WOODENWOOD

Integrating Wood Waste in Design through Robotic Printing and Traditional Craft

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Abstract. The architecture and design industries are committed to reducing reliance on new materials such as wood, a major contributor to industrial waste. This paper focuses on utilizing wood waste through traditional woodworking and 3D printing to improve material efficiency, recyclability, and develop new material design expressions. A parametric model and robotic printing workflow are developed to establish links between the design of prototypical seating elements, printing toolpaths, and material properties, addressing functionality, ergonomics, and material distribution for design customization. Through this process, we introduce a woven deposition of wooden-textile, repurposing wood waste into functional seating elements while highlighting the design's role in fostering sustainable transitions.

Keywords. 3D Wood Printing, Robotic fabrication, Circular design, Toolpath Design, Wood craft, Wood waste

1. Introduction

Wood, a commonly used building material, exhibits sustainability through its renewable nature and low energy requirements for processing when compared to materials like steel and concrete (Skullestad et al., 2016). It also offers versatile shaping capabilities, both through traditional hand tools and advanced digital fabrication methods. However, Europe alone generates over 50 million tons of wood waste annually, with less than half being recycled or converted into energy (Jahan et al., 2022). Inadequate disposal in landfills results in chemical leaching, odors, biodiversity loss, and fire hazards, incurring substantial financial costs (Kern et al., 2018).

In response to such challenges, this research explores the integration of wood waste within a design process centred on combining traditional woodworking techniques with robotic printing of a wood-based material. A series of seating elements (i.e. chairs and stools) are used as prototypes with the overarching goal of promoting circular

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principles throughout their design to fabrication workflow. Material is sourced from two wood-waste streams: solid wood for the modular prototype structure and wood paste derived from sawdust for robotic printing of a "wood-textile". A parametric model and manufacturing workflow are employed to establish connections between the design of the full-scale prototypes, the toolpath for robotic printing, and material properties. The exploration of diverse design possibilities for seating elements is closely linked to printing experiments, resulting in the weaving of wood into articulated textures that mimic traditional rattan craftsmanship and address variables related to strength, functionality, ergonomics, material reusability, design expression and customization to the modular structure. Through this nuanced process, we explore new design considerations seeking to unravel the interplay between the material, fabrication, and the design intention, all aimed at promoting sustainability in the context of wood waste.

2. Background

Digital fabrication is a process that encompasses the use of computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies from the initial design phase through to fabrication. In the timber construction industry, automation strategies have been developed to fabricate standard components and precise joinery details rapidly. Furthermore, these strategies have expanded to encompass the creation of unique components for free-form architectural structures, thanks to advancements in CAD and CAM (Menges et al., 2016). The availability of an iterative design to manufacturing process has facilitated experimentation and expanded the possibilities for creation and innovation in the field of design. Additive manufacturing (AM), also known as 3D printing, has emerged as an impactful approach within this context that facilitates the integration of biobased materials through tailored printing setups, optimizing material distribution and enhancing performance in various aspects such as strength, weight reduction, thermal transmission, and acoustic absorption (Breseghello et al., 2021; Armaly et al., 2023; Cohen & Barath, 2023). AM workflows also facilitate sustainability in industrial production, with environmental impact reduction of up to 50% compared to conventional construction (Mehrpouya et al., 2021).

2.1. WOOD 3D PRINTING METHODS

The 3d printing of wood in the form of sawdust combined with binders has been featured in various printing methods. Within FDM, wood particles have been combined with thermoplastics like PLA, PVA, or ABS. However, these composites face constraints related to robustness, small nozzle diameters, and limitations in wood particle content, typically remaining below 40 wt% (Kariz et al., 2018). Other methods involved combining wooden chips with powders such as cement, gypsum, methylcellulose, and sodium silicate, with water sprayed to activate the binders (Henke & Treml, 2013), combining wood powder with synthetic adhesives, or individual layer fabrication characterized by low binder content and high strength values that requires specialized machinery (Buschmann et al., 2023).

