CIRCULAR ECONOMY IN THE BIOMATERIALS SECTOR: CONCEPTS FOR THE WOOD PRODUCTS INDUSTRY

by

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I dedicate this work to my family and friends for supporting me throughout this process and inspiring me to do my best. A very special thank you to my Mom for being my biggest champion and the brightest source of encouragement!

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LIST OF ABBREVIATIONS

CE-	Circular Economy
OEM-	Original Equipment Manufacturer
VRPs-	Value Retention Processes
EOL-	End of Life
EOU-	End of Use
LCA-	Life Cycle Assessment
SME-	Small- Medium Enterprises
EPR-	Extended Producer Responsibility
GPP-	Green Public Procurement
DfE-	Design for Environment

ABSTRACT

The concept of the Circular Economy (CE) is proposed as a viable solution to the over-exploitation of natural resources with an economic and environmental backing. Although more commonly used in the context of non-renewable industrial materials and processes, there is a growing need to include these concepts into renewable materials that have technical functions. This thesis will discuss the concepts of CE in the context of the wooden furniture sector and how the inclusion of Value Retention Processes (VRPs) and other CE practices result in quantifiable environmental and economic benefits. Companies that are involved in these VRPs are consulted through a questionnaire. This is to better understand the processes and limits of their implementations. The issue of furniture waste is highlighted to demonstrate the need for circularity in this industry and how it fits within the context of CE. A case study is conducted utilizing three comparable furniture products to populate the data needed to utilize an established CE model showcasing their quantifiable benefits (IRP, 2018). This research will lead to a basis for continued research, improvements to current CE models, and suggestions for best practices that can be implemented by industry stakeholders and consumers. The results of the company questionnaire showcased that a viable VRP market exists for the wooden furniture industry, with “Reuse” being the most utilized by consumers. The outputs of the CE model revealed that the inclusion of VRPs results in significant decreases in environmental impacts when compared with new product manufacturing.

INTRODUCTION

Research Motivation

As society continues to develop research and solutions regarding the wide-reaching effects of the climate crisis, significant focus is put on the use and degradation of renewable and non-renewable materials. Biomaterials, specifically wood and wood products, are recyclable, renewable, biodegradable, and are used widely throughout the world. However, actions must be taken to utilize these materials in the most responsible and efficient way possible while also recognizing the products already in service. The concept of the "circular economy" (CE) actively addresses the concerns of material consumption, disposal, and general product sustainability. The CE has well-established frameworks that have been developed over the last two decades (Ghisellini et al., 2016), and although these frameworks include biomaterials, their role is often limited to energy production feedstock and agricultural processes. The concepts of CE were popularized by the Ellen McArthur Foundation (EMF), and have led to the development of widely accepted frameworks, strategies, and practices (Ellen MacArthur Foundation, 2015). Combined with the European Union's recent push for more sustainable actions within manufacturing and resource management (European Commission, 2015), CE concepts have been better received and implemented throughout a wide range of industries in Europe, one being the wood products and furniture sector. These current actions provide a base of motivation and potential for the further development and application of CE concepts within the United States.

Many companies have developed business models that include services, material sourcing, design, and products which reflect concepts of circularity. These are a source of positive examples that can be modified and mirrored in the U.S. (FURN360, 2018). Although companies are taking part in the circular economy and making positive strides, most designers, producers, and consumers are still making suboptimal decisions that lead to compounding furniture waste, i.e., through fast furniture. The growing fast furniture trend mirrors that of the fashion industry, in which high volumes of cheaply made furniture are produced, consumers are encouraged and habituated to buy new furniture frequently, product lifespan is limited, and items are ultimately disposed into landfills (Lauren, 2019). Problematic elements at each step of the furniture life-cycle process can be addressed with the implementation of circular economy concepts. Conversations need to be had amongst those involved (designers, manufacturers, and consumers), and standardization needs to be implemented to better assist those attempting to make changes to their practices and operations. For the purposes of this work, wooden furniture is viewed as a technical and functional product that can be cycled through multiple service lives. This view is not conventional within current circular economy frameworks.

Wood is one of the most widely used materials in the U.S. The forest products industry harvested around 450 million cubic feet of timber in 2017 (Howard and Liang, 2018). There is increasing demand for more sustainable material options in the U.S. market, and wooden furniture derived from sustainably sourced wood (e.g., certified sustainable forests) may satisfy this demand; it is also important that the life cycle and environmental impacts of both materials and products are considered and evaluated (Pulidindi and Prakash, 2020).

Research Problem and Question

Prominent and widely accepted frameworks for CE, like that of the Ellen McArthur Foundation, include the presence of biomaterials, but the representation of these materials and options are typically limited to that of feedstock and energy production (Brennan et al., 2015). Durable wood products (wooden furniture) are bio materials that cross between the biological and technical cycles; accordingly, a wider understanding is needed if a more standardized and inclusive framework for durable bio-based products is to be developed.

Current CE frameworksinclude "value retention processes" (VRPs), which include reuse, repair, refurbish, remanufacture, and recycle (International Resource Panel, 2018).These processes are more common to heavy industry and technical products and are less recognized in bio-based economies. However, the literature suggests that the related concept of "cascading" may be more prominent in wood products industries. Cascading refers to sequenced material 'flows' in which materials and/or products of a singular production process are recovered and immediately utilized for a lower-tiered application, i.e., utilizing waste branches and bark at lumber mills as bio-based, renewable fuel inputs (Höglmeier et al., 2015). However, even cascading-use practices do not adequately address how wood products, particularly furniture, can fit into the current CE or cascading frameworks. This research aims to address this problem by posing the question:

"How can the innate circularity of biomaterials, specifically wood furniture, be better represented, quantified, and included in current circular economy frameworks?"

The furniture industry consists of diverse, varied, and numerous stakeholders, and this research will be of particular interest to designers, manufacturers, consumers, and academia.

Research Goal and Objectives

This research seeks to include new insights to be utilized by developed U.S. wood products companies and other industry stakeholders, companies completing value retention processes (VRPs), and introduce a replicable model for quantifying environmental benefits of modified practices in the furniture industry. The wood products and furniture industry are vast, and there is great potential for them to have a more positive impact on the environment by participating in the CE. Accordingly, there needs to be a better understanding of the impacts that the wood products industry has on the environment and how the disconnect between manufacturers, designers, and consumers can lead to dynamic problems.

Non-wood furniture companies in the U.S. and abroad are increasingly taking CE into account when considering the design and manufacturing of their products and services provided (e.g., Room and Board, Steelcase, Circle Furniture, Rype Office, and Wehlers). Such CE initiatives differ from company to company based on specific products, business size, and distribution. This presents a gap in the research where sustainability actions being undertaken by those involved in upstream and downstream activities are disconnected and do not directly address prominent issues such as furniture waste. To fill the gap in current research, this project will be looking at CE and the wooden furniture industry holistically through two parts. To explore the opportunities for CE in addressing the problem of furniture waste in the U.S., Chapter 1 explores the role of consumers and industry and introduces VRPs as a potential solution. The role of independent companies engaging in VRPs for wood furniture is examined via semi-structured interviews of companies engaged in different VRP processes. Chapter 2 models, quantifies, and showcases the quantifiable environmental benefits that can be achieved through the adoption of VRPs for wooden furniture products. In this study, three furniture products are used as case studies to simulate and test the CE model developed by the International Resource Panel (IRP, 2018).

Combined, this research uses a qualitative methodology to explore business models, activities, behaviors, priorities, and barriers associated with fast furniture and the ongoing challenge of furniture waste; further, it uses a quantitative methodology to measure the expected benefits of increased adoption and practice of CE and VRPs for the wood furniture industry. This research will help to develop a betterpicture of the potential for CE actions within the furniture industry and provide evidence for effective implementation. The following diagram (Figure 1) outlines the flow if this research and thesis:

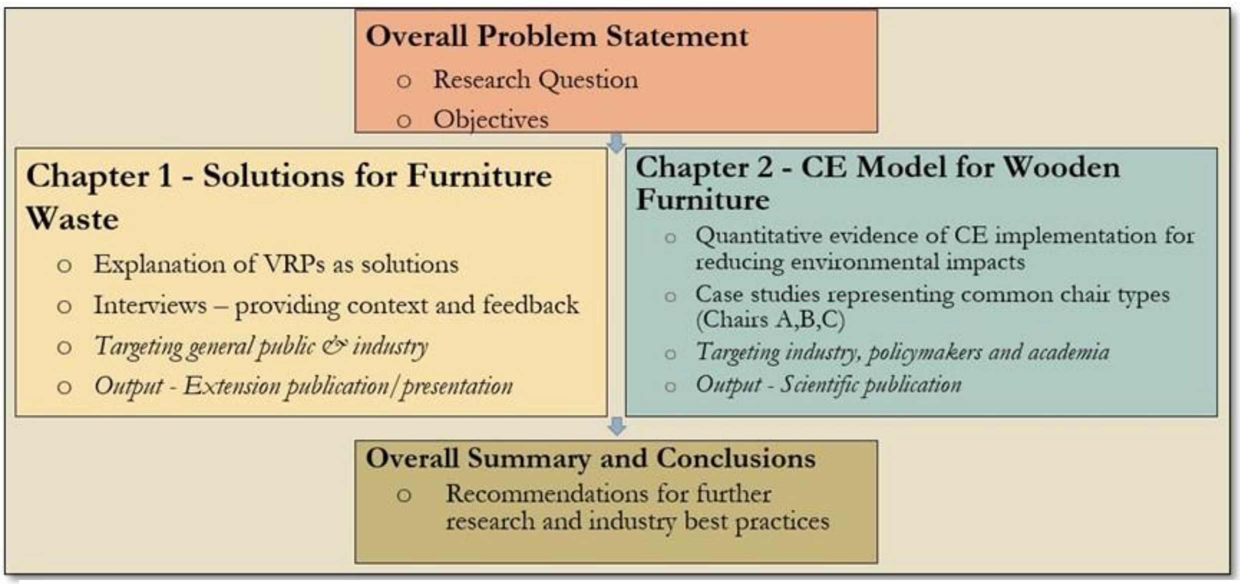

Figure 1. Thesis composition and flow

CHAPTER 1. SOLUTIONS FOR FURNITURE WASTE IN THE U.S.

This chapter will be submitted for publication to the following journals: Wood and Fibre Science, Wood Research or Forest Products Journal

Abstract

According to the Environmental Protection Agency's latest report, Americans threw out around 12 million tons of furniture and furnishings in 2018. The rapid growth of furniture waste can be linked to limited avenues for responsible disposal, shifts in design trends, and unsustainable consumer practices. The shift towards fast fashion, wherein trends are pushing the manufacturing of new products quickly and cheaply, has also emerged in the furniture industry. Less than 0.3% of wooden furniture is recycled in the US, but durable wood products play an essential role in a future circular economy (CE).

A growing number of furniture companies currently incorporate circular economy principles by offering take-back programs and repair services, using recycled material, developing innovative products for easy recycling, and extending product lifespan by applying strength design techniques such as reinforced joinery and applying performance testing. However, despite good intentions and CE aspirations, there is very little science-based data to support optimal decision-making for end-of-use/life (EOU/L) options. There are multiple opportunities to implement sustainability practices in the furniture production sector. The CE framework offers multiple pathways for product life extension and sustainable management via VRPs. While conducting this research, it was hypothesized that within the wood furniture industry, the application of VRPs would be mostly undertaken by third-party companies and organizations. This was confirmed through the semi-structured interviews of the eight companies and organizations. It was also unveiled that repair and refurbishment services are in need of skilled labor that presents an opportunity to expand this employment market. Reuse, being one of the most accessible and widely used processes represented in the study, was recorded as diverting more than 12,000 pieces of furniture from the U.S. waste stream. From the companies interviewed, those in Reuse, both for-profit and non-profit, handle most furniture. From the user's point of view, entering their products into the reuse market takes the least number of inputs in terms of costs and in most cases, transportation. This option also allows users to support social improvement within their communities.

Introduction and Background

Growing Problem of Furniture Waste

According to the EPA's report on municipal solid waste (MSW), about 12 million tons of furniture and furnishings ended up in the MSW waste stream in 2018. Some of this material was able to be recycled and combusted for energy recovery (19.87%), but the remainder was sent to landfills (Figure2), and these waste patterns have been steadily increasing since 1960.

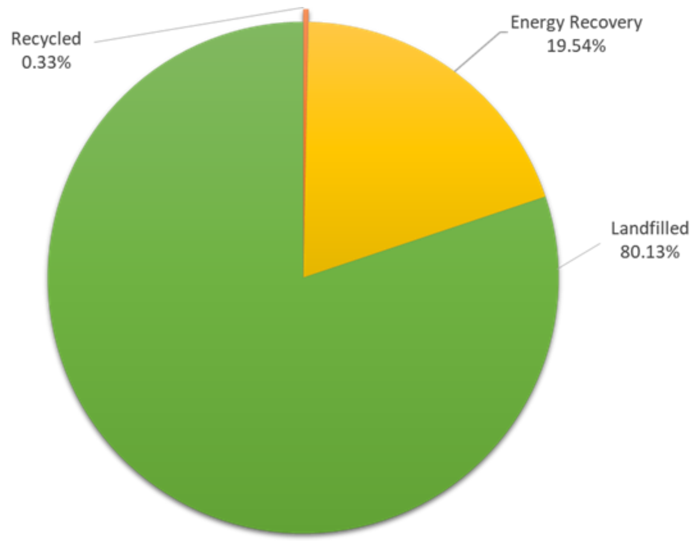

Figure 2. Percent of management pathways for furniture and furnishing in U.S. municipal solid waste stream in 2018

Because of the complexity of furniture structures and the inclusion of multiple materials such as wood (being the highest), metals, plastics, and glass, recycling them is greatly diminished. That same year, wood made up 13% of the total materials in landfills by material composition, see Figure 3 (EPA, 2020).

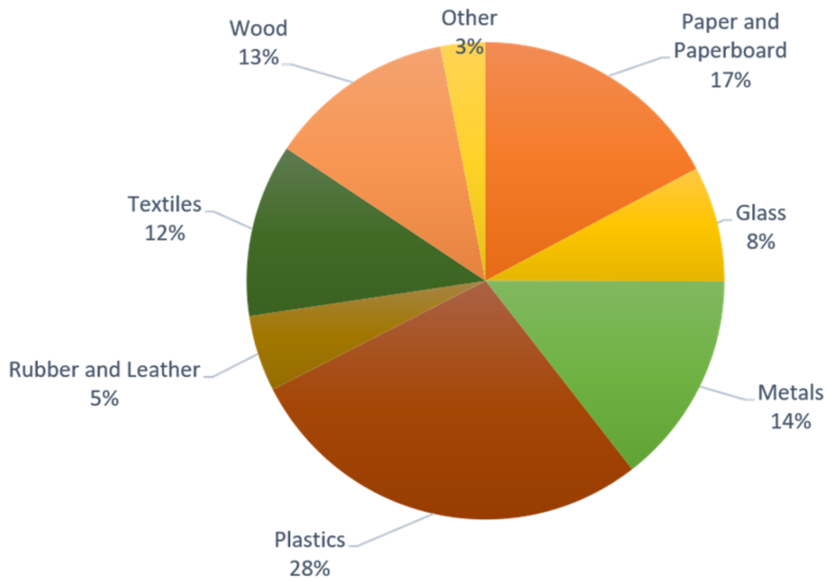

Figure 3. Percentage of total materials in U.S. landfills in 2018

Because of the complexity of furniture structures and the inclusion of multiple materials such as wood (being the greatest proportion), metals, plastics, and glass, recycling these mixed materials products can be complex. Further, other chemicals and materials commonly added to furniture (i.e., paints, finishes, and fabrics) can have adverse and polluting effects. It has become increasingly common in recent years to see piles of furniture accumulating in landfills and collecting on the roadsides in metropolitan areas (Cummins, 2020). Many of these wasted products are in a condition where they may still be salvaged for continued use.

Like the fashion industry, where products are being made with lower quality material, sold for lower prices, and bought and disposed of by consumers on a quicker turnaround, the furniture industry is seeing a similar business model emerge (Rauturier, 2020; Bischof, 2019). Design trends and increasing use of easy-to-assemble furniture have led to the growing phenomenon of "fast furniture," in which furniture sold at lower price points is being cycled through more frequently (Alter, 2019)**.** This results in ever-increasing volumes of furniture waste accumulating in landfills (Figure 4).

Figure 4. Accumulating furniture waste

Finding solutions can be difficult when considering the many groups of people that rely on this market of products; low-income households, college students, fans of minimalistic design, and those in transitional life periods. However, when looking through the lens of CE, there are innovative ways to address this problem and decrease the negative impact. Some contributing factors to this problem are a lack of consumer awareness, consumer markets that rely on these temporary products, and the lack of infrastructure to conduct more responsible EOU/L management practices (Brightly, 2020). Many prominent companies produce low-cost, low-quality furniture, using predominately wood-based composite materials that are difficult to recycle and maintain in life-extending processes (BizVibe, 2019).

These products are considered wastes, but many are technically in a condition that fulfills their useful purpose. In the context of this research, furniture waste is defined as including wooden household items, tables, chairs, and case goods within the US. This waste accumulation negatively impacts the environment by crowding landfills and potentially releasing harmful chemicals but can also negatively impact the social and economic sides of sustainability. There are many people in need of furniture and maybe in an economic situation where they cannot afford new pieces. Lightly used furniture has a great chance of being utilized by another user. Also, job opportunities coming from the value retention processes industry have great potential to revive a dwindling workforce.

Impacts of Landfills

According to the EPA, of the total durable goods landfilled in 2018 (25% of landfill composition), furniture and furnishings made up over 6%. Furniture, usually being some of the larger products present, have significant contributions to landfill crowding. Essentially, landfills are recesses dug into the ground, filled with refuse, and in instances where they are covered, layered with an impermeable covering (Figure 5) (EPA, 2021).

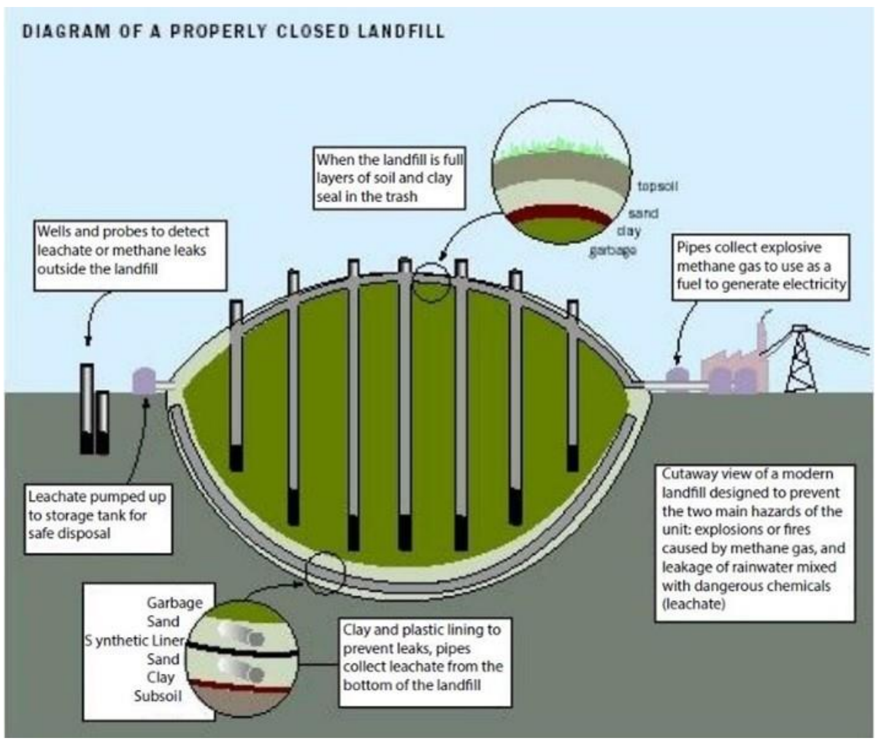

Figure 5. Diagram of closed landfill

Over the years, many types of landfills have been engineered to fit multiple waste types and reduce pollutants like leachate entering water systems. Most commonly, landfills include an initial liner that separates the waste materials from the soil, layered with another liner, and compressed with additional refuse (Adhikari et al., 2014**).** Municipal Solid Waste Landfills do not incorporate any type of separation in terms of material type. All products, if non-hazardous, ranging from paper, metals, plastics, food waste, etc., are packed into one central receptacle (EPA, 2021). Because of this mix of materials and little biological initiators such as worms, decomposition processes occur at much slower rates and vary throughout the landfill based on moisture contents (Blakey et al., 1995.

