Concrete Environments

Duane McLemore
Jacob Gines
Mississippi State University
dmclemore@caad.msstate.edu
jgines@caad.msstate.edu

Abstract

Concrete Environments was a two-week design charette in the Fall 2019 3a Housing Studio at the School of Architecture at Mississippi State University. Students explored how architecture created with 3d Printed Concrete can relate to the concepts of dwelling, interaction, and meaning typically explored in the Housing Studio - in addition to examining the materials and geometry of Advanced Fabrication.
Working toward Project Goals, the students were challenged to not just meet Physical and Functional Constraints, but to use these to equally examine the project's *epistemology*, *phenomenology*, and *technology*.

Seeking to understand the human body and its interaction with the built environment, students interrogated the meaning of "dwelling" through focusing awareness of light, space, and the senses utilizing industry standards of 3D printing.

The designs were subject to Physical and Functional Constraints: constructed only from interlocked or nested assemblies of 3d printed parts, and were to embrace a part of the human body and providing three openings and two vessels.

The project began with an introduction to 3d Printing in Concrete from sponsor Pikus Concrete, who also provided feedback throughout. The student pairs then created clay models and charcoal drawings to freely conceptualize possible forms and atmospheres. Each group moved their most successful idea(s) into Rhino3d and iterated them to better realize the Project Goals. Desktop 3d Printing was essential in testing, prototyping, and documentation.

The students developed experience designing for this novel production process and using an analogous process to prototype their ideas. They learned how Advanced Fabrication can help balance functional and expressive aspects of a project. Further lessons learned by professors, students, and the industry partner are discussed in detail in the full paper.
Concrete Environments interrogated questions around the Conference themes of *Practice, Measurement, High Tech,* and *Carbon*. These are expanded in the paper.

Figure 1: Audrey Eisner and Dany Morales - Charcoal Ideation Drawing

Introduction

Concrete Environments was a two-week charette in which students designed an environment for human inhabitation to be fabricated with 3d printed concrete. It was the first project for the Fall 2019 semester in ARC3536 Architecture Design 3A (Studio 3A) at Mississippi State University School of Architecture (S|Arc)The 3A Studio addresses housing. This meant that in addition to examining the materials and geometry of Advanced Fabrication, the project was used to explore how architecture built with these methods can relate to the concepts of dwelling, interaction, and meaning typically explored in the Housing Studio. The MSU S|Arc teaching team consisted of Studio Coordinator Associate Professor Jacob Gines, Assistant Professor Duane McLemore, Instructor John Ross, and Studio Assistant Ryan Ashford.

Project Partners

Concrete Environments was supported by Utah-based concrete fabricator Pikus Concrete[1].

Previous Scholarship

Reviewing prior scholarship on the implementation of Computer-Aided Manufacturing within architecture reveals an overwhelming wealth of information on the quantitative aspects of this practice[2]. This is to be expected, as much of this output is the intended product of the research. The research is often as important an output of this process as the objects being fabricated themselves. Analyses of the performative facets of these projects are very common: explorations structure, materiality, tectonics, spatial organization, and so on.

Far less has been said about the qualitative / phenomenological nature of Digital Fabrication. Many of the projects under this heading have goals with a qualitative function, often to filter light or views similar to this project. But as will be shown, the specific criteria of *Concrete Environments* exceed qualitative "functions" and achieve a greater significance.

There is ample scholarship on “Digital Craft,” and much has been said over the years about the phenomenology of virtual environments[3]. But rarely have the affective and experiential qualities of Advanced Fabrication been used to explore the phenomenology of the human experience of inhabiting these constructions.

Using digital technology to introduce these concepts within architectural education is also rare. By all indications, this project and the work done for it seem to be a fairly novel contribution to the body of knowledge.

Rivka and Robert Oxman have provided some theoretical framing useful in describing this work in *Theories of the Digital in Architecture*. Alvin Huang has similarly spoken of the work of his form Synthesis Design and Architecture in illuminating terms. Both will be quoted where appropriate.