An alternative approach that has found wide application in the 3D printing of clay and concrete is Liquid Deposition Modeling (LDM). With the increasing presence of

AM in construction, robotic arms, and large-scale 3D printers have been adopted for LDM printing processes, allowing architects and designers to explore design methodologies for large-scale printing (Mechtcherine et al., 2019). More recently, LDM has emerged as a promising technology for 3D printing wood, enabling significantly higher wood content by extruding a paste of sawdust, binders, and water in strands (Kam et al., 2019; Bierach et al., 2023), with potential wood contents of up to 89 wt% (Rosenthal et al., 2018). As LDM relies on a paste material with a certain amount of liquid content, shrinkage and deformation occur during the drying process. Although this phenomenon can be observable in concrete and clay, in wood, these behaviours are enhanced due to its hygroscopic nature (Kam et al., 2019). As wood waste by-products have often been underutilized and are commonly incorporated as secondary components in composites (Pinho & Calmon, 2023), while acknowledging shrinkage and deformation challenges, the ability of LDM to support scalability and high wood content is of great advantage for the reuse of wood waste.

3. Design and Material Methods

In formulating the design brief for this study, seating elements were selected as a case study following three fundamental principles: 1) The integration of wood waste streams as the primary material resource, with a focus on enhancing reusability and overall recyclability. 2) The utilization of traditional woodworking in conjunction with 3D printing of wood paste, highlighting the toolpath as a central design medium. 3) The development of a prototypical case study with inherent adaptability to a range of diverse design solutions.

3.1. SOURCING WOOD-BASED MATERIALS

Two waste streams were defined and related to modes of fabrication; solid wood to be crafted through traditional woodworking tools, and sawdust as the primary material for robotic printing (Fig. 1).

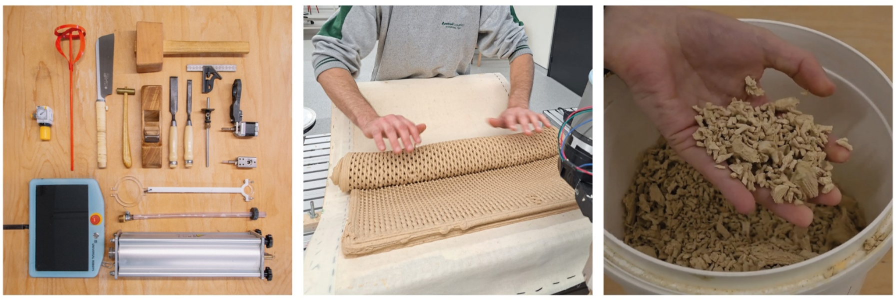

Figure 1-3 (left to right). Traditional and digital tools, Failed print for reuse, Shredded dry material

Solid wood slabs were sourced from waste leftovers at local sawmills to form the structural skeleton of the prototypes. Maple and Oak hardwood scraps, falling within two thickness thresholds (20-24mm and 40-46mm) underwent adjustments using wood planers and sanding to achieve two structural thicknesses for the prototype skeleton: 18mm and 38mm. The sawdust and scraps generated from this treatment were accumulated to be repurposed for the printing material.

The printing paste is derived from a sawdust-cellulose compound sourced from municipal wood cutting, foliage, and carpentry waste resulting in a natural material that is 100% biodegradable (Kam et al., 2019). Originally tested for printing relatively small-scale objects, the composite has been further developed by the company Daika, mainly for casting where it is pressurized into shape and allowed to dry (Daika Wood. n.d.). In our research, the Daika compound is adjusted for a continuous printing extrusion process at the scale of the seating prototype, requiring various wood-to-water ratio tests to achieve a suitable printing paste. The incorporation of significant amounts of water in the mixture affects the strength and shrinkage of the print, concurrently increasing the model's weight. This heightened weight may result in slumping during the printing process, impacting the success of the print. Following preliminary cylindrical printability tests (60mm diameter and an 85mm height), the chosen wood-to-water ratio (32:68) yielded an approximate dry wood content of 70 wt% with compressive strength of 5.8 MPA, 10% linear shrinkage and 29% vertical shrinkage. The incorporation of an entirely natural wood-based material facilitated recyclability of the end product, making it amiable to being shredded and repurposed as a source for printing paste material. This process, in essence, established a circular material workflow (Fig. 2-3).

