Quantifying materials in household furniture

A case study of dynamic furniture stock in American homes

MSc Industrial Ecology

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Abstract

Current cravings for *more* are taking a great toll on the Earth and its most vulnerable communities. The rise in 'fast furniture' has contributed to this issue, popularizing the idea that furniture can be cheap, to the point of being disposable. To understand the size of this issue and how much more damage to the environment might be in store if these trends continue, we need to measure the current amount of the furniture stock and project what might be needed in the future. Currently, there is a knowledge gap in understanding how much furniture is in our homes, especially on a national scale. This thesis aims to quantify the stock and flows of household furniture materials in the US, distinguished by income and area type (i.e., urban or rural). To inform strategies toward circularity in household furniture, a second object of the study is to investigate the effects of repair and reuse – lifetime extension strategies – on the behavior of the American household furniture stock. To quantify the stock of furniture units, the average number of furniture units per m^2 of residential floor space was collected using a bottom-up approach. The results were scaled to the national level using residential floor space data from the Integrated Model to Assess the Global Environment (IMAGE), scenario SSP2. Dynamic stocks and flows were calculated based on projected changes in residential floor space to understand how the stocks and flows might behave over time. The lifetime extension scenarios were simulated by extending the lifetime and adding mass (for repair) of a percentage of the furniture in the stock. Overall, demand for household furniture is not expected to saturate until the end of the 21st century. The highest-earning quintile owns half of the furniture stock mass, and material inequality is expected to remain until the end of the century in the base case. Urban residents own a majority of the household furniture and are expected to own a larger share as urbanization continues. About three-quarters of the furniture stock is wood-based, presenting opportunities for carbon storage but challenges in the volume of hard-to-recycle and low-durability particleboard. Circularity efforts to decrease furniture demand should target higher-income groups and separate strategies for lower-income groups should aim to increase affordability and access to more durable furniture. Urbanization also presents opportunities for local furniture circularity projects and hubs to attract skilled furniture repairers and secondhand distributors.

Keywords— furniture, material quantification, dynamic material flow analysis, circular economy, lifetime extension, industrial ecology

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Nomenclature

A summary of the abbreviations and terms used throughout the report is provided below.

Abbreviations and terms

Abbreviation or term	Definition
CE	Circular economics
DIY	Do-It-Yourself
DSM	Dynamic Stock Model
EOL	End-of-life
EOU	End-of-use
EPD	Environmental Product Declaration
FIPs code	Federal Information Processing Standard
Furniture intensity	Furniture units per residential floorspace in meters squared
LCA	Life-cycle assessment
Material intensity	Mass of a particular material type, as a proportion of a single unit of furniture
MFA	Material flow analysis
d-MFA	Dynamic material flow analysis
s-MFA	Static material flow analysis
MSW	Municipal solid waste
PP	Polypropylene
PSU	Primary sampling unit
VOC	Volatile organic compounds

1
Introduction

1.1. Defining the problem in current household furniture consumption patterns

Rising trends in material consumption due to industrialization in low- and middle-income countries and the maintenance of high material consumption rates in higher-income countries have given rise to the demand for cheap products. The low production cost needed to create these cheap products has led to the expansion into international labor and commodity markets and increases in material extraction, pollution, and waste generation. All of these negative effects are often displaced from the highest-consuming communities so the effects are disproportionately experienced by lower-income countries and communities.

