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Measuring the Benefits of Cascading-Use of Wood Furniture Within the Circular Economy via Value-Retention Processes

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Abstract: As *utilized* technical products, durable wood furniture has an important role to play in a future circular economy (CE). However, contemporary CE literature predominately focuses on the biochemical properties and potential for wood as *consumable* materials within the bio-cycle. This perspective prevents meaningful consideration of CE strategies for the wood products sector, particularly for value-retention processes (VPRs), including reuse, repair, and refurbishment. Adapting and applying the VRP model introduced by the UN International Resource Panel (IRP) (2018) to wood furniture products, we quantify select environmental benefits made possible through the use of VRPs (vs. new manufacturing) for wood furniture. Unlike traditional life-cycle analysis (LCA), this model accounts for the impacts incurred and avoided through product life-extension and VRPs, relative to new manufacturing, disposal, and replacement within a linear system. To demonstrate the model and the potential for wood furniture as technical products within the CE, three case studies of wood-based chairs are conducted and analyzed. In collaboration with industry partners, new material requirements (kg/unit), energy requirements (kWh/unit), emissions (kg CO2-e./unit), and waste generation (kg/unit) are calculated for newly manufactured chairs and subsequent reuse, repair, and refurbishment. Results highlight that, similar to industrial products, VRPs enable the avoidance of environmental impacts for wood furniture relative to linear single-life systems. Further, design configuration and material selection for wood furniture have significant implications for CE potential, thus reinforcing the necessity of an appropriate design perspective for enabling effective CE across all products and sectors.

Introduction

Increasing visibility and awareness of ‘fast furniture’ has contributed to concerns about the quantities of waste wood furniture being disposed into landfills each year (Bischof, 2019; Cummins, 2020). Despite being renewable and able to biodegrade and/or be recycled, these circular attributes of wood furniture are typically not realized within the sector. In addition to a predominately linear model in which timber is harvested, processed, manufactured, distributed, used, and then disposed, the chemical finishes and adhesives commonly applied to wood products often prevent the return of the wood materials back into the biosphere (Thonemann & Schumann, 2018).

Fast Furniture

In 2018, U.S. consumers spent more than USD 100 billion on furniture products (Coresight Research, 2019), and confirming the predominantly linear model, waste characterization data (U.S. Environmental Protection Agency, 2020), and grey literature (Bischof, 2019; Brightly, 2020; Cummins, 2020) note the increasing presence of discarded furniture at the curbbside and in landfills. Mirroring observed market trends of so-called “fast fashion”, “fast furniture” refers to the rise of easy-to-use, low-cost, fast-moving furniture that lacks durability and a long-lived aesthetic. The changing wood furniture marketplace has increased the ease with which people can access furniture, decreased the retention rate of furniture, and created a new norm of furniture disposal (Brightly, 2020). The growth of fast furniture is driven by the same factors behind fast fashion: Products are made with lower-quality, lower-cost materials; they are sold for lower prices with relatively higher profit margins; and they are purchased and disposed of by consumers at increasingly faster replacement rates (Bischof, 2019; Rauturier, 2020). The lure of the fast furniture business model has led to many prominent companies expanding their portfolios to include lower-cost, lower-durability furniture products made from wood-based composite materials that are difficult to recycle and maintain within the CE (BizVibe, 2019). Combined, these challenges of waste furniture contribute to the approximately 12 million tons of furniture sent to U.S. landfills in 2018, with furniture accounting for 8.3% of the overall U.S. landfill composition (U.S. Environmental Protection Agency, 2020). Not far behind, the European Union (EU) produces approximately 11 million tonnes of furniture waste (Forrest et al., 2017).

Design for Wood Furniture Circularity

Although the formal advancement towards circular wood furniture systems has been slow, there has been recognition of the need for policy-guided diversion and recovery infrastructure, consumer behavior changes, and adoption of circular design principles by the wood furniture sector (Forrest et al., 2017). Design concepts, including design for the environment (DfE), eco-design, circular design, and green public procurement, introduce environmental impact reduction strategies that can enable more sustainable and circular product development (Forrest et al., 2017). While DfE and eco-design have been studied for wood furniture across various products, CE principles (e.g., keep products in-use) may differ from conventional sustainability and environmental priorities, and may conflict with conventional business model priorities (e.g., volume-based revenue strategies). Design strategies that facilitate product-life extension and value-retention may include and are not limited to, modular design, design for disassembly, design for repairability, and the elimination of adhesives (Besch, 2005).