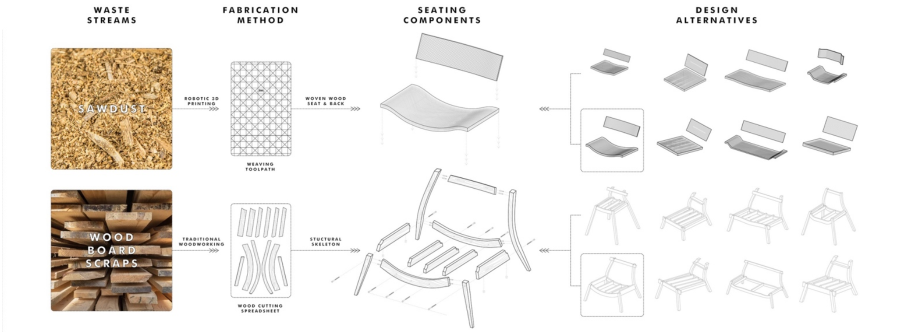

Figure 4. Two wood waste streams related to two modes of fabrication; Traditional woodworking and robotic printing for prototypical design of seating elements

Prior to embarking on the design process, we extracted ergonomic and structural considerations from iconic models (i.e. the Shell Chair by Hans Wagner, the Hank Chair by Jory Brigham, etc.) as design variables for the parametric model. A Grasshopper script was developed to relate variable thresholds such as the seat and back width (450mm-850mm), seat depth (400mm-750mm), legs height (300-650mm), and the angle between the seat and back (90°-115°), for the generation of design alternatives. Through these variables the amount of support and curvature for the seat and back, as well as the manual joinery type (dowel or pocket-screw) were computed for each alternative. Each design produced a corresponding toolpath for printing the seat and back, along with a fabrication spread for the traditional solid wood skeleton (Fig. 4). The generated catalogue of chairs enabled the evaluation of multiple design options in relation to material quantity for each waste source.

The central challenge in tool path design while printing with wood-based material lies in defining printing parameters and geometrical rules (e.g., line curvatures, angular turns) that effectively bridge the gap between the computed geometry and the material behaviour, ensuring the connection between the two wood-based systems: the structure and the woven wood textile. Following the craft of the structure and the drying of the printed components, the full prototype was assembled and the compatibility of the two material systems was evaluated. In the case of incompatibility, the printed components are shredded and reused for the formulation of a new printing paste. The suggested workflow implements the advantages of a CAD-CAM process in utilizing wood waste, sourcing waste in the initial steps of the design formulation, limiting waste in the fabrication process and reusing waste following prototyping experiment.

4. Robotic Printing Experiments

The following printing methods were examined during the experiments: planar printing, non-planar printing, and 5-axis non-planar printing. These methods facilitate the exploration of shrinkage and deformation throughout the printing and drying processes toward the development of the final prototype. The printing experiments employed a UR5e robotic arm, equipped with a StoneFlower clay LDM extruder. In order to enable the printing with a wood-based paste the extruder was connected to an air pressure feeding system. The choice of the air pressure feeding system was based on its capacity to facilitate high-pressure material feed, driven by the material's frictional behaviour. The extruder was augmented with an auger to shear the material during deposition, minimizing the occurrence of air gaps. The robotic arm setup allowed printing within an 80cm printing sphere, enabling the exploration of various printing methodologies.

4.1. 3D PRINTING ORTHOGONAL PATTERN

The primary aim of the initial experiment was to gain an understanding of the material behaviour within a large-scale printing setup, particularly post-drying. For this purpose, we crafted a linear base model measuring 20x20x5cm, incorporating a grid pattern (Fig. 5). A deliberate separation of each layer along the axis direction was implemented to prevent intersection with the tool path, that could potentially lead to cracks in the drying process. Upon completion of the drying process, a comparison to the computational model revealed both horizontal and vertical shrinkage. Through an iterative process, we established crucial printing parameters, including feed rate and robot speed, along with adjustments in the water ratio that were instrumental in minimizing shrinkage. Additionally, axial shrinkage was compensated for in the computational model achieving minimal deviations of 2-5% between the dry print and intended designed measurements (Fig. 5).

