INTEGRATED DESIGN LAB University of Idaho

University of Idaho College of Art and Architecture

University of Idaho College of Engineering

BOISE STATE UNIVERSITY COLLEGE OF ENGINEERING Department of Construction Management

University of Idaho College of Natural Resources

ISBOE HERC-IGEM
Cellulosic 3D Printing of Modular Building Assemblies

SECOND YEAR REPORT
FISCAL PERIOD – JULY 1, 2020 - JUNE 30, 2021

SUMMARY OF PROGRESS
June 30, 2021

Prepared for:
HERC-IGEM – Idaho State Board of Education
Dr. TJ Bliss

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ACRONYMS AND ABBREVIATIONS

3D printing	Three-dimensional printing
AM	Additive manufacturing`
IDL	Integrated Design Lab
UI	University of Idaho

1. Introduction

The project objective is to identify the methodology, process, and materials necessary to three-dimensional cold print (3D print) building assemblies utilizing, to some maximum extent, wood products. Moving a significant portion of construction into a factory setting where labor and work is organized and executed more efficiently will have the following benefits: 1) increase the quality and energy efficiency of buildings; 2) lower overall construction costs; 3) provide appropriate compensation for a more skilled labor force and, 4) assist in mitigating the current construction skilled labor shortage challenge in Idaho.

Tasks for Year 2:

1) Identify private industry investors and solicit financial commitment from industry partners
2) Build a small-scale printer and print a two foot by two-foot by eight-inch wall section
3) Program a computer model for running printer.
4) Perform heat transfer and structural tests on a wall section.

Summary for Year 2:

Significant discovery was made on each of the four tasks identified as Year 2 deliverables. We do not as yet have private industry support for the project as we are, 1) working toward a provisional patent that would allow our disclosure of the resins and process for creating our product and, 2) we are in process of building a new business model under a program developed through the Boise State University Venture College and funded through NSF. Our acceptance in the I-Corps Ignite program is providing a structured business development process that we plan to fully implement over year three of the grant.

U of I Engineering has designed and built a first prototype printer and we have successfully printed single-layer prints. Our refined goal for year three is to print in layers.

Our resin and curing process has successfully produced a hardboard product that looks to be competitive with other hardboards on the market. Unlike current market products, our hardboard has no toxic resins, looks to be highly moisture and fire resistant (testing begins in October 2021), sequesters carbon at a high rate (currently being documented) and, prints and is able to cure without added heat energy.

We have built a guarded hot plate for thermal testing our material and panel sections when complete.

This has been an excellent discovery process for faculty and students. Engineering graduate student, Conal Thie has completed his master's thesis, focusing on the flow characteristics of wood fibers and our resin and extrusion process. Environmental Science doctoral student, Berlinda Orji is documenting the flow and curing process of the mix as part of her dissertation.

2. Summary of Project Accomplishments for the Reporting Period Just Completed

Research and identify the printing mix of wood/natural fibers, binders and adhesives.

Prepared by: Armando McDonald, Ph.D

Second Year Report

Year 2, reporting Dr. McDonald staffing: 1 Ph.D. student in Environmental Science. 1 woman. Salary expenditures and student tuition in the McDonald lab have focused on supporting the research efforts of one Ph.D. student. Capital and operational expenses are in line with ongoing and projected research activities on wood-resin curing research. Appropriated funds will be expended by the end of year 2.

The second-year research focused on the use of a selected adhesive amongst the options available for wood composite production due to its ease of use and less squeeze out during extrusion. Continuous capillary extrusion using this wood and adhesive blend were performed using the INSTRON capillary rheometer at high shear rates to determine compressive pressure and viscosity values. Frequency sweeps of the wet blends was done using the purchased DHR2 rheometer between two 25 mm parallel plates, to attain viscosity values at lower shear rates as seen in Figure 1. Dynamic rheology temperature ramps (30°C - 200°C) on wet samples helped in understanding the curing reactions of different wood-adhesive blends.

