“Once my front door – now my coffee table”; Advanced computational design and robotic production with waste wood

Marta Malé Alemany, Tony Schoen, Marco Galli, Valentijn Bors, Angelina Kozhevnikova, Liselotte van Dijk; Amsterdam University of Applied Science; Feb. 4, 2022; presented at AMS Institute Conference ‘Reinventing the City’

Abstract

Growing volumes of wood are being used in construction, interior architecture, and product design, resulting in increasing amounts of wood waste. Using this waste is challenging, because it is too labor-intensive to process large volumes of uneven wood pieces that vary in geometry, quality, and origin. The project “Circular Wood for the Neighborhood” researches how advanced computational design and robotic production approaches can be used to create meaningful applications from waste wood. shifting the perception of circular wood as a simply harvested stream, towards a material with unique aesthetics of its own right. The complexity of the material is suggested to be tackled by switching from the object-oriented design towards designing soft systems. The system developed uses a bottom-up approach where each piece of wood aggregates according to certain parameters and the designed medium is mainly rule-sets and connections. The system is able to produce many options and bring the end-user for a meaningful co-design instead of choosing from the pre-designed options. Material-driven design algorithms were developed, which can be used by designers and end-users to design bespoke products from waste wood. In the first of three case studies, a small furniture item (“coffee table”) was designed from an old door, harvested from a renovation project. For its production, two principle approaches were developed: with or without preprocessing the wood. The principles were tested with an industrial robotic arm and available waste wood. A first prototype was made using the generated aggregation from the system, parametric production processes and robotic fabrication.

Keywords: *Waste wood, advanced computational design, robotic production, circularity*

1. Introduction

Construction, interior architecture, and product design are re-discovering wood as a sustainable material. Increasing volumes of virgin wood are used in buildings and interiors. Wood demand in the Netherlands is expected to increase from 0,9 m³ / capita in 2016, to 1,5 m³ / capita in 2030 (Nabuurs et al., 2016). Yet 25% of this wood turns into waste (van Bruggen & van der Zwaag, 2017). Moreover, high quality wood waste remains unused because it is too labor-intensive to process large volumes of uneven wood pieces of varying geometry, quality, and origin. Valuable wood is downsized or turned into worthless waste, contrary to the principles of the circular economy.

Various approaches are being researched to enhance the use of waste wood, such as the upcycling of old doors into new doors (Kuindersma, 2019), and the recycling of production waste from furniture industry (Zuyderwijk & Goossensen, 2020). In the project “Circular Wood for the Neighborhood” (CW4N), the Digital Production Research Group (DPRG) of the Amsterdam University of Applied Sciences at its Robot Lab, together with Amsterdam housing corporations Ymere and Rochdale, TU Delft, TNO, Metabolic, and building industry, research how to give new life to used wood that is released during home renovations, by using new and emerging opportunities offered by advanced computational design and robotic production tools.

The introduction of computer-aided design and manufacturing has radically transformed and expanded the creative and production opportunities across all design-related industries. In the domain of interior design and architecture, the possibility to directly fabricate building components described on the computer expands not only the spectrum of possibilities for construction, but it establishes (by implementing new material and production logic into the design process) a unique architectural expression and a new aesthetic (Giftthaler et al., 2017; Menges et al., 2016). Digital design and robotic production foster both mass-customization (high volume production of objects, each with unique features) (Ashley, 2016; Brinkman, 2019), and the design and production of objects from a variable source of material, such as waste wood. This paper describes the current findings of one of the three cases studied in the project, exemplary of a new future where harvested material streams will be paired with smart industry solutions towards viable circular business cases. In the paper, the digital design approach used for this case and the robotic production setup is presented and briefly discussed.

The paper is structured as follows: first an introduction to all three of the case studies is given in section 2. Section 3 details case study #1, starting with a generalized overview of the objectives, followed by descriptions of the computational design procedure and the robotic production approach. The challenge of accounting for non-structural wood segments is briefly discussed in section 3.3. Section 3.4 depicts the production of two prototypes according to two different production processes.

2. Case studies introduction

Design and production research in the CW4N project is centered around three case studies. The cases are carefully selected, to demonstrate various approaches to create meaningful applications from waste wood, harvested at residential building renovations by housing corporations. The cases research how to create value from waste wood for the tenant, the housing corporation and the neighborhood at large, but each of them on a different level.