4.2. NON-PLANAR ORTHOGONAL PATTERN

Following the planar orthogonal pattern, the subsequent phase involved an examination of the material printing behaviour on curved surfaces to achieve the desired shape of the seat. A foundational template was constructed for the purpose of evaluating the print. The overall form of the template, defined as a half-sine wave shape, encompassed two opposing curvatures, enabling the examination of printing parameters in both curvature types. The design of the tool path was based on the orthogonal grid, employing a curve layer fused deposition (CLFD) method for non-planar movement in the Z axis while the extruder is perpendicular to the XY plane of the printing (Jin et al., 2017). Given the absence of programmed coordination between material extrusion (i.e., feed rate) and robotic movement (i.e., printing speed), adjustments were made to the tool path, correlating the number of control points in accordance with the curvature of the printing path. Following the drying period (Fig. 6) it was observed that the print had failed due to inconsistent extrusion in the curved sections, a consequence of the chosen printing method. Additionally, cracks were evident, attributed to material shrinkage along the printing axis.

Figure 5-7 (left to right). 3D Orthogonal pattern printing, Non-planar orthogonal print failure, Non-planar weaving pattern printing

4.3. NON-PLANAR WEAVING PATTERN

In an effort to mitigate axial shrinkage during the drying process, a rattan pattern was devised, wherein each axis—both linear and diagonal—worked synergistically to balance the corresponding axial shrinkage. This weaving pattern, similar to the orthogonal grid, bypasses intersecting points during each layer, effectively minimizing cracks and deformation during the drying phase and enhancing the overall consistency of the printed prototype. The spacing of the pattern, which performs bridging of 8 mm to 12 mm, was determined based on the prior experiments (Fig. 7). The introduction of the weaving pattern presented a unique challenge in extrusion, primarily due to the dual curvature of the tool path, particularly when depositing material in diagonal layers across curved surfaces. The outcome of the printing process revealed a lack of consistency, particularly noticeable in curved sections. Nonetheless, the pattern demonstrated efficiency in controlling shrinkage during the drying process, ultimately preserving the intended form of the model.

4.4. 5-AXIS NON-PLANAR WEAVING PATTERN

To address the extrusion challenges arising from diagonal layers over curved surfaces while utilizing the pattern to preserve the model's form, a 5-axis printing approach was introduced. In contrast to non-planar printing, 5-axis printing enables the deposition of material perpendicular to the curvature of the surface. This methodology ensures precise and uniform extrusion across all segments of the model's curvature. A 5-axis tool path for the robotic system was structured and generated through the HAL

Robotics plugin, concurrently calculating the digital twin of the constructed template.

The printing results affirmed consistent extrusion throughout the entire printing process (Fig. 8), coupled with controlled shrinkage during the drying phase. Building upon the success of this experiment, a dedicated tool path was devised to print the comprehensive shape of the seat. A template for the full-scale dimensions of the seat (70x60x5cm) was constructed to facilitate the printing process, and the robotic tool path, as shown in Fig. 8, was successfully generated, and executed. This print served as a proof of concept for material deposition in 5 axis over a double curvature surface, while carefully considering the model consistency and printing parameters.


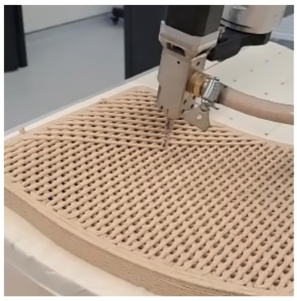

Figure 8-9 (left to right). Printing on a template, 5-axis non-planar weaving printing

Nevertheless, the overall geometry exhibited shrinkage, resulting in dimensions misaligned with the intended design. Attempts to scale up the 5-axis printing to match the intended design were constrained by the limitations of the robotic machinery. To demonstrate the capability of 5-axis non-planar printing for a specific design, two additional stools were designed, and their seats were successfully printed (Fig. 9).

4.5. 3D PRINTING WEAVING PATTERN ON CANVAS

Given the constraints imposed by machinery limitations and the imperative to align with the overarching design, a proposed solution entailed printing the seat component on a flat fabric surface. This approach was adopted to afford the robot unrestricted access to every point on the model, eliminating movement constraints (Fig. 10-11).