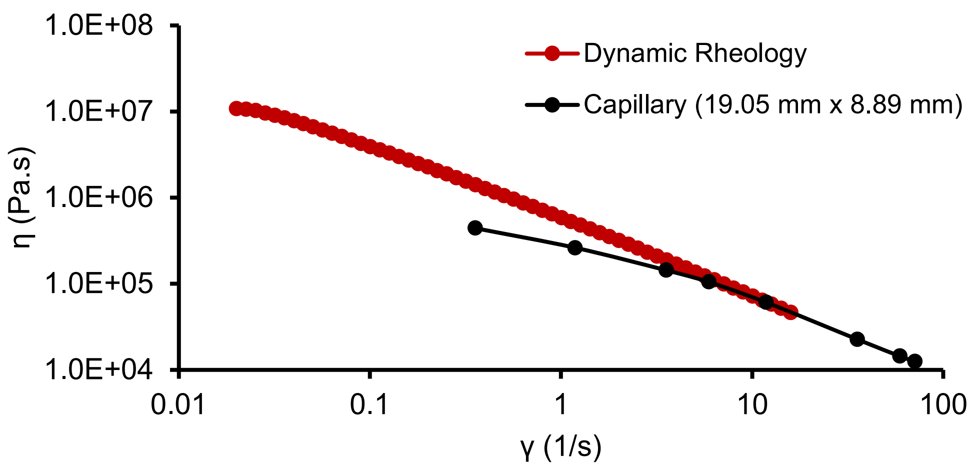


Figure 1: Dynamic viscosity and capillary viscosity from low to high shear rates

A larger capillary setup in Figure 2a, with large dies was machined for bigger sample load with thicker extrudate diameter. With the understanding of the vertical capillary rheology setup, a horizontal extruder setup was coupled together for extrusion and printing purposes. An industrial food processor was also purchased for mixing larger volumes of wood-adhesive samples (Figure 2b). Wet wood-adhesive blends were also pressed in 1-inch and 3-inch molds for characterization. Obtained extruded and pressed samples were cured at different temperatures (60°C - 105°C) and further characterized.

Figure 2: a) Large Capillary rheology setup and, b) Industrial food processor.

The use of carbon dioxide (CO_2) for curing was employed to understand its effect in improving the mechanical and thermal properties of the cured samples produced, whilst reducing environmental issues and improving sustainability. The adhesive used was exposed to 99% of pure CO_2 at different time intervals (0.5 to 20 min) to observe gelation crosslinking reactions before further curing of wood-adhesive blends. Adhesive showed effective gelation and cross linking. Post curing was attained in the oven at different temperatures (60°C - 105°C). Curing of the wet wood adhesive blends with CO_2 was done using a pressure vessel (Figure 3) and in a controlled temperature environment. For the controlled temperature environment, samples pressurized under CO_2 were placed in a water bath at 60 °C for specific times. Wet wood-adhesive blends were cured thermally in the absence and presence of CO_2 with further characterization. Physical and chemical changes were observed with the presence of CO_2 in the cured wood-adhesive blend.

a). Before curing

b) After curing at 105°C

c) After CO_2 (60 psi and 60 °C) and thermal curing

Figure 3: Pressure vessel used for CO_2 curing

Wet and cured extruded slabs from horizontal extruder setup are presently characterized to obtain their properties. Surface chemistry changes were observed with the addition of the adhesive to wood, presence of CO_2, and after curing using the FTIR analysis. Thermal degradation properties of the cured samples which was done using TGA, improved in the presence of CO_2. bending tests, dynamic mechanical analysis (DMA) for mechanical tests, dynamic rheology for flow properties and water soak tests.

Current and future studies involve the improvement of CO_2 curing techniques, use of different additives, catalysts, pressure and temperature modifications for curing, for improvements in properties of the 3D printed cured composite blends.

Build a prototype printer.

Prepared by: Michael R. Maughan, Ph.D, PE and Tao Xing, Ph.D PE

Year-End Update Report, IGEM, June 2021 – University of Idaho Mechanical Engineering

The University of Idaho (UI) Mechanical Engineering (ME) team has the responsibility of developing a 3D printing process and printer for depositing a wood waste composite mixture developed by researchers in the UI College of Natural Resources (CNR). The goal is to make bespoke small-scale composite structural building panels. UI ME is also responsible for thermal modeling and optimization of the 3D printed composite building panels.

