Recasting Concrete: A Case Study in Concrete 3D Printing as an Architectural Pedagogy

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This paper discusses a research-based architectural design called "Recasting Concrete," which was designed to explore the ways in which concrete 3D printing can be utilized as an architectural pedagogy. The paper begins by discussing how current architecture-oriented concrete 3D printing research is fixated on the technology's application in construction, and how such fixation has prevented architects from exploring other realms in which concrete 3D printing can have impact, for example, education. Recasting Concrete is then situated within digital fabrication-centric pedagogies that have increasingly been introduced in architecture schools worldwide. The studio's structure is detailed with particular focus on the ways in which students developed experimental concrete 3D printing methodologies. The work of three student research groups is presented. The studio's work is then put in conversation with contemporary affordance theory in order to illuminate some of the students' conceptual learnings. Finally, the paper discusses a novel architectural design approach that students learned through their investigations into concrete 3D printing.

INTRODUCTION

In his canonical treatise on the modernist movement, "Theory and Design in the First Machine Age," the architectural critic Reyner Banham quotes the architect Robert Mallet-Stevens: "Abruptly, everything changed. Reinforced concrete appeared revolutionising the processes of construction...science creates a new aesthetics, forms are profoundly modified."[1] Banham invokes Mallet-Stevens to verify the extent to which the advent of reinforced concrete shaped the development of modernist architects' simple and rational sensibilities—sensibilities that still largely dominate architecture today. However, we are now at the cusp of what some contemporary thinkers call the "second machine age," in which another fabrication technology is poised to change our perception of both concrete and the architecture that it is capable of producing: 3D printing.[2]

In the last decade, architects have researched several potential advantages of concrete 3D printing; for example, it can facilitate rapid small-scale construction, enable on-demand structural customization, and provide architects with a uniquely direct interface between digital building components and their material reproductions.[3] However, researchers have also identified numerous steep obstacles that need to be overcome before concrete 3D printing can fully revolutionize architectural practices. Such obstacles include, but are not limited to, difficulties in incorporating structural reinforcement into 3D printed concrete, challenges with standardizing concrete 3D printer parts and material mixes, the construction industry's reluctance to integrate concrete 3D printing into current supply chains and labor markets, and the technology's inability to produce foundations, slabs, or roofs.[4] And indeed, such a mass of obstacles has prevented concrete 3D printing from inciting the same self-reckoning in architecture that reinforced concrete once did; at the moment, such a reckoning appears to be far-off.

But, then, building architecture is not everything. Architects have been so fixated on utilizing concrete 3D printing towards new kinds of construction that we have failed to look at other realms in which it might be revolutionary. Most significantly, I want to insist, we continue to overlook the use of concrete 3D printing toward the renewal of architectural pedagogy. In this paper, then, I aim to demonstrate some of the specific ways in which architecture students might be trained to *think*, not just make, architecture through investigations into concrete 3D printing. The basis of this exploration will be a research-based architectural design studio that I led called "Recasting Concrete."

THE RISE OF DIGITAL FABRICATION TECHNOLOGIES AS ARCHITECTURAL PEDAGOGIES

In recent years, architecture schools have increasingly developed pedagogies that center on digital fabrication technologies. This development is evidenced by the new assortment of Master's programs across the world with concentrations such as "digital and material technologies," "integrative technologies," and "robotics and advanced construction."[5] Though the names and structures of these programs vary, they generally offer students some kind of "reexamination of techniques, methods, and theories of design" in relation to the fields of engineering, robotics, digital manufacturing, and material science; they also all mainly center on a particular digital fabrication technology: the robotic arm.[6] At the same time, 3D printers, which have also proliferated across architecture

