Wood Waste to Pumped Paste: Leveling the Playing Field Using Inventive Design Proxies

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3D printing has been opening new frontiers in the production of complex shape and form geometries using parametric design models over the past twenty plus years. These processes are transforming the nature of form, space, and materiality in architecture. Emerging capabilities to print varied material types have made new processes come into clearer views as having the potential to both transform the figural properties of things but also to save enormous amounts of material in the process. In this paper, we discuss 3D printing experiments accomplished using wood flour and a robotic arm extrusion printer in an interdisciplinary advanced research studio at the Fay Jones School of Architecture and Design and a follow-up project that explored some of the ideas that emerged from that studio.

The building sector in the United States contributes over 44 percent of total planetary carbon dioxide emissions. Because of this, and due to the advent of mass timber which is a more sustainable and renewable alternative to steel and concrete, many architects and engineers are now designing and building with wood materials in an effort to drastically reduce the built environment's negative impact on global climate change.

With the increasing use of mass timber, and timber products generally, we felt it imperative to address some of the difficult questions that arise by virtue of this change in construction methods. For instance, what happens to the by-products from the manufacture of cross-laminated timber? As harvesting and growing wood sustainably becomes more imperative, what might be done with undergrowth removal as many of these materials are difficult to economically incentivize due to their size, irregularity, and variety? In many cases, this waste or biomass is turned to fuel. However, some argue that this practice may not be deriving the full potential and economic benefit of the by-product. With this in mind, we decided to ask what we might do with all the waste from these emerging production methods.

The first part of our research, and the first half of this paper, deals primarily with the questions above. We were fortunate throughout this stage of the research to have access to robotic tools which will be described below, due to receiving funding from a Chancellor's Grant for Research and Innovation from the University of Arkansas. However, in conducting the research, we realized a couple of important things about it that needed to be addressed. First, we concluded that not all people who want to conduct this research would have access to the same kind of tools that we did. Second, the tools we used were precise, but also were relatively slow and therefore did not give us the feedback as quickly as we wished. Because of this, it became important for us to find ways to ask the same important questions but of doing so with a quicker feedback loop and with limited resources. To do so, we tested creative solutions that could be employed by those who lacked tools and significant funding. That said, the second part of the research, and second half of the paper, is about the creative manufacture of relative equity in research processes that expand audiences who choose to address these global challenges.

UNDERSTANDING TOOLS AND THEIR IMPLICATIONS

For the first stage of the project, to determine the appropriate wood paste printing tools, we vetted different robotic arms, their costs, operational capacities, and construction implications, conducting a cost-benefit analysis which (at risk of generalization) we have summarized as follows.

The build size that the larger robots provide is an asset and these machines work with anything from small applications at a product/object scale to constructions at a full building scale. These larger six-axis arms also print on a multi-axis surface which is essential to certain design applications. Though the assets of the large robotic arms are fairly clear, they do also have some drawbacks. First, compared to most other 3D printing types, printing with a robotic arm is slow. Some of the speed depends on the material, but in general, using a robotic arm is a much slower process than other forms of 3D printing. Second, large scale Robotic arms are expensive. The arm itself is often in the $120,000 - $150,000 range, unaffordable for those who do not have exceptional funding from their schools or who have not won a grant for the type of work we are discussing in this paper. In addition to the upfront cost of the arm, there is an extra $30,000-$50,000 expenditure for additional equipment to create a continuous flow system. [1,2] (Figure 1)

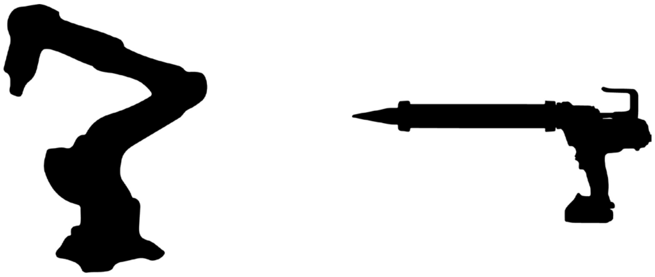

Figure 1. Equipment Exploration. Redacted.