To explore the potential benefits that may be achieved by the application and scaling of VRPs for durable wood furniture products, this study demonstrates the applicability of a validated VRP model for bio-based product analysis (International Resource Panel, 2018). It quantifies select environmental benefits that are possible through the use of reuse, repair, and refurbishment activities for case study wood furniture products. Further, the value-retention potential for wood furniture cycling via VRPs within the CE is demonstrated, along with design and material selection priorities specific to wood furniture.

Methodology and Materials

Case Studies

To quantify the environmental impacts of utilizing VRPs for wood furniture, three case study products (wood-based chairs) were selected to represent three common styles and markets: a) solid wood; b) plywood core with foam and fabric upholstery; c) solid wood and plywood mix (*see Figure 1).*

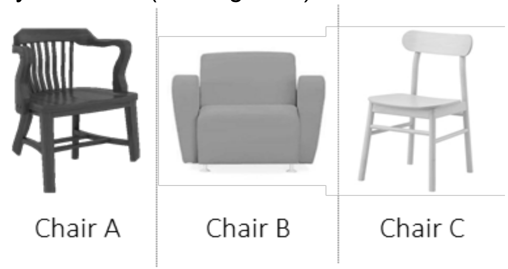

Figure 1. Case study chairs: Chair A – solid wood, bulky, durable, commericial-use; Chair B – upholstered, bulky, durable, commercial use; Chair C – mixed solid and plywood, light t, commercial/residential use.

Chair A - is made of solid wood, is bulky, durable and lasting traditional design. The chair is massive, sturdy, well made in the upper price range ($978), expected to last well past its projected life span.It is a more permanent structure and not built for disassembly. *Chair B* - is also in the upper price range ($1,998) and not meant to be disassembled. Its core structure has the potential to last past its projected service life, but the upholstery would be limited to tearing and sanitary concerns. *Chair C* - is a mix of solid wood frame (legs and rails) and plywood seat and backrest. With a simple frame construction, this low price range product ($89) comes disassembled in a flat package and is easily assembled by the consumer. This feature also compromises its strength and contributes to a shorter life-span. *Chair A* and *B* were selected from the same manufacturer who was willing to provide primary information regarding the production process and bill of materials. *Chair C* was purchased independently by the research team and required the use of publicly-available online information and empirical production data conducted in the Purdue Wood Research Laboratory on a comparable product. These furniture pieces were chosen for their complementary functions, as chairs used in commercial settings and a life-span requirement of 10 years (conforming to the BIFMA Product Category Rules). Case study chair samples were brought to The Wood Research Laboratory at Purdue University. They were subjected to the performance testing, which included a front-to-back cyclic load test, conducted according to the American Library Association (ALA) specifications. Loads were applied on chairs at 20 cycles per minute. The test started with a load level of 50 Lbs. and stayed at that level until 24,000 cycles were completed. Each subsequent load was increased by 50 Lbs. Tests were continued until non-recoverable failures occurred on any joint or horizontal deflection exceeding 50.8 mm. Once performance testing was completed, the chairs were disassembled by hand, and all components were counted and weighed. Product-level data collection involved complete disassembly, material characterization, and weighing of each component. Component characteristic data that was collected included material weight, material type, and associated production waste generation. In addition, component-level reusability was assessed (e.g., how much of each component could be retained as a result of each VRP), as well as the expected service life potential of each component (e.g., the number of years the product can be cycled via different VRPs).