The nearby environment around landfills can also be at risk because landfills are among the top sources of greenhouse gas pollution, generating methane, one of the most prominent and efficient greenhouse gases (Lee et al., 2016). Soil contamination is constantly trying to be avoided, usually undertaken by the inclusion of impermeable surfaces between the waste and soil (Themelis and Ulloa, 2006 **).** Although these strategies are helpful, they will eventually wear, and the potential for leakages increases over time. Leachate, a pollutant constituting the accumulated liquid running through a landfill, is a prime substance meant to be avoided. This leachate can reach water systems and harm the water quality for wildlife and plant life. In cases where landfills are developed near populated communities, various negative impacts are incurred. Aside from the lack of aesthetic appeal and foul smells, the proximity to landfills can expose humans to harmful pollutants (Palmiotto et al., 2014). Several studies outlining the long-term effects that landfill pollutants have on human health as they enter the water and can be taken up by agriculture (Ahmade, 2013; Micales and Skog, 1997; Vaverkova, 2019).

Wood Product Types Typically Found in Waste

Many of the furniture products that can be seen in landfills or stranded on the sides of the road are well-built, bulky items, including tables, upholstered chairs, dressers, and storage furniture (Augusta Free Press, 2020). Bulky old items that might be out of style because of ever-shifting interior trends are a prime suspect of furniture waste (Genchev and Marinova, 2013). It does not help that these products are heavy, hard to move, and even more difficult to find alternative homes for if transportation costs are high (Mosaic, 2020). Recently, consumers have been more inclined to include minimalist furniture designs into their homes (Figure 6), which limits the attractiveness of the more classic designs and builds (Genchev and Marinova, 2013). Some producers intend to create long-lasting and sturdy products, but this can also have negative impacts. Users typically buy these bulky products pre-assembled, and they are made in such a way that limits disassembly. When considering upholstered products, they also include various components such as foam padding, wiring and textiles, that make the separation process and potential recycling efforts more difficult. With users concerned with hygienic factors associated with upholstery, the motivation to reuse or go through the process of replacing the fabric is low and could become expensive (Lazboy, 2020).

Figure 6. Minimalistic furniture designs

On the other hand, some products are not made to last a long time. These pieces have been deemed “fast furniture” because of their quick turnaround of production and waste. These products are usually made with composites or particleboard, pressed together with adhesives (usually containing harmful chemicals like formaldehyde), sandwiched between individual laminates, plywood panels, or veneers (Figure 7) (Maloney, 1996).

Figure 7. Composite based furniture 1

These products, which can also be deemed ready-to-assemble (RTA), are expected to see increases (Statista Research Department, 2020). RTA products come as easy-to-build and breakdown, contributing to the CE by being easily repairable and having replaceable parts. Still, because of user's perception of their low value, the effort to follow through with CE processes is non-existent.

These composites are sensitive to moisture and usually meet their fate when exposed to water resulting in swelling and separation of the layers, which is not an easy fix without an industrial press (Maloney, 1996). These products are also usually set at a fairly low price to satisfy a market of buyers like college students, low-income households not wanting to rent bulkier furniture, and people moving or in transition looking for easy purchases. In some cases, these products are beneficial because they create a use stream for wood wastes from larger production or recycled materials (Stark and Cai, 2021) contributing to CE efforts by creating value from wastes. Still, this benefit can be lost when the product is not brought back into the cycle and ultimately discarded in a landfill.

The quality of these furniture products is usually low in terms of strength and long-lasting durability (Guntekin, 2002). They are usually mass-produced abroad, so negative impacts of transportation must be factored in. Many of the issues associated with these products can be attributed to the multiple parts that make up the construction. The mix of laminates, plywood, adhesives, and various types of composites make for challenging if not impossible recycling processes.

Consumer Habits

Although many environmental considerations (i.e., responsible raw material sourcing, recycled materials, durable/modular designs) are being undertaken on the production side by designers and manufacturers, some actions may fall short if dismissed by the consumer. Users have the ultimate decision as to a product's end-of-life determination, and if they are reliant on poor options such as the landfill, then the environmental considerations are not being fulfilled. One of the biggest obstacles to environmental concerns is the lack of awareness and education amongst consumers concerning the impacts of their actions (Buerke et al., 2016**)**. A study conducted in the UK outlines how most people throw away reusable furniture because of convenience, cost, and lack of unawareness of other options (BHF, 2019).

If consumers become aware and want to make better decisions, they also must worry about the predatory nature of “green-washing.” Greenwashing is a marketing and product labeling issue where sustainability claims are made of a product that might be an overstatement or entirely false (Laufer, 2003). If adequate research is not conducted into the validity of the claims, consumers could be misled to make decisions that are not helping the environment. These occurrences may also appear with waste management services. Entities offering furniture removal often advertise material recycling but do not clarify if the furniture is included.

More recently, consumers have an expectation of products changing and updated quickly (Abraham and Harrington, 2014). It was more common for furniture to be kept and passed down throughout familial generations in earlier years. The long-lasting attributes that were characteristic of wood products were realized, and processes of repair and refurbishment were utilized. These actions were attributed to furniture being of higher value and solid wood products being more prevalent than composites or engineered wood products. Now that products have become more accessible and affordable with lower quality, which has benefits for some users, but has shifted the users' relationship with the product. With its lower price, it has a perceived lower value which then leads to the take-make-waste mentality.

Research Aim and Objective

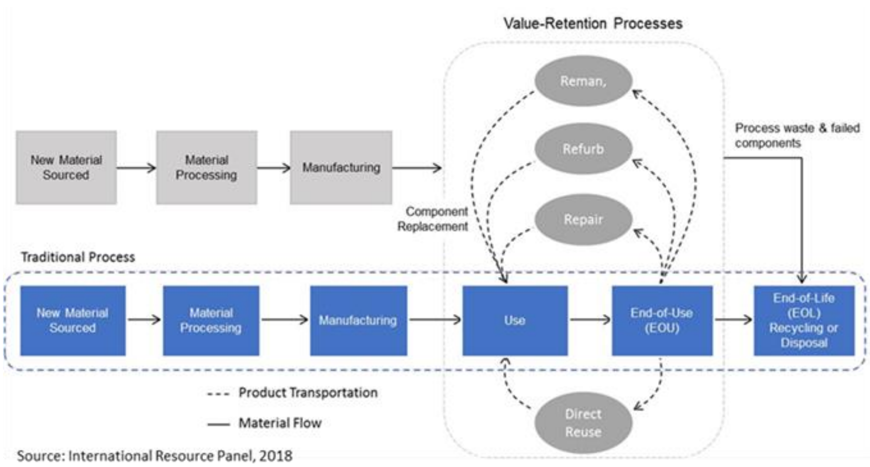

Figure 8. Value retention processes

The Circular Economy (CE) is a concept rooted in efficient material utilization and reduced environmental impacts. Specifically, the CE actions are deemed Value Retention Processes (VRPs), which include reuse (for-profit and not-for-profit), repair, refurbish and recycle (Figure 8)

(IRP, 2018). These practices help to keep the inherent value of products and materials (e.g., embodied energy, embodied emissions) cycling within the economy for longer (e.g., retaining value), while also significantly reducing the need for virgin material extraction and production activities**.**

As these processes are undertaken, the products stay in service longer, ultimately avoiding negative waste streams and the need for new material extraction. All of these processes can be conducted on furniture products, and this paper seeks to showcase the viability of the industry that works to extend these products' lives. Current research on CE in the furniture sector discusses VRPs and the benefits of their application but does not elaborate or include insight on the actual entities that will offer these processes (EEB, 2019; Furn360, 2018). The VRPs relevant to wooden furniture are defined as follows:

Direct Reuse: The collection, inspection, testing, cleaning, and redistribution of a product back into the market under controlled conditions (IRP, 2018).

Repair: Fixing a specified fault in an object that is a waste or a product and/or replacing defective components in order to make the waste or product a fully functional product to be used for its originally intended purpose (IRP, 208).

Refurbishment: modification of an object that is waste or a product to increase or restore its performance and/or functionality or to meet applicable technical standards or regulatory requirements, with the results of making a fully functional product to be used for a purpose that is at least the one that was originally intended (IRP, 2018).

In the context of wood furniture products, and for this study, VRPs are defined as follows by the research team:

Repair: the replacement or maintenance of a failed component to be restored to original functionality

Refurbish: updated aesthetic qualities with no inputs or alterations to products original structure, i.e., reupholstered

Reuse: continued use of a product as is with no inputs or alterations; this can include informal reuse (passed down through family) or formal (for-profit and non-profit donation, i.e., purchasing second-hand)

Recycle: separating and breaking down each component to base materials for further processing at the material level, i.e., mulch.

Within the wooden furniture sector, the inclusion of VRPs is offered mainly by third-party companies and organizations. The objective of This paper aims to highlight the issue of furniture waste in the U.S. and CE concepts as a viable solution. To determine the effectiveness of VRP implementations, this paper will conduct a search to identify companies and organizations offering VRP services for furniture products. For each VRP, two to three entities will be chosen to administer a questionnaire that will reveal quantitative and qualitative information regarding the individual processes and their viability as CE solutions to furniture waste.

Methodology

Study Current Literature on Furniture Waste

To understand the extent of the furniture waste issue, a literature review was conducted. Searches of online databases such as Scopus, Google Scholar, Science Direct, and Research Gate resulted in little to no publications discussing the issue of furniture waste. Multiple papers focused on the impacts that landfills have on the environment and considering that most furniture ends up in landfills. These papers were used as a reference to evaluate the problem. Along with these papers, online articles and blogs were also more vocal on the issue of furniture waste and the evolving concerns of “fast furniture,” in which cheaply made and disposable furniture is becoming more prominent on the furniture market and eventually reaches landfills.

These online blogs and articles were used to assess how companies and the average consumer view this issue, how it impacts their environments and the currently proposed solutions. These insights established a base that would better inform the inclusion of circular economy concepts.

Identifying VRP Companies

To gather both, qualitative and quantitative, supportive evidence regarding VRPs and their participation within the wooden furniture industry, at least two companies per process were addressed. All companies were identified through online searches on the Google search engine. Since the research is being conducted in Indiana, USA, the initial search only included companies in this state. Once recognizing the limits to this method and realizing that these products are shipped all over the country, the geographical scope was broadened to nearby major cities, including Indianapolis, IN, USA, and Chicago, IL, USA. Through the course of the study, relevant acquaintances of the research team were also approached, and the company locations broadened to include San Diego, CA, USA, Ontario, CA, and Big Pine Keys, FL, USA. Companies' websites were scanned for advertising VRP services. After it was determined that the company followed through with VRPs, as defined by the research team, and worked primarily on wooden furniture, they were chosen to be contacted.

Constructing Questionnaire

Once the overall scope of the project was identified, the research team was able to establish the information needed to conduct the research. In order to identify what questions would be included, the following steps were taken:

1. Identify the nature of questions (i.e., qualitative or quantitative)

2. Establish the length of the questionnaire

3. Construct questions that would pertain to all VRPs to analyze processes

4. Identify differences in each process and assign questions specific to the individual process

5. Review and deliberate questions amongst the research team

6. Submit completed questionnaire to Purdue University Institutional Review Board in order to confirm that questionnaire was not "humans subject research" and receive approval as "exempt."

Administering Questionnaire

An interview script was prepared to establish consistency across all company interviews. A general base survey was generated to all companies and was followed by a subset of questions particular to each service. Because these services are usually small businesses, we didn't want to place geographical restrictions on the companies. The main goal was to have at least three representative companies for each VRP. Once the companies were identified, they were contacted by phone, and either the interview took place then or was scheduled for a later date.

The questionnaire works as a semi-structured interview guide (Kallio et al., 2016) consisting of a set of general questions asked of all companies and a smaller set of questions specific to that industry. The questionnaire results were anonymous when analyzed in the final report, which companies were made aware of. The questionnaire and potential company contacts can be found in the Appendix section. The methodological steps for conducting the questionnaires are as follows:

1. Conduct an online search to identify companies. There were no geographical barriers considered for the companies, but those located in the same state (IN) as the case study company were preferred.

2. Companies are initially contacted by email based on the information provided on their websites. If no response is received within a week, a phone call will be made for more direct contact.

3. Once a response is received, perspective time and dates for availability are proposed, a call is set, and the company is sent the questionnaire in advance in order to better understand the nature of the meeting and to gather the needed information.

4. During the call, the company representative is reminded of the background of the study and the role that their information plays in the overall research to ensure that they are still

willing to answer the questions. They are also informed that their company information will not be identifiable in the data presentation and analysis or in the final report.

5. Each company is asked the questions from "Questionnaire A" as general baseline questions and then are transitioned into the questionnaire that relates to their individual process (See Appendix A).

These companies were chosen because they specifically advertised the VRPs for furniture products. There were not any restrictions on the size of the business, but efforts were made to include companies that differed in some way so that a more comprehensive scope of the VRP industry was covered. A few companies also covered multiple VRPs, especially repair and refurbish. Once the companies were found, phone calls were placed. Emails were sent in place of phone calls if they were not answered. Most of the interviews took place over the phone, while a few were able to be done over Zoom.

Results and Analysis

Company Profiles

Interview responses were collected from ten companies. Four companies were related to the “Reuse” category, while “Repair” had three and “Recycling” (technically upcycling) had one representative. One company was contacted twice for “repair” and “refurbishment” because they offered both services. The descriptions of each company are detailed below:

Reuse

Company A: An environmental firm that works with larger corporations to offer sustainable furniture redistribution services such as reselling, recycling, and donating. Most services occur in large office buildings and company headquarters and present companies with a cost-effective disposal service that repurposes used furniture to organizations or individuals in need. As of the year 2020, they have diverted over 70,000 tons of furniture and equipment from landfills and provided in-kind donations to over 5,000 non-profits and communities across North America (Interview Anonymous A, September 10, 2020).

Company B: A newly emerging for-profit furniture reuse and resell company that offers on-site and online used furniture purchasing. They handle about 4 tons of furniture products, primarily wooden, coming from residential and commercial sources. They have about 30 employees that manage the site, handle minor repairs and product transportation. Partnerships with local recyclers are in place to sustainably manage pieces that can be recycled (Interview Anonymous B, January 13, 2021).

Company C: A non-profit organization that accepts donations of a range of household items and furniture to service those in need that reflect a predetermined set of criteria. In 2019 they donated around 30,000 pieces of furniture to those in the greater Chicagoland area. They have about 22 employees that manage the intake, minor repairs, cleaning, and product delivery. Many of their employees come from workforce development organizations that offer employment opportunities to those with previous records who have difficulty securing employment, and then a small percentage are volunteers. The majority of their donations consist of wood products and upholstered pieces. About 60% come from the residential sector, while the remainder comes from corporations (furniture manufacturers or donated used pieces from businesses). About 5% of their intake is beyond repair or does not meet standards and is discarded. They have about six box trucks, driving 45-75 miles/day on average, that service the Chicagoland area, including Evanston, Oak Park, and further distances if coordinated in advance (Interview Anonymous C, November 2, 2020).

Company D: A non-profit furniture bank that diverted over 60,000 pieces of furniture from landfills in 2019. By partnering with about 150 social service agencies, this organization is able to donate furniture for complete home furnishing. They receive 85% of donations from the residential sector and the remaining 15% from the business sector. They employ around 46 people to handle the product transportation, minor touch-ups and have recently begun to train employees in furniture repair. These repairs include reworking seats and joinery of tables (Interview Anonymous D, November 23, 2020).

Company E: A non-profit organization that accepts donations from corporations and individual community members of various furniture and household items to distribute to those in need or transitional life stages. Partnerships are in place with non-profits helping vets, those in domestic violence situations, and homeless persons in transition, as well as churches and community centers. They service around 15-25 households per week with a complete furniture package that corresponds with the number of people in the household. Along with staple furniture products like bedding and living room pieces, they also offer sets of dishes, cookware, and other small household items. Most furniture pieces they receive are solid wood and upholstered furniture. They are rarely offered composite products. They have criteria that discourage items that have stains, rips, or are beyond minor repairs. Any items that are brought on site that do not fit the criteria are ultimately sent to a landfill. Once calls are received at the facility, they coordinate pick-ups and drop-offs in similar areas to maximize the use of their one truck, as well as to limit carbon emissions. Their labor force consists primarily of volunteers who work on minor repairs, cleaning, and organizing products. There is also a small set of employees, “care specialists,” that manage the transportation, moving, and more involved repairs. The organization also coordinates with a woman who takes in furniture for repairing and works with various organizations throughout the community. Their service area consists of Marion county but are willing to make longer commutes within the state if organized in advance (Interview Anonymous E, October 29, 2020).

Repair and Refurbish

Company F: A for-profit furniture repair company that employs multiple local repair technicians across the U.S. They receive about 15-17,000 service calls/month, with some individual calls, including multiple orders. The majority of their repairs consist of electrical issues (50%), while about 25% come from upholstery, 13% are wood related, and the remainder is leather repairs. Along with taking calls from residential customers (about 15% of business), they also work with manufacturers and retailers as the company that repairs items under warranty. All jobs are done on-site, either at the customer's home or the manufacturer's site. The company has a small, centralized warehouse for spare parts but not for large amounts of storage or machinery. They employ about 200 technicians nationwide with backgrounds in upholstery and wood refinishing. Each technician is designated several zip codes that they service, some being within a 300-mile radius, but many are willing to travel further to other regions if needed. Partnerships are formed with suppliers, retailers, and manufacturers to reach customers. They see issues with finding qualified technicians and those willing to work a rather solitary job but state that the pay is competitive, with technicians being able to earn up to $5,000 a week (Interview Anonymous F, November 4, 2020).