1. Case #1: ***Once my door, now my coffee table***:
   Tenants receive a new (small) furniture item made from wood that is harvested from their own home (e.g. the front door). It is an item that can be highly personalized. This test case is focused on renovation projects for a small number of dwellings, with occupants well connected to their homes and their neighbors. It is intended to create tenant awareness for circularity in and around their home, to foster community spirit between neighbors, and increase the emotional value of the (renovated) dwelling.

2. Case #2: ***Once their windows, now our playground***:
   Creating outdoor objects from larger volumes of material. This case is focused on larger renovation projects in neighborhoods with a low sense of community. The design and installation of a communal outdoor structure could be used to strengthen a sense of belonging through co-creation and collective ownership. In addition, this case could be used to address tenant awareness for circularity, and to reduce anonymity in their neighborhood.

3. Case #3: ***Once incinerated waste, now shared value***:
   sharing larger volumes of waste wood between housing corporations through the creation of collective material banks that can help defy the logistic and planning hurdles of harvesting sufficient waste wood for viable applications in upcoming renovations. These applications could be modular indoor structures that facilitate varying occupational needs (e.g. room dividers), which are designed for disassembly and conceived for multiple material life cycles.

3. Case #1: *Once my door, now my coffee table*

3.1 General Process

The following is a generalized description of the proposed design and production process that is currently being researched by the DPRG at its Robot Lab; first, the available waste wood is scanned and its properties digitalized into a database. These databases are integrated within an advanced computational design procedure that aggravates multiple versions of possible furniture pieces. A feedback loop with the end-user enables a final design to be co-created. Once the design is finalized, it is produced using 6-axis CNC milling. A selection of waste wood obtained within this study is shown in figure 1 to illustrate the overall material stream.

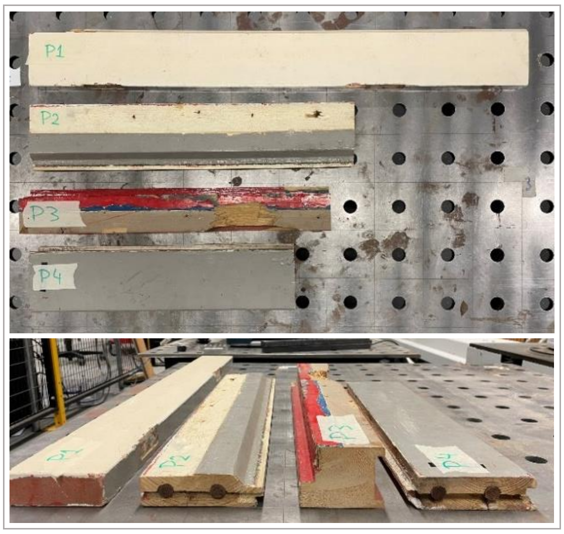

Fig. 1. *Pieces of waste wood originating from a door and its frame.*

3.2 Digital design system

This case study deals with a small, personalized item for a tenant (a coffee table), made from a limited amount of wood, which could be the tenant's former front door, wall cladding, window frames, etc. There is a direct connection between the renovation and the item which is produced. The design of the object is fully determined by the available material. To create designs, a material driven and generative design system was developed, moving away from classical mechanism and reductionism, towards complexity and non-linearity (Kwinter, 1993), creating a soft system that can tackle a very uneven material stream and convert this problem to a design opportunity.

The system uses algorithms and is based on rule-sets that are defined by the designer (and potentially the end-user). The system takes as an input an available set of available pieces of wood with varying length, cross-section, wood type, etc. Outcomes are tailored to a specific set of available pieces of wood (which can be a set of pieces with varying length, cross-section, wood type, etc.). Rule-sets can include the global dimensions of the resulting object, the type of joinery between wood components, the colour gradient of the object surface, the structural performance of the resulting object. The algorithms have a material-oriented approach or "self-assembly" logic which generate (virtual) forms that fulfill the requirements of the rule-sets, using all available pieces of wood. In figure 2, six tables obtained through different rule-sets are depicted.

This generative design system opens up the possibility to embrace the whole complexity of an heterogeneous material stream (typical of waste wood) and the forming of unique designs from a given material stock, while minimizing the creation of additional waste. Most importantly, this design logic could help shifting the perception of waste wood towards being a material with unique aesthetics of its own right, which could result in designs which cannot be produced from another material

Fig. 2. *Six tables generated within the advanced computational design methods in relation to the rule-sets used.*

or virgin wood. The design approach also create opportunities for end-user engagement. The system can have user preference as one of the inputs, leading to a new approach of co-design, as opposed to the choosing from pre-designed options.