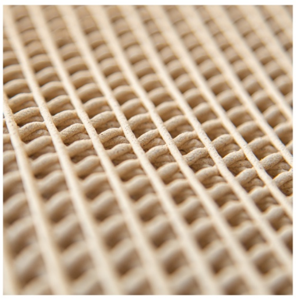
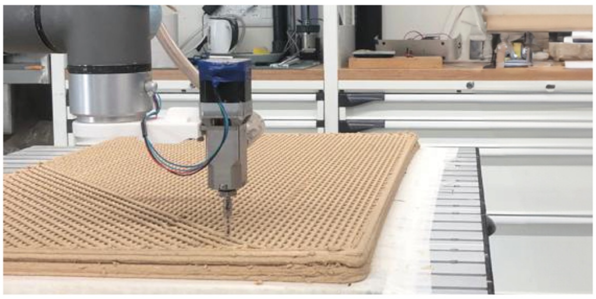

Figure 10-11 (left to right). 3D Printing weaving pattern, Planar pattern on canvas

After the printing phase, the resulting print was positioned on the curved template to undergo drying while assuming the desired form. The folding of the print onto the curved template during the drying process induced shrink forces at specific points in the model. To mitigate these forces, adjustments of the built drying template were made by manually tensioning the wood template during the drying process.

5. WoodenWood - Results and Discussion

Following the experimentation phase, the solid-wood skeleton and printed seat and back were fabricated, resulting in physical components that align with the digital model. However, some processing was necessary to ensure seamless integration and assembly of the various parts. The resulting full-scale prototypical chair measured 65x75x55cm, with the largest print being the seat measuring 60x50x3.5cm (after drying), capable of comfortably supporting an adult (Fig. 14, 16). Further design customization was explored through the CAD process, involving the removal of the chair back, higher legs, and a smaller seat. This resulted in a prototypical stool of 60x45x40cm, with the printed seat measuring 45x40x3.5cm, following the same design principles and fabrication processes (Fig. 15). Additional variation was introduced through natural processing of the wood and the incorporation of natural colorants into the printed paste. The two stool prototypes showcase these variations, the first stool utilizes the same materials as the chair, while the second, made from oak hardwood, underwent an ebonizing process. The paste in the second stool is combined with natural earth pigment and pine bark, resulting in a natural darker tint (Fig.12-13).

Figure 12-16 (left-to-right then top-to-bottom). "Detach" of printed seat, Natural colorants in WoodenWood Stools, Sitting on the WoodenWood chair, WoodenWood stool, WoodenWood Chair

Overall, the research demonstrates the utilization of wood waste materials within the design and manufacturing process, involving the creation of two prototypical seating elements through traditional woodworking and robotic printing. The use of natural wood paste posed challenges, such as shrinkage and deformation during the drying process, resulting in cracking and potential inconsistency with the structural elements. Experimentation with various printing methods and the development of a weaving tool path helped address these challenges, enhancing strength, control over shrinkage and deformation, and generating a wood textile expression. Nevertheless, further research is needed to explore the full potential of toolpath manipulation for different printing forms and applications. The printing paste was examined to align the water ratio for constant material composition and extrusion. It currently serves as a basis for further research into natural additives that could enhance material properties without compromising its reusability throughout the design process and recyclability at the end of the product's life cycle. The recursive design workflow, integrating robotic printing and traditional craftsmanship, can be applied to various objects, incorporating inexpensive wood waste sourced from recycled and locally available materials. The achieved printing and manufacturing workflow underscore the potential performance of wood waste to enhance functionality and expression in design applications.

6. Conclusion

The paper explores the integration of wood waste, encompassing solid wood and sawdust, into both traditional fine woodworking and 3D printing processes. The aim is to foster innovative expressions in material design while addressing material efficiency, reusability, and recyclability. The presented design-to-fabrication process of wood-based elements establishes a foundation for the development of design solutions, emphasizing the manipulation of the printing toolpath. This approach holds the potential to significantly improve the fabrication process and generate novel aesthetic and performative solutions. Future work will concentrate on developing design protocols to investigate potential performative aspects of wood within the realm of architecture and construction, representing a significant step toward advancing sustainable building materials within large-scale additive manufacturing.

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