Company G: A for-profit furniture repair business in Newport News, Virginia, that offers repairs on a variety of furniture products. On average, they work on about 18-20,000 pieces a year but have been much lower because of the ongoing pandemic. 90% of the pieces are wooden, and the remainder is the upholstery. Typical repair jobs include simple glue-ups, refinishing, some part replacements, and antique restorations. The company recognizes a pattern in the types of projects and products being worked on based on the time of year (e.g., primarily commercial work during Jan.-May and mostly tables and chairs from Aug.-Dec.). Their customers include residential repairs and commercial clients like universities, government agencies, and those in the hospitality industry. They only have about 3 permanent staff (difficulty to find qualified workers) and seek out subcontractors for direct repairs. Work is done in the shop for smaller projects and refinishing for commercial projects, but most jobs will be completed on-site. The geographic range of service is about a 25-mile radius, but customers bring pieces from all over the world, and further distanced on-site projects will be accepted if organized in advance. Most common repairs are seen on glue lines and joints. Some repairs are done on composite pieces if they have the necessary equipment, but usually, these repairs require heating and drying processes that the company is not equipped to complete (Interview Anonymous G, November 13, 2020).

Recycle

Company H: A for-profit furniture producer that does not complete the recycling process as outlined for this study but was interesting to include because of its proximity to the process and uniqueness within the wooden furniture sector. The process this company undertakes would be referred to as upcycling. They utilize wood (mostly tropical species) from decommissioned fishing boats that would ultimately be discarded and create unique furniture products. They are able to create around 3-4,000 pieces a year. Their labor requirements vary with the nature of the designs, but on average, they have about ten to twelve workers. They work in conjunction with local fishermen to collect materials and sell final products. Because of the nature of their work being highly region-dependent and variable, this type of operation would most likely stay small-scale, one-of-a-kind artisan operation (Interview Anonymous H, December 29, 2020

Questionnaire Responses

Most of the interviews took place over the phone, while a few were able to be done over video calls using the Zoom platform. For those in reuse, two different markets exist – for-profit and non-profit. Those in the non-profit space ranged from small local organizations to large city-wide organizations.

The responses to questions were collected in a spreadsheet, then deduced to terms that made the comparison. The results of the interviews are summarized below, along with a detailed table located in Appendix B.

Reuse

This market is growing in terms of scope – there are multiple companies offering for-profit and donation-based reuse services. Because of its multiple formats and ease of the process, this VRP is the most widely used throughout the furniture sector. It is being done directly, but some companies are also offering options to shop and sell online. From the companies that were interviewed, pieces of furniture go through these processes annually. Compared to the other VRPs, reuse required the least number of inputs and skilled labor. It also carries the least amount of impact on the environment, mainly if redistributed locally. Depending on the size of the operation, not much labor is required. Smaller organizations, primarily non-profit, can be maintained with less than ten permanent employees and volunteers. Larger companies with more extensive inventories and geographical service range require more staff and labor for furniture maintenance, displaying, and transportation. The energy requirements for these processes are limited to essential hand tools. Still, for overall operations, most of the energy needs are used for the building where materials are stored and fueling vehicles. The majority of pieces were retrieved from users, usually about 70%, and the remainder from businesses, except for one company that intentionally works with the business sector. These processes are those that can be undertaken by manufacturers, third-party companies, and users. Reuse efforts would require the least number of inputs seeing that no new materials would be needed, and only minor fixes or touch-up would be applied. Along with redirecting from the waste stream, reuse also has social benefits. Many reuse markets are offered to those that are in need.

Repair and Refurbishment

Companies that were considered for the "repair" VRP also fell into the "refurbish" category. This service area sees a decline in skilled labor, so there is an opportunity to grow this market in terms of employment offerings. Most service requests come from other businesses, and these can be seen following a cyclical pattern. There is a mix of products that these businesses address. Services can range from large commercial orders from hotels or restaurants to work on groups of products, mostly seating. There is also a significant amount of custom and antique work from individuals in the residential sector or specialty clients like government entities and museums.

Recycle

Unfortunately, throughout the search, recycling was not something that a particular company offered. Instead, it was municipal facilities or businesses that dealt with junk removal – all of which included more than just furniture products. Companies where furniture recycling was advertised meant to reuse or donate. In cases where furniture could be recycled, it was only the furniture that was all one material and broken down into an acceptable stage.

Three companies were identified as offering furniture recycling services, but once they were contacted, it was realized that their definition of recycling was not conducive to our study. These companies were initially advertised as junk removal. They included furniture recycling as an offered service, but this meant donating (essentially reuse) when possible, but ultimately sending the items to landfill. There was no process of disassembly, material separation, and subsequent recycling. Because these companies did not fit the definition of recycling that was referenced for the study, these interviews were not conducted. Through this process, it was found that furniture recycling in the way that is defined in this study (separating and breaking down each component to base materials for further processing into a new product) is rare if at all, completed. It was also observed that many of these recycling organizations, whether privately owned or part of the municipality, were elusive and challenging to gather precise information.

Discussion

Recycling is the only VRP market that is essentially non-existent. The junk removal companies that were contacted advertised recycling, but what they considered recycling did not fit with the definition outlined for this study and instead was closer to reuse. Recycling efforts in the U.S. are currently low compared to other developed nations and can be expensive when introducing multi-components products such as furniture. Unless the product is already pre-disassembled when arriving at a recycling facility, the most likely chance of recycling, as defined for this study, would be conducted by the original manufacturer. They would have the knowledge and resources needed to separate all components and would assumably have waste streams for the materials commonly used in their production facility.

Although the businesses contacted were doing well financially, those in Repair and Refurbish expressed problems finding and securing skilled labor. Like the wood products industry, not many young people are interested in entering this career field even though employment is available and the compensation is competitive. If this problem persists, it could create issues down the line for the security of a CE within the furniture sector. But if looked at differently, it also further promotes the benefit of CE inclusion for the opportunities to create jobs and further develop this market. The distribution of jobs conducted for individual users and other businesses (i.e., restaurants, hotels, offices) was reasonably even, but it can be assumed that more profit is gained when doing more extensive projects that include more furniture pieces.

The incorporation of VRPs into the furniture sector also creates opportunities for furniture manufacturers to develop innovative business models. When furniture companies initially hear that their products are going through processes to make them last longer, it could be worrisome if that means that users are buying less of their products. To stay connected with the consumers, manufacturers can play a role in these product life-extending processes. For example, companies like IKEA are implementing these services into their offerings and integrating CE principles into their business models. This opens a new market for any furniture manufacturer while maintaining their customer base. There is also the opportunity for manufacturers to develop partnerships or collaborations with smaller-scale VRP companies that will allow them to extend their reach while addressing customers locally and limiting transportation impacts.

This research established an initial base, but there is still room for further research and developments. The ideal next step to progress CE concepts within the furniture sector would be to change user's perceptions on how furniture should be used. Furniture has such a wide range in product offerings, design, materials, and price points, but their inherent value should be recognized. If users are more inclined to change their tastes and products frequently, then the idea of furniture as a service instead of an owned product should be amplified. Producers and designers must also consider what aspects of furniture will keep users interested and find more ideas of value besides the price. Product customization, which would fit a product to a specific function or service, could reduce waste and give the user more agency in the production process. Also, larger institutions such as universities and corporate headquarters can develop systems that account for their large amounts of furniture to be refurbished and cycled back to avoid masses of waste accumulation. The EU has been a big proponent of these implementations, but adjustments need to be made for the U.S. market. There are differences in policy and product standards that may affect how manufacturers and users participate in CE concepts.

Conclusion

From the questionnaire results, it can be concluded that a viable VRPs market exists for the wooden furniture industry. From the companies interviewed, those in Reuse, both for-profit and non-profit, handle the most furniture. From the user's point of view, entering their products into the reuse market takes the least number of inputs in terms of costs and in most cases, transportation. This option also allows users to support social improvement within their communities. Economic opportunities are also present when considering the role that manufacturers can play in developing VRP services within their current offerings. There are also opportunities to grow the employment sector of the VRP industries.

CHAPTER 2. CIRCULAR ECONOMY CONCEPTS FOR FURNITURE

This chapter will be submitted for publication to the following journals: Wood and Fibre Science, Wood Research or Forest Products Journal

Abstract

The dominant circular economy (CE) model, proposed by the Ellen MacArthur Foundation (EMF), reflects the cascading use of products and materials based on CE principles. However, the EMF model only accounts for biomaterials that are consumed and technical materials that are utilized within production-consumption systems. There is a little account of the opportunities for long-lived wood products that are utilized but not consumed. The literature extensively discusses the opportunities for cascading use of wood within the bioeconomy. However, most studies utilize secondary research methods and do not quantify the environmental benefits that result from industry- or consumer-decision to reuse, repair, or repurpose a wood product instead of replacing it. Compounding this challenge, wood furniture constitutes a significant share of the waste stream in the U.S. (12 million tons of furniture accumulated in landfills in 2018, as reported by EPA (EPA, 2020). Despite many positive attributes of wood, such as durability, aesthetics, and environmental qualities, it is not simple to associate contemporary furniture with these properties. Furniture today is produced mainly of wood-based engineered materials (i.e., plywood, laminatedparticleboards, or fiberboards). Only less than 0.3% of wooden furniture is recycled in the U.S., and it is mainly out-of-style, large and bulky solid wood furniture. Durable wood products play have an essential role in a future circular economy. However, despite good intentions and CE aspirations, there is often little available data to support optimal decision-making for end-of-use (EOU) items.

Adapting the value-retention process (VRP) model, introduced by the UN International Resource Panel (IRP) (2018), this study intends to quantify the selected environmental and economic impacts of various VRPs. These include CE practices of reuse, repair, refurbishment, and recycling, as they are undertaken for durable wood products. Unlike traditional life-cycle analysis (LCA), our model accounts for the impacts incurred and avoided by utilizing these VRPs multiple times over the product's life, rather than disposing and replacing the product when it reaches end-of-life (EOL). In addition to environmental impacts, the study assesses economic metrics of production cost, and labor requirement of the VRP decision relative to a disposal and replacement decision.

To demonstrate the function of our model, case studies are conducted for three different models of wood-based chairs. In collaboration with industry partners, our analysis quantifies the new material requirements, energy requirements, emissions and waste generation, and labor requirements of new chair manufacturing, chair repair, refurbishment, and reuse within the context of a circular economy.

In addition to the quantitative reductions of material use, solid waste, energy consumption, and emissions, the findings of the study highlight some distinct differences between the wood furniture sector and sectors more commonly associated with the CE (e.g., heavy-duty equipment, vehicle parts). For example, unlike industrial practices of remanufacturing that typically occur within the origin production facilities, these processes are conducted outside of industrial settings and across a highly distributed third-party network of businesses. These businesses offer lower-tech repair, refurbishment, refinishing, redistribution, and repurposing services. However, similar to the industrial products modeled in the UN IRP report (2018), the design configuration and material types used for these products significantly impact whether VRPs are even possible for wood furniture. Ultimately, the model showcases that the implementation of VRPs on the selected wood furniture products significantly decreased environmental impacts.

Introduction and Background

The Problem of a Linear Economy

Traditionally, manufacturing systems have adopted a linear framework that consists of resource extraction, production, use, and disposal (Figure 9). For many industries, this linear process has contributed to the current state of environmental degradation and the scarcity of natural resources. Brennan et al. (2015) showed that as society becomes more advanced and lifestyles improve, humans are taking more from the earth than what can be replenished.

Figure 9. Simplified model of linear economy

The global population has been steadily increasing, and it is projected to reach 9.7 billion by 2050 (Roser, 2013**).** Aside from the basic needs of food, shelter, and water, technological advancements also strain natural resources. Humans see a higher quality of life, resulting in longer lifespans and the need for increased industrial products and energy consumption (WHO, 2018). Consequently, if not managed, all of these needs come with environmental impacts that will create an uninhabitable environment. CE seeks to be a solution by managing the products already in service to ensure a responsible life cycle that avoids environmental harm and the need for unnecessary resource use. Implementing a circular framework is necessary if we want to continue fulfilling society's needs while avoiding contributions to adverse environmental impacts.

The ongoing growth and development leading to society’s current advancements have relied on a linear economic system of resource extraction, product manufacturing, distribution, use, and disposal. Along this linear process, unnecessary wastes occur in the manufacturing stages, as well as use phases and end-of-life (Michelini et al., 2017). These waste products filter back into the environment, causing negative impacts, such as chemical pollution, greenhouse gas emissions, and environmental degradation (EMF, 2015). The exploitation of labor in developing nations has allowed producers to extract materials and manufacture products at lower costs, which has only propelled the acceleration of resource depletion and waste accumulation (Sariatli, 2017). It has become apparent that this isn't a responsible or efficient use of the world's natural resources. Over the years, we have seen significant declines in non-renewable resources, such as minerals and fossil fuels. The idea of “planetary boundaries” was established by (Rockström et al., 2009), wherein seven impact areas were identified. The passing of these impact thresholds signifies the reaching of irreversible environmental change. An updated report details that since entering the

Anthropocene, we have surpassed four of the nine impact areas (Steffan et al., 2015). Reaching these thresholds can be attributed to the over-exploitation of natural resources and increased pollution of greenhouse gases from industrial processes.

Continuing with a linear economy system also has negative social and economic impacts. If resources are not being utilized efficiently, they become scarce. Those at lower socioeconomic levels become at risk because they also have to deal with the environmental disasters around them.

How the Circular Economy Addresses Problems of the Linear Economy

To counteract the negative impacts that a linear system has on the environment and society, the idea of a circular economy (CE) has emerged where materials and processes are strategically cycled through different value retention processes (VRPs) to reduce waste and the need for new raw material extraction. The Ellen McArthur Foundation (EMF) has become a leading proponent of CE (Ellen MacArthur Foundation, 2013) and has established three principles that guide CE implementation:

1. Design out waste
2. Prolong the lifespan of products and materials in the system
3. Transition to renewable resources

As opposed to the current linear economy, CE will implement processes, infrastructure, and policies that will develop a closed-loop cycle with minimal inputs and waste that will ultimately alleviate strain on the environment and finite resources (Brennan et al., 2015).

Like most sustainability actions, the CE aims to consider the social, economic, and environmental benefits of creating value in prolonging a product's life span and potentially developing new markets and economies (Araujo et al., 2019). To successfully implement a circular economy, it is also imperative to cross-collaborate among the different actors in a value chain (Ghisellini et al., 2016). With disconnects between designers, producers, users, and end-of-life options, positive upstream actions can't be fully realized if downstream processes aren't supporting or following through with the cycle. Others have also discussed CE in the context of "material efficiency," which sees CE as an avenue to promote material services with less input of materials (Prendeville et al., 2014).

Principles of Circular Economy

When looked at systematically, the CE can be organized into biological and technical systems (McDonough & Braungart, 2002). As shown in Figure 10, the biological system reflects the cycling options for bio-based materials, including inputs such as farming and biomaterials and outputs such as biogas and energy. The technical side is reserved for non-renewable materials that can go through various processes, including remanufacturing, reuse, and maintenance. Traditionally, wooden furniture, produced from a renewable biomaterial, exists on the "biological" side of EMF's CE diagram.

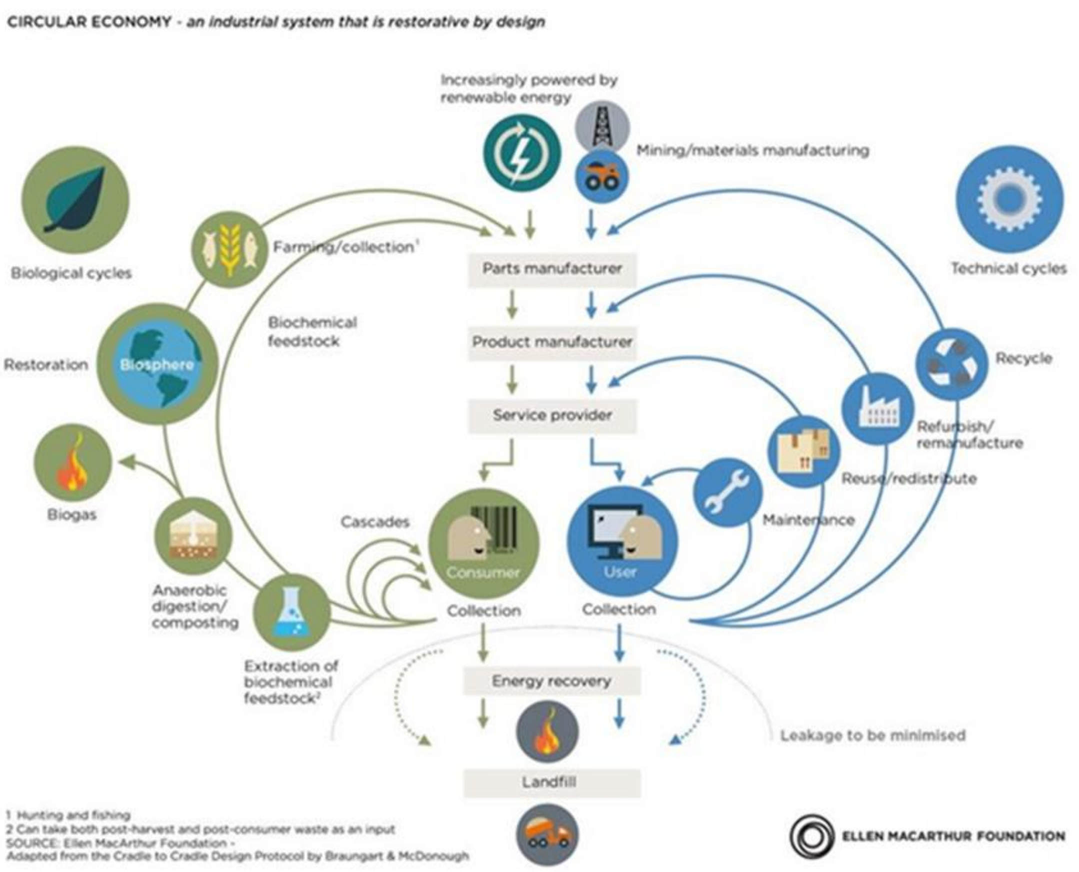

Figure 10. CE diagram by EMF

CE practices, such as remanufacturing and repairing, have been better received in industrial sectors and focus on recycling, which has some negative feedback when considering the more significant energy necessary to complete a recycling process (Allwood, 2014). This could be a limiting factor for some industries that can't easily be integrated into current recycling systems.

According to BIFMAs PCRs, seating is expected to last ten years (BIFMA, 2019), but in reality, these furniture pieces can last much longer, possibly up to 40 years, if appropriately utilized. When these products reach the end of life, they are likely to be disposed of in a dumpster and then landfill. Here, it takes many years to decompose while potentially releasing chemicals and contributing to greenhouse gas emissions.

Although wood products are made from a material that is biodegradable, recyclable, and renewable, these CE attributes are not typically realized in the sector. Some attributes impeding these biological processes are the addition of finishes and paints that might be present on the wood at the time of disposal. The process of cascading, where waste materials are utilized in lower-quality production levels during manufacturing processes, is more common within the wood products sector (Fraanje, 1997). This does provide a system to achieve the full utilization of a material and be more efficient in feeding processes. Aside from cascading waste materials within manufacturing facilities (Thonemann and Schumann, 2016), the industry is fundamentally linear. Conventional wood furniture systems follow a standard supply chain in which timber is harvested, processed, manufactured into various products, distributed, used, and disposed of (if not utilized as a fuel source). According to a 2018 EPA report on municipal solid waste recycling, paper and paperboard products made up more than 60% of the total recycled materials, while wood made up less than 5% (EPA, 2021). Seeing that wood constitutes a small percentage of recycled material, it would benefit the environment and the industry to incorporate wood products into the CE to avoid landfills and loss of valuable materials.