In 2021 the Mechanical Engineering team has continued to make progress on the development and implementation of the system. We have refined the previously identified extrusion technique to eliminate defects on the surface known as shark-skin. This defect is caused by friction and shear gradient within the flowing mixture. In addition to improving extrudate quality, we have identified a suitable hose and attachment method to convey the wood product from the extruder barrel to the nozzle. A nozzle system has been developed with geometry acceptable to print prototype panels. Fig. 4 shows a prototyping progression of the nozzle.

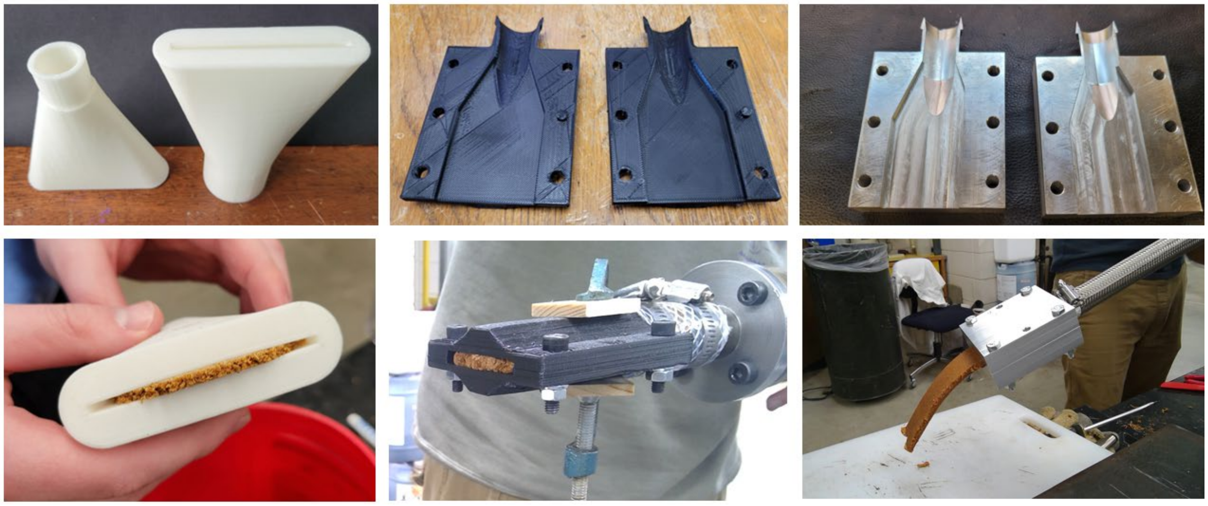


Figure 4. Progression of printer nozzle design.

Continuous flow extruder – We have added a 1hp motor to the extruder. This is necessary to overcome the high pressures required to move and form the composite mixture. Adapting the motor require machining a custom adapter and alignment blocks to support the motor. The machine is now capable of higher output and operates effectively. We have used this machine and a round nozzle to make cylindrical samples which were used to test strength and modulus. We have identified a curing method that achieves properties equal to or exceeding those of particle board. Preliminary moisture and fire testing have been conducted.

Direct extrusion frame and simulation – Using the direct extrusion frame and prior computational model, the simulation has been refined and is being incorporated into a student's Master of Science Thesis. The team has identified a state-of-the-art Discrete Element Modeling (DEM) based simulation software that is fully integrated with ANSYS multiphysics, which will be used to improve the simulation accuracy.

Modular 3D-printer frame – Since December 2020, we have completed the primary wiring and motion gantry. The computer numerical control components of the printer have been installed and the printer has functional motion control. Figure 5 shows the printer with the extruder. In testing with the extrudate, we have learned that adhesive and pressure are required to make the layers bond, so our next task is to incorporate an adhesive spraying system and pressure panel that can be used to maintain adhesion during the first stages of curing. The system utilizes stepper motors for position control. The target layer geometry is wide and thin, which enables a large surface area to promote interlayer adhesion.