Project Framing

> *“Today, due to the computational processes enabling the mediation between form, structure and material properties, tectonics is again becoming a seminal and operative concept of design. Traditional tectonic relationships are undergoing a revolutionary transformation; these relationships are now*

> *capable of being explicitly informed and thus mediated through digital media from conception to production."* Oxman. *Theories of the Digital in Architecture.* p. 230

As with any material, concrete has fabrication methods to which it is particularly suited, and those to which it isn't. Similarly, 3d printing as a method has constraints which can cause an object to be ideal to build with the method, or very difficult (or impossible). [GIVE EXAMPLES] This project explores the fit between these material and technical demands and the will of the designer imposed upon it.

In *Concrete Environments*, the students were tasked to use the exploration of inhabitation as a way to propose novel challenges for fabrication with 3d printed concrete. This allowed them to understand how these two ideas typically not brought into dialog could help negotiate their seemingly opposed requirements.

Methods

Project Details

The project was the creation of a small, inhabitable "Environment." The type was not specifically stipulated. Instead, the assignment set out a series of Functional Requirements and Physical Parameters:

1. Less than 20 square feet
2. Less than 10 feet tall
3. Constructed from 3 or more printed parts
4. Openings
   a. Allow for entry of an enclosed space
   b. Allow for a view
   c. Allow for an intentional light effect
5. Vessels
   a. To hold water
   b. To hold an everyday object (of the students' choice)
   c. To embrace a part of the human body

These Goals challenged the students to not just meet quantitative Constraints, but to use these to examine Dwelling Practices via this project's *Epistemology*, *Phenomenology*, and *Technology*. (See *Results and Discussion* for more details.)

To quote Prof. Gines' Assignment text, "Dwelling practices are on one hand primal and instinctive, yet they can be manipulated and controlled depending on the environment and conditions surrounding the day-to-day rituals of life. This situates the project as an investigation of the *Experiential* (See *Results and Discussion* for more details).

Realization

In their own words, Pikus 3D sponsored this charette to:

> *...spread awareness of 3D Concrete Printing technology and begin to educate future design professionals about the advantages and constraints involved in working with this technology as well as encourage a new way of thinking about design... Educating designers at an early stage will allow them to take full advantage of the possibilities and push the constraints of the technology to encourage future developments. The collaboration with MSU architecture students gave Pikus 3D a unique perspective on how designers will approach the use of 3DCP in their future projects... (Lockard. 2021.)*

Pikus 3d was a generous industry partner, providing:

1. Skills Training in how to design for the unique parameters of 3d printed concrete.
2. Feedback for the students throughout the process.
3. Small Monetary prizes for the three teams of students judged to have designed the projects most suited to the unique possibilities of 3d printing concrete.

Skills Training – 3d Printed Concrete

The project was initiated with a tutorial from Kirby Lockard from Pikus. She began by presenting a series of important works which use 3d Printed Concrete. She then introduced the students to the material properties and design parameters of the process (Fig. 2).

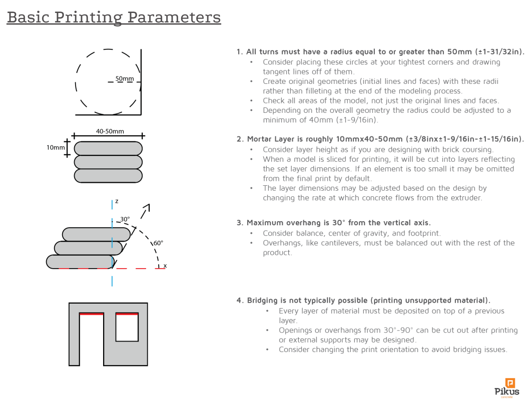

Figure 2: Basic Printing Parameters. ©2019 Pikus Concrete

At the end of the session, the students selected partners and began to ideate design ideas for the next class.

Ms. Lockard continued to provide feedback throughout the project on both the large and small scales – from the suitability of overall partis and concepts to minor optimizations of individual pieces.

Ideation

In an exercise that Prof. Gines often uses at the beginning of a new project, the student pairs began by creating clay models and charcoal drawings. This allows them to freely conceptualize possible forms and atmospheres, unconstrained by the specific requirements of the fabrication method. (See Figs. 1 and 7)

Student John Spraberry had this to say:

> *The most helpful quality of these mediums was the malleability of the clay and the imperfection of the charcoal. By working without precise dimensions or scales, we were able to explore the qualities we wanted from each part of the project, and we were able to explore numerous iterations with less concern for material waste or time spent in the shop. Despite a small amount of disconnect between the clay and 3D printing modeling processes, the clay still felt appropriate and satisfying as a way to develop a concept without the limitations such as a lack of in depth understanding of 3D modeling software. (Spraberry. 2021.)*

Sam Carpenter and Henry Rice made especially effective use of this process by building their clay model as if it were fabricated from 3d printed concrete parts from the outset. As can be seen, their final design bore a heavy resemblance to their initial concept (Fig. 3).