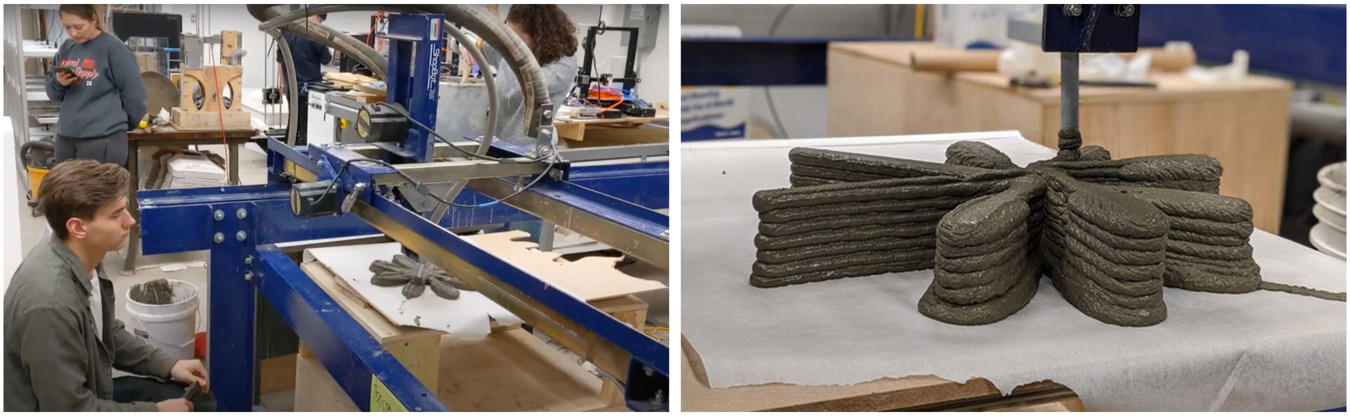

Figure 1. Students worked with the instructor to set up their own concrete 3D printing lab and design their own fabrication tools.

schools, are generally tucked away in dark corners of their fabrication labs, left to busily churn out students' physical models—they are used as tools for production, not pedagogy.

In this discussion, I intend to more precisely detail the conceptual "reexamination" that architecture students glean from digital fabrication-centric architectural pedagogies. I also intend to show that 3D printing, and concrete 3D printing in particular, has unique pedagogical strengths that warrant its move from the shadows of fabrication labs to the centers of design studios.

RECASTING CONCRETE

I taught Recasting Concrete over the course of a semester in spring of 2020 at the Knowlton School of Architecture at The Ohio State University. The class was offered as an option studio to Bachelor of Science in Architecture students in the final semester of their degree.

I positioned one question at the center of Recasting Concrete's research: What are the architectural affordances of concrete 3D printers? I worked with my students to develop concrete 3D printing methodologies and speculative architectural design proposals that responded to this question.

WHAT IS AN AFFORDANCE?

Before we began our investigation into the architectural affordances of concrete 3D printers, I first had to answer the question: what is an affordance? In his book "The Design of Everyday Things" (DOET), the cognitive engineer Don Norman states that the "the term *affordance* refers to the relationship between a physical object and a person (or for that matter, any interacting agent, whether animal or human, or even machines and robots). An affordance is a relationship between the properties of an object and the capabilities of the agent that determine just how the object could possibly be used"; in other words, an affordance is neither a provision nor a property, but rather an evolving interaction between an object and a subject that is defined in equal parts by the ontology of both.[7]

The continually changing landscape of design and fabrication technologies in architectural practices has resulted in increased use of the term in architectural discourse. When we are introduced to a new design or fabrication technology, we necessarily, though not always consciously, ask ourselves: what does it do? And, what can I use it for? Another way to phrase such internal questioning would be to ask: what is its architectural affordance?