Environmental considerations, geared towards impact reductions in the forest products sector, target efficiency and improvements in primary forest harvest operations and manufacturing processes (Buonocore et. al., 2014). Although there are still some significant sources of emission and environmental damage from these primary processes, such as harvesting equipment and transportation, there are opportunities to offset these impacts (Kilgore and Blinn, 2004). With sustainable forestry certification bodies such as SFI, FSC, and PAFEC, the opportunity to maintain healthy and regenerative forests has been a central goal for many in the industry (Moore et al., 2012). Having actions related to sustainable primary forestry operations attribute to CE principles by providing the material that is responsibly sourced and impeding overexploitation and associated environmental impacts. Since a successful CE includes all levels of the value chain (Lieder and Rashid, 2016), having this base for the forest products industry is beneficial, but now efforts need to be put towards completing this cycle.

The forest products industry spans multiple products and sub-industries. This creates a rather diverse industry. It includes pulp and fiber for paper products and clothing, fuel, rubber, building materials, furniture, and other less prominent sectors. Having these multiple avenues for products makes standardization difficult but at the same time opens the opportunity for collaboration and innovation in terms of CE within the industry.

Of all of the sectors generated from forestry, the furniture sector is one of the most prominent industries. According to a report generated by Coresight Research, consumers spent over $100 billion on furniture products in 2018 (Coresight Research, 2019). The furniture market includes multiple business types, from small-scale custom woodworkers to large-scale international companies. Not only are there differences in size (i.e., number of employees, square footage of manufacturing site, annual output), but the differences in product offerings (i.e., case goods, seating, tables). This situation calls for CE frameworks that address not only wooden furniture but also specific processes related to these particular sub-industries. The ability of these companies to implement CE concepts should also be considered. Small and medium enterprises (SMEs) may have more barriers related to capital and supply chain management than a larger international corporations. In contrast, they might have difficulty organizing standards across a longer supply chain.

Environmental Considerations in the Wooden Furniture Sector

Although production systems are more advanced today and utilize more energy (Iritani et al., 2015), the environmental benefits of using wood as a material have not diminished compared to nonrenewable materials. Studies have shown a decrease in environmental impact when substituting non-renewable materials such as metal and plastics with wood from sustainably managed forests (J. Taylor, K Van Langenberg, 2003).

However, some of these strategies can be problematic because they expect consumers to carry out responsible practices for end-of-life (use) actions, such as disassembly, recycling, and repairing to maintain use. Suppose resources are not available or put in place for users to follow through; this might also put extra work in the user's hands by expecting them to locate facilities equipped to take their materials or carry out life-extending processes. This is a problem because it takes responsibility away from the producer, who would assumably have a better understanding of their products' impacts and end-of-life capabilities. Having encompassing strategies involving every level of the products' life is critical if a practical CE is in place. All levels must have adequate resources to carry out the responsibilities.

The inclusion of CE concepts in the furniture sector has been widely discussed and carried out in the European Union (EU). Like the U.S., the issue of furniture waste is significant —with member states sending around 11 million tonnes of furniture waste to landfills annually (EEB Report, 2017). The European Environmental Bureau (EEB) addressed this issue and transitioning the European furniture market towards a CE (see Figure 11).

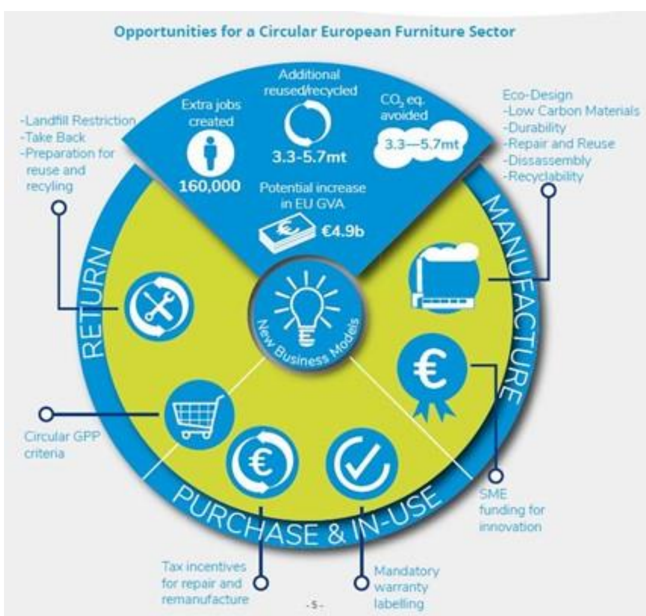

Figure 11. EEB diagram of CE in furniture

They outlined the many barriers and failed connections present in the attempts to transition the furniture industry towards circularity. These include product material choice and design, lacking consumer awareness, little to no infrastructure for furniture takeback, weak policy impacts, and so on. To address these barriers, the EEB developed a set of potential "packages" that can be implemented by countries within the EU that address both the demand and supply sides. These include supply-side actions such as Extended Producer Responsibility (EPR) with take-back efforts, EU-wide incentives for CE innovations in small-to-medium enterprises (SME), and a standardized information system from manufacturers to drive CE actions. Demand-side strategies include mandatory Green Public Procurement (GPP), tax incentives for refurbished and remanufactured items, and mandatory labeling of the warranty period.

IKEA, one of the largest global furniture manufacturers, is leading the charge by producing furniture that is more conscious of its environmental impacts. To transition their business into one more circular, IKEA is taking note of end-of-life stages, offering take-back services and incentives for having furniture as a service instead of an owned product (Sabri, 2020; Taylor, 2020). According to their 2020 Sustainability Report (IKEA, 2020), their implementation of "furniture as a service" allows users to lease the product for an established period and then return it. During this leasing period, repair and maintenance services are offered, and when the period is up, the product is refurbished and cleaned to be utilized by another customer. This type of business model and service offerings embody the CE by looping products to the point of origin and allows them to be restored to a renewed state and continued use. It also ensures that the materials used have their value fully realized through this extended life. By offering these services, IKEA can also redirect their products from landfills back to their facilities, where they have all the necessary resources to handle them responsibly.

Circular Economy Practices in Furniture

The concept of Circular Economy has had more time to develop in the EU and other places around the world and, as a result, has expanded beyond the industrial sector. A report developed by FURN360 (Furn360, 2018) details opportunities and barriers for CE concepts to be implemented into the furniture industry in Europe. Ten companies throughout Europe are shown as case studies and interviewed to outline their implementation of CE concepts. A few companies throughout the U.S. have also incorporated CE principles. Selected positive examples are detailed in Table 1.

Table 1. Examples of CE Concepts in Furniture in the U.S. and Europe

U.S.	Europe
(1) Room and Board - Company includes furniture that is made from recycled materials to reduce waste going to landfills. They also offer products made from reclaimed wood. 	**(5) Wehlers** - Makes furniture pieces composed of ocean plastic and recycled metal. The infamous R.U.M chair is assembled so that it can be easily disassembled and reused or refurbished. 
(2) Steelcase - Along with products made from minimum parts for recyclability and responsibly sourced material, they offer services for consumers that minimize furniture waste. 	**(6) Vepa** - Company in Holland that creates the majority of their products from renewable materials that are responsibly sources and use a lot of post-consumer plastic materials. 
(3) Circle Furniture – Member of the Sustainable Furnishings Council, commits to sourcing sustainable materials and making products easily recyclable. 	**(7) Rype Office** - UK based company that incorporates circular design concepts like remanufacturing and creating furniture from waste. 
(4) Cisco Furniture - Utilizes natural materials and sustainably sourced wood. Better and easily recycled material add to an increased product life and its sustainability. 	**(8) Arcadia Design** - Italian furniture company that creates modular children's furniture from responsibly sourced solid wood and uses non-toxic finishes. 

The CE rationale for Wooden Furniture

Because wooden furniture is made from a renewable, recyclable, and biodegradable biomaterial, its representation in the biological cycles of current CE frameworks is plausible. The theoretical fate of these materials is to return to the land as compost or energy fuel (Trifonova, 2017). However, wood furniture may be better represented on the technical cycle because as a product, wood furniture is intended to be used (vs. consumed). Thus it can also move through VRP cycles as part of a CE. Because of the complex structure and composition of furniture, often using multiple materials, it isn't easy to fully recover all of these materials back into a feedstock position after they have been manufactured into the final products. This limits the potential of realizing and utilizing the total value of these materials and products throughout their lifespan. This is because most of these materials still have the chance to exist in the whole product (i.e., wooden core structures) or, if considering recycling efforts, can be removed and utilized in other products (i.e., fabric shredded for carpets). Having multiple materials allows for concentrated efforts on that singular material while allowing the majority of the product to stay in service and eliminating unnecessary wastes of the whole product. Some furniture companies have recognized the amount of waste their products produce and the value that still resides in many materials after users want to discard them. This realization attempts to include CE concepts into their products, operations, and service offerings have been made.

Value Retention Processes

As established in Chapter 1, the inclusion of VRPs within the wood furniture sector are viable avenues for CE efforts. When studying the effects of including VRPs in industrial sectors, the IRP report states that environmental impacts could be reduced by 60-99% (IRP 2018).

Although this study was conducted on industrial materials, it still showcases the effectiveness of CE practices in high-impact industries. Since wood products originate from forests that are renewable, if managed properly, they have considerable potential for inclusion in the CE. With wood products that already have environmental benefits, such as sequestering carbon and being sourced from renewable material (i.e., able to regenerate within the average human lifetime) (Patterson and Coelho, 2009), optimizing these processes will better equip the industry for adaption in a CE. With this added potential of renewability, similar positive results are expected when VRPs are introduced. As these VRPs, shown in Figure 12, are applied to furniture products, their original function and structure are meant to be maintained. These processes avoid the linear economy by looping the products and materials back into another use cycle. While avoiding waste, these products can go through processes that maintain or add value and contribute to another economic sector (the VRP) (Russell, 2018).

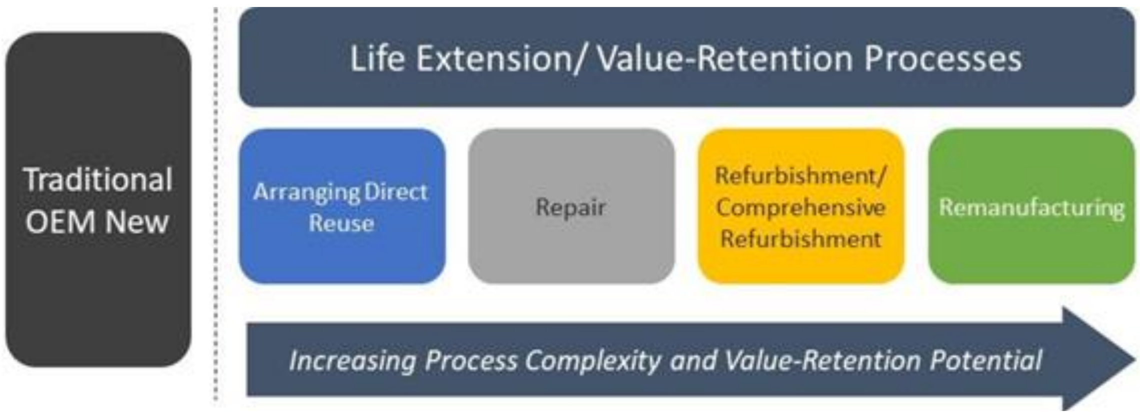

Figure 12. Value retention processes

The current inclusion of VRPs in the furniture market is undertaken by a variety of businesses, as established in Chapter 1. Depending on the retention process, these can be attributed to small businesses, non-profit organizations, or large corporations. The user access to these organizations also differs depending on their type. The idea of upcycling can be a critical process to include when considering wooden furniture. Although this is not an official VRP, it is a prominent action within this industry, which constitutes creating furniture from larger entities such as barns and boats. The VRPs, as defined by the International Resource Panel, that are relevant to the wooden furniture industry can be referenced in Chapter 1. Because these definitions were utilized when studying industrial sectors, the definitions specific to wooden furniture outlined in Chapter 1 were also utilized for this study.

Design for Environment and Eco-Design

Many studies and publications have focused on various concepts and actions related to making the furniture industry more environmentally conscious. Strategies and methods, including design for the environment (DfE), eco-design, and green public procurement, provide manufacturers with strategies that have a relatively lesser impact on the environment and utilize resources more efficiently (Hamza Çinzr, 2005; Michelsen et al., 2010; Bovea et al., 2004; Parikka-Ahola, 2008; González-García et al., 2012). Life cycle assessment (LCA) is a widely used and accepted methodology for measuring the environmental impacts of a product over its life cycle (Werner, 2001; McDonough et al., 2003; Mirabella et al., 2020; Wenker et al., 2017). Although able to offer sound results for better decision-making, LCAs only model the impacts of a traditional linear process (take-make-waste) and do not model the differing impacts of reuse and other circular processes (Bosch et al., 2017). Design for the Environment (DfE) and eco-design concepts have become more common in the wood furniture sector (Figure 13).

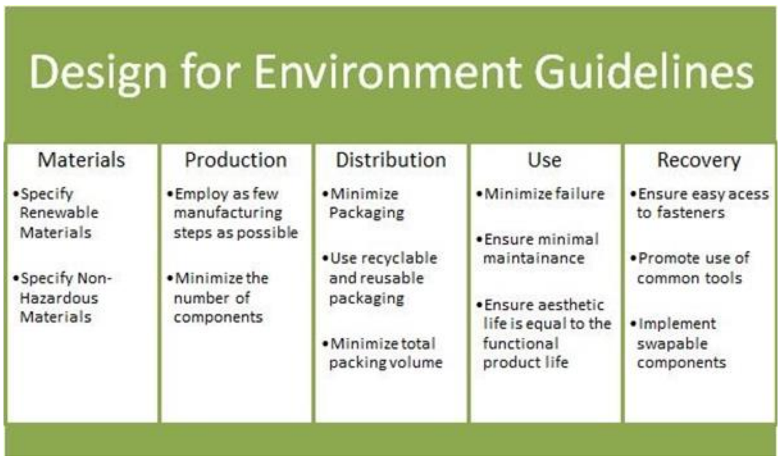

Figure 13. DfE guidelines

These concepts are commonly applied across procurement, design, and manufacturing stages of the wood furniture item in a manner that seeks to diminish environmental impacts (McDonough et al. 2003). DfE concepts can also be implemented via innovative approaches to the product's shape, form, whether it is designed for disassembly, via durability, or life span extension strategies. DfE and eco-design typically also facilitate manufacturer consideration of the manufacturing and assembly process, including any associated emissions, resource use, or eliminating harmful chemicals in the product finish. Although furniture, being more widely used and complex, utilizes the concepts more frequently, some studies outline how these concepts relate to other wood products. For example, wine boxes, where implementations related to the production process systematically, included using primary materials from closer sources, using transport vehicles with lower environmental impacts, and defining maintenance protocols for the products (Gonzales-Garcia, Silva. 2010). These considerations can be mirrored in other products when considering where their most harmful environmental impacts lie. Eco-design practices can be defined by notably different approaches like "design for recycling, design for modularity, design for disassembly, design for eco-of-life, etc." (Erasmus+, 2017). Eco-design studies have also described how product life cycles can be extended through design considerations, a clear alignment with the circular economy (Besch, 2005).

Cascading

Another measure that is undertaken by the wood products industry to improve resource efficiency is cascading. Cascading is the act of utilizing outputs of materials during their processing stages to feed into lesser production processes (Armstrong and Hamrin, 2020). For example, they are shredding the wood scraps from a furniture cutting operation and using the scrap wood to make a composite wood panel. In a study that explored the impacts of cascading-use via LCA, the processes of a forestry operation in western Germany showed beneficial environmental impacts, such as reduced global warming impact (by 7%) from including cascading practices and reducing waste by preserving 14% of the primary wood supply in the studied area (Höglmeier et al., 2015). Cascading is a beneficial concept when considering the multiple uses that wood may have within its early life cycle. Still, these processes may be limited if they are only contained within the origin facility and not practiced throughout the entire value chain. When considering wood products, the limits to cascading are that it stays within this one life cycle process. To fulfill the concepts of a CE, resource efficiency measures need to be undertaken at all levels of the life cycle to eventually arrive at an origin and be cycled back into valuable use. By optimizing the efficiency of using these products, there is a reduction in environmental impacts and an environmentally preferable source for secondary products or energy production (Jarre et al., 2020).

Statement of Research Problem and Questions

Current models of the CE are extensively focused on the industrial sector. Where biomaterials are included, they are limited to simple cycling processes that ultimately end as feedstock for energy production. Wood products, specifically wooden furniture, are biomaterials, and thus their participation in the CE is limited to those of renewable materials. Because furniture is a product that is used and not consumed, it has the ability to go through the cycles outlined for industrial products (i.e., repair, reuse, and refurbishment). To what extent are wooden furniture products able to participate in Value Retention Processes? Are there quantifiable environmental impact reductions that can be identified when wooden furniture products go through VRPs? This study seeks to answer these questions.

Project Goals

The strategies mentioned above and actions concerning the impacts of furniture on the environment are notable efforts, but there is still room for further advancement. This study seeks to provide further evidence of the benefits of including Value Retention Processes as Circular Economy tools in the wooden furniture sector. This is being accomplished by addressing three objectives:

1. Identifying proper test products
2. Gathering data on products for the VRP model
3. Running VRP model

The following sections of this paper will detail the methodology used to conduct this research and associated materials. The results of the study findings will be stated and showcase the values obtained from the CE model.

Methodology and Materials

To understand the relative implications and opportunities of CE approaches, as well as VRPs for wood furniture, the environmental impacts of relative repair, refurbishment, and reuse activities were calculated and compared across select environmental impacts (International Resource Panel, 2018). Three case studies on chairs were conducted to demonstrate the varied results of the material, design, and assembly strategies for wood furniture.. These products were carefully selected to demonstrate both the relative environmental impacts of VRP processes and the opportunity for CE for wood furniture across three diverse chair designs. The model, data collection, and descriptions of these case studies on chairs are presented below.

Case Study Chairs

Three products (wooden chairs) were selected to represent three common styles and markets: a) solid wood; b) wood core with fabric upholstery; c) solid wood and plywood mix. See Table 2 for further details on the material composition and product life span.

Table 2. Descriptions of case study chairs.

Product	Material Composition	Life Span (years)	Use	Description
Chair A 	Solid Maple Wood and Metal Fasteners	10	Commercial setting, domestic housing	Solid-wood chair known for its simple, classic, long-lasting design and strong build, but not built for disassembly
Chair B 	Plywood Core, Polyurethane Foam Padding, Metal Fasteners and Fabric Upholstery	10	Commercial setting	Plywood framed upholstered chair that is composed of various material components. Long lasting core structure, but not meant for disassembly
Chair C 	Solid Birch Wood, Birch Plywood, and Metal Fasteners	5	Commercial setting, domestic housing	Commonly related to "fast furniture" that is easy to assemble and disassemble, but shorter lifespan

Chair A: Solid Wood, Boston-style Chair – Commercial Use

Chair A is constructed of solid wood, it is a bulky, durable, lasting traditional design intended for commercial settings. Chair A has a wholesale price of $978 USD. Estimated service life, following BIFMA Product Category Rules, is assumed to be ten years; however, Chair A is expected to last well past its projected life span. This chair is not being designed for disassembly. Chair A was selected from a US-based manufacturer (Company A) product portfolio and was manufactured entirely on-site in IN, USA. Company A collaborated and provided preliminary information regarding the production process and bill of materials.