1.1.1. Waste and pollution caused by increasing consumption

The global estimated total municipal solid waste (MSW) produced each year is 2.24 billion tonnes (The World Bank, 2022). That is approximately 280 kg per person per year, given a global population of around 8 billion people (Population Division, 2022). In truth, there is a large gap between the waste produced in high-income countries and low-income countries. With a wide range of 0.11 to 4.54 kg of solid waste produced per person per day, 16% of the world's population disproportionately produces 34% of the world's MSW (Kaza et al., 2018). Lower-income countries and communities tend to suffer the environmental consequences of the consumerism of others. The consequences, such as toxic pollution and over-extraction of resources, not to mention the rising rates of illness, loss of biodiversity, and social unrest that follows, culminating in a phenomenon that Rob Nixon (as cited in Davies, 2022) has coined "slow violence". Yet, wealthy countries continue to embrace the take-make-waste, linear model of consumption (Ellen MacArthur Foundation, 2019) that is responsible for the bulk of this waste, and the adoption of this economic model is spreading as more nations accumulate wealth and industrialize. Growth in global waste production is expected to be twice the increase of the global population by 2050 (Kaza et al., 2018). Given these projections, improved waste and resource management strategies must be developed to equitably support and enrich the quality of life around the globe. To achieve this goal, the displacement of the consequences of consumerism needs to cease, leading to more environmentally sustainable patterns of consumption. For wealthy nations, this means that material consumption per capita needs to decrease (Wiedmann et al., 2020).

1.1.2. The environmental and social impacts of furniture

One market on the rise and contributing to this industrial pollution and MSW is the furniture industry. In 2020, the global furniture market was valued at 509.8 billion USD (€4.67 billion) and is expected to increase by almost 1.5 billion USD (€1.37 billion) by 2027 (Statista Research Department, 2022a). There has been a concerning trend in "disposable" furniture, popularized by the Swedish brand IKEA and other affordable furniture retailers. The growth of IKEA due to innovations in lightweight, flat-packed, and inexpensive furniture has contributed to an overall trend in what has been termed "fast furniture". In much the same way that fast fashion has normalized the consumption of inexpensive products with short lifetimes, fast furniture companies provide offerings at very competitive costs, and the effect of this business model is spreading. IKEA's sales have increased by €5 billion, and the company is steadily increasing its global presence (IKEA, 2022). Wayfair, another company that is known to provide a large selection of furnishings at low cost, reported 14.145 billion USD, an increase of 54.98% from 2019 to 2020, although growth has since transformed into a (slower) decline (Wayfair Inc., 2021, 2023). Furthermore, the popular use of obsolescence in electronics and other durable goods may have decreased consumer expectations of the lifetimes of durable goods in general (Cooper, 2020; Cox et al., 2013), causing increased public satisfaction with decreased quality in durable goods and shortened lifetimes.

The trend in low-cost furniture and higher furniture turnover is problematic because it increases demands for materials, puts more strain on waste management systems, and consequently causes pollution and over-extraction of natural resources. In a phenomenon called "telecoupling", (Liu, 2013, as cited in Fuller et al., 2019) many of the environmental impacts stemming from the furniture industry are displaced to countries that are vulnerable to extraction and pollution from environmentally damaging industries. Their vulnerability due to corruption, trade conditions, and population dynamics (Geist & Lambin, 2002) is often taken advantage of by large companies to extract resources and produce at the lowest possible cost to themselves. However, the "externalities," or the environmental and social costs that are not usually reflected in economic terms, are incurred by the locals that live and work in the environments that are affected by the businesses' activities.

One of the biggest challenges the world faces today is climate change, and land use change, which is primarily deforestation, is estimated to contribute 12-20% of the world's greenhouse gas emissions (The OECD, 2013). Wood products, which includes wood-based furniture products, are within the top four drivers of deforestation. In particular, demand for wooden furnishings contributes to forest degradation by increasing the economic incentives for harvesting tree species, leading to selective logging (Sanford et al., 2011). Selectively cutting down some species causes depletion in forest biodiversity and harm to the health of remaining trees as habitats and tree-interaction networks are disturbed (Addo-Fordjour et al., 2022; Magrach et al., 2016). A snow-balling effect then ensures, as degraded forests are more likely to be targets for future land use conversion (e.g., deforestation in preparation for agricultural activities) (Sanford et al., 2011). While these impacts are being driven by consumer demands for wood-based consumer products in wealthier countries such as the US, Germany, and Japan (OEC, 2021), the environmental effects are often distributed unevenly. In a study by Fuller et al. Fuller et al. (2019), furniture produced in China was found to be linked to deforestation in central Africa (namely Cameroon, the Central African Republic, the Republic of the Congo, and Gabon). The US is a top importer of Chinese wood-based products, contributing 40% of the demand for wood-based products from China in 2006-2016, more than even Chinese domestic demand. American consumer demand for wood-based products, therefore, is a driver of deforestation in the central African region.