STUDIO STRUCTURE

I divided Recasting Concrete into two parts: research and development and design speculation. In the research and development segment, I gave students precedents in cutting-edge 3D printing research, tutorials in 3D printing and computational design, readings that discuss digital fabrication's role in architecture, and open-ended making assignments that I call "material-thought experiments." I also provided each group of three or four students with a desktop plastic 3D printer and full access to a 4'x8' ShopBot CNC machine that I transformed into a concrete 3D printer through the addition of a pneumatic grout pump, a solenoid valve circuit, and an end effector that could accommodate nozzles of various shapes and sizes (Figure 1).[8]

My intention in designing the material-thought experiments was to push students to unpack concrete 3D printing's unique parameters and their potential to inform architectural designs. In the first material-thought experiment, for example, I asked students to 3D print something in plastic that could not be cast in concrete, and cast something in concrete that could not be 3D printed in plastic. Shortly after, I assisted students in hacking their desktop plastic 3D printers into desktop concrete 3D printers by rewiring the printers' electronics, designing their own extruders, and writing their own g-code compilers in Grasshopper. I provided students with a baseline concrete mix

Figure 2. In the first half of Recasting Concrete, students worked primarily through iterative material prototyping and analysis. Here, the prototyping and analysis of the Imperfect Perforations group.

to begin printing with, but they eventually had to tailor mixes to their respective mechatronic setups.

Once the students had functional desktop concrete 3D printers, I led them in a series of experiments aimed at rethinking the defaults of 3D printing technology. For example, I asked them to print something with their g-code compilers that proprietary printing software would flag as an error, to print a box through a non-layered deposition process, and to print onto, into, around, or through "build plates" of their own design. Through these experiments, and their parallel investigations into theories and practices of digital fabrication, the students cultivated their own concrete 3D printing methodologies. I then had the students translate their methodologies from their desktop systems to the ShopBot system in order to consider questions of scale, tectonics, and construction logistics.

At the midterm, I requested that each group propose two architectural components (e.g., columns, walls, slabs, etc.) that their methodologies were capable of producing, and to prototype them at quarter-, half-, or full-scale (Figure 2). I also asked them to genealogize their methodologies and demonstrate the research processes that led them to their speculative proposals.

In the second half of the semester, I had the students test their speculations in their own architecture school building, Knowlton Hall: a building that is defined by its large amounts of exposed cast-in-place concrete. I asked each group to pick a typical cast-in-place condition within the building (for example, where columns meet floors or how walls turn corners) to redesign through the implementation of their concrete 3D printing methodologies. Prior to the pandemic, I expected students to produce full-scale mock-ups of their redesigned conditions that would be exhibited next to the architectural originals. However, the School's move to remote learning (and away from the fabrication lab) demanded that I make construction documents, digital montages, and assembly diagrams the primary means of design speculation.

STUDENT WORK

Each group's concrete 3D printing methodology and speculative proposal reflected the architectural affordances that they perceived in the technology, as well as their own individual design sensibilities.

VECTOR PRINTING

The Vector Printing group observed that the printer's deposition speed had to be tuned to the concrete's flow in order to print anything at all, but, once harnessed, it could be further

