisms are introduced that grow self-reinforcing networks or self-actuate in response to atmospheric conditions, the cyber-physical model becomes increasingly productive as the two intelligent systems may collaborate in the form of conversation. In this way, the cyber-physical model leads to a product that is the result of a shared agency between the designer, process, and material. With this model, we may finally reach the latent potential of a digital craft.

CONCLUSION

The reality of our climate crisis forces us to reconsider the industrial traditions and technologies that have brought us to this point. However, it is a mistake of the environmental discourse to focus only on what must be given up and on the necessary frugality. In what is admittedly a techno-optimistic position, there is much to be gained by developing novel biomaterials with low-to-negative carbon footprints. It is clear that a shift in how we conceptualize matter and materialization has already been underway through research on cyber-physical systems, one that can be expanded to encompass more types of material behavior. This research reframes computation as a method to explore materialization and matter, working with specific and dynamic notions of materiality rather than the abstract ones that were common during industrialization and in the first generation of digital fabrication. In many ways, biomaterials that exhibit a dynamic behavior do not change these conversations as much as they instrumentalize them. Cyber-physical systems may feel like an intellectual project when explored firmly in a realm of industrialized, homogeneous materials. Biomaterials, especially those that are used while still living, make the dynamism of matter inescapable, leaving no other choice than to cater to their whims and tendencies through a closed-loop fabrication method. What is critical is that our engagement in these new modalities of computational materialism occurs in support of efforts to solve our climate crisis. We may find promise in this future of increasingly hybrid conditions between the technological and the natural.

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