3D Print as Corporeal Design Medium

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Because it produces representational models, not full-scale architecture, 3D printing often supports the study of form, not architectural materials, structure and tectonics. This research asks how 3D printing can support material study and contribute to a process of design by making, similar to that achieved with mock-ups and other full-scale constructions. It clarifies the nature of design by making through an elaboration of key activities, and then shows how 3D printing can support each activity. The research includes a design experiment in which students used unique 3D printing techniques to enhance the experience of design by making. These techniques include 1) confronting a material foil, 2) embedding material placeholders in parametric models, 3) oscillating between representational and literal interpretations, and 4) using 3D prints as a corporeal medium. With these techniques, 3D printing offered a unique flavor of design by making, which can complement full-scale computer-aided manufacturing techniques.
1. INTRODUCTION
By the second half of the 19th century, the influence of industrial machines extended into the average home through a growing assortment of mass-produced artifacts [1]. As part of an early resistance movement, William Morris condemned machine production for severing the artisan from direct contact with materials [2]. Direct contact is lost when artisans conceive work through scaled drawings and models and then delegate production to a machine. By wedging abstract representation between an artisan’s imagination and the material outcome, iterative trial-and-error negotiation with a material product is replaced by rational planning [3]. Seventy years after Morris, Frank Lloyd Wright delivered his Princeton lecture “Machinery, Material, and Men,” which expresses a contrary view. Wright laments the artisan’s nostalgic desire for handcraft, and he urges architects to stop squandering opportunities made possible by the machine. He calls the machine “the modern emancipator of the creative mind” [4].

Digital simulation further emancipates abstract design methods by enabling the free play of geometry apart from the constraints of traditional scale drawings and models [5]. More than an enhancement of traditional media, however, digital simulation inserts a new layer of abstract representation between imagination and architecture. Because scale models are often still desirable, the translation from idea to reality now encounters two intermediary states, from imagination to digital simulation to scale model to full-scale architecture. This is not meant to suggest a linear sequence, but rather, distinct manifestations of a design, each possessing a unique degree of abstraction. As architects embrace digital simulation, the weight of their attention falls to the abstract end of the scale. Just as Wright and the Modernists embraced industrial production, architects now embrace computer simulation, along with the abstraction it entails.

According to Greg Lynn, increasingly abstract design methods are part of the natural flow of progress.

“…architects have always been, and will continue to be, mandated to operate with progressively increasing levels of abstraction in order to plan the outcome of material processes. This action at a distance on material form has been the perennial task of architects. It is in response to this necessity for abstraction that architecture’s repertoire of spatial, organizational and representational techniques has developed.” [6]

Even model-building materials possess physical limitations and a convention of use [7]. If architects fail to surpass these lesser modes of abstraction, they retain biases that promote a narrow view of architecture and undermine innovation. For the advocates of abstraction, computer simulation is a liberating medium.

Some resist the trend toward abstract design, and instead seek to reconnect conceiving and making. Rather than advocate a nostalgic return
to handcraft, they use Computer-Aided Manufacturing (CAM) techniques to streamline the flow between idea and reality, and to shift attention from abstract representations to the full-scale architectural product [8]. While a CAM design process often incorporates scale model-building, the influence of models is curbed, and preference is given instead to mock-ups, field tests or prototypes. The advocates of making warn that model-fabricating processes like 3D printing are impure substitutes for full-scale work, which leave architects still disconnected from the making [9]. Other than photorealistic rendering, no digital technology has been more criticized for supporting design in the abstract. Critics have recognized that in common use, a 3D print is a pure and pristine final product, made once at the conclusion of a design effort [10]. Used in this fashion, it faithfully translates a digital form into a material equivalent, unchanged by iterative material fitting and adjustment [11]. Consequently, a 3D print often acts as an “appearance model” used to study surface qualities rather than component assembly and other aspects of construction [12]. The materials used in 3D printing are highly refined, homogenous substances, purposefully characterless and pliable in order to maximize the range of allowable forms [13], [14]. Materials such as starch powder and liquid resin allow architects with an appetite for the abstract to forego the normal limitations of matter even as their formal diagrams are printed in matter [15].