Life-span characteristics were assessed for each component in accordance with the methodology established by the IRP (2018). Additional key data points were estimated for each component and for reuse, repair, and refurbishment processes: the probability of salvage at end-of-use; the maximum number of times a component can be effectively reused; additional new materials that would be needed as inputs to the process; and the cause of the component or material end-of-use which may include predetermined/scheduled maintenance, fatigue (or wear-and-tear), and hazard damages. Performance testing results informed where the damage occurred during testing and thus the likely location, material, and quantity of replacement that would be required to complete an average repair. The repair was assumed to respond to the likely damage, through wear-and-tear or hazard, to affected components. The refurbishment was assumed to address aesthetic issues (e.g., stains, scratches, fabric tears) and thus involved refinishing and/or reupholstery of each case study chair. Reuse was assumed to be direct, with no energy or material inputs required. For Chairs A and B, the primary data needed for the model was retrieved from the collaborating company. Through emails and video calls, the Bill of Materials, energy consumption for product manufacturing, labor requirements, waste production, and manufacturing processes was gathered. Because of the ongoing COVID-19 pandemic, direct data collection on-site at the facility was not possible.

The Model

The MATLAB model utilized for the IRP Report (2018) was also utilized for this study. Accordingly, the methodology described below reflects the same methodology used by the authors of the IRP Report to assess VRP implications across industrial digital printing equipment, vehicle parts, and heavy-duty and off-road equipment sectors. Using this stochastic model, raw data collected, as outlined above, was imported into a Monte Carlo simulation that enabled the output results of average new material requirements across 10,000 simulations. The parameters guiding these simulations was determined based on the nature of the reusability mechanism assigned to each component, informed by the results of performance testing results:

Fatigue: Components that typically wear down over time had a durability curve applied to their established useful life, using a Weibull distribution and analysis.

Hazard: Components that typically fail as the result of some impact damage or misuse by the user had a cumulative exponential probability distribution curve applied over multiple service life cycles.

The following general formula (IRP, 2018) was used to model the new material requirements (*M*)(Equation 1), as well as associated embodied emissions (Γ)(Equation 2) and embodied energy (ρ)(Equation 3):

$$M_{j,m}^{i} = \sum_{s}\sum_{c} \frac{\alpha_{j,m,c}\gamma_{j,m,c,s}\delta_{j,m,c,s,h}}{\eta_{c,s}} \quad \forall_{i,j} \quad \textbf{Eq.1}$$

This formula is repeated for each process i (OEM New, reuse, repair, and refurbishment), for each material type: α is the material weight, Υ is the upstream material intensity (e.g., processing or machine scrap) or waste factor, δ is the end-of-life burden multiplier (waste = 100%, 0 < recycling efficiency < 100%), and η represents the number of expected service life cycles. Subscripts are also included as follows: product (*j*), material type (*m*), component (*c*), service life cycle (*s*), and end-of-life route (*h*). Material-based embodied energy requirements are reflected via τ (kWh / kg) and embodied emissions are reflected via ω (kg CO2-e. / kg).

$$\Gamma_{j}^{i} = \sum_{m}\left(M_{j,m}^{i} \ x \ \tau_{m}^{i}\right) \forall_{i,j} \qquad \textbf{Eq.2}$$

$$\rho_j^i = \sum_m \left(M_{j,m}^i \, x \, \omega_m^i\right) \forall_{i,j} \quad \textbf{Eq.3}$$

Results

Performance Testing

Performance testing determined the components that were most likely to fail in service for each chair, and thus the necessary repair and refurbishment intervention and associated impacts (e.g., joinery failure and component breakage from performance testing informed the component salvage rate and service life assumptions in the model). Performance testing also informed the distribution used to model different forms of failure, i.e., fatigue vs. hazard. Structurally, Chair A and Chair B are very strong. Chair A reached 350lbs and 173,327 cycles in total; Testing on Chair B was conducted until the testing machine reached its limits and then discontinued: 500lbs at the 252,923 cycles in total. Such high load-levels would not be achieved in the regular service life. Chair C was tested until product failure at 250lbs. and 135,824 cycles in total.

Material Efficiency and Consumption

Relative to newly manufactured chairs, reuse, repair and refurbishment required significantly less new material inputs to restore functionality and aesthetic to the chair (Table 1). For each chair, direct reuse consumes no new materials thus enabling a 100% reduction in the material requirement, while fulfilling functional requirements. After reuse, refurbishment presented the relative greatest material offset, ranging between 75.3% (Chair B) to 83.7% (Chair A), reduction in new material required (Table 1). At a minimum, repair enabled the reduction of new material requirements of between 74.7% (Chair B) and 80.8% (Chair C) (Table 1).