3.3 Robotic production approach

The potential added value of robotic production techniques is the ability to centralize all subtractive production processes into one handling with one tool, while producing non-standard parts. E.g. after placing the piece of wood, it can be cut to size, receive surface treatments, and have connecting elements milled, all in a single procedure. Once the machines are set up, the only variable cost per unit is milling time (Thompson, 2007).

In order to investigate the possibility of a closed loop material stream (the wood is used to create an object, after usage the object is able to disassemble easily, and its materials re-used to create a new object etc.) a limitation was set to only use the waste wood made available per individual object to create a new object. This means that no external fasteners, such as glue, screws and nails, could be used to connect wood pieces together. Instead, several highly complex joints were developed that rely on geometry, friction, and tension introduced by shims. Complex joints can be used almost effortless, when using a computational design process which can automatically adapt these joinery systems according to the designed object and the varying topology of the wood. The use of 6-axis industrial robots for the production then creates the possibility to produce angled and composed cuts in an automated and scalable manner.

3.4 Accounting for non-structural segments

One of the difficulties of working with waste wood, as found during this study, is accounting for non-structural segments. Due to their source and the nature of harvesting, the wood pieces vary extremely in topology and quality. Local volumes that are damaged, contain metal, glass and other contaminants, and segments of profiles that are too thin can be considered as non-structural segments that are to be avoided when assigning the location of connecting elements. Accounting for these segments within the design and production processes described in this paper was done by defining a bounding box that encloses the full geometry of the wood, further referred to as $BBOX_{max}$, and a bounding box that encloses the volume of the wood that is defined to be structurally sound, further referred to as $BBOX_{min}$. Where $V_{BBOXmax}>V_{wood}>V_{BBOXmin}$.

It should be noted, that defining and optimizing these bounding boxes is complex. Depending on the algorithm used, a variety of $BBOX_{min}$ can be found within a 2D profile (Abellanas, et al., 2004), as shown in figure 3. The possibilities found increase substantially when the axial alignment of BBOXmin does not need to coincide that of the wood piece (Chaudhuri, Nandy, & Das, 2003).

Expanding the same question into 3D results in even greater number of possible $BBOX_{min}$ in various configurations. This is because the piece of wood can be divided into multiple volumes, each containing a $BBOX_{min}$ which is optimized for that specific volume. Increasing the amount and resolutions of $BBOX_{min}$ per piece of wood could result in an increase in accuracy, and material yield. Additionally it allows the choice of whether surfaces

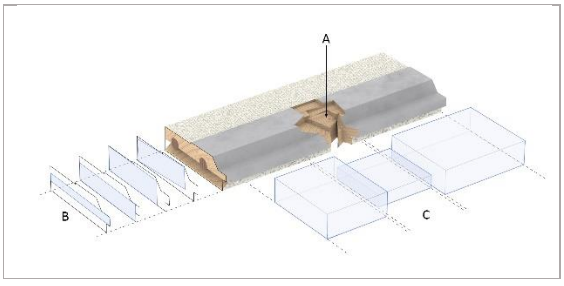

Fig. 3. *Various possible minimum bounding boxes $BBOX_{min}$ for a specific piece of wood. Where A is a damaged area, B are various 2D possibilities for $BBOX_{min}$ according to the cross-sectional profile, and C are locally optimized 3D $BBOX_{min}$.*

should be (partially)treated or not at all. This enables the original paint to be left on the wood which enhances its capability of telling the story of its heritage and circularity. But, it also increases complexity: in both the design and production process.

A different way of dealing with non-structural segments is to preprocess the wood before incorporating it within the design and robotic production procedure. This preprocessing can entail cleaning the wood manually until a piece of wood is square, and free from debris and damage. The resulting piece can then be digitized and processed further without the need for additional surface treatments or accounting for non-structural segments.

3.3 Production of the prototype

To test the influence of pre-processing the wood versus using unprocessed wood two design and production processes were formulated, as shown in figure 3.

For case study #1, wood was obtained from an old door and its frame, harvested by project partner GP Groot. The doors were taken apart, cut into smaller sections and cleaned from debris. Four pieces of wood, shown in figure 1, were selected and cut in half. Half of the resulting pieces were preprocessed manually and the others were left untreated.