2. THE CORPOREAL NATURE OF THE 3D PRINT
For the advocates of abstract design, the promise of 3D printing lies in this ability to 1) transcend the traditional limitations of material, 2) keep hands free of the sullied work of making, and 3) press architecture closer to a Rational ideal. Despite these affordances, 3D printing is a material process. This paper argues that with an alternative approach, 3D printing heightens awareness of materials and strengthens the process of design by making. Additionally, the paper argues that 3D printing is not a redundant or lesser means of design by making, as compared to full-scale CAM. 3D printing offers distinct creative values that complement full-scale efforts. This empirical potential has not generally been realized in 3D printing-based design research [10], [12], [15]. Some suggest this is due to an inherent bias in 3D printing technology, which inevitably diminishes material awareness during design activity [14], [16], [17], [18]. The research presented here resists this conclusion, instead pursuing the potential of 3D printing to foster creative insight in a manner akin to handcraft or full-scale CAM.

To demonstrate the first claim – that 3D printing can augment design by making – it is necessary to identify the distinctive attributes of this approach to design. Design by making incorporates three activities that distinguish it from design by rational planning. First, it incorporates a negotiation with materials [19]. This can be characterized as deference to the unforeseen limits of a material. Whatever their intentions or preconceptions, makers
pursue their motives tentatively, and adjust them incrementally to suit the natural inclinations of material. When material resists conformance to a preconceived idea, makers redouble their creative efforts. By adapting, they satisfy the material and fortify the idea. Rational planners, in contrast, design for pre-calculated quantities such as span, weight and expense, which are available from reference tables. This minimizes unforeseen incompatibilities between idea and material, and allows planners to disregard the subtleties of material resistance, which they leave for others to resolve in the field.

The second characteristic of design by making is the search for materials' unforeseen potential [20]. This is the inverse of the previous activity. While makers adapt ideas in the face of material resistance, they also follow paths of opportunity discovered through trial-and-error testing. Makers see material as a collection of latent possibilities, which offer surprise and inspiration. Rational planners, on the other hand, see material as inert substance, silent until imbued with their ideas. Finally, the third characteristic of design by making might be called corporeal thinking – the process of subdividing a material thing into interdependent systems and components.

The concept of corporeality is often used interchangeably with materiality, but there is an important distinction. Corporeality refers to material that is of or related to a body, consisting of flesh and bone, or something like flesh and bone. The concept includes a metaphorical aspect, which has roots in the doctrine of the Eucharist (corporalis), in which bread becomes or represents the body of Christ [21]. Corporeality has an anatomical connotation, referring to material subdivided into systems of interrelated parts, which though distinct, work together to produce a larger action or effect, as in a living body. Architecture can be thought of as corporeal matter because it too is segmented and heterogeneous while unified in function. Corporeal thinking acknowledges the need for a distinction and specialization of architectural parts, as well as a mutual effect. It observes and responds to the tension between parts, seeking to make them at once articulated and integrated. Corporeal thinking therefore involves an interest in tectonics. Just as corporeality defines a sub-class of materiality, corporeal thinking describes a special approach to tectonics. Corporeal thinkers see the joint as a generative force affecting the whole. Since the type and articulation of joints depends on the materials used, joints provide a vehicle through which the properties of materials shape the whole [22]. Rational planners also design joints, but for them joints play a pragmatic and subservient role. Planners' preference for pre-tested catalog details mutes the identity of joints and places them in the instrumental service of form-making.

These three activities of the maker – 1) negotiation with materials, 2) inspiration through materials, and 3) corporeal thinking – were pursued in the following design experiment, in which 3D printing played an integral role.
3. DESIGN EXPERIMENT

So far this paper has questioned prevailing notions of 3D printing as a tool of abstract representation. To understand the potential role 3D printing can play in a process of design by making, the paper identified activities that help give design by making its distinctive feel. Now the results of a design experiment are described, which further temper conventional wisdom about 3D printing. This atypical design experience shows 3D printing in the service of making, and sheds new light on techniques capable of producing this effect generally in the work of architects.