We also explored small robotic arms and found similar assets and liabilities as described above but for a difference in cost. We determined that the affordability of the small-scale robotic arms would be most beneficial as a teaching tool and for small-scale prototyping. The reach on the arm is often around 22" radius and 36" high but varies depending on the specific piece of equipment. These arms can be used for furniture scale objects maximum but are often used for smaller object creation and their cost is typically in the $20,000-$25,000 range. Additionally, 3D printing setup with continuous extrusion for these arms will be an additional $10,000-$15,000. The exact cost numbers are less important here as they are changing daily. What is most important is to note that even the small arms require quite a bit of investment. Additionally, and not to be taken lightly, is the investment in knowledge required to operate these robotic arms effectively. This is often treated as an expertise outside the knowledge bounds of most faculty, especially if it is not their primary area of research.

After extensive research into robotic arm 3D printing, we became aware of a small company named 3D Potter which produces a SCARA robotic arm most often used by potters. The SCARA printers are three-axis, rather than the six-axis options discussed above. With special programming, you can get it to print on a non-planar surface, but it is more limited than the six or seven axis robotic arm multi-axis surface printing capabilities. Similar to the other robotic arms discussed above, the SCARA printers come in multiple sizes depending on the scale of work one is interested in accomplishing. In terms of cost of equipment in relation to scale of production, we found the 3D potter SCARA to be our most affordable means to getting a scale of production we desired at the time for the large-scale paste extrusion project discussed in this paper.

Because we had grant money, we chose the XLS-2 SCARA which was $15,000 at the time but is now approximately $24,000. This allowed a print size of up to 72" diameter and 57" high. This was large enough for us to create building elements that we would then construct into a larger structure. The XLS-2 SCARA printer saves us quite a bit of money in cost but had similar slow processing issues to the robotic arm described above. Because the XLS-2 SCARA does not come with a continuous flow system one is constantly filling and replacing tubes of material. This is not only time consuming, but it also jeopardizes the integrity of the paste material itself. In addition, because of the type of material we used, we could only print as fast as the material viscosity would allow. In other words, when the printing speed was too rapid, the material would slump due to lack of drying time, and when the printing speed was too slow, the paste in the tube would tend to dry out and therefore would no longer release from the tube to print.

In addition to the XLS-2 SCARA, we purchased one 3D Potterbot Super 7, which are the desktop versions of the printer. These were $6,200 at the time of purchase but are now approximately $8,000 and they have a build area of 17"x14"x20". Similar to the XLS-2 SCARA, the Super 7 printers are most often used by potters to print clay objects through paste extrusion. The benefit of the Super 7 printer is that it allows quick production of small prototypes, and the size still allows for a brick like dimension for comparison in full-scale building. This machine does print fairly quickly when using ceramic material. However, if you are using other paste material besides the intended ceramic, it can be a slow process and cause stress on the motor. Perhaps the primary downside of this machine is its size, as you can only print one or two units at a time which slows down the construction process in relation to the XLS-2 SCARA.

THE FUTURE OF WOOD STUDIO

To explore the opportunities of wood byproducts and help contribute toward the evolution of a zero-waste economy, we created a design studio titled The Future of Wood. This was an interdisciplinary studio, in collaboration with Civil Engineering faculty, conducted in fall 2019 which explored possible futures in wood construction instigated by emerging tools, materials, and building processes such as mass-timber, CNCing, and 3D printing.

The pedagogical intent was to inquire how we might convert wood by-products into buildings or building materials using 3D paste extrusion printing.

The semester began with the students learning how to operate the 3D Potterbot Super 7 printer described above using clay materials. We chose this path for two reasons. First, the students needed to learn how to operate the SCARA robot in order to eventually use it to test wood paste recipes. Second, the clay materials would provide a target viscosity and develop the students' intuition with regard to future wood paste material development. The effective use of this specific 3d printer meant that we had to simulate the properties of clay. With this in mind, for the first eight weeks of the studio, we developed multiple recipes that closely aligned with clay's viscosity and moisture content. (Figure 2)