A video call was placed with a representative from Company A to get a detailed account of Chair A's manufacturing process. The company representative works at the production site and has witnessed the process first-hand. The production process for Chair A begins at the manufacturing plant with green lumber that is kiln dried in place (powered partially by wood waste generated in the plant). After drying, the lumber then goes through further processing into furniture parts. The manufacturing processes includes cutting, plaining, and sanding to clean stock of planks of required dimensions. This dimensional lumber is then sent to its respective component processes (legs, arms, seat, stretchers, corner blocks, backrest, and back rungs). A few curved components are also processed by steam bending. Individual boards are glued up, conditioned, and then shaped by a CNC (computer numerical control) machine into the final shape for the seats. After being shaped, the parts are sent to a conditioning chamber for at least a week to stabilize. After moisture content stabilization, the parts are sent for the chair assembly. The chair is assembled by hand, fastened with various joinery techniques, like wooden dowels and screws, along with adhesives. Glued joints are clamped for twenty-four hours to allow the adhesives to cure. Once fully assembled, the chair is leveled, inspected for any defects, and repaired if needed. It then goes through multiple steps of sanding and finishing. The finishing process consists of a coat of water-based stain and two applications of topcoat. The chair is then sent to a drying oven to cure the finish. Each step includes an inspection by a quality control manager before continuing. Afterward, the chair is packed and ready for shipment.

Chair B: Upholstered Armchair – Commercial Use

Chair B is mainly constructed of furniture grade hardwood plywood (¾ inch thickness), polyester textiles, polyurethane foam and is intended for commercial settings (see Table 3 for material-level details). Chair B has a wholesale price of $1,998 USD. Estimated service life, following BIFMA Product Category Rules, and is assumed to have a life span of ten years. The core structure, the - hardwood plywood frame, of Chair B has the potential to last longer than its projected service life. Still, reuse and repair of the upholstery and padding (polyurethane foam) may be limited to tearing and sanitary concerns. Chair B was selected from a US-based manufacturer (Company A) product portfolio and manufactured entirely on-site in IN, USA. Company A collaborated to provide preliminary information regarding the production process and bill of materials.

Similar to the previous chair, a video call was placed with the same company representative from Company A to get a detailed account of the manufacturing process of Chair B. The production process for Chair B begins with plywood panels that arrive at the plant pre-cut to shape by a local CNC producer. These plywood panels are then assembled with adhesive, metal screws, and nails into a very sturdy base chair frame. The frame is wrapped up with polyurethane foam that comes pre-cut to shape and is fastened with adhesives to the seat, back, and sides. The upholstery fabric is cut to shape with a laser, and then it is sawn and attached to the chair and armrests with staples.

Chair C: Mixed Solid and Plywood Chair- Residential or Commercial Use

Chair C is constructed from a solid wood frame (legs and rails) complimented with a plywood seat and backrest. With a light and straight forward light-frame construction, Chair C has a retail price of $89 USD and comes disassembled in a flat package with required fasteners and joinery. By design, Chair C must be assembled by the consumer/owner, and thus Chair C is also inherently designed for disassembly. As a result of these design priorities and the likelihood of residential use (vs. less rigorous commercial settings), it was estimated that the product's service life would be only 5 years due to the potentially compromised strength of joinery, as well as the uncertainty in consumer (vs. expert) assembly.

Chair C was selected from the product portfolio of a Europe-based manufacturer (Company B). Chair C was manufactured in Romania. The sample chair was purchased independently by the research team. Additional data regarding energy consumption and production processes required the use of publicly available online information, as well as secondary empirical production and assembly data conducted at the Purdue's Wood Research Laboratory for a comparable product (Owen, 2013).

The research team was unable to collaborate with Company B, so the expert knowledge of a research team member, who has conducted research on a similar product (Haviarova et al., 2012)**,** was interviewed, and details of the production process were obtained. The production process for

Chair C begins with green lumber being dried and processed similarly to Chair A. Frame components in this chair are turned into cylindrical shapes. Side frames were joined by the traditional mortise and tenon joinery, then sanded and finished with paint along with other components needed for the full chair assembly. Side frames will be assembled to the full chair with steel fasteners by the user. The seat and backrest are made of shaped plywood, outsourced from a plywood manufacturer, then CNC'd into the final shape and finished with paint. The product is flat packed and ship to the store. Final product assembly is left to the consumer. It is easy to assemble and disassemble

Data Collection

Performance Testing (Product Lifespan Assessment)

A performance test machine is a device for measuring force and displacement for various products (materials) as they are subjected to horizontal or vertical loadings. The test machine has built-in load cells (strain gauge transducer) capable of measuring up to 600 lbs or cyclic load. The test machine consists of a computer, control unit, load head, and machine bed. The load cell's force and displacement data can be recorded, displayed, and analyzed. Universal Laboratory (UL) Furniture Performance Testing Equipment was used with the outputs in ultimate cyclic load failure and the number of cycles at the failure.

To certify the case study products' bill of materials, assess and compare product life span, and determine specific points of failure of product's components, selected furniture products (three chairs) were brought to Purdue University's Wood Research Laboratory for performance testing. A front-to-back cyclic load test was selected as the most informative strength test was conducted on all three chairs. Chair frames were subjected to stepwise cyclic loading as shown (Figure 14).

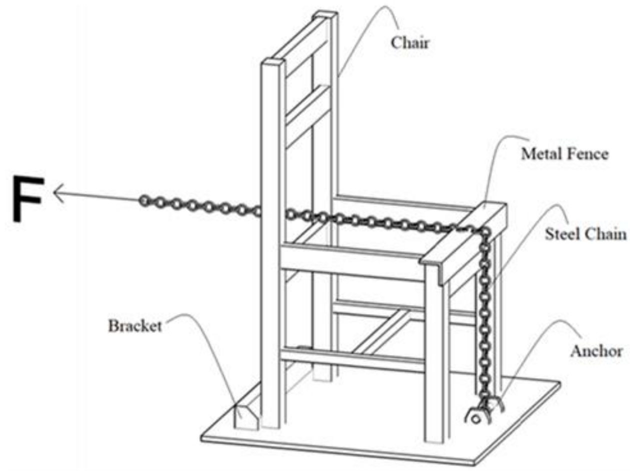

Figure 14. Front-to-back cyclic load test set up

The tests were conducted according to the American Library Association (ALA) specifications. The applied speed of loading on chairs was 20 cycles per minute. The test started at the load level of 50 Lb. and stayed at that level until 24,000 front-to-back loading cycles were completed. After the completion, the following load was increased by another 50 Lb. These load increments and cyclic testing of 24,000 front-to-back loadings continued until non-recoverable failures occurred on any joint or horizontal deflection exceeds 50.8 mm. Chairs A and C were tested as received, according to ALA standard. Chair B had to be partially disassembled before testing because the thickness of foam and upholstery impeded the performance test.

After completing the performance test, furniture was disassembled by hand to their essential components and materials; then, they were measured, weighed, and recorded (Figure 15).

Chair A and B were obtained from a well-established local furniture producer (Company A). Chair C was purchased from a large global retailer. Because Chair A and B came assembled and the performance testing was conducted first. The larger components were weighed using a beam-balance floor scale, able to weigh up to 1000 pounds. All other smaller components were weighed on a laboratory scale with higher precision.

Figure 15. Disassembled case study chairs- Chair A; Chair B; Chair C

Product-level Data

Data collection for each case study chair involved the 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 could be cycled via different VRPs).

Life-span characteristics were assessed for each component according to the methodology established by the IRP (2018). The following 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.

Process-level Data

For Chairs A and B, the primary data needed for the model was retrieved from collaborating Company A, based in the USA. Through emails and video calls with the company's Sustainability Manager, data regarding energy consumption associated with product manufacturing and waste production was gathered. Because of the ongoing COVID-19 pandemic, we were unable to visit the production site directly. Empirical evidence from interviews conducted with companies offering VRP services (addressed in Chapter 1) of the repair and refurbishment processes was used to estimate the energy consumption of the repair and refurbishment activities. With information on the process and tools needed to conduct repair and refurbishment, online research was conducted to find the most comparable tooling and associated energy requirements. Once the tools' energy requirements were identified, furniture product experts were consulted to estimate the amount of time the tools would be in use. The energy requirements and tooling time were multiplied to calculate the overall energy consumption of each repair and refurbishment process for Chair A, B, and C. A detailed write-up with the chosen tools and energy calculations can be found in Appendix C.

Chair C was produced by Company B (non-collaborating), and data was gathered from the website for the BOM (RÖNNINGE chair, birch, 2021). Because of the lack of publicly available data on the production process, a comparative study on a similar chair was used to calculate energy consumption (Haviarova et al., 2012). This empirical data was chosen because of the complementary design, material composition, and knowledge that the study was conducted legitimately (in the laboratory conditions). The process for determining energy consumption can be referenced above.

Data Entry Validation

After receiving the primary information from the products' producers, this data was then utilized to populate the impact and resource consumption data points. After the base information was inputted, values had to be assigned for various categories related to each value retention process. These included: Max Number of Effective Additional Service Lives, Probability of Salvage, Failure Mechanism, and End of Service. For the "Repair" category. The results of the previously conducted performance tests were used to determine which components would fail and to what degree they could be salvaged. Expert opinion and anecdotal evidence from interviewed VRP companies (reference Chapter 1) were used to populate the remaining data values. A detailed description of the explanations behind the value assignments can be found in Appendix D (*Notes on VRPs*).

The Process-Level 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 was used to model the new material requirements (*M*)(Equation 1), and associated embodied emissions (*Γ*)(Equation 2) and embodied energy (*ρ*)(Equation 3):

$$M_{j,m}^{i} = \sum_{s}\sum_{c}\frac{\alpha_{j,m,c}\gamma_{j,m,c,s}\delta_{j,m,c,s,h}}{\eta_{c,s}} \quad \forall_{i,j} \qquad \text{Equation 1}$$

This formula is repeated for each process i (OEM New, reuse, repair, and refurbishment), for each material type: α is the material weight, Y 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).

$$\Gamma_j^i = \sum_m \left(M_{j,m}^i \; x \; \tau_m^i\right) \forall_{i,j} \qquad \text{Equation 2}$$

$$\rho_j^i = \sum_m \left(M_{j,m}^i \; x \; \omega_m^i\right) \forall_{i,j} \qquad \text{Equation 3}$$

The model approach and outcomes are described in the IRP Report (2018) accordingly (please refer to Figure 16):

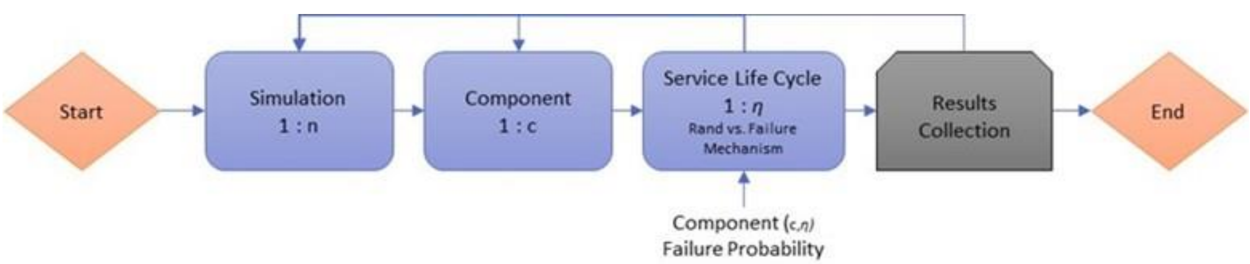

Figure 16. MATLAB program flow chart of modeling process

"As the nature of the model is stochastic, a MATLAB program to perform Monte Carlo simulation to obtain and estimated new material requirement for the average component, by material type, during a single VRP service life cycle. In order to determine whether the component will be reused for additional service lives, the program imports the component-level reusability and material information to simulate that component over multiple service lives against randomly generated probabilities. Utilizing the reusability mechanisms, assigned based on the characteristics of each component, the probability of reuse for each additional service life is assessed and compared to the randomly generated probability to determine whether the component will fail and require

replacement. Once the product BOM is imported into the model, the user then defines the number of simulations or representative products (n=10,000) that the model will run. Each component (c) is run through multiple service life cycles (η) until it fails. Component failure is determined for each component within the BOM through the comparison of a random distribution variable to the reusability mechanism distribution for each specific component and service life. The model then returns to the next component and repeats the process. After each of the components have been assessed, the program stores the results for the product and moves on to the next simulation." (IRP, 2018, p. 223).

Results

Performance Testing Results

The performance testing for each chair took approximately one week and was conducted until the product failed or until non-recoverable failures occurred. The performance testing results are summarized in Table 3 and concluded that Chair A and Chair B are structurally very strong. Chair A reached 350 pounds and completed 173,327 cycles. Chair B was stronger when considering its robust interior frame made of tight-fitting furniture grade plywood components connected by very precise CNC joinery. The performance test was conducted until the testing load was closer to the testing machine's load limits. The test was discontinued without product failure at 500 pounds and completion of 252,923 cycles. Such high load levels would not be achieved in the product's regular service life. Chair C was tested until the product failed at 250 pounds and completed 135,824 cycles. This chair would be in the lightweight category.

Table 3. Performance testing results

Chair Type	Ultimate Load (Lbs)	Cycles at Load Level	Total Cycles
Chair A	350	5,327	173,327
Chair B	500	12,923	252,923
Chair C	250	15,824	135,824

When considering the expected service life, Chair A (Boston) would last longer than the upholstered Chair B (Encore), which would reach the end of first life sooner because of failures like rips and tears in fabric upholstery. According to ALA standard, both chairs would be in the category of heavy-duty products.

Damage on individual components on each chair was assessed and recorded:

Chair A

The chair is very well built and did not suffer any significant failure. The visible fracture was recorded at the back rail and joints connecting the front chair legs and side stretchers. A new back rail would have to replace the failed component and joinery repaired with fasteners (inserted dowels or screws) to repair this specific chair. Images of major chair failure are included in Figure 17.

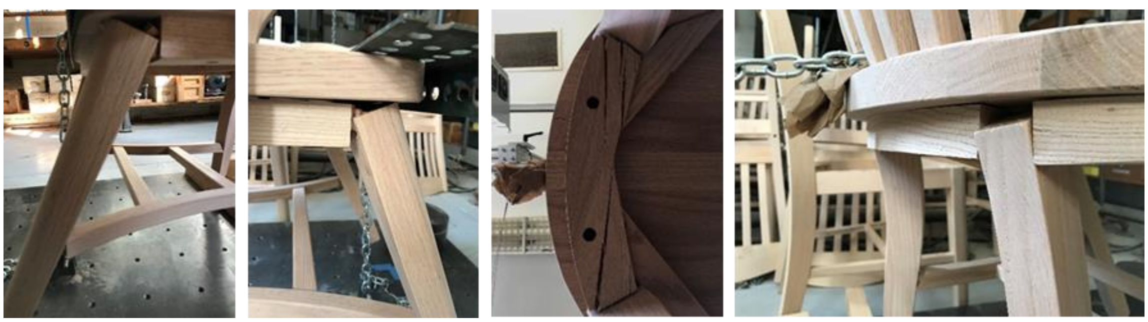

Figure 17. Chair A performance test failures

Chair B

The chair frame was tested and did not suggest any damage. No sign of failure or loos joints were apparent (Figure 18). However, it is expected that after the first life of the product, there will be a need for upholstery repair or reupholstering. Reasons for reupholstery could also be related to hygiene or aesthetics.

FIgure 18. Chair B performance test failures

Chair C

The chair frame suffered a significant failure, mainly in joints, which became loose and withdrawn from its initial stage (Figure 19). For the chair repair, most of the joints would have to be reglued and reset into their original place. Joints connecting front legs and side stretchers were broken and would have to be repaired with fasteners (dowels or screws). If the chair is painted, it would have to be retouched.

Figure 19. Chair C performace test failures

The testing method's limits were that only one performance testing method was utilized, simulating the motion of front-to-back cyclic movement (sitting and standing), which are the most common user motions. Chair B was not able to reach its ultimate cyclic load limit because of its strong frame produced with precise CNC equipment and very low tolerances. The chair was tested without upholstery, which is not a direct reflection of its use in real life. However, upholstery removal was necessary to proceed with the test and to obtain tangible results.

Model Results

The impact factors that were assessed in the model included New Materials (kg), which is defined as the input of primary materials listed in the BOM, Production Waste (kg), which is defined by excess materials that aren't able to be utilized in that process, Embodied Emissions (kg CO2 -eq.), which is defined by all of the emissions associated with that materials total production process, and Process Energy (kWh), which is defined as the energy consumed during the processes needed to produce the component at the manufacturing site, and Process Emissions (kg CO2 -eq.), which is defined as the emissions associated with the processes needed to produce the product at the manufacturing site.

Along with evaluating each VRP, the impacts of Original Equipment Manufacturer (OEM) New were also included. OEM New represents the original manufacturing process of the product with all new inputs of components within the manufacturing facility.

Across all products, the results showcase that participating in VRPs reduces the impacts of the measured factors as compared to OEM New. The results should be evaluated on a case-by-case basis when determining which VRP to undertake depending on the impact factor the user wants to address. To present the scale of impact that each VRPs has, four graphs and accompanying tables were chosen. The results for each chair and description of graph information is detailed below:

Chair A

Table 4. Table 1A-Chair A New Material Inputs by VRP and Material (kg)

Chair A New Material Inputs by Process and Material (kg)							
	Solid Oak	Solid Birch	Steel	Plastic (General)	Finish (Water-Based)	Adhesive (Polyurethane)	TOTAL
OEM New	12.107	0.077	0.096	0.237	0.887	0.002	13.41
Refurbished	1.054	0.000	0.002	0.237	0.887	0.000	2.18
Repair	1.988	0.002	0.003	0.180	0.634	0.000	2.81
Reuse	0.000	0.000	0.000	0.000	0.000	0.000	0.00

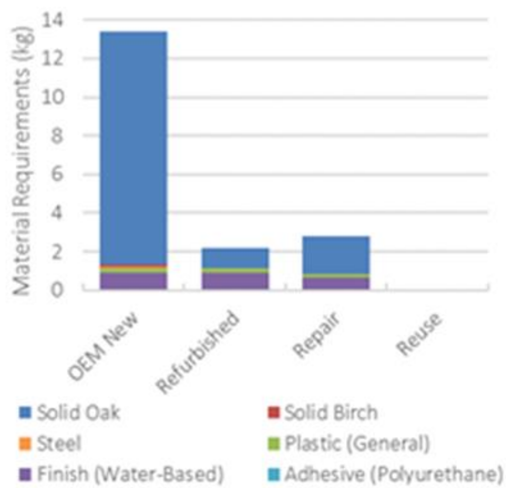

Figure 20. Graph 1A- Chair A new material inputs by VRP and material (kg)

The total material requirements needed for repair and refurbishment have only a difference of .63, with refurbishment needing less. For this product, the repair and refurbishment processes can be quite similar, seeing that maintenance from ware and failures are likely to occur in the same areas (i.e., locations that take much of the structural stress).