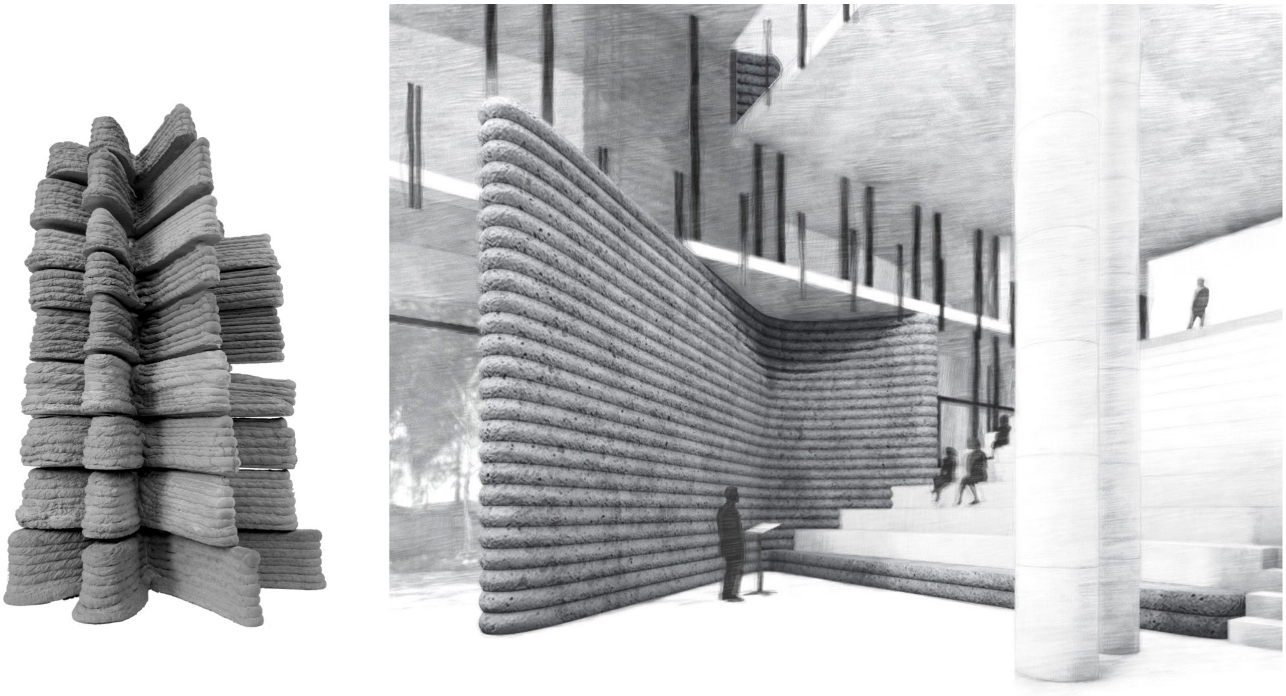

Figure 3. The Vector Printing group's tentacled column-walls unify discrete cast-in-place concrete elements.

tuned to augment the materiality of the thing being printed. In their methodology, tentacled drums of concrete were deposited on top of one another to produce "column-walls" that spread in multiple directions. To create each tentacle, the group specified only its start- and end-point, and the speed at which the printer should traverse between the two. The form of each tentacle was therefore determined almost entirely by the speed at which it was printed: slower printing speeds resulted in thicker tentacles, whereas faster speeds made them thinner. Tentacles could also have variable thicknesses by gradating between slow and fast printing speeds; they could, thus, be thinner at the point at which they converge with other tentacles and thicker where they needed to be self-supporting.

The team speculated that a column-wall's tentacles could be merged with existent elements in Knowlton Hall. They envisioned creating this fusion by instructing the concrete 3D printer to dwell, but not stop extruding, at the tentacles' termini: the concrete would then continue to slowly spill outwards and engulf architectural elements in its path. In this way, the tentacled column-wall could be an architectural intervention that unified discrete cast-in-place components (Figure 3).

SALTING SUPPORTS

The Salting Supports group was interested in concrete 3D printing's potential to be a form of digital craft. This interest led them to develop an interactive methodology in which they strategically placed support material by hand at different moments during the printing process. In this methodology, the team instructed the printer to create a hollow circular column through layered deposition. However, they also programmed long pauses in between each layer. When a member of the group identified a potential weak point or imminent collapse, they would use the time in between layers to build a small mound of coarse salt beside and/or within the structure in order to provide it with temporary support. The temporary salt supports also enabled them to construct small cantilevers that branched off their columns. Once a salted concrete print was complete, the team would scrape away its supports and allow it to cure unsalted.[9]

The team envisioned their concrete 3D printing methodology as a script for a collaborative performance between craftspeople and fabrication technologies. In this performance, pairs of humans and robots work together to craft architectural structures that neither could have made on their own (Figure 4).

IMPERFECT PERFORATIONS

IIn contrast to the Salting Supports group, the Imperfect Perforations group studied the extent of concrete 3D printing's inherent material control. The group cultivated this control by focusing on the development of truncated, pyramidal blocks that required the concrete to be precisely corbelled. The group established such a high level of precision that they could use the tip of their nozzle to pull or nudge the concrete and, thus, produce slight deformations in each block's surface, for example, bulging, twisting, or warping. The group envisioned these controlled deformations as means to subtly individuate the aesthetics of each component.

