Case Study Title (25 words)

BioHome3D: World's first fully bio-based, fully recyclable, highly insulated 3D-printed house.

Contributors - List of contributors to the innovative case study of AM technologies and their affiliation. Include who would sell the final product and who did the design.

- The Advanced Structures and Composites Center (ASCC) is a world-leading, interdisciplinary center for research, education, and economic development encompassing material sciences, advanced manufacturing, and engineering of composites and structures located on the University of Maine campus. The ASCC is the largest university-based research center in Maine and among the fastest growing research laboratories globally. The facility includes 13 integrated laboratories with more than 260 part and full-time personnel, including faculty, staff, and students. [Role]: Structural design, additive manufacturing, materials testing and installation.
- Oak Ridge Ridge National Laboratory (ORNL) is the largest science and energy national laboratory in the U.S. Department of Energy national laboratory system. The ASCC works with ORNL through the Hub and Spoke Program, a partnership which combines the ASCC's extensive forest-derived bio-based composites expertise with ORNL's advanced manufacturing capabilities through its Manufacturing Demonstration Facility. [Role]: Oak Ridge National Laboratory and the Hub and Spoke Program were key partners in the conceptualization, design, and development of BioHome3D.
- The Maine State Housing Authority (MaineHousing) is an independent authority created by the Maine State Legislature in 1969 to address problems of unsafe, unsuitable, overcrowded, and unaffordable housing. At its core, the agency couples the efficiencies of the private financial markets with public purpose goals to provide affordable home ownership and rental housing opportunities for Maine people. [Role]: MaineHousing was a key partner in developing and reviewing the specifications for the home in alignment with low-income housing standards.
- The Maine Technology Institute offers grants, loans, equity investments, and services to support Maine's innovation economy. Maine Technology Institute supports new ideas, products, or methods with the potential to grow and diversify Maine's economy and increase the number of quality jobs through direct support of innovators and through support of

programs and infrastructure that encourage innovation. [Role]: Maine Technology Institute financially supported the design of the prototype.

- WBRC, Inc. is an Engineering and Architecture firm headquartered in Bangor, ME. [Role]: WBRC, Inc contributed to the interior design and layout of the house.

Problem Definition or Need Statement (250 words) – Why is your solution needed and disruptive? Describe the challenge your team was facing and/or the design/market opportunity. Explain why it was an important problem to solve and its potential for disruption.

The U.S. and the state of Maine, in particular, are experiencing a crisis-level shortage of affordable housing1. The National Low Income Housing Coalition reports that nationally, there is a need for more than 7 million affordable housing units. 2017 UN Report states that by 2060, global build environment need to be doubled2, i.e., the productivity has to be doubled to achieve ~13k buildings/day.

In Maine alone, the deficit is 20,000 housing units and growing each year, according to the Maine Affordable Housing Coalition. Nearly 60% of low-income renters in Maine spend more than half of their income on housing3. This untenable situation is exacerbated by the double challenges of labor shortage and supply chain-driven material price increases.

This technology is designed to address labor shortages and supply chain issues that are driving high costs and constricting the supply of affordable housing. Less time is required on-site building and fitting up the home due to the use of automated manufacturing and off-site production. Printing using abundant, renewable, locally sourced wood fiber feedstock reduces dependence on a constrained supply chain. These materials support the revitalization of local forest product industries and are more resilient to global supply chain disruptions and labor shortages.

Additionally, housing is responsible for 21% of U.S. primary energy use, and printing 100% biobased homes illustrates the capabilities of large-scale AM using lower carbon materials than conventional construction materials4. The combination of housing and labor shortages has led to a great need to innovate and redesign the construction industry.

Background Perspectives (150 words) – How does your solution compare to the state of the art? Describe the current approach / existing alternative solutions to this problem. Describe how your innovation differs from this state of the art.

BioHome3D is a 600 square foot single family unit, designed as printed, separate modules for ease of transportation. Each module is 100% additively manufactured—the floors, walls, and roof—which differentiates this house from current commercial 3D printed homes. Each module was printed using the world's largest polymer 3D printer and fully bio-based composite material formulations developed by ORNL and ASCC, helping revitalize Maine's forest products industry while addressing affordable housing and labor shortages.

The house was manufactured through highly automated, off-site, modular fabrication and assembly. BioHome3D was printed in four modules with patented 45° angle approach, then moved to the site and assembled in 2 days. Modules were insulated and pre-wired before shipping, enabling electricity to be turned on in the house within hours after the last module was joined. The home was designed based on the Maine State Housing requirements for the Orono, Maine region including snow loads.

Technical Overview (750 words) – Provide details into methodologies, tests, results, deployment and performance analyses, or implementation methodologies and outcomes. Whether its analysis of performance and/or of cost, the submission needs to have an assessment demonstrating the quality of the solution. Include what machine and material was used to print the part and what software was used for design. The part does not need to be in production, but it needs to be printed and tested.

BioHome3D is a fully bio-based 600 ft2 single family unit, designed as printed, separate modules for ease of transportation. Each module was 100% additively manufactured—the floors, walls, and roof—which differentiates this house from current commercial 3D printed homes.

The material formulation used in this work was developed by ORNL and ASCC as a part of large Hub&Spoke Program. The formulation developed combines special grade biopolymer with locally sourced pine fibers. The biopolymer was developed in collaboration with one of the world's largest biopolymer manufacturers, specially designed for large scale AM processes. It is currently being produced in pilot scale and in the process of commercialization. Wood fibers were utilized to control and optimize the rheology, cooling behavior and material properties of the formulation to enable printability and minimize distortion. Local wood residuals were used with bio-based polymers to create a renewable and more sustainable feedstock.