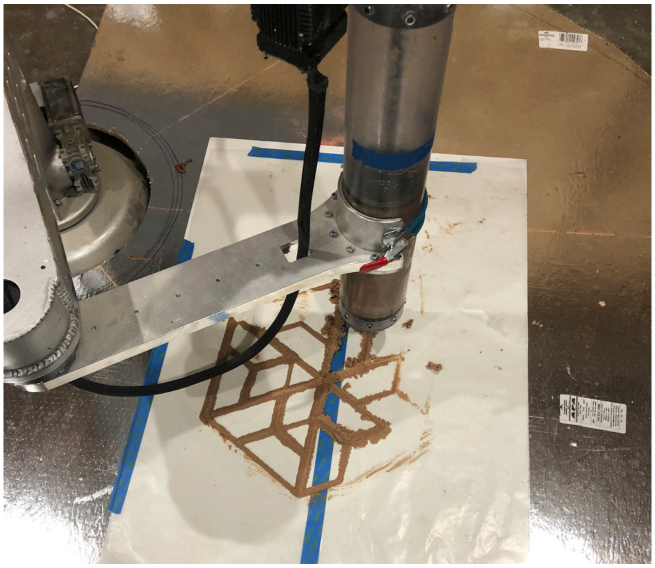

Figure 2. Equipment Exploration. Redacted.

Once the students developed expertise with the 3D Potterbot Super 7, they were able to begin developing and refining wood paste recipes. Over the previous summer a research assistant had explored and made progress on a wood paste recipe that contained 33% wood flour, and yielded prints that varied in their levels of success but were very informative about the strength and weakness of this product (images). Ultimately, we were unsatisfied with the fact that the recipe contained only 33% wood flour and set a target of 80% wood flour use for the studio. We determined this percentage through an understanding of the amount of wood used in Medium Density Fiber Board (MDF), which is a commonly used wood product. Part of the rationale behind increasing the amount of wood flour was a desire to use more wood waste to construct the final product, while the other rationale was the hopeful minimization of adhesives required to create a working recipe.

For the next several weeks, students experimented with numerous mixture types, using various adhesives and wood flour proportions. Each mixture was then tested in the 3D Potterbot Super 7 printer. Eventually, we were able to develop a printable recipe that contained 65% wood flour. Although this did not meet our 80% goal, it represented a substantial improvement from the common wood/plastic hybrid spool-based printing techniques which contain only 20%+/- wood product and 80%+/- plastic. As a part of the recipe testing process, we had the students print brick modules which gave clear indication of material properties, including slump and the effects of drying and hardening. (Figure 3)

Figure 3. Early Wood Paste Printing Samples. Redacted.

The consistency of the wood paste mixtures proved vital with respect to developing a consistent printable extrusion. When the mixture was too moist the pressure exerted by the printer would push the water out of the nozzle and dry out the wood paste before it could be effectively extruded. When the mixture was too dry the machine could not exert enough pressure without jeopardizing the tube or the robot's motor.

The order in which we mixed the material, and the open time between when we mixed and when we printed, radically affected the success of our final extrusions as well. Certain wood paste recipes that extruded effectively could not be printed at all when mixed in a different order. In addition, the recipes had to be kept at their relative viscosity and moisture levels for a long enough period of time that they could be transferred from the mixing stations to the tubes without drying out. The wood paste mixture's open time within the printing tube was also critical. When the material sat too long in the tube moisture would migrate toward the bottom, thereby drying the upper portion of the material, rendering it unprintable.

Additionally, the glue within the wood paste mixture is important for printing success and overall structure of the material. Not only did the glue affect the ability to successfully print via its effect on the material viscosity, but it also greatly impacted the strength of the dried material. We tested numerous glues but ultimately chose a formaldehyde-based epoxy powder resin, often used in musical instrument repair. The powder resin gave us a long enough drying time to help maintain the appropriate viscosity while transferring material and setting up the printer. Ultimately, the use of formaldehyde-based glues is not ideal and part of our efforts in the future will be to find a more sustainable alternative that still offers the required strength and open time needed for successful printing.

Simulating the viscosity of clay was not only vital in terms of the consistent physical extrusion of the material but was also important in terms of how the material handled the layering process involved in 3d printing. Unlike plastics printing, where the previous layer is dried and hardened before the next layer is extruded, the wood paste mixtures take longer to harden. This meant that the load distributed from one layer to the next caused the layers below to compress. When too many layers were applied too quickly the printed form slumped and eventually failed. (images)

Control and consistency of the distribution of material from the nozzle was also tested. Any air pockets within the material or inconsistencies within the mixtures would cause variation in the bead dimension as it left the printer's nozzle. Deeper inquiry into the wood paste's properties and heightened controls over material loading would likely alleviate these issues.