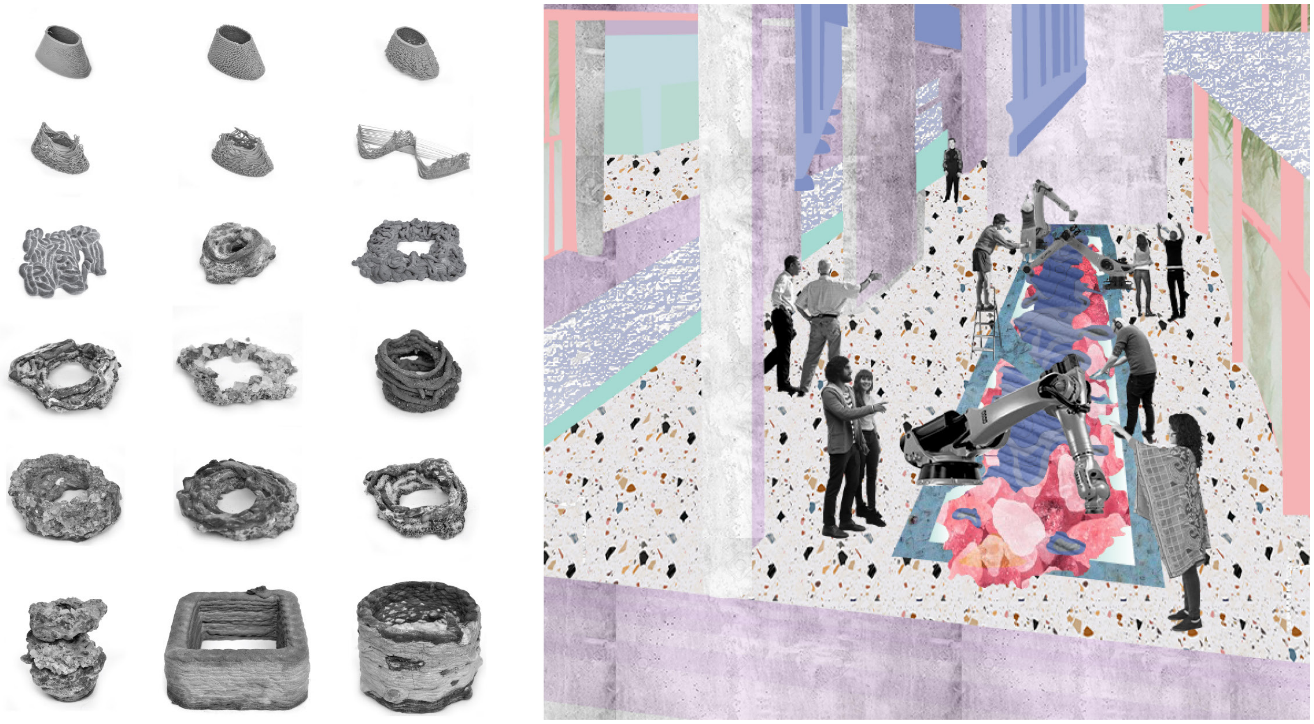

Figure 4. (left) The Salting Supports group's research genealogy, from desktop 3D printed plastic experiments to their experimental concrete 3D printing methodology. (right) A speculative montage portraying the collaborative concrete 3D printing performance the group envisioned for Knowlton Hall.

Rather than propose their perfectly imperfect blocks as alternative concrete masonry units, the students viewed their components as accent pieces that builders could deposit into formworks during the process of slip-forming concrete walls. They suggested that these punctuations would create textures and openings that would dissolve the walls' opacity and homogeneity (Figure 5).

RECASTING CONCRETE LEARNINGS

I have so far presented Recasting Concrete's structure and the students' work. I will now strive to illuminate some of the students' conceptual learnings by putting the studio in conversation with Norman's affordance theory.