In addition to contributing significantly to climate change, deforestation also causes and drives other forms of environmental harm such as biodiversity loss, desertification, changes in rainfall, higher frequency of flooding, land erosion, and water pollution (Becerril-Piña & Mastachi-Loza, 2020; Bradshaw et al., 2007; Duku & Hein, 2021; Karamage et al., 2016). These affect local residents' living conditions and food security, driving the prevalence of social problems, as well. In the case of Indonesia, where timber harvesting has been found to be a main driver of deforestation (Austin et al., 2019; Hartini et al., 2019), the demand for wood-based products has a particularly large effect on living and working conditions. A social life cycle analysis (s-LCA) of the furniture industry in Indonesia concluded that the worker impact can be categorized as “poor”, according to impacts on work hours, working pressure, and work health and safety (Wicaksono & Kadafi, 2020).

Plastics and ferrous metals such as steel, which are also major components of modern furniture products, contribute unique and negative environmental and social impacts. Steel production is estimated to have contributed about 9% of greenhouse gas emissions from 1900 to 2015 (P. Wang et al., 2021). While steel is recycled at a high rate, the production of recycled steel has not been able to match the demand, which is projected to continue its growth. An analysis of the steel industry by P. Wang et al. (2021) predicts the demand for steel will be enough to derail the industry from achieving Paris climate goals. Plastics are derived from crude oil and are categorically also carbon-intensive to extract, refine, and manufacture. Polypropylene (PP), which is a plastic commonly found in furniture items, is recycled globally at a rate of about 9% at the post-consumer stage, with everything else contributing to plastic pollution, being landfilled, or incinerated (OECD, 2022). Demand for both steel and plastics needs to be curbed to reduce the environmental impacts of these materials. Furthermore, binders (for engineered wood), paints/varnishes, and adhesives are chemicals that are often used in home furnishing products. While present in relatively smaller amounts than wood, steel, and plastic, these compounds can be very damaging to human and environmental health. Studies of the impacts of furnishings on human health found that the indoor emissions from furniture products from volatile organic compounds (VOCs) are more harmful during the in-use stage than in the production and disposal stages combined and that these emissions wane over time (Skaar & Jørgensen, 2013). This means that the use phase of household furniture is an important consideration in terms of the product category’s impacts on human health and safety. This is a strong argument in favor of achieving longer furniture service lifetimes and less frequent replacement of household furniture products.

1.1.3. Furniture waste in the US

In the US, the increase in turnover of furniture stock is said to be due to the rising inability to afford necessities such as housing, and cultural norms. Some consumers turn to cheap furniture out of need. On the other hand, fast-tracking trends, disposable income, and low-quality construction of furniture can overlap to contribute to the idea that furniture can now be simply trendy, affordable, and replaced or purged when there is an opportunity to "upgrade" (Kamin, 2022). In 2018, American consumers reportedly produced 12.1 million tonnes of furniture waste, 80% of which was landfilled and 20% combusted for energy (US EPA, 2021). These methods for disposing of furniture in the US add to the persisting issues of environmental classism and racism, where communities of non-white (particularly Black Americans and American Indians/Alaska Natives) and low-income residents are more likely to be exposed to unsafe environmental conditions (Kaufman & Hajat, 2021; Martuzzi et al., 2010). Although no new incinerators have been built in the US since the 2000s, existing incinerators are guaranteed to run continuously due to contracts with local municipalities that have cemented quotas for waste that is to be provided by the municipalities and fed into the incinerators (Peischel, 2022). The toxicity from incineration of fabrics in furniture contributes to the presence of PFOS and PFOA (from fabrics), dioxins (from wood and plastics), and heavy metals (paint and leather) released into the air around incineration plants, which are found to be disproportionately located in or near communities with higher poverty rates and higher proportions of non-white residents (Baptista & Perovich, 2019). When the incinerators are eventually all retired, the disposed furniture will all go to landfill if business continues as usual. In a landfill, the furniture parts that can decompose will release methane gas (a potent greenhouse gas that has 27-30 times the effect of carbon dioxide toward climate change, according to the US Environmental Protection Agency (US EPA, 2023b)).