In a two week exercise, nine seniors and four graduate students each produced a conceptual design for a screen wall system. Four design process constraints were imposed. First, like any commercially available screen wall, the design was to consist of a set of components, which, when fastened together, created a repeatable and extensible screened surface. Second, the product of the exercise was a material model representing a portion of screen wall, which was contained in a light box of fixed size and shape (Figure 1).

A third constraint required students to incorporate two distinct types of components, which would interact in a single screen wall system. In the final model, one type would be made of wood, while the other would be made of starch powder solidified by a 3D printer. Despite this duality, students were required to create an integrated system, in which each kind of component physically attached to the other. Finally, students were required to make the printed components mass-customizable. These components should accommodate variable parameters, and each parameter should allow a range of incremental states. Students used commercially available parametric modeling software to accomplish this, as well as generative scripting.

These constraints pressured students to modify their habitual approach
to 3D printing, which favored rational planning over making. For instance, by introducing a set of wood components external to the parametric design process, students had to accommodate a direct physical interface between their digital work and a constraining material. To resolve this interface, students could not isolate design to a digital medium. Instead, they had to iteratively print preliminary parametric designs in order to empirically test joints between printed and wood components. The limitations of both materials required students to participate in a negotiation. In like order, students adopted all three activities characteristic of design by making. The following two sub-sections describe how this occurred.

3.1 Material negotiation and inspiration

As mentioned above, by combining 3D prints with non-printed material, students were motivated to get designs out of the computer for iterative empirical testing. Each student made an average of three generations of prints over a two week period. In each generation, prints were interfaced with wood components to test compatibility and effect. A reciprocal process followed, in which students channeled feedback from empirical testing into parametric design. Although oscillation between digital and material studies has been widely advocated [12], [23], this research suggests a different answer to the pivotal question of when to oscillate. Dorta offers a version of the usual answer: "The idea is to take out the information from the computer when it reaches its limits, to treat it by hand and with acquired techniques, and then to return it to the system in order to take advantage of visualization and form processing" [24]. The problem with this answer is that those with a propensity for rational planning have difficulty recognizing when a computer has "reaches its limits". Even those who appreciate the value of material testing can become preoccupied with the details of a computer simulation and stay there too long. The answer offered here to the question of when to oscillate is: The digital work should be organized so that architects feel a constant need to return to material testing. This greater impetus to oscillate was instilled through the use of a foil medium, which remained in a constant material state while a digital/material oscillation occurred in reference to it. In the screen wall experiment, the requirement to use wood components provided the foil. The imperative of interfacing with wood pressured students to oscillate frequently regardless of their natural inclination.

Working parametric components against wood components, students experienced material negotiation and inspiration. An example of both arose in the project of Dan Merkel (Figures 2 and 3). Dan began with a simple parametric arrangement (Figure 2, left). It generated a random distribution of node locations within a given volume, and then generated a set of linear spans between nodes. The nodes located 3D printed components and the spans located wood components (Figure 2, right). In an early empirical test,
Dan learned that the purely random distribution of nodes produced joint conditions that could not be accommodated by the thickness and tolerances of the wood. When the angle between intersecting spans became too small, wood members crowded each other (Figure 2, middle). Dan modified his generative script to perform angle checks, which eliminated crowding, produced more diverse compositions, and produced a kind of joint mutation called a “flower” (Figure 3, right). These effects were evaluated as improvements. Later in the project during component assembly, Dan enjoyed a moment of inspiration. He discovered that printed and wood components need not be finished before assembly. Taking advantage of this insight, he developed an approach in which components were “roughed out” prior to assembly and then shaped and smoothed after assembly. This led to the design of tapered joints, which were also evaluated as an improvement (Figure 3, left and right).