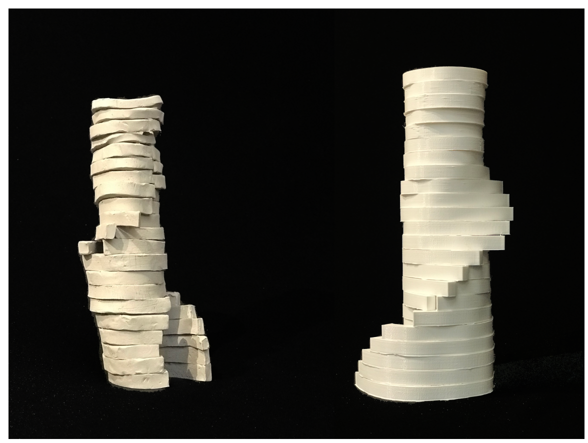

Figure 3: Sam Carpenter and Henry Rice - Clay (L) and 3d Printed (R) Models

Skills Training – Rhino3d

Each group moved their most successful idea(s) into Rhino3d or Sketch-Up and began iterating Prototypes of these to better suit the Project Goals. The students had all used Sketch-Up in 2nd year, and a few defaulted to using it here. However, because Rhino3d is more suited to the formal goals of the assignment, Prof. McLemore taught tutorials on the software. Most students were interested to learn the program and by the end 19 of 21 groups completed their project in Rhino3d.

Prototyping

Desktop 3d Printing was essential in testing, prototyping, and documentation. Despite the many differences between the technologies, the Concrete 3d Printers used in the industry bear a fundamental similarity to the typical desktop FFF[4] printer. Both technologies extrude a continuous and predictable supply of the fabrication material as a viscous liquid from a nozzle. In Concrete 3d Printing, admixtures are included which maximize the relationship of flow and cure time. In FFF, the material (typically PLA[5]) is a thermoplastic, melting when heated and hardening when cooled.

The materials have similar design constraints due to the similarity in their behavior while working and cooling / curing. Both are deposited in layers, and continuous support is necessary for each layer. Both have a maximum angle ("overhang") by which one layer can project beyond the previous. One crucial difference is that in 3d Printed Concrete, the layers must be in a continuous "spiral" as it is much more difficult to stop the flow of material and "retract" to move the print head without depositing material.

Due to these similarities, the students were able to prototype their design ideas for 3d Printed Concrete with the FFF printers already in use at the School of Architecture[6].

However, few of the students had significant previous experience with 3d printing. So after the students had begun to bring their designs into 3d modeling software, Prof. McLemore gave a tutorial in preparing files for 3d printing. As the students encountered printing issues, he and Prof. John Ross provided feedback and troubleshooting.

As shown in Fig. 4 and 5, desktop 3d printing was a useful method for prototyping - and final model preparation for even the most divergent project types.