Table 5. Table 2A- Chair A New Material Inputs by VRP and Material (% of Product Weight)

Product Weight (kg):	13.41						
New Material Inputs by Process and Material (% of Product Wt.)							
	Solid Oak	Solid Birch	Steel	Plastic (General)	Finish (Water-Based)	Adhesive (Polyurethane)	TOTAL
OEM New	90.3%	0.6%	0.7%	1.8%	6.6%	0.0%	100.00%
Refurbished	7.9%	0.0%	0.0%	1.8%	6.6%	0.0%	16.26%
Repair	14.8%	0.0%	0.0%	1.3%	4.7%	0.0%	20.94%
Reuse	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.00%

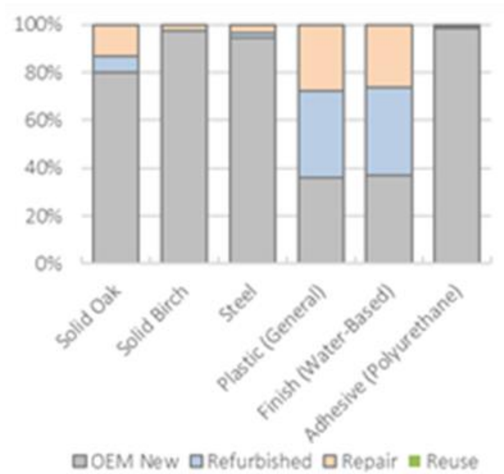

Figure 21. Graph 2A- Chair A new material inputs by VRP material (% of product weight)

The material needs, as a percentage of the total product weight, for a new manufacturer (OEM New) and each VRP as a percentage of the product's total weight can be seen in Graph 2A. The least number of materials, as a percentage of the total product weight, is needed for the refurbishment. This is because refurbishment only requires the replacement of key structural components (made from solid oak) that may wear from use over time. The remaining materials, plastic, and finish would also need replacing, but since they are such a small portion of the product weight, they don't appear significant.

Table 6. Table 3A- Chair A impact factor level by VRP

Chair A					
	New Materials (kg)	Production Waste (kg)	Embodied Emissions (kg CO2-eq.)	Process Energy (kWh)	Process Emissions (kg CO2-eq.)
OEM New	13.41	15.42	9.41	8.40	3.43
Refurbished	2.18	2.18	5.86	3.80	1.55
Repair	2.81	2.81	4.60	0.70	0.29
Reuse	0.00	0.00	0.00	0.00	0.00

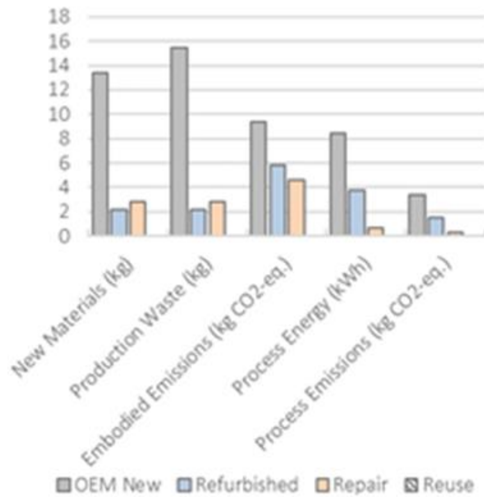

Figure 22. Graph 3A- Chair A impact factor level by VRP

In absolute values, Graph 3A showcases the totals of each impact factor as they relate to OEM New and each VRP. The highest value recorded is the Production Waste (kg) during OEM New. Since all of the operations to produce each part occur on-site, this number is plausible. Discussions with the Company A representative revealed that about 90% of this waste is wood, which is then recycled back into the company operations as heating fuel. The most reductive impact that can be had when implementing VRPs is through Process Emissions.

Chair B

Table 7. Table 1B- Chair B New Material Inputs by VRP and Material (kg)

Chair B New Material Inputs by Process and Material (kg)								
	Hardwood Plywood	Cardboard	Steel	Plastic (General)	Polyurethane Foam	Polyester Fabric	Adhesive (Polyurethane)	TOTAL
OEM New	23.369	0.518	3.559	0.072	3.749	2.041	0.473	33.782
Refurbished	6.095	0.069	0.216	0.009	1.566	0.170	0.237	8.361
Repair	7.714	0.130	0.276	0.009	0.009	0.170	0.237	8.544
Reuse	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

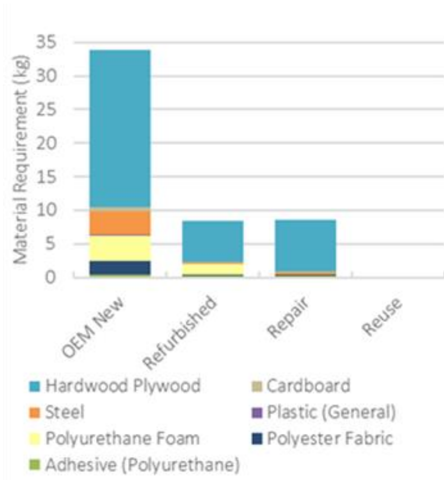

Figure 23. Graph 1B- Chair B new material inputs by VRP abd material (kg)

For this product, the repair and refurbishment processes can be quite similar, seeing that maintenance from ware and failures are likely to occur in the same areas (i.e., rip and tares in the upholstery). But these processes require about four times as fewer material inputs.

When participating in VRPs, 75% of materials can be saved from refurbishment and 74% from repair. Over 70% of materials can be saved when implementing VRPs.

Table 8. Table 2B- Chair B New Material Inputs by VRP and Material (% of Product Weight)

Chair B	Product Weight (kg): 33.782							
New Material Inputs by Process and Material (% of Product Wt.)								
	Hardwood Plywood	Cardboard	Steel	Plastic (General)	Polyurethane Foam	Polyester Fabric	Adhesive (Polyurethane)	TOTAL
OEM New	69.18%	1.53%	10.54%	0.21%	11.10%	6.04%	1.40%	100.00%
Refurbished	18.04%	0.21%	0.64%	0.03%	4.63%	0.50%	0.70%	24.75%
Repair	22.84%	0.38%	0.82%	0.03%	0.03%	0.50%	0.70%	25.29%
Reuse	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

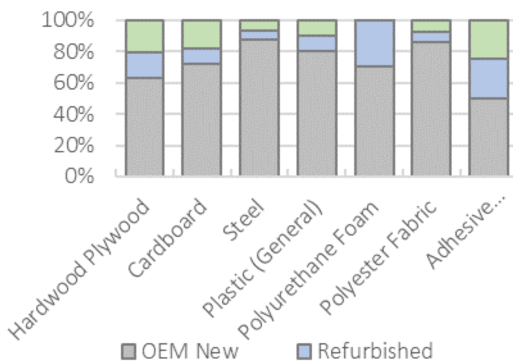

Figure 24. Graph 2B- Chair B new material inputs by VRP and material (% of product weight)

Table 9. Table 3B- Chair B impact factor levels by VRP

Chair B					
	New Materials (kg)	Production Waste (kg)	Embodied Emissions (kg CO2-eq.)	Process Energy (kWh)	Process Emissions (kg CO2-eq.)
OEM New	33.78	10.70	62.38	8.40	3.43
Refurbished	8.36	8.36	17.13	5.42	2.21
Repair	8.54	8.54	10.85	8.06	3.29
Reuse	0.00	0.00	0.00	0.00	0.00

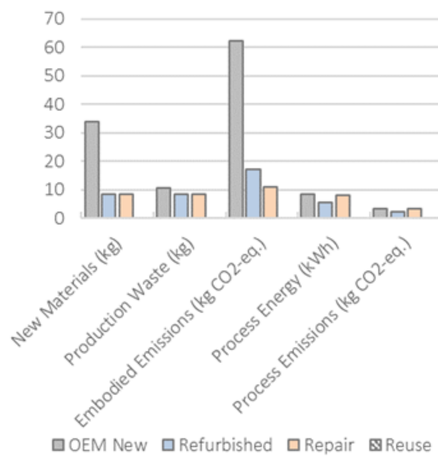

Figure 25. Graph 3B- Chair B impact factor levels by VRP

For Chair B, the highest impacts during original manufacturing are embodied emissions which can be attributed to the plywood and upholstery fabric, which have high impact upstream activities such as forest harvesting operations and textile production. Even though this product has the most varied material composition, the process emissions are the lowest category because most of the components come to the manufacturing site pre-cut and ready for assembly processes. This also accounts for the closeness of values between the VRPs and OEM New for Process Energy and Process Emissions. This is close to how the user would experience managing this product; they wouldn't replace the plywood core. The most impact that can be had when implementing VRPs is with new materials and production waste.

Chair C

Table 10. Table 1C- Chair C New Material Inputs by VRP and Material (kg)

Chair C New Material Inputs by Process and Material (kg)						
	Solid Birch	Hardwood Plywood	Steel	Finish (Water-Based)	Adhesive (Polyurethane)	TOTAL
OEM New	3.256	2.722	0.218	0.418	0.112	6.725
Refurbished	0.282	0.387	0.005	0.418	0.112	1.204
Repair	0.663	0.385	0.020	0.205	0.020	1.292
Reuse	0.000	0.000	0.000	0.000	0.000	0.000

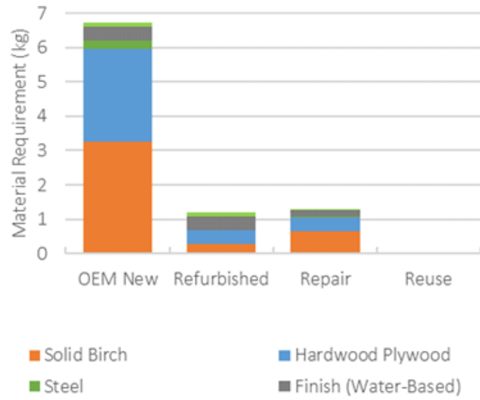

Figure 26. Graph 1C- Chair C new material inputs by VRP and material (kg)

For this product, the repair and refurbishment processes can be quite similar, seeing that maintenance from ware and failures are likely to occur in the same areas (i.e., locations that take much of the structural stress).

Table 11. Table 2C- Chair C New Material Inputs by VRP and Material (% of Product Weight)

Chair C	Product Weight (kg):	6.725				
New Material Inputs by Process and Material (% of Product Wt.)						
	Solid Birch	Hardwood Plywood	Steel	Finish (Water-Based)	Adhesive (Polyurethane)	TOTAL
OEM New	48.4%	40.5%	3.2%	6.2%	1.7%	100.00%
Refurbished	4.2%	5.8%	0.1%	6.2%	1.7%	17.91%
Repair	9.9%	5.7%	0.3%	3.0%	0.3%	19.22%
Reuse	0.0%	0.0%	0.0%	0.0%	0.0%	0.00%

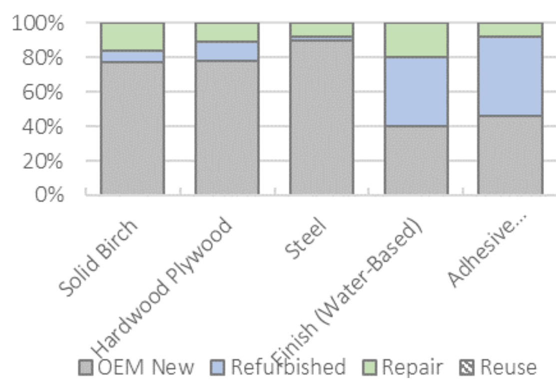

Figure 27. Graph 2C- Chair C new material inputs by VRP and material (% of product weight)

The material needs, as a percentage of the total product weight, for a new manufacturer (OEM New) and each VRP as a percentage of the product's total weight can be seen in Graph 2C. The least number of materials, as a percentage of the total product weight, is needed for refurbishment. This is because refurbishment only requires replacing crucial structural components (made from solid birch and plywood) that may wear from use over time. The remaining materials, adhesive, and finish, would also need replacing, but since they are such a small portion of the product weight, they do not appear as significant

Table 12. Table 3C- Chair C impact factor values by VRP

Chair C					
	New Materials (kg)	Production Waste (kg)	Embodied Emissions (kg CO2-eq.)	Process Energy (kWh)	Process Emissions (kg CO2-eq.)
OEM New	6.73	2.02	7.12	4.43	1.78
Refurbished	1.20	0.36	4.36	1.87	0.75
Repair	1.29	0.39	1.89	0.29	0.12
Reuse	0.00	0.00	0.00	0.00	0.00

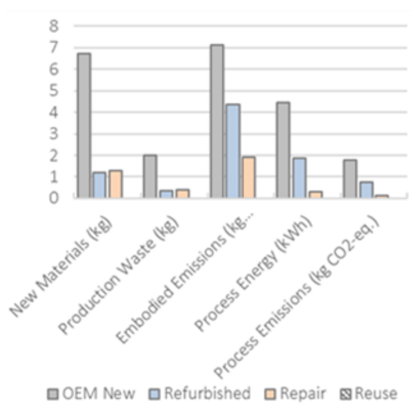

Figure 28. Graph 3C- Chair C impact factor levels by VRP

Repair ranks lowest in most impact factors, excluding New Materials (kg) and Production Waste (kg) because of the replacing of parts and the waste associated with that. The most impact seen by implementing VRPs is in Production Waste (kg) because of the avoidance of processes from virgin materials and Process Emissions when Repairing because of the low energy inputs for repair processes which mainly include hand tools.

Discussion

The results not only show that the inclusion of VRPs has less impact than new manufacture but also that designing simpler products (those with fewer differing material components) results in lower environmental impacts. For example, Chair B has the most varied material composition, resulting in higher values in all impact factors, except for waste, because most of its pieces come pre-cut to the manufacturing facility. Since furniture trends turn into more simplistic designs, this could be another attributing factor for designers to reconsider material choices.

When making decisions for best practices, designers, manufacturers, and users must consider the impact factor that they are most concerned with. No single VRP solves all the issues or presents impact-free results. For example, when considering the Boston chair, repair has less of an impact than refurbishing in process energy but a more significant impact on production waste. This variability within product types may allow for more specified circularity standards within the furniture industry following general umbrella actions.

The results do not account for subsequent processes that might occur outside of the system. Although waste might be a high valuing impact factor, it might not include instances where the waste is recycled back into the manufacturing processes as fuel or fabric being recycled into the carpeting.

The best practice for each chair type is first reuse because it has no inputs, resulting in no energy use or associated emissions. The reuse market can also be the easiest for users to access. Not only is there the option to donate or gift the item to someone, but there is also a well-developed for-profit reuse market. Here, if their product has minimal aesthetic flaws, they have the chance to make back some of the product’s costs. In the wooden furniture sector, VRPs are undertaken by third-party companies, including non-profits, so there needs to be a vehicle to promote these services, which could come from producers making collaborative efforts.

Depending on the product's material composition, the level of impact of repair and refurbishment can differ. For upholstery products, refurbishment processes (applying new fabric) require very low energy, with processes being mostly done by hand with stapling being one of the only energy requirements. The refurbishment of the fully wooden piece (refinishing) is more energy-intensive. This process can also be done by hand, but in most professional settings, the finishes are applied using a spray gun requiring compressed air. Also, the processes of repair and refurbishment can be blurred in most cases, where minor repairs might be involved in the refurbishment process, and reapplication of finishes would be required after repairs.

The IKEA chair shows less impact as compared to the others because it has a lower weight and fewer materials. But, because it is ready-to-assemble and more commonly considered fast furniture, this perception will potentially lead users to limit its lifespan or dismiss the opportunity to apply VRPs. The more simple material composition and construction would also make it a better product for recycling, as opposed to other fast furniture pieces that include particleboard or medium-density fiberboard, fairs less during VRPs, and has a limited lifespan. This product uses solid wood, which is more durable and includes less mixture of materials.

Even though there is evidence for these benefits, users must also have this perception if CE practices are meant to be implemented. For more simply designed products like chairs A and C, the repair and refurbishment processes have similar impacts, but for chair B, the refurbishment process can be similar to OEM, so the drive to do VRPs is nott as high.

Conclusion

The overall results align with the initial hypothesis that the inclusion of VRPs results in less of an environmental impact than manufacturing a new product. It was also discovered that with more complicated products (Chair B), VRPs closely mirror the original manufacturing processes, so the drive to do so is not as high, but this opens up the conversation for design considerations that could change this.

The CE principles' implementation is not one size fits all — even within the wooden furniture sector. Each product type must be looked at individually to determine which VRP would be the most effective, considering the impact factor users and manufacturers want to address. These focuses may change depending on future regulations of materials or increased environmental compliances. In addition to regulatory bodies, consumers' demands or needs may alter what producers want to highlight regarding their products' sustainability efforts. Having a general overview of best practices is beneficial. It will give producers and users a starting point for how these improving actions can be altered to fit their situations best.

When considering real-world impacts, the results showcased a significant savings of materials across all products, which could forecast a redistribution of economic activity from upstream to downstream with more focus on labor and less environmentally intensive processes. With the furniture industry already being labor-intensive, this could have interesting impacts on the distribution of labor within the industry or provide more opportunities for those already involved. Although there is a cause for concern if current labor numbers are not increased, the potential for scaling up VRPs could be diminished.

This research intended to provide additional insight into a growing conversation around the circular economy and the integration of the furniture industry. Even though there were valuable and insightful results, the study was not without limitations. The research only focused on one chair from each of the established product types. The furniture industry has a wide range of chair products with many designs and material compositions when looked at holistically. Future research can include a broader range of products that is a better reflection of the industry. Although the failures occurred during the performance testing, there are more variabilities in the failure types and degree in actual use. These variances could also impact the VRPs that can be undertaken and to what extent materials are salvageable. Another limiting factor was the exclusion of transportation in the model results. In any manufacturing process, transportation is a prominent component that impacts the product's overall environmental impact. In the case of furniture, the weight and composition of materials and packaging can significantly affect emissions.

As with many research projects, the lack of available data is an unavoidable limitation. Chair C, which was purchased independently, lacked the detailed data gathered for Chairs A and B and most information relied on what was publically available. Because of this, assumptions had to be made using comparable empirical data. If future studies could gather direct data from the manufacturers, these results could be even more informative for decision-making. This was also the case with chairs A and B, where the original plan was to gather precise data from the production facility directly, butbecause of COVID-19 limitations, onsite visits to the production facility were not allowed. However, the essential part of the study was the establishment and proof of methodology.

A common VRP for industrial materials is recycling, but as stated in Chapter 1, this process is virtually nonexistent for furniture products. If this were a process that could have been witnessed and recorded, it would have offered a more holistic view of the extent of CE concepts and information on the scenario that constitutes the end-of-life for the product. But this also opens up the conversation about waste management and updates to infrastructure that need to occur to better reflect the major waste materials. This is especially true, seeing that these are biomaterials, and they can ultimately be returned to the environment if processed correctly.

Implementing these processes and the chance to make more informed decisions has many benefits for the environment. Still, to be a truly sustainable system, the considerations of all those involved in the value chain are essential. Since manufacturers are early in the supply chain, their choices have the opportunity to impact all of the steps to follow. This system-wide thinking could alleviate stresses on ill-equipped municipal facilities or uninformed users. Suppose the processes are increasingly implemented, and users are keeping their furniture longer, then manufacturers have an opportunity to develop new markets or services so they can continue to have economic gains. These developments could occur internally or externally. If implemented externally, there is a chance for localizing the services or reaching customers through a different medium.