Dan’s experience also highlights a special use of computer simulation. When Dan modified his parametric model to account for crowding, he simulated a property of the wood – its thickness. By transferring a material property into a digital environment, computer simulation reverses the flow of 3D printing. Researchers have generally seen this as a beneficial way to bridge the digital/material divide [10], [11]. However, simulation can be dangerous if architects treat it as an adequate substitute for material. It can lead to reduced empirical testing and risk of bad assumptions. This seductive aspect of simulation can be seen in the popularity of computer rendering. Many architects spend hours or days testing rendering materials and little time testing real materials. This disproportionate use of time shows the power of a simulation to replace the object of design. In the screen wall experiment, students used simulation in a special way to protect against seduction. They remained aware of the selective and limited nature of their simulations by thinking of them as material placeholders. This allowed students to simulate specific material properties when needed without assuming that a reductive digital representation of wood is ever adequate, and without reducing the amount of empirical testing. A material placeholder emphasizes its incompleteness through a diagrammatic visual representation. This purposeful crudeness persists, even as other parts of a parametric model acquire visual refinement. In Dan’s case, while nodes were described by detailed solid geometry, wood spans were still described by single lines (Figure 3, middle). Students found that by making placeholders look as different as possible from real materials, a simulation’s artificiality was stressed. By thinking about the wood as never more than a little bit digital, students were less prone to make bad assumptions about wood based on its digital representation. This technique challenges the dumb inertia of mainstream CAAD, which seeks always to heighten the realism of simulations, regardless of the consequences.

The screen wall experiment asked students to achieve a balanced
composition of wood and printed components, in which each type played a significant role in the screen wall system. Despite this mandate, a few students resisted, choosing instead to emphasize the printed components. In one case wood members provided a neutral framework for the showcase of printed components (Figure 4). Typically, however, students successfully used wood and printed components symbiotically (Figure 5).

Figure 2: Left: An early parametric design for a screen wall system. The white spheres are node connectors and the black lines are placeholders for wood components, which span between nodes. Middle: Detailed design for a node connector, showing a crowded condition (-) and a good condition (+). Right: Final screen wall model constructed of printed and wood components.

Figure 3: Left: Close up of final screen wall model, showing tapered joints. Middle: Later version of the parametric model, showing an incongruous state of representation in which node connectors appear in detail while wood beams appear as diagrammatic lines. Right: Close up of final screen wall model showing three “flower” mutations.

Figure 4: Wood components used as a neutral backdrop for printed components.

Figure 5: Wood and printed components used symbiotically.
3.2 Corporeal thinking

Architecture has always been subject to piecemeal construction, which requires the whole to be segmented into components. Design by making therefore involves the study of components and assembly. Makers need 3D prints to reflect this kind of study, but the typical approach shows only the sum effect of hundreds or thousands of construction components, which are fused into an undifferentiated mass in order to facilitate study of form. To take control of the medium, makers should print components. When each print represents a single component, building form becomes one step removed from the printing process. It emerges later, after component assembly (Figure 6). The shift from printing buildings to printing components of buildings reorients architects from the abstract sculpting of a singular form to the construction of corporeal matter.

Corporeal thinking was encouraged in the screen wall experiment by restricting 3D printing to discrete components. Only afterward could prints be assembled into larger fabrics. The fixed frame of the light box reinforced this approach. Like a microscope focused at the cellular level, it channeled student attention to components and their relationships, rather than a macro-scale fabric the components might generate in larger quantities. In fact, an overall building form was not designed until the following project, when students used the screen wall system to enclose a specific program on a specific site. The students’ customary process of rational planning was inverted. Instead of starting with a formal parti and gradually elaborating its details, students worked from detail to form.

Rather than hide components behind finished surfaces, makers tend to articulate them. With grooves, pins, clamps or notches, elaborated joints visually accentuate components. Because they are exposed to view, and because they use tighter tolerances, such joints require close attention during design. In the screen wall experiment, the need to manage tolerances encouraged empirical study. There was no way to test such things as snugness of fit and direction of slippage in the parametric model. By accentuating segmentation, the screen walls acquired a cellular quality...
The use of mass-customization with generative scripts also contributed to this quality by introducing incremental changes in component size and shape. This produced patterns reminiscent of the aggregate cellular growth of plants [25]. An additional factor was the structural performance of components. Printed powder is weak in tension, and prints with thin bodies or appendages broke easily. Consequently, students favored compact shapes, which encouraged cellular packing.