Figure 5. 3D printer with extruder system.

Graduate research assistants – UI ME has been staffed with two graduate research assistants (GRA) since December 2020. GRA1 has focused on the deposition process and performance modeling of the material. The GRA2 has wired and finished the printer frame and developed the extrusion nozzle.

Develop guarded hot plate for thermal testing

Prepared by: Damon Woods, Ph.D, P.E., Ralph Budwig, Ph.D, P.E.

Staff: William (Bob) Basham

Graduate Students: Tais Mitchell and Conal Thie

Over the last year, we pursued two separate methods to characterize the thermal properties of the 3D-printed wood composite. Initially, we used a transient probe from East 30 sensors to measure the thermal conductivity of the samples. The transient probe is useful for measuring small samples produced by the rheology press. We used the thermal conductivity results to develop a numerical model and estimate the insulation properties of a full wall assembly made from these materials. We ran further simulations to estimate the potential energy savings for residents compared to other wall types. We used DOE’s scout energy analysis tool to estimate the potential market penetration and total energy savings.

Figure 6. Thermal Testing Using a Transient Probe Method.

Once we collected preliminary results with the probe, we worked on a secondary method to measure more thermal properties in accordance with building code requirements. This secondary testing method will provide details on how the layering effects of the 3D printed process impact the thermal properties of the material (Fig. 6). To meet this goal, we have designed and fabricated a thermal testing apparatus in accordance with the ASTM Standard C177 (Fig. 7). In addition to complying with the ASTM standard, the apparatus was designed as a modular assembly for ease of manufacturing. Renderings and photos of the device are shown below. It consists of an aluminum frame to hold the materials, heating plates and sensors controlled by an Arduino board, and a water refrigeration system.

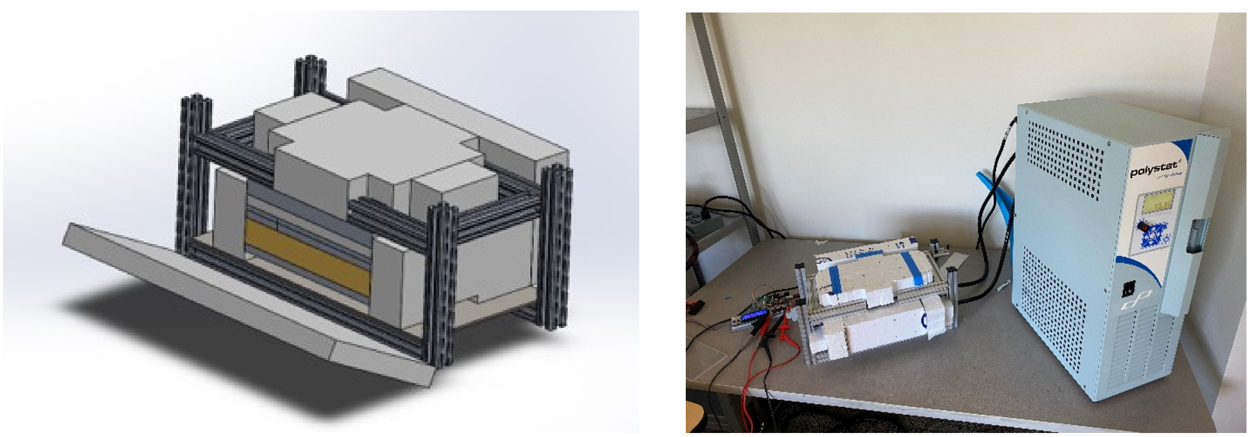


Figure 7. Rendering of 2nd Apparatus (Left) and calibration testing of Apparatus (Right).

The apparatus shown above (Fig. 7) is currently undergoing verification experience with a standard reference material to ensure reliability and compliance towards the standard. We are planning further refinements to make the device computer automated during the test and process the recorded data. The device will characterize the thermal properties of the printed material so that we can optimize the panel materials and configuration.