	Chair A	Chair B	Chair C
Refurbishment	83.7%	75.3%	82.1%
Repair	79.1%	74.7%	80.8%
Reuse	100.0%	100.0%	100.0%

Table 1. New material consumption reduction enabled via each VRP (vs. OEM New) for case study Chair A, Chair B, and Chair C.

It is important to note that each VRP also enabled a different type of material to be avoided/offset (Figure 1). Given the damage anticipated in repair simulation, wood remains the most significant material input to each chair under repair conditions. For refurbishment involving the refinishing of the wood chairs, 100% replacement of water-based finish was required.

Based on the materials required to complete each new vs. VRP process, associated embodied emissions, production waste, process energy, and process emissions were also calculated using the IRP model (2018) (Figure 2). These results further demonstrate the potential environmental impact reduction that the systematic adoption of VRPs for durable wood furniture can enable.

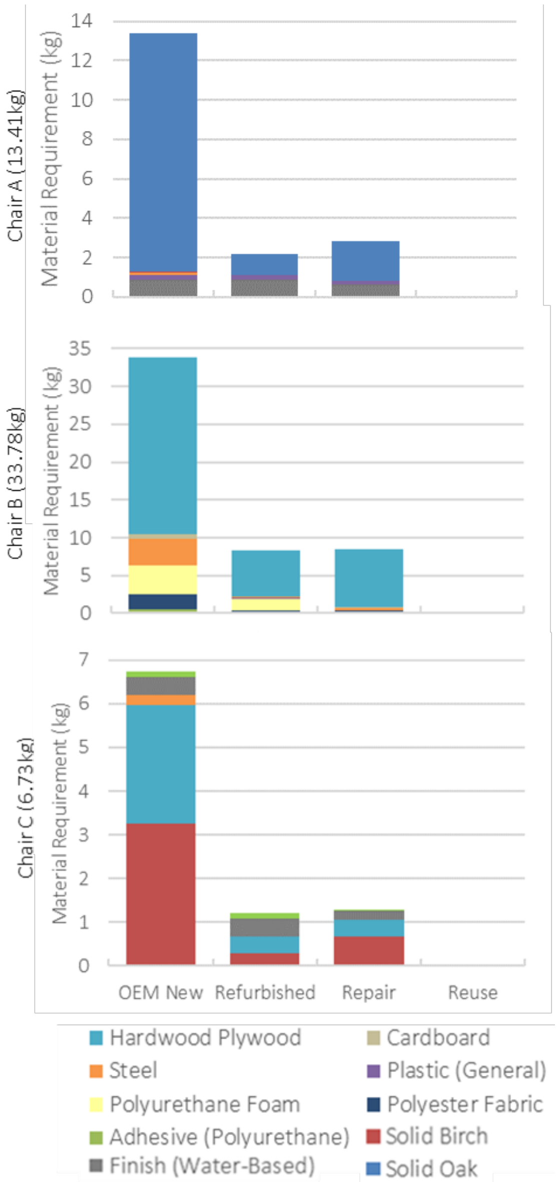

Figure 1. Material requirements of OEM New, Refurbished, Repair, and Reuse processes, by material type, for Chair A, Chair B, and Chair C.

Analysis & Discussion

The environmental impacts calculated for each chair (Figure 2) confirm the contribution that design can have: Chair A, while almost entirely constructed from solid wood, required more than double the new materials of Chair C. The use of engineered wood (e.g., plywood) and polyester-based textiles for Chair B significantly increased the embodied emissions relative to lower-carbon, bio-based materials (Figure 2).

Further, the complexity of the design and assembly of each chair contributed to significantly higher process energy consumption and associated emissions.