CONCRETIZING ARCHITECTURAL KNOWLEDGE

In DOET, Norman writes that we can use "cultural constraints" to determine affordances; he defines such constraints as "learned artificial restrictions on behavior that reduce the set of likely actions."[10] Architecture clearly has its own set of cultural constraints—architecture students, for example, learn to work, think, and communicate in particular ways that are intended to guide their design processes—yet it has no universally established conventions or constraints when it comes to the digital fabrication technologies that are ever more in its midst. According to Norman, we should, however, be able to use the constraints we *do* learn to develop individual approaches to such emergent technologies; in other words, we can and should use our individual understandings of architecture to develop distinct, architectural approaches to digital fabrication technologies.[11]

The students in Recasting Concrete were still in the process of learning architecture's cultural constraints. The challenge of determining the architectural affordances of a specific emergent technology, the concrete 3D printer, was thus an opportunity to realize their own emerging architectural knowledge. For instance, Vector Printing's development of a methodology capable of printing variable thicknesses drew from their knowledge of line weight conventions; in other words, that printed lines, whether they be in ink or in material, can have thicknesses that connote specific values or functions and, further, that these thicknesses can be controlled by modulating the duration for which the printing material is allowed to bleed. Salting Supports similarly drew on the material intuition they gained from previous fabrication experiences to determine when and how the 3D print needed to be supported. Finally, Imperfect Perforations utilized their knowledge of relationships between architectural tectonics and aesthetics to develop new forms of ornamentation. Each of these approaches reflected the students' individual, internalized understandings of architectural design: design as drawing; design as material performance; design as aestheticization. The exercise of situating the concrete 3D printer in an architectural design context enabled the students to crystallize these understandings and, perhaps, present them to themselves for the first time.

Figure 5. The Imperfect Perforations' concrete 3D printing methodology produces blocks that can be placed in slip-formed concrete shear walls to create ornamental punctures or punctuations.

INTERNAL MODELMAKING

Concrete 3D printers are certainly not the only emergent technologies that could be used to concretize students' emerging architectural knowledge; they do, however, have characteristics that offer particular pedagogical benefits. To begin with, concrete 3D printers, like the one used in Recasting Concrete, are not "black boxes," like robotic arms; instead, they are (often makeshift) assemblages of physical objects (e.g., nozzles, tubes, sensors) and machines (e.g., computers, motors, and pumps) that work together to perform a specific task, i.e., 3D print material.[12] In this sense, a concrete 3D printer is closest to what the philosopher of technology Gilbert Simondon calls an "abstract technical object": a "system of isolated partial ways of functioning."[13] Such abstraction makes it difficult to locate concrete 3D printers within Norman's physical object-interacting agent binary and, thus, begin to perceive their affordances; at the same time, it can also be an asset in design education. In DOET, Norman hints at how to approach ontologically-abstract things:

> For us to function in this social, technological world, we need to develop internal models of what things mean, of how they operate. We seek all the clues we can find to help in this enterprise, and in this way, we are detectives, searching for guidance we might find. If we are fortunate, thoughtful designers provide the clues for us. Otherwise, we must use our own creativity and imagination.[14]

In Recasting Concrete, students created "internal models" of the concrete 3D printer in order to learn to work with it: Vector Printing imagined the printer as a drawing instrument, Imperfect Perforations imagined the printer as a material shaper, and Salting Supports imagined the printer as a robotic collaborator. The literal and conceptual openness of the concrete 3D printer necessitated *and* invited such diverse imaginings. Once the students created their internal models, they were able to more readily define the parameters of their investigations. For example: Vector Printing initially developed a high precision nozzle that was akin to a large concrete-filled pencil, Imperfect Perforations mixed concrete that had greater plasticity, and Salting Supports started to introduce pauses within their g-code, just in case they wanted to intervene—the students' internal models became templates for the designs of their fabrication methodologies. Students, thus, learned that design and fabrication technologies, which often appear to be determinate, can actually be approached according to their individual design sensibilities and, further, that such conceptualization of their technological means can inform their architectural ends.