In addition to the thermal testing, the team also worked to develop a life cycle assessment analysis comparing the environmental impacts of the preliminary wall assembly to other wall envelops in residential and light commercial buildings. The scope of the analysis focused on quantifying the embodied energy of a typical 8-foot by 8-foot wall section in each stage of its life. This includes the material, manufacturing process, building energy usage, and end of life stages. We worked to quantify other Eco indicators including acidification, global warming potential, and Ozone depletion. We learned from the study that the stage responsible for the largest environmental impact is that of the building energy usage phase. Based on our estimates, the 3D printed wood-waste wall showed the some of the lowest energy impacts of any wall assemblies that we studied.

Constructability Analysis

R. Casey Cline, Boise State University, Department of Construction Management
Kirsten A. Davis, Boise State University, Department of Construction Management
J. Ty Morrison, Boise State University, Department of Construction Management

The Boise State University Construction Management (BSU CM) research team has focused on three areas supporting the research efforts: assisting in developing the business case, developing a construction sequencing model, and continuing with the constructability reviews.

Assisting with business case development:

The UI team has been developing the business case for the 3D printed panels. The BSU CM team has been providing assistance in reviewing this work and adding to it based on our areas of expertise in the construction industry.

Discussions have been held with the Idaho Associated General Contractors (AGC) about the progress of the 3D printing project. (Note: The AGC provided a letter of support during the grant application process). The main takeaway at this time is that approaching contractors to participate in testing of the 3D product will be easier, and more likely to be successful, once a product is available.

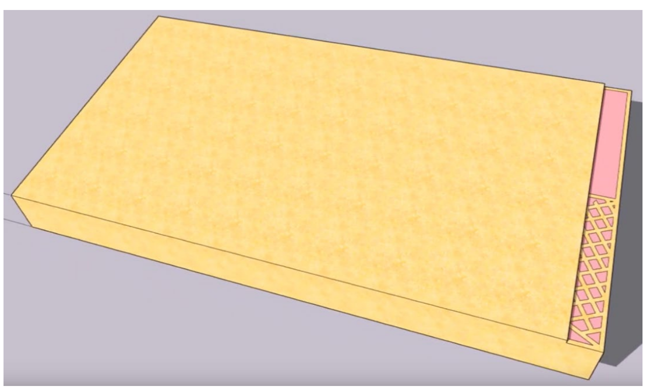
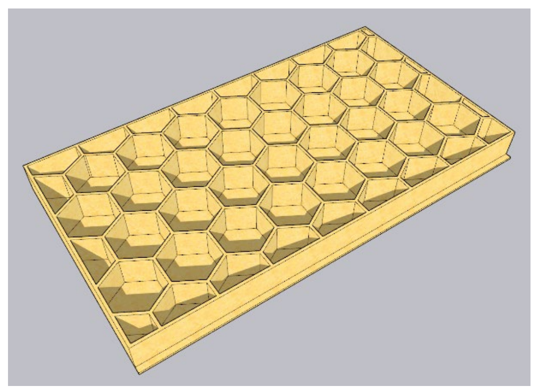
There have been preliminary discussions with the Idaho Forest Products Commission (IFPC) and other building related companies about the concepts and products this work is creating and they are interested in learning more once the details of the panels are more fully developed.

The BSU CM team has also been evaluating the best market (residential, light commercial, etc.) for panels like this based on constructability, using the current and projected panel and material info from the UI teams. For either market, the adoption and use of a 3D printed panels in construction will depend on cost, schedule, and availability of skilled labor. The intent is to have a process where the panels are manufactured in a local factory setting, or possibly fabricated on site.