We have also conducted a preliminary life cycle assessment (LCA) and techno-economical analysis (TEA) on the feedstock material comparing it to the most commonly used large scale AM feedstock CF-ABS. The LCA and TEA showed that the developed fully bio-based feedstock material developed is projected to have less than 1/3 of cost of CF/ABS, less than 1/5 of CF/ABS embodied energy and less than 1/20 of CF/ABS carbon footprint (The bar charts are attached)

Additionally, a preliminary cradle-to-gate life cycle assessment (LCA) and life cycle cost model (LCCM) have been performed. These models compare the BioHome3D to that of a traditional stick-built home of the same size (600SF). The environmental LCA showed that with only minor print optimizations, future iterations of BioHome3D are on track to surpass the efficiency baselines set using traditional building materials. The LCCM found that while the initial moonshot demonstration was more expensive than a traditional stick-built home, value is derived and costs are recovered at the end of life, with an increased capability for recycling and reuse as compared to the conventional alternatives.

Ingersoll MasterPrint 3x, the World's largest thermoplastic additive manufacturing 3D printer was utilized for printing the BioHome3D. It is a pellet-fed fused filament fabrication (FFF) system with a print volume of 60 ft wide by 10 ft tall, which is expandable to 100 ft long. Finite element analysis (FEA) was used to predict distortion behavior of the developed formulation and for toot-path optimization. Entire volume (roof, walls, floor, interior wall) was printed in a single toolpath at an average 120 lbs/hr rate. Different printing approaches including patented 45-degree printing and 90-degree printing were utilized. Because of the size of the house and length of the print time, start and stop tests were carried out to optimize the manufacturing process without compromising interlayer adhesion significantly. The printed house has the dimensions of 35'7"x9'4"x26'6", and longitudinal and perpendicular walls via 45-degree printing were demonstrated.

The home is manufactured through highly automated, off-site, modular fabrication and assembly. BioHome3D was printed in four modules, then moved to the site and assembled in 2 days. Modules were insulated and pre-wired before shipping, enabling electricity to be turned on in the house a few hours after the last module was joined. The home was designed based on the Maine State Housing requirements for the Orono, Maine region including snow loads. Upon completion of the printing, both material level and structure level testing have been conducted on the printed structures. Printed walls demonstrated an average of 39.0 MPa ultimate tensile strength in printing direction and an average of 22.9 MPa tensile strength in interlayer (Z) direction based on mechanical characterization. The elastic modulus of the printed walls was measured as 4.23 GPa and 3.27 GPa for printing and z-directions, respectively. The relatively small difference between the printing and z-direction mechanical properties are indicative of success of the material formulation and printing process.

In addition to material testing, more structural tests including insulation (R-Value) and blower door testing have been carried out. Module 2 of the 3D house print was blower tested and achieved a 3.025 ACH 50 nearly meeting our goal of the Maine State Housing Authority's requirement of 3 ACH 50 or less for new single-family homes built in Zone 6 and 7. R-Value for the roof system calculated to be 29, the gable end walls are 24 and R-Value for the floor system is 18. The calculated R-value for the walls exceeds MSHA standards, while the roof and floor do not meet the MSHA standards. The windows and doors installed meet or exceed the MSHA standards for fenestrations.

Reflections (250 words) – Include the impact, importance, relevance, and/or benefits to your team's approach.

The U.S. and the state of Maine are experiencing a crisis-level shortage of affordable housing. The National Low Income Housing Coalition reports that nationally, there is a need for more than 7 million affordable housing units. According to the Maine Affordable Housing Coalition, the deficit in Maine alone is 20,000 housing units and growing. This untenable situation is exacerbated by the twin challenges of a growing construction labor shortage and supply chaindriven material price increases.

This technology is positioned to address both of these issues, enabling homes to be built using significantly fewer labor hours than traditional construction methods and providing laborers with a much safer work environment due to the use of automated manufacturing and off-site construction. In fact, BioHome3D was constructed in its entirety without a single reported injury. High-precision printing using abundant, renewable, locally-sourced wood fiber feedstock reduces dependence on a constrained supply chain and supports the revitalization of local forest product industries while nearly eliminating construction waste.

Housing is responsible for 21% of U.S. primary energy use, making it a critical target for greenhouse gas emission reductions. According to the United Nations Environment Programme, buildings account for nearly 40% of global carbon emissions5. Sustainably grown wood fiber is a renewable resource that captures carbon during the tree growth cycle, so BioHome3D may be thought of as a carbon storage and sequestration unit during and after its lifetime. BioHome3D is fully recyclable and highly insulated with 100% wood insulation and customizable R-values.

References

1. https://nlihc.org/gap

2. https://www.unep.org/news-and-stories/press-release/co2-emissions-buildings-andconstruction-hit-new-high-leaving-sector

3. https://nlihc.org/sites/default/files/gap/Gap-Report_2022.pdf

4. https://www.eia.gov/tools/faqs/faq.php?id=86&t=1

5. https://www.unep.org/news-and-stories/press-release/co2-emissions-buildings-andconstruction-hit-new-high-leaving-sector

Images (max 3) – Include a maximum of 3 images that are referenced in the technical narrative.

Attached