As stated in the study by Davies (2022), the depletion and contamination of natural resources harm the health and well-being of nearby communities, threaten political stability, and affect the poorest and most vulnerable members of these communities. People in these situations often lack the resources needed to escape the situation and are not empowered to educate others about their experiences. Therefore, it is the responsibility of those with the power and resources to be educated and conscientiously manage the effects of their material consumerism.

Certainly, there are promising studies that find that eco-design and increased use of bio-based products are decreasing the potential environmental impact of the furniture sector. However, there is still much to be done in to decrease the impacts of the furniture supply chain (Coloma et al., 2022), especially as overall demand for, and the turnover of, furniture products increases. Furniture waste generation has gone up by 450% since 1960 (US EPA, 2021), compared to an 84% in population in the same period (US Census Bureau, 2021), signaling an increasing trend in furniture waste per capita in the US.

1.2. Finding methods for managing and decreasing furniture waste

Circular economics (CE) is an economic model that has been popularized as a set of strategies to address the unsustainable nature of the linear economy by curbing resource extraction and changing consumption patterns. The basic goals of CE lie in closed-loop consumption, production, and waste treatment that increase the efficiency of resource use, paired with cleaner production strategies (Ghisellini et al., 2016). According to Kirchherr et al. (2017), CE can be broadly understood as "an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes". Additionally, these pathways should be realized at the lowest cost of additional resources, meaning that the materials need to be reused, recovered, etc. when the original materials are at the highest value possible. To capture materials at their highest economic value, a hierarchy of recovery processes has been developed in the literature. The Ellen MacArthur Foundation (2023) distinguishes between technical and biological loops in material pathways, as shown in Figure 1.1. The inner loops of the technical cycle represent those pathways with which the highest value of the material is maintained, such as reusing and sharing the product and keeping it whole. The outer loops necessitate a decrease in the value of the product or a higher cost of processing, such as recycling. Wilson (2015) summarizes this hierarchy as the minimization of waste (e.g., reuse, repair, refurbishment), followed by material recovery (i.e., recycling), then energy recovery (e.g., incineration) in a publication from the UN Environment Programme. While CE principles are being adopted by organizations all over the globe, this transition must occur at all levels, from the producer to the national or global economy, and often requires system change to take place (Kirchherr et al., 2017).

1.2.1. Circular economics

With increasing awareness of the negative environmental impacts of furniture production and disposal, consumers are waking up to new solutions in furniture design and business models. US Environmental Protection Agency (EPA) and the executive branch of the US government seem to acknowledge the statement that recycling alone is not enough, but still maintain focus on recycling in its research and outreach strategies (EPA Office of Resource Conservation and Recovery, 2022; The White House, 2022, 2023). In 2021, the US EPA published a National

Recycling Strategy as the first part of a series on a plan for developing the circular economy in the US (US EPA, 2015). No other parts of this series have since been published. As of the conduction of this study, the government has also failed to set any firm goals for circularity, as some members of the European Union and other nations have done (Circle Economy, 2023; EC, 2023; Fraser, 2022). The only circularity goal that could be found stated by the US government was the goal to reach a recycling goal of 50% by 2030 (US EPA, 2023a).