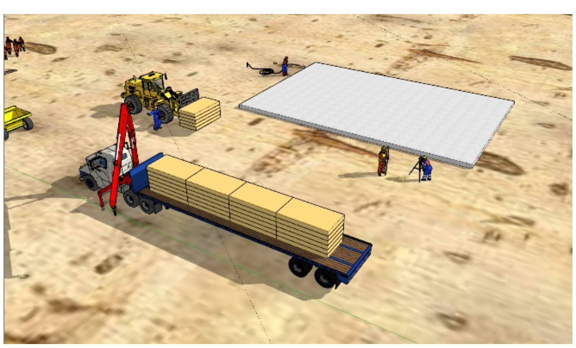
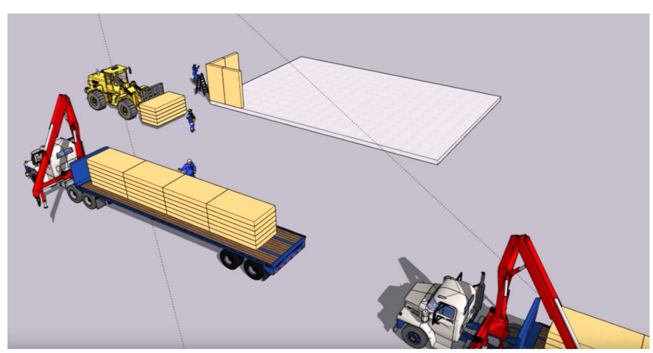
Developing construction sequencing model:

Using 3D modelling and video editing software, models and a video have been developed to begin determining the panel configurations and ideal construction sequencing of panels. This work includes a simulation of full-size panel printing, proposed panel shapes, and a possible construction sequence. Several iterations of the panel configuration have been explored, reflecting the initial fabrication and tests of extrudent. Final refinement of the ideal panel shape and structure is dependent on completion of the extrusion manufacturing process and related properties testing. The modelling and sequencing will continue to evolve and improve as more details about the panel fabrication processes from the UI teams become available. Limitations in the panel fabrication process may affect delivery and erection requirements, causing changes to the final panel shapes and construction sequencing. Several screen shots included below depict examples of the refinement of conceptual design ideas.

Also, as mentioned above, the BSU CM team has identified the possibility of panels for use in residential and light commercial applications which will require adaptation of the basic panel concept (configuration and sequencing) to better facilitate implementation in these two distinct arenas of construction markets.

Examples of possible panel makeup with interior honeycombing revealed

Beginning of possible construction sequence

Continuing constructability review:

The constructability review has continued to evolve as the details of the panel materials have been developed by the UI teams. The BSU CM team has provided troubleshooting on the project and has developed priorities for the wood fiber material and panel development, based on constructability aspects. These priorities include items such as:

- water resistance,
- dimensional stability,
- durability,
- ability to modify panels at job site with common tools such as saws, drills, routers, etc. with minimal damage to panels,
- suitability of panel for paint, adhesives, sealants to stick to panel with minimal prep,
- size and texture of finished panels, and
- ability to embed metal and/or plastic items during 3D printing process to facilitate transportation, connections, utilities located in or attached to panels, and finishes applied to panels.

Future Plans:

We are looking forward to experimenting with small sections of full-thickness panels to help ensure that the panels will meet our constructability priorities. Samples of 3D printed material will also allow us to determine how panels can be connected together to create a wall or other part of a structure, as well as whether those connections actually work. Aspects such as durability of the panels and suitability for finishes will also be explored over the next year.