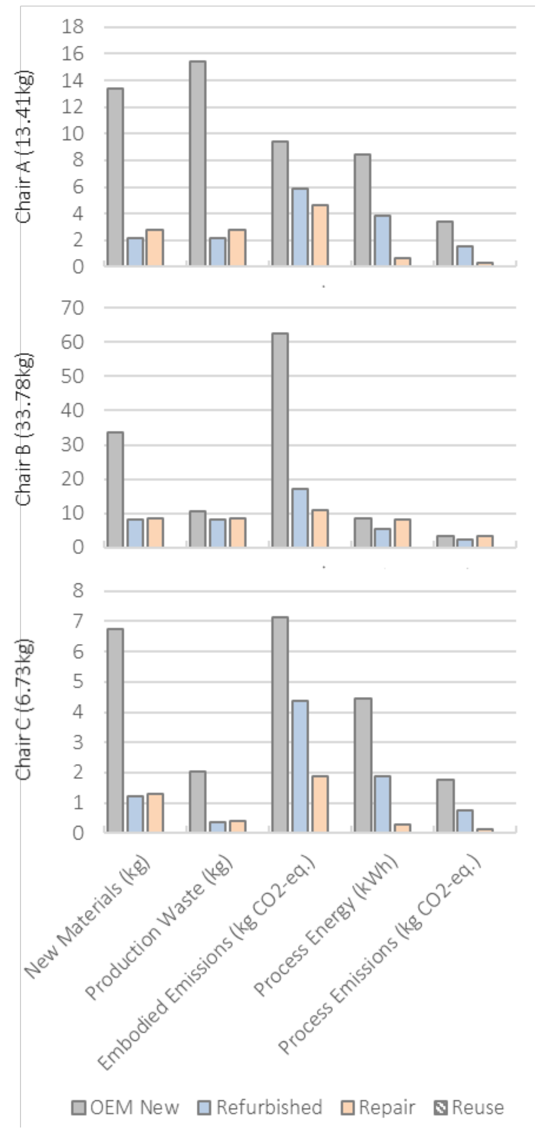

Figure 2. Comparative select absolute environmental impacts associated with VRPs for Chairs A, B, and C.

Chair C was considered to be the most representative of 'fast furniture, given its composition of plywood, its low relative price, and its lower durability, as evidenced in performance testing. To approximate the implications of lower durability upon environmental impacts, an additional analysis was completed to assess performance equivalency. Setting Chair A as the performance standard (350lbs), an approximate equivalency factor of 1.4 (350lbs / 250lbs) was determined and applied to the environmental impacts of Chair C (Figure 3). Effectively, this implies that 1.4 Chair C's would be needed to fulfill the performance (durability) achieved by a single Chair A.

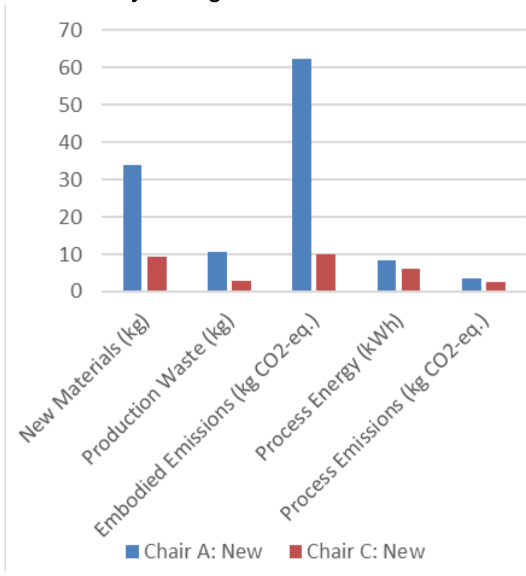

Figure 3. Comparative assessment of select impacts of Chair A (New) and Chair C (New), when both were set to equivalent performance standard of 350lbs.

However, even with a 40% increase in anticipated material use and associated environmental impacts, 1.4 Chair C's are still environmentally preferable to a single Chair A (Figure 3). This suggests that durability does not necessitate an environmental advantage within the context of CE. Further, it suggests that where VRP access and adoption can be scaled for wood furniture to reduce disposal to landfill, so-called fast furniture may actually present a lower-footprint alternative within the furniture sector.

Conclusions

This research demonstrates the applicability of the IRP model (2018) for assessing the value-retention and life-extension potential of wood furniture. Adopting VRPs can enable substantial environmental impact avoidance when used at wood furniture's end-of-life.

Further, circular design considerations, including material reduction, modular product design, and design for disassembly, can increase the probability and impact of VRPs in practice. Finally, although durability may lead to the longer product life, the associated higher material requirement, and/or material type (e.g., textiles and foam) may result in durable wood furniture having significantly greater environmental impacts than a less-durable fast furniture alternative. Thus, design considerations for circularity, value-retention, and product life-extension remain a critical component of the CE transition.

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