ARCHITECTURAL DESIGN THROUGH MATERIAL ORCHESTRATION

I have argued thus far that concrete 3D printing can enable architecture students to realize both internalized architectural knowledge and the value of making internal models of their design technologies. Concrete 3D printing can also train students in an architectural design approach that is similar to what the architect Adam Fure calls "digital materiallurgy." In his essay of the same name, Fure advocates for architectural design "in which computational codes are coupled with eccentric materials to produce unusual results;" he writes "that materials do work; and part of our job as designers is simply to let them do it, all the while attempting to support, extend, and guide them."[15] Fure offers digital materiallurgy as an alternative to modes of design in which materials are coerced into forms that are predetermined by digital models—such modes dominate conventional, project-based architectural design studios.

Concrete is an eccentric material that works uniquely: it slumps and spreads, sets and hardens, and then, finally, cures and perspires. In concrete casting, the material is literally molded into a preconceived architectural form; once it is poured into the formwork, its formative processes are out of sight. In 3D printing concrete, however, the material is unbound from formworks and open to observation. Such unveiling provides designers with an opportunity to learn to "support, extend, and guide" concrete's unique behaviors—our relationship to the material can be recast. The students in Recasting Concrete studied this new kind of designer-material interaction.

Each group evolved their concrete 3D printing methodologies by tuning the computational or physical parameters of their fabrication systems to the parameters of their custom concrete mixes, for instance: Vectoring Printing modulated their printing speeds to work with their concrete's rheology, Imperfect Perforations shaped their nozzles to resist their concrete's stickiness, and Salting Supports experimented with different concrete retarders so that their printed material would not immediately set during their long, programmed pauses. After each computational, physical, or material tweak to their methodologies, I asked the students to perform a fabrication experiment and to observe how their modified preparations altered the concrete's formation. After each experiment, I then asked the students what they found to be successful and/or interesting about their results, and what aspects of their experimentation they wanted to carry forward; their architectural design speculations emerged from this iterative tuning, testing, reflecting, and re-tuning. Through this digital materiallurgic design approach—what I call "design through material orchestration"—the students learned to view their designs as bottom-up, everchanging material processes rather than top-down, finished architectural products.[16]

The ability to teach this kind of process-oriented thinking is critical at a time in which the creation of finished architectural products—i.e., buildings—accounts for over a third of the world's carbon emissions.[17] Concrete production and construction is a significant contributor to these emissions. If we teach aspiring architects new ways of designing with concrete, and materials in general, we can instill more ecological approaches to architectural production.

CONCLUSION

In this paper, I have argued that as architects continue to explore the affordances of concrete 3D printers in construction, we should also recognize that this digital fabrication technology can renew the possibilities of architectural education. The Recasting Concrete studio attempted to demonstrate what concrete 3D printing as an architectural pedagogy could look like. Placed in this unfamiliar design context, students learned to exercise their individual architectural knowledge bases, create and use internal models of abstract technical objects, and find architectural designs in the orchestration of complex material processes; their notions of what architecture could and should be were simultaneously expanded and strengthened, not unlike the material that they were learning to print.