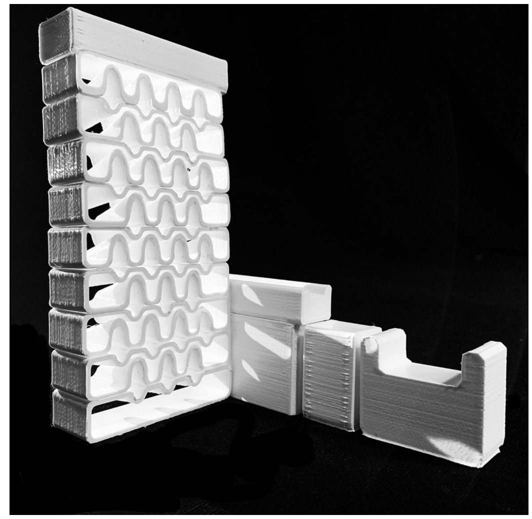

Figure 4: Audrey Eisner and Dany Morales - 3d Printed Model

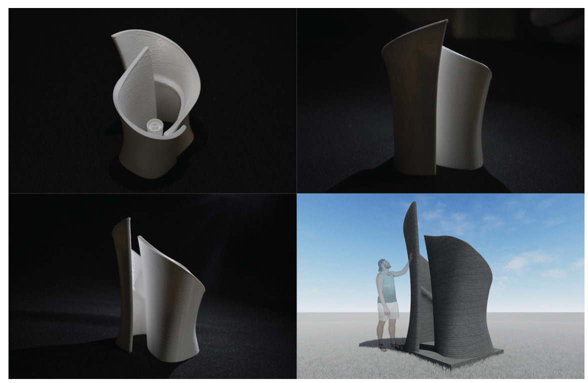

Figure 5: Joseph Thompson and Will Watson - 3d Printed Model and Rendering (For Scale)

Feedback

Given the fast-paced nature of the charette, each group met with their studio professor during every studio session to review progress and answer questions. This included reviewing their charcoal drawings, clay models, Rhino3d models, and 3d printed prototypes.

As the students were on a steep learning curve with two different technologies (Rhino3d and 3d printing), the meetings also entailed a lot of technical advice. But these technical ideas were framed within more qualitative aspects of design. So the discussions were just as likely to include more abstract ideas about the relationship between technology and human experience or "Dwelling."

Results and Discussion

In the end, 21 projects were submitted, with a wide variation in their nature. The large majority of students worked hard to reconcile the affective and technological goals of the assignment.

One very notable gradient of variation was from full customization to full modularity of each piece. At one end were projects where the pieces were all completely unique from each other (Figs. 5, 6, 8). At the other were purely modular projects which endeavored to find the minimal number of piece variants for the design intent, and instead create algorithmic rule sets and relationships for and between projects (Figs. 10 and 11).

The majority were somewhere between, but these extremes are helpful to keep in mind when looking at them. A useful way of categorizing the variation is to look at core concepts and projects which best exemplified them, as follows.

Epistemology

The requirements for Openings and Vessels were not just functional, but forced relationships between the Environment and the Occupant. In this way, students were challenged to use the human body and its interaction with the built environment to create a sense of meaning.

The full text of View criterion is: *"Allow for a particular view (not what you're looking at, but how)."* Through creating a specific relational understanding between the Occupant and the world outside, the created Environment took on the role of mediating the understanding of the world. Similarly, the Vessel to hold an everyday object of the students' choice created a relationship between the students' intentionality of which ideas were incorporated into the Environment, and which were excluded from its "world."

For example, The everyday object for Will DeLisle and Daniel Knoll was a book, and the Vessel to *"embrace a part of the human body"* was a seat for reading the book. (Fig. 6)

Will and Daniel took as their inspiration the narrow, tightly winding spaces of a slot canyon because of the close relationship it forces between the occupant and the space. Their creation of a continuous space whose continuous formal deformations shape the experience of the occupant recalls the idea from Oxman that

> We must be prepared to view digital tectonics as both the continuity with modern tectonics as well as an emerging radical departure from the idea of tectonics as an order of the physical component systems of architecture. Digital tectonics begins in the transition from the modernist poetics of the spatial/structural to a new poetics of the material/structural, or a material tectonics. (Oxman. 222)

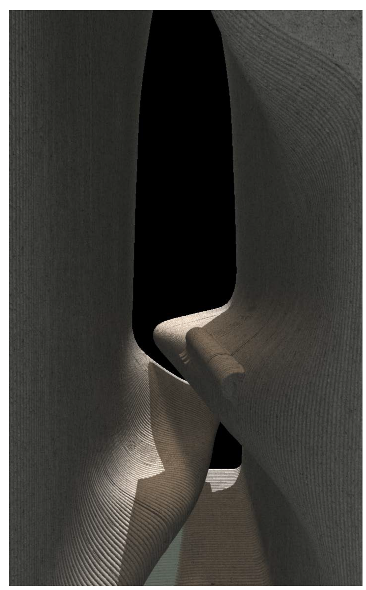

Figure 6: Will DeLisle and Daniel Knoll - Seat and Bookrest

The ability to construct this sinuous, doubly-curved, naturally-inspired space without any formwork represents this transition to a Digital Tectonics.