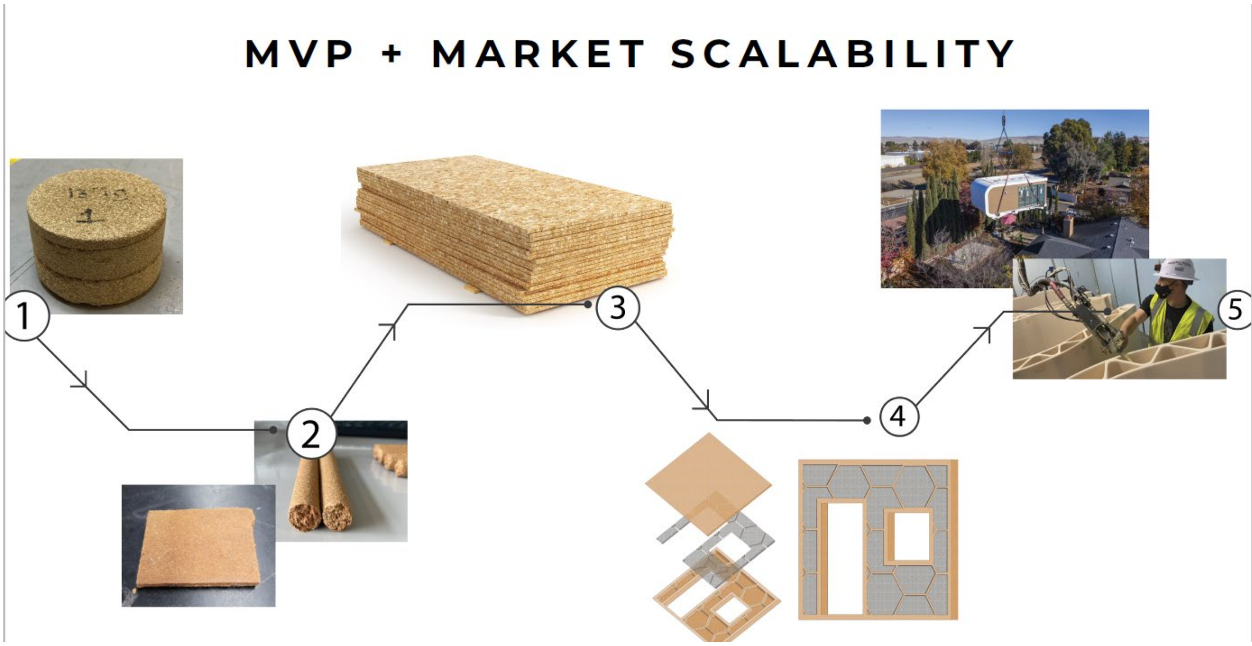
The construction process and sequencing will be updated to reflect improvements made by the UI teams.

3. Summary of Budget Expenditures

Salaries:	$152,528.40
Temp Help	$18,090.00
Fringe	$ 30,993.12
Travel	$ 00
Operating	$ 28,549.67
Small Equip	$ 844.95
Capital Equip	$9991.11
BSU Sub	$28,908.15
Tuition	$46594.00
TOTAL	**$316,499.4**

4. Demonstration of economic development/impact

- Patents, copyrights
    - We are actively working on a provisional patent for the cold-setting process.
- Technology licenses signed
    - None at this time
- Private sector engagement
    - PI Ken Baker and masters' student Kelsey Ramsey were selected by the I-Corps Ignite committee to participate in a four-week three-university class on lean startup business development. We are engaged in moving our product to date forward and finding private funding and a new business case. A large aspect of this class is identifying private sector clients and performing client interviews. These will take place beginning this summer.
- Jobs created
    - None outside the universities at this time.
- External funding
    - We submitted on an NSF Track 2 grant proposal (Michael Maughan PI) and were notified on June 29 that it will be funded. Under this proposal we will expand our current research to other bio-based materials for our panel prints and explore the architectural resiliency expressions of materials in design applications .
    - We have submitted a DOE BENEFIT grant proposal (Ken Baker PI) and are awaiting confirmation of award. This proposal would work toward development of the scale up panel manufacturing process and, solicit a manufacturing partner.
    - We have submitted an ARPA-E concept paper to DOE (Armando McDonald PI) to develop products from our cold-setting mix of wood, sodium silicate and carbon dioxide. We are waiting to receive a go ahead for a full proposal.
- Other pertinent information
    - Although we do not yet have a printed panel, we do have a minimum viable product in the form of a hardboard that we believe will be competitive with current products. The goal under this grant is to get to image #4 below. We are currently approaching #3.



5. Numbers of Faculty and Student Participation

There are nine faculty participating in the grant, six from the U of I and three with BSU. There were five Research Associates working on the grant in year two.

6. Description of Future Plans for Project Continuation or Expansion

Four key outcomes were expected in year 2 of the three-year grant:

1. The print mix for cold setting print will be identified. Completed.
2. The printer specifications and printer will be further defined as a product that could scale up for manufacturing large-scale panels. Completed
3. Business/industry partners will be engaged and private investment will be solicited. We are currently reworking our business plan under the I-Corps Ignite program.
4. The thermal characteristics of printed panels will be assessed. Ongoing as new prints are developed.

7. Commercialization Revenue

None to date.