Our experiments showed that room temperature directly affected the drying time and movement of the material before it hardened. Colder spaces in which the temperature was not as carefully controlled caused delayed drying time and more overall material movement. In warmer spaces with greater temperature controls the material warped less and dried more quickly overall.

With the refined recipe of printable wood paste we were then able to determine, through extensive iterative work, the construction possibilities, and limitations inherent in the printing process. It's worth citing a few of the main principles that effected the construction logic. First, due to the SCARA printers' three-axis capacity, we had to print our objects as two-dimensional extrusions. This meant that we needed to print these objects as modular blocks, in sheets, or in two-dimensional frames. Second, due to the nature of the wood paste material, we could not print anything taller than approximately three inches. Exceeding three inches meant that the material began to slump under its own weight due to its viscosity and slow drying time.

Because this was a collaborative course with Civil Engineering faculty and students, we were able to analyze the structural properties of the dried wood paste material through break testing and found that it had approximately the same tensile strength as wood. For instance, a wood dowel of approximately the same diameter of the dried wood paste frame shared approximately the same structural capacity.

With this growing body of knowledge, the next assignment involved testing joinery and assembly techniques, which grew into a speculation on formal possibilities. Students began to assemble test pieces together through various joinery methods which included drilling through and tying pieces together with string, the use of Hide glue as a laminating material, and even steel screws and metal clips. (Figure 4)

Figure 4. Joinery Testing. Redacted.

Once we had a good sense of how to make a workable paste, how to print that paste successfully, and how to join the dried frame elements effectively, we were ready for the project that would last us the rest of the semester. Desiring to take on something relatively large scale and prove the potential effectiveness of this material and process for construction, we opted to design and build a full-scale shade and seating pavilion. Without belaboring the intentions behind the design process it's worth saying that it was important to us that we built something which would both test the structural capacity of the build material while also testing its potential shape making capacities.

To this end, the students created curved formwork that two-dimensional latticework pieces of wet printed paste material could be laid upon to let dry. Once dry, these pieces would take on the property of the formwork itself. The eventual design became a tiled assembly of lattice pieces, connected by string set in Hide glue.

The outcomes of this interdisciplinary studio experiment gave us a new perspective as to what the future may yield in the deployment of such green materials in the design and construction of buildings. It also taught us great lessons with respect to the processes of wood past extrusion printing. We learned about the specific material viscosities required to make printing possible, how strong these printing frame elements were, how to attach them to each other, and how to think creatively about three-dimensional shape making in a process that is inherently two-dimensional. (Figure 5)

THE PROXY CHAIR

Following The Future of Wood studio, we had a lot of questions regarding what we had learned, how to advance that knowledge through new projects, and how to ensure that critical inquiries like this were available to anyone who desired to experiment with them, rather than just to those who could afford expensive equipment. The process of building the wood pavilion created

Figure 5. Final Pavilion Legs. Redacted.

stresses that resulted in some of the ideation we brought to the next project. For instance, on several occasions during the Future of Wood project the 3D Potter equipment malfunctioned due to our constantly taxing it with materials that it was never intended to handle. Because of this we were always speculating on backup plans, or proxies, for the equipment that would be used in the case of total failure.

One of the tools and techniques we discussed was the use of an electric caulk gun as a proxy for the robotic arm. This was an easily accessible $40 piece of equipment, which meant that we could purchase several of them and even test the tool to failure when necessary. We decided to take on a smaller scale project using this method, resulting in the Proxy Chair. The Proxy Chair is built with wood paste using an electric caulk gun which acts as a proxy for robotic arm extrusion printing. The most essential aspect of this project is that it indicates a method of asking critical questions about the development of sustainable materials and processes without requiring equipment that is unaffordable to the vast majority of researchers. In fact, it places the possibility of these types of exploration in the hands of lay people.

There were several goals that we set for ourselves in the Proxy Chair project. First, as stated above, we wanted to test the use of inexpensive tools as proxies for robotic processes. Second, we wanted to continue the exploration of the wood paste material properties and capacities from the Future of Wood project. Third, we wanted to experiment with techniques that three-dimensionalized inherently two-dimensional processes.

We achieved our first goal by testing the exact same material recipe as was used in The Future of Wood project and mapping the extrusion effects from one project to the other. There was no significant difference in the extruded profile, its structural capacity, or the shape making we could achieve with the process.