Phenomenology

Students interrogated the meaning of “Dwelling” through focusing awareness of light, space, and the senses.

The full text of View criterion is: *"Allow for a particular type of light (diffused, direct, raking, etc)."* The students used solar modeling in Rhino or Sketch-Up to understand the relationship of their constructed Environment to the Sun, and to fine-tune the orientation. Some students used the requirement for a Vessel as *"a place for holding water"* to create a hand-washing basin as part of a cleansing ritual for occupying the Environment. Others used the reflective property of the water along with the opening for light to create play of reflected sunlight as an effect.

For example, Spurgeon Sanders and Nicole Columbus had a very specific idea for the interaction of the "dripping" ceiling and the light entering from above would create an intimacy to the space. (Fig. 7)

Figure 7: Nicole Columbus and Spurgeon Sanders - Charcoal Drawing of Light Effect

Tying all three of these areas together, Sanders said:

> Our studies in charcoal began to help us understand the type of lighting we wanted to create and the experience of space we wanted to achieve. These informed the shape and composition of parts that we needed - giving us an end goal to work towards rather than starting in form and seeing what it would yield. This led into our ideation in clay and the physical sensation, developing the path and configuration of the vignettes and the order in which one might experience them. This also gave us a better understanding of the true extents of the size of our space and how that affects the structuring of spaces. (Sanders. 2021.)

Technology

Students learned and utilized industry standards of the direct 3D printing of building materials. They investigated the unique tectonic expression driven by 3d printed concrete, as discussed in Section 2.6. The assignment criterion to construct the final design from 3 or more parts challenged the students to interrogate the conception of spatial and formal structures through defining and implementing their own understanding of unit geometry and part / whole relationships.

These took many forms based on the students’ ideas, and as is the nature of student work with an open-ended prompt, some were more successful than others. Some designed for a minimum number of parts (3) with each being highly distinct in form and function. (Fig. 5)

Others, (most notably DeLisle and Knoll), imagined them as large U-shaped pieces printed flat then stood up - each being a section of a larger whole which contained all functions in a single surface. (Fig. 8)

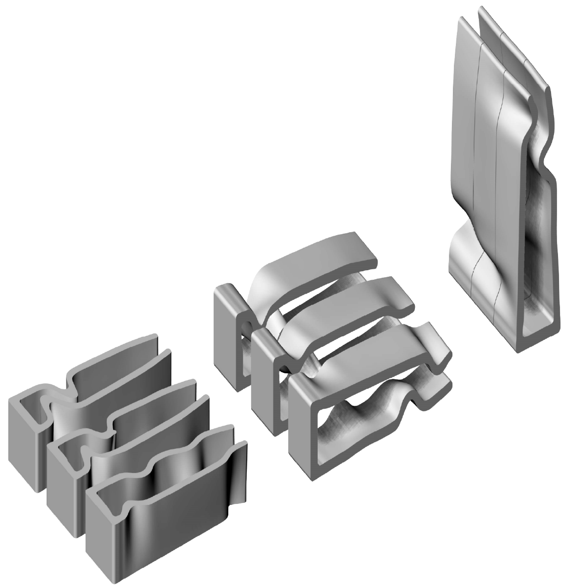

Figure 8: Will DeLisle and Daniel Knoll - Fabrication / Assembly Diagram

Others (for example Fig. 3) used repetition with incremental variation to create a series of similar but unique pieces.

At the more modular end, Eisner and Morales imagined theirs as fourteen smaller units in six variations: three singletons (11,13,14), two with two copies each (12,10,1,9), and one of seven copies (2-8). (Fig. 9)

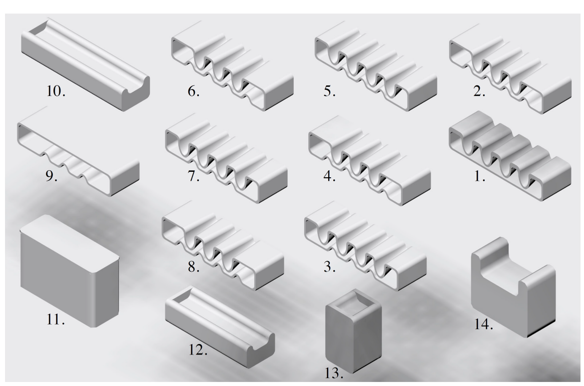

Figure 9: Audrey Eisner and Dany Morales - Part Diagram

The most fully modular, from Rice and Slade, will be considered more fully in the next secction.