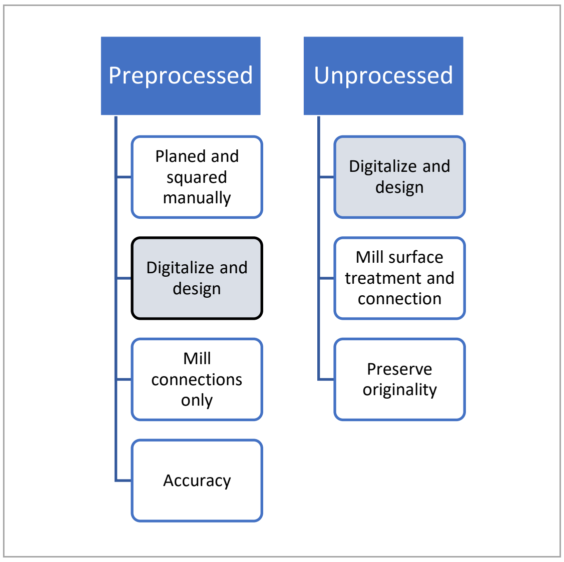

Fig. 4. *Diagram depicting the procedures that use preprocessed wood versus unprocessed wood.*

Working with the preprocessed wood resulted in a prototype shown in figure 5. Computational work for the second prototype, shown in figure 6, which uses unprocessed wood (requiring optimized bounding boxes) and optional surface treatment is still ongoing and planned to be completed in Spring ’22.

4. Discussion

The design and production of the first prototype has demonstrated the possibilities to create bespoke objects from waste wood. Using material-driven design algorithms leads to unique objects, connecting the origin of the material with its new function.

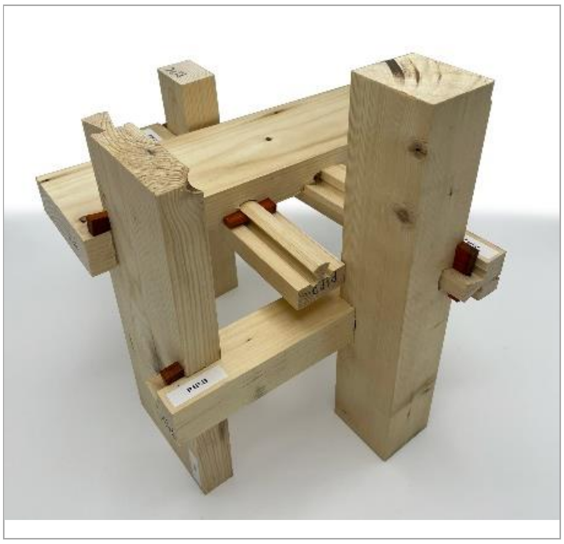

Fig. 5. *Prototype made from preprocessed wood.*

The production of the object still requires a substantial amount of manual labor, e.g. for dissection of the door, for detection and removal of metal and for precise clamping of the wood on the production table of the robot. Fully automated processes for the intake of wood are still under development by DPRG at the Robot Lab.

In the first prototype, preprocessing of the material required manual labor, but reduced robotic production time, limiting it to the milling of the connections only. In future, this preprocessing might be integrated into the aforementioned intake processes of wood.

Using unprocessed wood for the second prototype will reduce manual labor, but requires more design (addressing the bounding box problem) and more robotic production. It however creates possibilities to preserve originality of the wood, adding to the “circular story” of the case study.

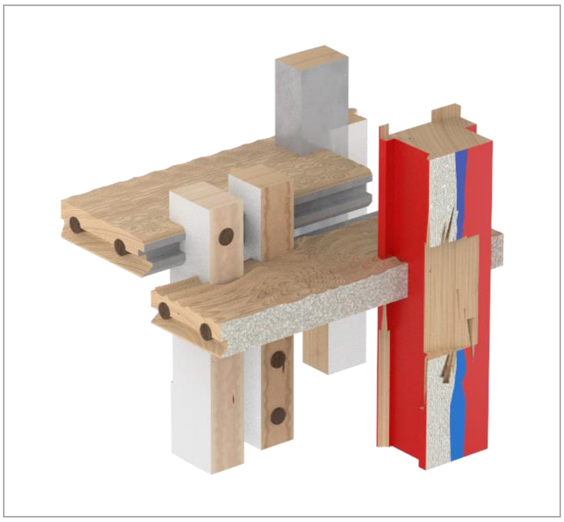

Fig. 6. *Proposed prototype to be made from unprocessed wood.*

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Acknowledgements

The “Circular Wood for the Neighborhood” project is a collaboration between AUAS, housing corporations Ymere and Rochdale, their co-creators Lenferink and Rutges, the municipality of Amsterdam, Platform31, Metabolic, TNO, TU Delft, GP Groot and Ter Steege. The project is co-financed by SiA (RAAK-Publiek programme).