With the implementation of VRPs, users/consumers have significant chances to participate in these processes themselves and use their demand power to incentivize producers. It is becoming more common for consumers to expect more transparency on the material origin and production processes. Continuing these efforts for wood furniture and becoming more knowledgeable about the composition can provide them more insight into what processes are available to them or what resources within their communities can handle them. During the research process, Chair B was disassembled by hand, which took multiple hours. It can be assumed that most users will not go through this process to make repairs or refurbishments. This would also be very time-consuming and expensive for recyclers, which affirms why recycling is virtually non-existent for furniture.

This laborious process would be better handled by the manufacturer, who fully understands the construction and would have more compatible resources for its reverse engineering. Services such as these could be further advocated by users and lead to the development of new offerings by the manufacturer. Table 13 showcases an example of an infographic that could be distributed to users to offer examples of how VRPs can be implemented.

Table 13. VRP Processes Applied to Case Study Chairs

VRP	Reuse	Repair	Refurb	Recycle/Upcycle
Description	Maintaining original form with no inputs. Can be formal (i.e., organizations and companies) or informal (i.e., passing down).	Fixing or replacing failed components to achieve full functionality. Visually looks the same, but repairs made to high stress areas.	Altering aesthetic components (i.e., finishing and upholstery).	Breaking down components by material type and forming into new product.
Chair A 				
Chair B 				
Chair C 				

With any form of production, there is waste involved. The introduction of VRPs does not eliminate wastes but seeks to reduce them where possible and eventually reach the original source of extraction. There are still associated wastes from replaced product components and tools used to conduct them during repair and refurbishment processes. But in limiting or removing the need for new manufacture, other related impacts are reduced, which collectively will put less strain on the environment. It is also essential to consider the material choice and the importance this has on subsequent impacts. This research showcased the delicate balance between choosing materials that are perceived as environmentally friendly because of their sturdiness or simplicity but may also incur trade-offs such as weight and associated carbon accumulation.

In addition to the environmental benefits, there are also social and economic impacts. A well-established drive for CE is that it couples environmental considerations with continued economic growth. The increased use of VRPs within this industry will provide associated growths within these markets. Companies offering the services, small businesses working on specialty products can all be beneficiaries of an advancing VRP market. There would also be a push for another sector of labor within an already labor-intensive industry, with refurbishment and repair activities that can be revitalized. Since many of these businesses are aggregated, large manufacturers have the opportunity to form a partnership with these local VRP industry participants, such as SMEs.

This study reveals many opportunities for further research. The furniture industry is vast, so adding additional products or material mixes can offer a more cohesive view of how VRPs would impact the industry. The range of environmental indicators can also be expanded to include landfill impacts, transportation emissions, and the substitution of materials. Besides environmental indicators, research can investigate social indicators such as consumer habits, marketing strategies, municipalities, and likely VRP participants' demographics. To gauge the sustainability of VRP inclusions, a long-term study on how these processes impact the primary forest products industry and harvesting patterns could also provide important insight.

CONCLUSION

As the implementation of CE has become widely prominent and most successful in an array of industrial and biological sectors, this research further showcases its relevance in the wood products sector of furniture. Although wooden furniture is sourced from a renewable, recyclable, and biodegradable biomaterial, once made into a product being used and not consumed, these processes are slightly diminished. Although still technically possible, to reach this state, considerable effort is needed to strip away all of the added materials and chemicals. This does not dismiss that these primary materials still carry less impact than other non-renewables. Still, a new perspective is needed when considering how to manage these products as they are. = This research set out to answer the question: “ How can biomaterials, specifically wooden furniture, be better represented, quantified, and included in current circular economy frameworks?” This research proposed that inclusion of wood furniture exists within the middle ground between the biological and technical cycles (Figure 29).

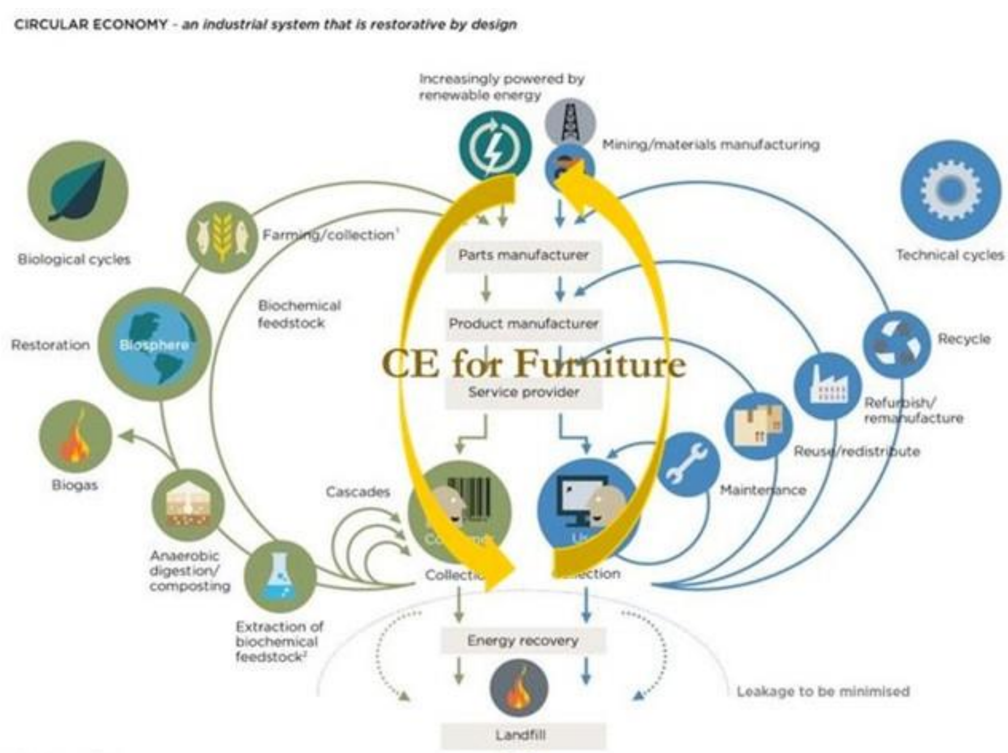

Figure 29. Proposed inclusion of furniture in CE

In terms of representation, Chapter 1 showcased that VRPs are a viable avenue for wooden furniture to be involved in CE concepts. The "technical" side of current frameworks is available and prominent within the industry. Although still in need of increased visibility and added skilled labor (for repair and refurbishment services), the foundation is present. Chapter 2 displayed quantitative evidence of the impacts that VRP implementation had on the studied wooden chair products. Significant reductions in material usage and subsequent environmental impacts were seen throughout the product types.

Through this research, it became apparent that to successfully integrate the furniture market into a circular economy;multiple value chain levels will have to be addressed. The inclusion of VRPs not only rests in the hands of the users or service companies. An interconnected system must be fully realized in order to be effective. These elements include Designers, Manufacturers, Consumers, and the Systems they exist in (Figure 30).

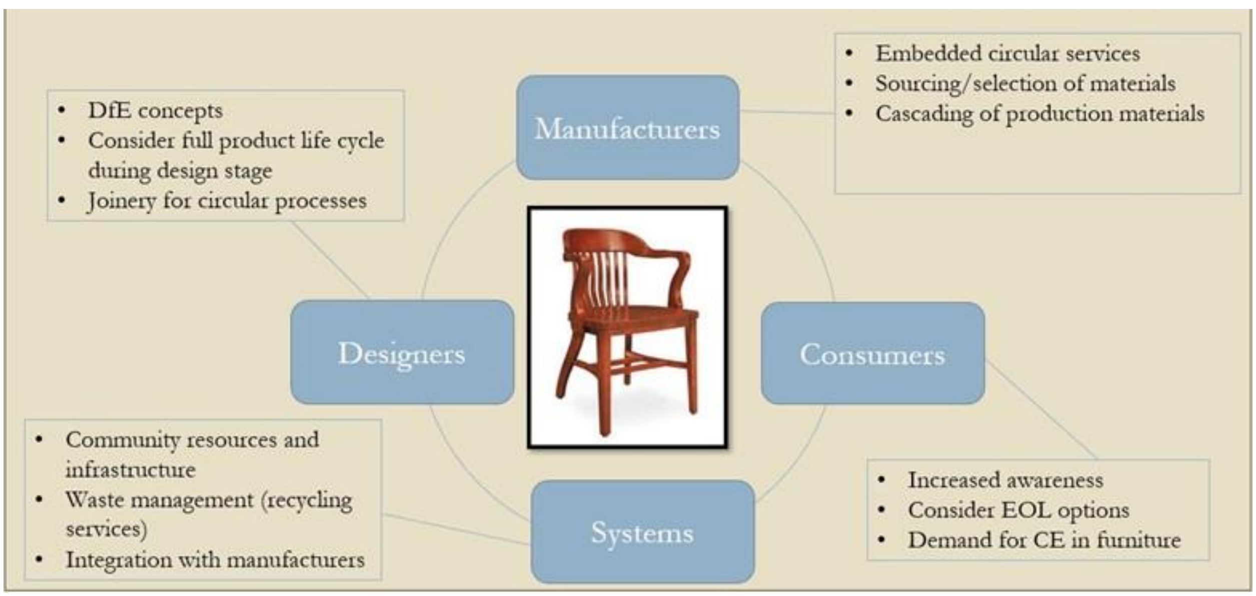

Figure 30. CE model for wood furniture

Design is the first step in the product development process, and it impacts all decisions made down the line. The materials choice, use function, labor needs, life expectancy, and end-of-life options will all be determined based on design decisions and subsequently affect the degree of environmental impacts. Design actions, such as modularity, will benefit repair and refurbishment processes by allowing components to be easily replaced or interchanged for a change in aesthetics. This would also allow for ease of disassembly and potential recycling efforts. Also, as the user evolves, these attributes allow the product to adapt and stay relevant, so the frequency of replacement would be diminished. Designers can also consider the merit of customization and how having unique products will increase users' value and sentiment. Designers also play a pinnacle role in the demand of a specific product type; if they were to promote the efficacy of including these options, users might be more inclined to demand them. Joinery is an impotent aspect of furniture design, so opportunities for further research are available for looking into joinery techniques for furniture to be better integrated into CE concepts. Along with material choice, which has significant impacts on end-of-life options, the mechanisms that make up the construction of the products can be addressed. This can provide further insight and analysis into how our results would change across the multiple product types when implementing a series of joints focusing on circularity. Well-built products are conducive to CE principles seeing that they stay in service longer and eliminate the need for new manufacturing and waste. But, in terms of furniture construction, this can create issues for following through with certain VRPs.

Products like Chair A have been built to last almost 40 years, but there may be resistance when they eventually reach their end of life and completing VRPs. They are difficult to disassemble for making repairs or separating for recycling. This showcases the importance of design and a middle ground that needs to be reached. Products like Chair C have shown that their environmental impacts are much lower than the other two chairs but are a product type that perpetuates a take-make-waste mentality among consumers. What design decisions can Chair C’s manufacturer make to alter this perception of their products? This product type addresses a gap in the market for those who can not afford expensive furniture pieces or are not ready to invest in pieces that they plan to keep for forty years. However, innovations need to address how this important group can still be served without the associated negative impacts. The material types are the main attribute to its low cost — using composites that come from wastes (which is also a benefit and circular attribute of these types) allows manufacturers to provide a premium price point. But what are the actual costs of these products if they eventually end in landfills?

The manufacturers, or the business, have many opportunities to develop offerings and services that can shift how consumers utilize their products. It is becoming more common for producers to have continued responsibility for the products they put into the world, but this doesn't always have to be viewed as regulatory measures. Having a continued relationship with users allows producers to better understand how their products are being used and how functional needs might change over time. Through leasing, take-back, and scheduled maintenance services, manufacturers can stay connected with the user and maintain business throughout the product's life.

The users, who handle the product for the majority of its life, are of prime importance. Their demands will be reflected in the designer's and manufacturers' decisions and what they feel are worth pursuing. Not only do users have impacts on upstream activities over time, but they have the ultimate power over how that product will finish its final days. Because of this, users need to be better informed on the impacts of these routes. If they can see the real and attainable actions, they can make better decisions, which could have immense impacts. Also, suppose users are incentivized to follow through with these processes through store credits, boosting local economies, or receiving discounts on other products, it will further motivate them to make conscious choices. This research has also peered into the effects of consumer perception of value and their decisions. Things that are valued are kept, maintained, and able to endure over time. When perceptions of value are diminished, products are easily discarded and mismanaged. These ideas of value also differ when considering demographics, socio-economic status, and culture.

Lastly, CE requires an interconnected network of stakeholders to function correctly. Currently, the economy of VRPs exists within the furniture market, but it is independent of the production sector. If more of these businesses had the opportunity to work with manufacturers, it could make the processes more efficient and direct. Many of the VRPs are small businesses scattered throughout the U.S., taking advantage of this situation, manufacturers could extend their reach and have an opportunity to better connect with users. This extension should also reach other sytems that could ultimately handle furniture waste. Currently, municipal waste management facilities are not equipped to dispose of furniture in a sustainable manner. This could be altered if they had better resources or information on how to manage these products. Policy actions also plays a vital role in regulating waste streams and product development. If landfills were no longer accepting furniture waste, this would put pressure on users and producers to find alternatives that would ultimately have better impacts.

The furniture industry has been making strides towards environmentally conscious efforts regarding their products, and these have been dominant in the supply and production side. Manufacturers use recycled content, raw materials from sustainable forests and put more effort into eco-design and design-for-environment concepts. These upstream efforts have significant benefits for responsible consumption and increased users' interest in supporting products. These actions are on the right oath, but downstream issues are still prominent. Consumers could view these actions as all that needs to be done without considering how the loop is incomplete when these products cannot return to their origins or participate in life-extending services.

The furniture industry is already highly labor-intensive, and similarly, CE is promoting the creation of a more developed labor market working with products already in service. This appears to be a natural coupling. As opposed to taking virgin materials and straining the environment, skillful jobs can be created for those within the furniture industry through reuse, repair, and refurbishment services. Also, seeing that the recycling sector lacks the infrastructure to handle furniture, this is an opportunity to create new job opportunities.

Reuse is the most common VRP being undertaken in the wooden furniture sector. Networks of socially conscious organizations offering furniture to those in need are very well developed throughout the county. It is interesting to think that these products have cycles within these larger cycles. Not only can a piece of furniture cycle from repair to refurbish, but it can also have many cycles within one process. It is especially prominent in reuse, where a product may begin at a company's headquarters, then offered to a small business, and then ending in someone's home office. This visual further expands the opportunities with a circular economy and its similarities with a shared economy. There is no ownership within a shared economy; products are held by the central distributor and used by customers when needed and returned at the end of use. Routine maintenance is carried out, and the full use is realized from the product. This concept happens within a CE to offer specific products to avoid overproduction for materials that consumers do not need.

As the country continues to expand and develop further innovations, it is essential to remember the simple cycles that exist and the value of returning to them. But even when products were built to last or repair and refurbishment processes were more prominent, waste was still a significant issue. This leads to the belief that the solution rests with implementing these value-retention processes and further evaluate the systems that these products exist in.

While looking into this research, the most significant overall problems are how people view consumerism and the mismanagement of waste. At this moment, we are creating a positive feedback loop of overconsumption, collection of waste, and not replenishing the resources we take. The breaks in the cycle are compounding to multiple problems attempting to be solved at once.

But as with any solution, there are also trade-offs. If we seek to create less waste, we must consume and discard less. In a heavily capitalistic society, the notion of making and selling less is counterproductive to growth. The Circular Economy challenges this concept by asserting that economic growth is still possible while using Earth's resources responsibly. Using a systems-wide mindset to consider all of the inputs and outputs related to creating a product or service is paramount in genuinely creating a sustainable future. All of these need to be considered when evaluating the fundamental aspects that develop into the problems seen today. There is still hope when acknowledging the direct impacts that the general public can have within a circular economy and how this collective power can be mobilized into effective solutions and lasting change.

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APPENDIX A: VRP COMPANY QUESTIONNAIRE

Questionnaire A:

1. What is the annual amount of furniture your company recycling/ repair/ refurbishing/ reuse (tons/lbs)?
2. What is the general makeup of products (in terms of materials) that you receive (e.g., 40% metals, 50% wood)? -- what % is wood-based?
3. Describe the general process of furniture recycling/ repair/ refurbishing/ reuse conducted by your company
4. How are recycling/ repair/ refurbishing/ reused products redistributed back into the market?
5. What are the labor requirements needed to complete recycling/ repair/ refurbishing/ reuse processes?
6. Can you quantify the average energy requirements needed to complete recycling/ repair/ refurbishing/ reuse?
7. Do you rely on partnerships, and are they in place?
8. Do you face any employment issues (shortage of qualified employees)?
9. What is the geographical scope of product collection and distribution?
10. Where do you mainly source furniture from (Individuals, companies, etc.)?

Questions for individual industries:

Questionnaire B:

Recycling: *Breaking down products into different/new primary products*

<u>Questions:</u>

1. What is the minimum weight or number of products needed to proceed with the recycling process?
2. What does "recycling" actually mean within your business/operations?
3. Next life steps — where do the broken-down materials go? Are there partnerships in place to receive these items?

Questionnaire C:

Repairing: *Replacing failed parts/ introducing new components*

<u>Questions</u>:

1. What are the most common repairs made to chairs?
2. Have you ever repaired Boston or Encore chairs?

Questionnaire D:

Refurbishing: *Replacing old/worn-out finishes and upgrading aesthetic based components*

<u>Questions</u>:

1. What are the most common material inputs needed for refurbishments?
2. Are there any waste products during the refurbishment process, and if so, how are they treated?
3. In what capacity are products sent to you? Users, brokers? (supply chain)

Questionnaire E:

Reuse: *Redistributing furniture as is to new market/consumer*

<u>Questions:</u>

1. What is the breakdown, by percent, of end-of-life/use channels that your products flow into? (e.g., 10% recycled, 55% direct-reuse, 40% repaired)
2. What percentage of your annual collection is diverted from landfills?
3. What is the average number of miles driven annually for furniture transportation?