This gradient from customization to modularity is reminiscent of Alvin Huang's description of how the design logic is embedded in fabrication process his own work: …an opportunity has emerged for digital media to be utilized as more than simply an enabler of automated production protocols (representation), but rather as a medium for embedding and communicating design process (realization). (Huang. 87)

Experience

Uniting the Epistemological, Phenomenal, and Technological was the notion of how these environments were to be Experienced. This took many formal expressions - some students imagined them as closely enveloping the occupant (Fig. 6). Others were objects that could be approached from all sides (Fig. 4). Yet others imagined the 3d printed pieces as discrete figures in a field that created a space between[7].

Kristin Rice and Mileena Slade incorporated flower planters in their design (Fig.10 and 11), and in their project description,

> We also felt that it necessary to include plants because they have the ability to improve concentration, reduce stress levels and also boost your mood. ...Experiencing nature is an intricate and assorted process in which vision, smell, contact, sound and kinesthetics overlap. (Rice and Slade. 2019)

Figure 10:Kristin Rice and Mileena Slade - Digital Imagery of Design

Figure 11: Kristin Rice and Mileena Slade - Images of 3d Printed Model

Evaluation and Competition Results

The evaluation of success for grading was completely separate from the competitive aspect. Pikus had no part of grading. Grades took into account how successful the students were at achieving the goals of the assignment, not just 3d printing in concrete. The students were given extensive written feedback to help better contextualize the work they had done. But the aims of the graded evaluation and the competitive evaluation were by nature somewhat interrelated.

In the competitive aspect, three prizes were awarded: 1st Place was awarded to Will DeLisle and Daniel Knoll. 2nd place went to Audrey Eisner and Dany Morales. And 3rd was awarded to Kristin Rice and Mileena Slade.

Learning Outcomes / Lessons Learned

By allowing students the opportunity to consider space creation through abstract means, yet manifesting their ideas within the realities of 3d printing, students developed a better understanding of the technicalities of constructed world and the difficulties associated with bringing their phenomenological ideas into being.

The students developed experience designing for this novel production process and using an analogous process to more accurately prototype their ideas. The students learned how to balance not just functional and expressive aspects of a project, but how an advanced fabrication process can help do both.

Students learned to value the analog processes alongside their digital counterparts. The clay modeling and charcoal drawings set forth a series of desired conditions and experiences that the students worked diligently to execute in through the precision of digital means. They learned the difficulties associated with making translations and the value of simplification and reduction in order to produce something within the constraints of the project parameters.

Students also learned to value the expertise of other design and industry professionals. This knowledge sharing/dumping provided students with undeniable expertise that advanced each project. The knowledge share established project constraints based fabrication realities that sought to ensure feasibility of the proposals. Students utilized these constraints to develop workable solutions, yet pushing the boundaries of what concrete 3d printing can actually do.

For example, multiple teams (Rice and Slade most specifically, see Fig. 10 and 11) imagined their design as a modular system that could be configured multiple ways. Their design was not just that of an object, but a rule set for sizing cells, and for which to use adjacent to others, resulting in rules for which ones could contain plants or water, which would need to be filled with concrete to maintain structural integrity, and so forth. Played out to its logical conclusion, this brings to mind a quote from Oxman: *"Digital Tectonics describes not physical object relationships as in modernist tectonics, but rather system contingencies as in algorithmic relationships." (Oxman. 223)*

The ambition and potential of this idea is beyond the scope of a two week charette, but the team's success in the competition shows that this line of thinking is suited to 3d printed concrete, and could be developed further.

Conclusion

Concrete Environments presented a relatively sophisticated set of learning outcomes for a two week charette. The students explored the material and technical aspects of designing for 3d printing. But they also explored how Advanced Fabrication could be used to create human environments which explored the more affective and ephemeral aspects of architecture.

Equally examining Epistemology, Phenomenology, and Technology, the students not only designed an Environment, they also established an agenda for Inhabitation that would propel their further explorations in the 3A Housing Studio.