4. 3D PRINTS AS THINGS-IN-THEMSELVES

Even if 3D printing can promote design by making, using it this way might be unwarranted. Why use 3D printing rather than full-scale CAM? Working at full-scale seems superior because it eliminates intermediary abstractions and places architects in direct contact with architectural materials. 3D printing seems at best to support an inferior kind of design by making. Contrary to this view, the claim made here is that 3D printing is a potent medium for design by making. Used in conjunction with full-scale CAM, 3D printing compensates for a weakness inherent in full-scale designing. Those who predominately engage in full-scale designing can become engrossed in conventions of construction, which limit innovation [26]. While the advocates of abstract design methods prescribe digital media as the cure, thinkers such as Robin Evans suggest a more subtle tactic – architects should embrace the moment of transition between the abstract and the real [27]. Evans describes inspiration found at the point of translation from drawing to building, but the issue is wider than drawing. Facilitated by any medium, this shift in perspective is sometimes called “reframing the problem” or “reinterpretation”, and it ranges widely through accounts of inventors, artists and scientists, who purposefully suspend selected aspects of the known in order to discover the not-yet-known [28].

Perhaps more than any medium, scale models facilitate selective reinterpretation. Models combine elements of abstract representation and material making in a single activity, and this allows architects to oscillate easily between two perspectives. On one hand architects interpret models as a representation of architecture, and on the other hand, they interpret them as things-in-themselves – material objects constructed for their own
sake. This might occur, for instance, in the construction of a traditional cardboard study model of a trussed roof. When an architect twists a piece of cardboard and glues it onto the model, the structural properties of the cardboard influence its curvature. The architect knows she wants a curved truss, but she lets the behavior of the cardboard suggest a particular curve. In one moment, she chooses to see the cardboard as representing a truss, and in the next, it is merely cardboard, explored for suggestive purposes. Like traditional model-building materials, 3D printing offers this suggestive behavior.

In the screen wall experiment students used 3D prints in this way. Although they were asked to develop innovative designs, some students struggled to overcome assumptions about construction. For example, one student assumed a conventional distinction between structure and skin, which underlies most commercial curtain walls. In the resulting design, wood and printed components interact in a predictable way, one as structural grid, the other as hanging panels (Figure 8). This was evaluated as a weakness. Other students were able to break free of conventions by studying 3D prints as things-in-themselves. Rather than print joints and spans with proportions appropriate to steel, for instance, they accepted the material limitations of the prints. Powder-based prints are heavy and brittle, and they lend themselves to thick components and dense fabrics (Figure 9). By viewing the model as a self-sufficient material artifact, students found new surface features, jointing techniques, lighting effects and structural strategies. When once again viewing the model as a representation of a screen wall, students translated the discovered effects into architectural terms. This activity often disrupted assumptions about the screen wall, leading to unconventional designs such as a non-rigid screen that changes shape under lateral loads (Figure 10, left), a light-directing screen with integral shading panels (Figure 10, right), a thickened screen composed of ribbed fiber glass “balloons” (Figure 9) and a light-filtering screen with degrees of translucency (Figure 1, right).
Free of the constraints on full-scale construction systems, 3D printing disrupted the conventional thinking associated with those systems. At the same time, because 3D printing remains in the realm of material (as opposed to digital media), it shares features with full-scale systems of construction, most notably its corporeality. When tied to corporeality, the interpretive use of 3D printing played a dual role – broadening creative search while curtailing proliferation of implausible ideas.

5. CONCLUSION

The screen wall experiment created an observable struggle as students altered their thinking habits in response to the constraints. Some retained aspects of a formalistic habit or assumptions about construction, and yet, overall, the results exceeded the “appearance models” typically produced with a 3D printer. Although students used methods of digital/material integration identified previously in the literature, the following new or revised methods were also used, which strengthened students’ tie to the process of making. First, students used a foil medium, which helped them decide when to end a period of parametric design and return to material.
testing. Second, students used material placeholders, which helped them simulate material behavior during parametric design without overstepping the limits of the simulation. Third, students printed individual building components and assembled them by hand, which helped them relinquish a central concern with form-making. Finally, students viewed 3D prints as both abstract representations and literal objects, which helped them overcome preconceived ideas about building construction. Through these means, 3D printing became an effective tool for design by making.

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