APPENDIX B: VRP QUESTIONNAIRE RESPONSES

Refurbish	Recycle	Repair			Reuse (non-profit and for profit)				
G	H	G	D	F	E	D	C	B	A
	3-4k pieces/y	18-20k pieces/yr		15-17kk servicec calls/month	15-25 households/wk	60,571 furniture items in 2019	30k	300-350 cu ft of materials (50% furniture)	70k tons as of 2020
	wood from boats, mostly tropical	90% wood, 10% upholstery		50% issues are electrical 25% upholstery, 13% wood the rest leather	80% wood	Break down by type- sofas, tables. Tables c average weight and carbon impact, bulky major furniture items, dabbling in new goods	~11,887 wood products	50% furniture (mostly wood)	varied mix, majority office furniture
	dismantle collected boats, sort and build	receive service calls and do onsite repairs and get pieces sent to shop		get service call from customer or manufacturer and repairs at customer house	picked up, clean, stored, delivered to family	go through agencies, families look through showroom, pick then pay for delivery	don't accept items too large	people send pictures or bring to site, get assessed then resold	
	sold in shop	returning to original customer		Don't have to deal with redistributing- 15% of daily consumers regular people	donations	donations	donated	sold onsite or online	donations and B2B
	varies on time of year, usually 10-12 workers	subcontract with external workers, only about 3 actual staff, issues finding skilled workers		over 200 techs nationwide, each woth about 300 mile radius	volunteers and "care specialists"	46 employees	22 employees and volunteers	30 employees	transportation and minor repairs
	handbuilding joints, and connections	air compressors and hand tools		hand tools at the clients' site	Disshwasher, W+D, trucking	building operations	Chicago, surrounding counties (Evanston, oak park, burren,	building operations and trucking	facility maintanance
	work with local fisherman who sell them their boats	no stable partnerships		partner with orgs, suppliers, stores, manuf	partnerships with non-profits, vets, domestic violence, homeless.	150 agency partnerships	several partnerships	yes, with recyclers	thousands of non-profit and businesses
	issues with time mnagement, but able to find workers	yes, not many skilled workers available		having issues finding skilled workforce, can make up to 3-5/wk	no	no	no	no	no
	all south pacific region	25 mile service radius for onsite but people deliver pieces from all over		technicians thoughout the country	marion country and 7 surrounding counties, will go further if requested	greater toronto area, an hour in any direction	Chicagoland area	san diego area	throughout North America
	individual fisherman	half and half commercial and residential, but work is cyclical		warranties with retailers, residential	mostly individuals, but some companies	85% residential and 15% buz	60% residential, 40% corporate mix (furniture biz)	residential and commercial	mostly businesses but some residential
sand paper and finisshes	98% usage	glue lines and joints	reworking seats and joints (80% wood)	many different repairs and cleaning upholstery	only pieces that need minor fixes (95% direct reuse)		95% direct reuse	90% direct resue	95% direct reuse
sand paper and finishing cans	large scale don't have capacity to do detailed work	most repairs from wood shrinking, wood glue lasts 30-40 years and 2nd gen has failure	removals cant be easily recycled, textile industry doesn't consider upholstery	yes, have parts in their warehouse	N/A		5% thrown away	N/A	N/A
50/50 between residential and commercial	N/A	can work on composites if wood veneer	atleast 3 times if designed well	have seen composites	1 box truck delivering to 2-3 homes/day		45-75 mi/day on avg	N/A	N/A
50/50 for repairs and refurbs	N/A	will add additional items	chair seats need replacing, tables need new joints	N/A	N/A		N/A	N/A	N/A

APPENDIX C: CASE STUDY CHAIRS VRP ENERGY CALCULATIONS

Chair Analysis: Process Energy

Boston Chair

- *Refurb* (sanding and re-staining/ energy would be needed for electric sander for the seat and backrest, and legs— other components are too small and would only need hand sanding, and the re-staining process could use air compressed powered sprayer)
    - Electricity (handheld power tools/air compressor for finishes)
        - Finding watts from volts- https://toolsowner.com/drill-wattage
            - **Drill:** (https://toolsowner.com/drill-wattage)
                - **.**026 kW x 1 hour = 0.26 kWh
            - **Orbital sander**: https://www.lowes.com/pd/CRAFTSMAN-120-Volt-3-Amps-Random-Orbital-Sander/1000596265
                - **.**36 kW x 2 hours = .72 kWh
            - **Compressor (spray painting):** https://www.grainger.com/product/53JT58?ef_id=CjwKCAiAmrOBBhA0EiwArn3mfInhKNW1q2RbyTKCTfdTB04TejNW48Dq7oAyunQFyln-9-buxxudJRoC_oUQAvD_BwE:G:s&s_kwcid=AL!2966!3!281698275759!!!g!472569961188!&gucid=N:N:PS:Paid:GGL:CSM-2295:4P7A1P:20501231&gclid=CjwKCAiAmrOBBhA0EiwArn3mfInhKNW1q2RbyTKCTfdTB04TejNW48Dq7oAyunQFyln-9-buxxudJRoC_oUQAvD_BwE
                - **1.**32 kW x 2 hour = 2.64 kWh
        - **Total "process energy" for refurb = 3.62 kWh**
- *Repair* (When considering the break that occurred during the performance test, I would say you would only need hand sanding, to clean up the repair surfaces because they aren't that large, a drill to create new openings, and a hand saw to remove dowels)
    - Electricity
        - **Drill:** (https://toolsowner.com/drill-wattage)
            - **.**026 kW x 1 hour = 0.26 kWh
        - **Hand saw:** https://www.walmart.com/ip/BLACK-DECKER-3-4-Amp-Powered-Hand-Saw-Corded-PHS550B/19239453
            - **.**408 kW x 1 hour = .408 kWh
    - **Total "process energy" for repair = .668 kWh**

Encore Chair

- Refurb (staple gun would be the only tool needing energy (**but also a sewing machine for shaping fabric?)**, everything else is done by hand, cutting, and sewing)
    - Electricity

- **Staple Gun:** https://www.homedepot.com/p/Freeman-Pneumatic-22-Gauge-5-8-in-Upholstery-Stapler-P2238US/206891564?MERCH=REC-_-pip_alternatives-_-100609337-_-206891564-_-N&#product-overview
  - Powered by an **air compressor**: https://www.harborfreight.com/21-gallon-175-psi-oil-free-vertical-air-compressor-64858.html?cid=paid_google|||64858&utm_source=google&utm_medium=cpc&utm_campaign=&utm_content=&gclid=CjwKCAiAyc2BBhAaEiwA44-wWx8tUPyZoPDkBGCh54rCL_sz-ZwPPQ2PsaaISdlkYKv1b5lwjETs9RoC2pgQAvD_BwE
    - 1.68 kW x 3 hour = 5.04 kWh
  - Info on air compressors: https://www.quincycompressor.com/industries/woodworking/
- **Sewing Machine:** https://www.singer.com/Tradition-2277-Sewing-Machine?gclid=CjwKCAiAyc2BBhAaEiwA44-wWyoFswXRtSjWFMy5M6dx3V8GW9Hy4sTNkDtGu15lUxMMh1BZqZ128BoCSw8QAvD_BwE
  - **.**06 kW x 2 hours = .12 kWh
- **Total refurb "process energy" = 5.16 kWh**

- Repair
  - Electricity
    - **Upholstery Cleaner:** https://www.janilink.com/shop/promotions/best-sellers/jl-premium-i-heated-500-psi-carpet-extractor-w-hose-wand/?gclid=Cj0KCQiAst2BBhDJARIsAGo2ldVpu4N8r1agVRnKHoRBeDt0EJtkMG2n8rVqmR07X76H99OV2_D6d-oaAg1uEALw_wcB
      - **7.**68 kW x 2 hours = 15.36 kWh
    - **Total "process energy" = 15.36 kWh**

Ikea Chair "This chair has been tested for public use and meets the requirements for safety, durability and stability set forth in the following standards: EN 16139-Level 1 and ANSI/BIFMA x5.1" (IKEA site)

- **Standards from EU (**cost money to download and read)
  - **EN 12520: 2015 – Furniture Strength, durability and safety requirements for domestic seating**
  - **ANSI BIFMA X5.1- Office chairs (**https://www.techstreet.com/bifma/standards/ansi-bifma-x5-1-2017?product_id=1944483**)**
- Repair
  - since the failures were mainly the joints detaching, I don't think any power tools would be necessary. You would probably only need some adhesive to reapply the joints.
- Refurb (Similar tools as Boston Refurb, but less time, maybe half?)
  - Electricity

        - **Drill:** (https://toolsowner.com/drill-wattage)
            - **.**026 kW x 0.5 hour = .013 kWh
        - **Orbital sander**: https://www.lowes.com/pd/CRAFTSMAN-120-Volt-3-Amps-Random-Orbital-Sander/1000596265
            - **.**36 kW x 1 hours = .36 kWh
        - **Compressor (spray painting):** https://www.grainger.com/product/53JT58?ef_id=CjwKCAiAmrOBBhA0EiwArn3mfInhKNW1q2RbyTKCTfdTB04TejNW48Dq7oAyunQFyln-9-buxxudJRoC_oUQAvD_BwE:G:s&s_kwcid=AL!2966!3!281698275759!!!g!472569961188!&gucid=N:N:PS:Paid:GGL:CSM-2295:4P7A1P:20501231&gclid=CjwKCAiAmrOBBhA0EiwArn3mfInhKNW1q2RbyTKCTfdTB04TejNW48Dq7oAyunQFyln-9-buxxudJRoC_oUQAvD_BwE
            - **1.**32 kW x 1 hour = 1.32 kWh
    - **Total "process energy" for refurb = 1.693 kW**
- Electricity Infrastructure Efficiency Factor: Would this be similar to the EU's "Primary energy factor"?
    - EU Energy Efficiency Directive
        - mentions "primary energy factor" (PEF): https://ec.europa.eu/energy/topics/energy-efficiency/targets-directive-and-rules/energy-efficiency-directive_en
        - paper on EU's PEF: https://www.irbnet.de/daten/iconda/CIB_DC26383.pdf

Paper on Sweden's energy efficiency- mentions Sweden's PEF is 1.92: http://www.diva-portal.org/smash/get/diva2:640808/fulltext01.pdf

APPENDIX D: NOTES ON VRPS VALUE ASSIGNMENT

Clarifying Statements and Exceptions:

1. All refurbs' "Failure Mechanisms" are from fatigue.
2. For refurb, it doesn't need the same scenario as repair. For refurb, both chairs would only need refinishing; everything else should be intact or only need minimal attention.
3. For "adhesives" and "finish" -- we are considering these as an aggregate, so since we put down the whole amount being used on the chairs, consider what small percentage would have to be replaced when doing repairs – for refurbs, it is always all for finishes but a percent for adhesives.
4. The category "Non-Replacement Material Added" does not relate to furniture items. Therefore all components are given a value of 0.

Boston Chair

Base: Initial data entry.

1. *Max Number of Effective Additional Service Lives: If kept in good condition, what is the maximum service life of the Boston chair? ~40 Years*

Reuse: The product has reached its EOU, and the user puts it on the market to be consumed by someone else. No aspects of the product are altered, and no new components are added. The product retains its original function and is given to new consumer as i

1. *Probability of Salvage:*
   a. **Back legs; front legs; front to back stretchers; apron side; apron front; and apron back** -- given a value of .90 because these are high-stress areas that might need little attentions over the course of the products use, but the majority of the structure will be intact. Essentially, there is a 10% chance that these components will not be salvageable for reuse. (or 10% of the component will not be salvageable?)(after seeing results, numbers were updated to 1 because in a reuse scenario, everything is salvaged, and no new components are added when considering the structural elements. If something was not in the full use state, then it would fall into the repair/refurb categories.)
   b. **Adhesives, finishes and fasteners(wooden dowels**) – given .80 because they would not have to be replaced all over, but some areas might need to be added to or touched up for optimal use.
   c. **Wood plugs** -- given a value of .75 because of their chance of being lost over the product's service life and needing to be replaced. (Updated to .90 because this is not a part that people would necessarily replace, it is an aesthetic choice, but there is a 10% chance that it would go missing over the course of its life)
2. *Max Number of Effective Additional Service Lives:*

a. **Adhesives, Finishes, wood plugs, and fasteners (wooden dowels)** — given a value of 0 because we believe they will have to be reapplied after every service life.
b. **Back legs; front legs; front to back stretchers; apron side; apron front; and apron back —** are given a value of 2 because these are high-stress areas that would probably see failures or need repairs after 2 additional service lives.
c. We assume that the chair will be able to sustain 3 additional service lives when in functioning condition, so all other components are given the value 3.

3. *Failure Mechanism:*
   a. In the context of "reuse," all components would fail under Fatigue.
4. *End of Service:*
   a. All components were assigned "Landfill" as EOL because that is the common practice with furniture products.

Repair: A component has failed and needs to be replaced or fixed with some added materials.

(#'s based on performance test results)

1. *Probability of Salvage:*
   a. **Back legs; front legs; front to back stretchers; apron side; and apron front** were given a value of .95 because their failures occurred at the joinery, which could be fairly easy to repair or replace while the majority of the main structure of the component is intact and could be kept.
   b. **Fasteners (small)** – given a value of .65 because a few of the screws were attached to fail components and could not be retrieved, or they also failed and would need to be replaced.
   c. **Adhesives** – given a value of .70 because of the glue that would have to be replaced at the areas of failure.
   d. **Finish** – given a value of .85 because of the areas of failure that would need to finish reapplied.
   e. **Apron back; wooden dowels --** given a value of 0 because they failed completely and would have to be replaced.
   f. All other components were intact after the performance test, so they were given a value of 1.
2. *Max Number of Effective Additional Lives:*
   a. **Adhesives, Finishes, wood plugs, and fasteners (wooden dowels)** — given a value of 0 because we believe they will have to be reapplied after every service life.
   b. **Back legs; front legs; front to back stretchers; apron side; apron front; and apron back —** are given a value of 2 because these are high-stress areas that would probably see failures or need repairs after 2 additional service lives.
   c. We assume that the chair will be able to sustain 3 additional service lives when in functioning condition, so all other components are given the value 3.
3. *Component Reusability:*
   a. All components that failed during the performance testing were marked "Hazard."

4. *End of Service:*
    a. All components were assigned "Landfill" as EOL because that is the common practice with furniture products.

Refurb: The product no longer fits the aesthetic that the customer desires, so they plan to apply a new finish or upholstery. The function of the product does not change.

1. *Probability of Salvage:*
    a. **Back legs; front legs; front to back stretchers; apron back; apron side; apron front**; were given a value of.95 because these are stress components that would have a chance of needing repairs or replacements.
    b. **Large fasteners:** given a value of .95 because they might need replacing because of rust or wearing away.
    c. **Wood plugs:** given a value of .95 because there a chance they would get lost and need replacing.
    d. **Wooden dowels**; given a value of .90 because of their chance of failing and needing to be replaced.
    e. **Small fasteners;** given a .90 because of their chance of needing to be replaced because of rust or wearing away.
    f. **Big and small corner blocks; floor pins;** were given a 1 because these are components that aren't seen, so wouldn't need a new finish, and aren't highly stressed so they wouldn't need to be replaced.
    g. **Back rest and arms; inner braces, back rungs; seat***;* were given a value of .99 because only a small percent of the component would be lost to sanding.
    h. **Adhesives***;* given a value of .75 because of the adhesive that would need to be replaced at major joint areas.
    i. **Finish**: given a value of 0 because all would be replaced.
2. *Max Number of Effective Additional Lives:*
    a. **Finish; adhesives; and wood plugs were** given a 0 because they would have to be addressed after each service life.
    b. **All other components:** given a *3* because they would be back to functional capacity.
3. *Component Reusability:*
    a. In the context of "refurbishment," all failures would be from Fatigue
4. *End of Service:*
    a. All components were assigned "Landfill" as EOL because that is the common practice with furniture products.

<u>Chair B</u>

Base: Initial data entry.

1. *Max Number of Effective Additional Service Lives: If kept in good condition, what is the maximum service life of the Encore chair? ~20 years*

Reuse:

1. *Probability of Salvage:*
    a. **Leg component (plastic cover);** given value of .90 because there is a likely chance they will need to be replaced or repaired.
    b. **Upholstery:** given value of .85 because there is a likely chance there will be minor fixes.
    c. **All other components:** given a value of 1 because they should be salvageable during a reuse process.
2. *Max Number of Effective Additional Service Lives:*
    a. **Poly-seat and lower front; poly-left arm; poly- left arm; poly- front back rest; and plastic leg components** were given a value of 1 because it is assumed that these components will need replacing after the second service life.
    b. **Plywood components, steel components;** were given a value of 2 because they should be able to function for the additional service lives.
    c. **Upholstery: and staples** were given a value of 0 because they would need to be replaced after the first service life.
3. *Component Reusability:*
    a. All components were given "Fatigue."
4. *End of Service:*
    a. All components were assigned "Landfill" as EOL because that is the common practice with furniture products.

Repair:

1. *Probability of Salvage:*
    a. **The cardboard; polyurethane; leg components (plastic); adhesive; leg components (floor pins); staple components**; were given a 0 because I assume that if these components were to break or wear out, they would be completely replaced.
    b. **Plywood; steel components;** given a value of .90 because I think they would only need minor repairs or refurbishments and that the majority of their structures would be intact.
    c. **Upholstery;** given a value of .50 because the upholstery needs repairing, you may not have to replace all of the fabric, so some could be salvaged.
2. *Max Number of Additional Lives:*
    a. **Plastic leg components; upholstery; staples**; given a value of 0 because they would have to be replaced after single service life.
    b. **All other components:** given a value of 2 because once brought to full functionality, they should be able to withstand 2 additional service lives.
3. *Component Reusability:*
    a. All components were given "Fatigue" because of wearing away over time.
4. *End of Service:*
    a. All components were assigned "Landfill" as EOL because that is the common practice with furniture products.

Refurbish:

1. *Probability of Salvage:*
    a. **Leg component (plastic), upholstery, staples;** were given a value of 0 because these components would be replaced during refurbishment.
    b. **Polyurethane seat and lower front, front backrest, left arm and right arm; and cardboard** was given a value of .95 because these are high contact areas that might need to be updated or fixed.
    c. **All other components:** given a value of 1 because they wouldn't be replaced during refurbishment.
2. *Max Number of Effective Additional Lives:*
    a. **Leg component (plastic); upholstery, staples;** were given a value of 0 because these components would be replaced for each service life.
    b. **Polyurethane seat and lower front, front backrest, left arm, and right arm;** was given a value of 1 because these are high contact areas that might need to be updated or fixed after additional service life.
    c. **All other components:** given a value of 2 because once brought back to functionality, they should maintain another 2 service lives.
3. *Component Reusability:*
    a. In the context of "refurbishment," all failures would be from Fatigue
4. *End of Service:*
    a. All components were assigned "Landfill" as EOL because that is the common practice with furniture products.

<u>Chair C</u>

Base: Initial data entry.

2. *Max Number of Effective Additional Service Lives: The expected lifespan of the previous chairs was based on information directly from the producer who stated that they adhere to BIFMA's PCR (product category rules" for establishing EPD (environmental product declarations). This standard stated that the chair must have a lifespan of at least ten years. Based on performance tests that conducted, which showed the chairs lasting up to 450 lbs of 24000 cycles, and the IKEA chair only lasting about half of that (failing at 250 lbs), we deduced that the expected lifespan could be reduced by half and considered to be **5 Years.***

Reuse:

5. *Probability of Salvage:*
    a. All components were given a value of 1 because there would not be any replacements or additions during reuse.
6. *Max Number of Effective Additional Service Lives:*
    a. All components were given a value of 1.5 because after the chair's initial expected lifespan; I believe it would only have 1.5 of different service lives.
7. *End of Service:*
    a. The landfill is the standard practice.

Repair:

5. *Probability of Salvage:*
    a. **The back legs: and front legs** were given a value of .98 because the whole of the structure was intact; the pieces were just dissociated from them. They might need some minor work done to the opening.
    b. **Side stretcher:** was given a value of .99 because they only detached from the joint; they didn't break, so they would only need more adhesive.
    c. **Side curtain:** was given a value of .95 because, along with their detachment, there is a possibility that the dowels cracked and would need to be replaced or repaired.
6. *Max Number of Additional Lives:*
7. *Component Reusability:*
8. *End of Service:*