The Studio's main project, a Mixed-Use Housing development for the West Loop neighborhood of Chicago began with two interrelated conceptual tasks. First was the definition of five Practices, or Rituals, of Dwelling: *Nourishing, Cleansing, Reviving, Celebrating,* and *Reflecting*. This was the basis of the second task, the writing of a "Manifesto" outlining the student's individual approach to these Practices. As stated by student John Spraberry,

> The constraints of the Concrete Environments were helpful in studying anthropometry and containing inhabitants with effective use of a space. Understanding the needs a dwelling fulfills, and the processes that are contained within it was introduced in the charette through the design of vessels (each meant to contain a variety of objects) and openings (each meant to facilitate different experiences). This part of the charette was helpful in the writing of our manifesto, and addressing the needs of the five rituals we were asked to consider when designing our units. (Spraberry. 2021)

In sum, the biggest success of *Concrete Environments* was that by trying to reconcile the quantitative and qualitative aspects of constructing a small environment led the students to start thinking of "both/and" solutions to problems, rather than "either/or." In this case, the affective and cognitive were not opposed - driving focus on the qualitative through the quantitative led to an enrichment of both.

Conference Themes

As a final thought, these projects interrogate questions around the BTES 2021 Conference themes of *Practice*, *Measurement*, *High Tech*, and *Carbon*.

Practice: Pikus 3d offered continuous guidance. An industry partner working directly with students to use cutting edge tools to interrogate conceptions of space and form is a novel and exciting collaboration. Like new tools throughout history, the Concrete 3d Printer challenges existing modes of practice, favoring the production of some forms and discouraging others.

Measurement: The students implemented industry standards for Concrete 3d Printing. Successful projects inscribed within their forms the shape, function, and perception of the human body - itself a sophisticated system of quantitative and qualitative measurement and calibration.

High Tech: The complex constraints of concrete 3d printing require computational control. The 1st place project was developed using Grasshopper. The final Desktop-3d Printed models were not just representative of the forms but presented the same advantages and challenges as the full-scale fabrication process.

Carbon: This is the area least addressed above, because it was not a specific part of the project formulation. However, it bears discussion. Like many concrete contractors, Pikus's interest in 3d printing concrete emerged from seeking ways to create novel forms while still achieving higher sustainability goals. Although concrete is a very carbon-intensive material, by directly depositing a finish building material rather than using wooden formwork, less material waste is generated in the construction process. This is relevant to *Concrete Environments* - conceptualized as special, one-off constructions, these would have had an unreasonable amount of construction waste per square foot, which would be ameliorated by 3d printing them from concrete.

Notes

1. https://pikus3d.com/
2. References available upon request.
3. References available upon request.
4. Fused Filament Fabrication.
5. PolyLactic Acid.
6. At the time, MSU S|Arc had the following FFF 3d Printers: (2) Ultimaker 3 and (1) 3dSystems CubeX in our Advanced Fabrication Shop and (5) Anet A-8 printers embedded in the 3rd Year studio.
7. Contact authors for more information.

Bibliography

Huang, Alvin. 2018. "Integrating Digital Materiality" in *Digital Fabrication.* ed. Yuan, Menges, and Leach. Tongji University Press. Tongji. 80-89.

Lockard, Kirby. In discussion with authors. May 2021. (Contact authors for full transcript.)

Oxman, Rivka and Oxman, Robert. 2014. "From Material to Material Tectonics" in *Theories of the Digital in Architecture.* ed. Oxman, Rivka and Robert. Routledge. New York. 2014. 221-226.

Oxman, Rivka and Oxman, Robert. 2014. "Informed Tectonics and Material-Based Design" in *Theories of the Digital in Architecture.* ed. Oxman, Rivka and Robert. Routledge. New York. 2014. 227-250.

Pikus Construction. 2019. *Basic Printing Parameters.* Presentation Slide. 2019.

Rice, Kristin and Slade, Mileena. 2019. *Dwelling Practices.* Student Work. Mississippi State University. 2019.

Sanders, Spurgeon. In discussion with authors. April 2021. (Contact authors for full transcript.)

Spraberry, John. In discussion with authors. May 2021. (Contact authors for full transcript.)

Acknowledgements

The authors would like to thank:

Pikus3d for their generous sponsorship and assistance – especially Rob Pikus and Kirby Lockard.

The School of Architecture at Mississippi State University