Our second goal was tested successfully by virtue of the newfound speed of electric caulk gun printing in relation to the robotic arm. Because we could test each recipe quickly, we were able to expand the use of wood flour in the recipe to 73%; any percentage of wood flour in the recipe over this resulted in brittle material that cracked during the drying process.

Our third goal was met through the use of inventive formwork design. Similar to the SCARA robotic arm, the electric caulk gun is primarily a two-dimensional extrusion process. The designer must be creative with the formwork in order to develop a third dimension effectively. We designed a form for the Proxy Chair which could easily be converted from two-dimensional to three-dimensional in a relatively short amount of time to contend with drying time. The two-dimensional form, a flat sheet shaped like the outer profile of the chair, allowed for easy application of the paste without having to work along acute angles or vertical surfaces. This was constructed by CNC milling a piece of Baltic Birch and kerfing the underside to allow flexibility in the parts that needed to be bent into the third dimension. In addition, we created a housing element that was mounted to the underside of the flat piece to give the bendable panel something to which it could be affixed upon conversion to three-dimensionality. We then used a red plastic tape as a bond-breaker so that the wood paste could move slightly while drying and so that it wouldn't break when we lifted it off the form. (Figure 6)

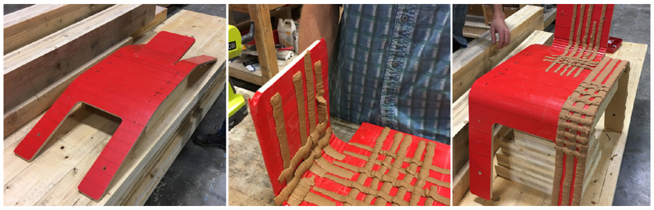

Figure 6. Proxy Chair Formwork. Redacted.

In addition to meeting the above goals, we were also able to modify the common plastic caulk gun tips for different profiles using an FDM 3D printer. In addition, we purchased extra empty canisters and easily switched them out during the printing process, partially simulating a continuous flow material process. The electric caulk gun also allowed live feedback and on-demand adjustments. All told, the electric caulk gun proved to be an easily hackable, inexpensive, imminently adjustable process which fairly replicated the extrusion capacity of the SCARA robotic arm printers.

The primary downside to the electric caulk gun printing process was a problem shared by the SCARA robotic arm, there was no continuous flow feeder which meant we were dealing with a material open time that we had to be conscious of during the construction process and which limited our capacities to print larger runs of material. The only way to overcome this issue (for now) is to purchase the more expensive continuous flow feeders. Another method we plan to try in the near future is the adaptation of a reel to feed reenforcing material into the wood paste as it extrudes. (Figure 7)

Figure 7. Proxy Chair Final Print. Redacted.

CONCLUSION

Asking critical questions about emerging material and tooling processes is an important step in the evolution toward developing zero-waste construction practices. Even though the increasing use of wood in the construction industry is desirable in terms of its positive planetary impact with respect to global climate change, we must continue to refine processes that are waste inducing in these processes. The Future of Wood and Proxy Chair projects described here are our first attempts at doing so.

Through taking on these challenges we have learned about the capacities for wood paste extrusion, the possibilities for positive future experiments, and the challenges that still remain. There is still work to be done with respect to maximizing the amount of wood flour used within wood paste extrusion processes, increasing the strength capacity of the wood paste members, using adhesives that are more sustainable, gaining control over the drying and movement of the members themselves, and relatedly, creating controllable and beautiful connections between members. This research is ripe for exploration and likely requires partnerships with civil engineering, mechanical engineering, material scientist and others to be explored more deeply.

As designers and academics, the tools we have access to become critical instruments for evolving our ideas and bringing new work into the world. Unfortunately, not everyone has access to similar equipment, making the advancement and promotion of new ideas accessible only to a select few. The projects described here are an attempt to not only explore wood paste extrusion techniques but also to level the economic playing field so that more people can explore these issues in the future.

ENDNOTES

1. http://papers.cumincad.org/data/works/att/acadia18_276.pdf
2. https://utw10945.utweb.utexas.edu/sites/default/files/2019/134%20Large-Scale%20Additive%20Manufacturing%20of%20Concrete%20Usi.pdf