ENDNOTES

1. Reyner Banham. *Theory and Design in the First Machine Age* (Cambridge, MA: The MIT Press, 1960), 202.
2. Erik Brynjolfsson and Andrew McAfee, *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies* (New York: W.W. Norton & Company, 2014).
3. Adele Peters, "One day, you might live in a 3D-printed house," ***Fast Company,*** April 28, 2020, https://www.fastcompany.com/90483273/one-day-you-might-live-in-a-3d-printed-house; Zeeshan Ahmed et al., "On-demand additive manufacturing of functionally graded concrete," *Virtual and Physical Prototyping,* Vol. 15, No. 2 (2020: 194-210); Ana Anton et al., "Concrete Choreography: Prefabrication of 3D-Printed Columns" in *Proceedings of Fabricate 2020: Making Resilient Architecture,* Jane Burry et al. (London: UCL Press, 2020), 286-293.
4. Swash Paul et al., "A review of 3d concrete printing systems and material properties: current status and future research prospects," *Rapid Prototyping Journal,* Vol. 24, No. 4 (2018: 784-798).
5. "Master of Science in Architecture concentration in Digital and Material Technologies," University of Michigan, Taubman College, accessed November 1, 2020, https://taubmancollege.umich.edu/architecture/degrees/master-science/digital-technologies; "International M.SC.Programme: ITECH," University of Stuttgart, Institute for Computational Design and Construction, Accessed November 1, 2020, https://www.icd.uni-stuttgart.de/teaching/itech/; "Master in Robotics and Advanced Construction," Institute for Advanced Architecture of Catalonia, accessed November 1, 2020, https://iaac.net/educational-programmes/masters-programmes/master-in-robotics-and-advanced-construction-mrac/.
6. "International M.SC.Programme: ITECH," University of Stuttgart, Institute for Computational Design and Construction, Accessed November 1, 2020, https://www.icd.uni-stuttgart.de/teaching/itech/
7. Don Norman, *The Design of Everyday Things, Revised and Expanded Edition* (New York: Basic Books, 2013), 11. The term "affordance" was first introduced by the psychologist James J. Gibson in his 1979 treatise "The Ecological Approach to Visual Perception." Gibson defines "the affordances of the environment" as "what it offers the animal, what it provides or furnishes, either for good or ill". In his 1988 book "The Psychology of Everyday Things," Norman appropriated and popularized the term in the context of human-computer interaction (HCI). Here, Norman defined affordance as "the perceived and actual properties of the thing, primarily those fundamental properties that determine just how the thing could possibly be used." However, in the following two decades, steep technological advancements (e.g., the Internet) and Norman's own frustration with HCI's vague use of the term compelled him to revise his definition several times.
8. The ShopBot computer controlled the solenoid circuit, which, in turn, controlled the flow of shop air that powered the pump.
9. The students' research was greatly inspired by the "Fossilized" project by Amalgamma, see: Beau Peregoy, "A New 3D-Printing Technique Creates these Sculptural Concrete Tables," *Architectural Digest*, February 1, 2016, https://www.architecturaldigest.com/story/new-3d-printed-concrete-method.
10. Norman, 76.
11. Norman, 128.
12. The Oxford English Dictionary defines a "black box" as a "device which performs intricate functions but whose internal mechanism may not readily be inspected or understood." "black box, n.2," OED Online, 2003, Oxford University Press.
13. Gilbert Simondon, *On the Mode of Existence of Technical Objects*, Trans. by Cecile Malaspina and John Rogove (Minneapolis: Univocal, 2017), XV, 27.

14. Norman, 17.

15. Adam Fure, “Digital Materiallurgy: On the Productive Forces of Deep Code and Vital Matter” in *Proceedings of the 2011 Association for Computer-Aided Design in Architecture (ACADIA) Conference: Integration through Computation*, Ed. by Joshua M. Taron, (ACADIA, 2011), 90-97.

16. “Design through material orchestration” is similar to architect and educator Mark Cabrinha’s concept of “(in)forming,” but the latter approach is much more interested in the ability of digital fabrication to precisely translate digital geometries into material forms; in design through material orchestration, and digital materiallurgy, materials are given significantly more agency. See: Mark Cabrinha, “(In)Forming: The Affordances of Digital Fabrication in Design Education” in *Proceedings of the 95th Annual Association for Collegiate Schools of Architecture (ACSA) Conference: Fresh Air* (ACSA, 2007), 418-425.

17. Matthew Adams, Victoria Burrows, and Stephen Richardson. *Bringing embodied carbon upfront: Coordinated action for the building and construction sector to tackle embodied carbon* (London: World Green Building Council, 2019).