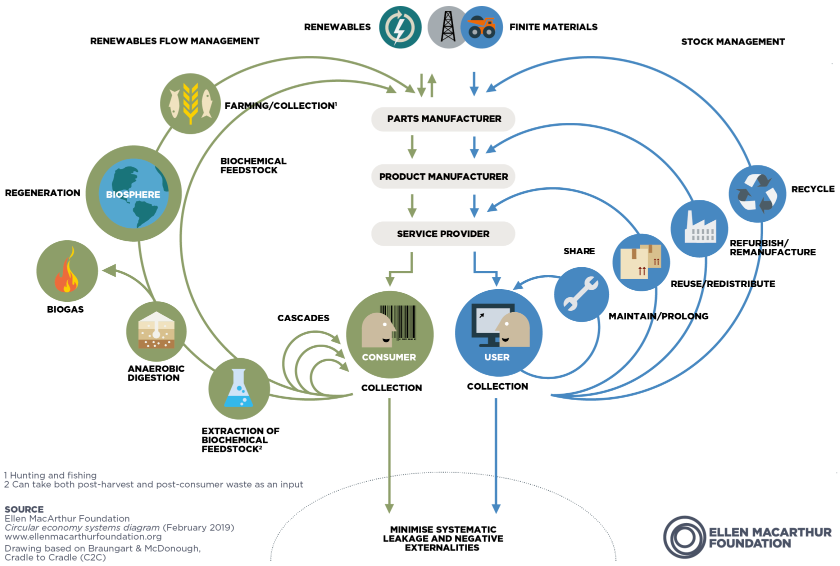


Figure 1.1: The Butterfly Diagram: A representation of the material flows of a circular economy by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2023)

1.2.2. The potential of furniture in the circular economy

Commodities in the durable goods product category have different functions that, in their use phase, may require energy to function and emit toxins and/or cause greenhouse gas emissions. The variation in these features means that the effects of lifetime extension of the lifetime environmental performance of these products can differ.

In the case of automobiles, a common perception is that older vehicles should be phased out of the material stock due to their low fuel-efficiency, and replaced with relatively fuel-efficient or electric vehicles, instead. The idea has been featured in the form of policies such as the US's Car Allowance Rebate System (CARS), or Cash for Clunkers, which encouraged Americans to turn in their older cars (25 years old or older and in working condition) for a rebate on a new, more fuel-efficient car. Although this program occurred for one month in 2009 mainly to jump-start a lull in car sales the added condition that the new car has a certain fuel efficiency suggests the intention for a vehicle stock with higher overall fuel efficiency (Romer & Carroll, 2010). The program ended with a reported overall short-term increase in average miles-per-gallon and 9-28.2 millions tons in avoided emissions (Li et al., 2013). A separate study on Japanese vehicle stock by Kagawa et al. (2011) concluded that extended lifetime of all cars in the 1990-2000 period would reduce overall lifetime CO2 emissions of the supply chain, and replacing all less fuel-efficient cars with the more efficient models available at the time would have resulted in marginal emissions reductions. The main argument against extending the lifetime of the current vehicle stock is that older vehicles tend to produce more toxic emissions and have lower fuel efficiency than that of newer models, although there may be other market and legislative solutions to this issue.

Like automobiles, it is popularly believed that replacing electric household appliances such as washing machines with more energy-efficient models are better for the environment. Indeed, in some cases, household appliances were found to have larger environmental impacts in its use phase, although this is very dependent on the energy mix being used (Hischier et al., 2020; Kwak, 2016). Additional studies add nuance to these findings, such as the study by Alejandre et al. (2022), which urges designers to consider the extent of improvements in energy efficiency and lifetime of new models, also confirming the need for renewable energy to achieve actual reductions in environmental impacts with new products.

Consumer electronics are an example of a product group where the service or end-of-use lifetime tends to be much shorter than the actual end-of-life (Thiébaud-Müller et al., 2017, as cited in Bieser et al., 2022) due to consumer preferences for up-to-date technology and rapidly changing market offerings (Khan et al., 2018). Electronics such as smartphones mostly reach end-of-use with no attempts at lifetime extension strategies such as repair due to perceived obsolescence of the phones' functionality, high cost of professional repair, and disempowered consumer attitudes towards the challenge of self-repair (Wieser & Tröger, 2018). However, in the face of issues such as supply risk and the labor exploitation surrounding critical raw materials (Dunlap & Riquito, 2023; Goe & Gaustad, 2014; Graedel et al., 2015; van den Brink et al., 2020), as well as accumulation of e-waste in poorer nations (Suckling & Lee, 2015), lifetime extension of electronics toward the decrease in demand for new products is becoming increasingly urgent. Since the manufacturing phase of consumer electronics is so dominant in their lifetime environmental impact, reduced demand of products due to lifetime extension is estimated to make greater overall reductions in environmental impacts than those made with new models with better energy efficiency (Wieser & Tröger, 2018).

Similar to other durable goods products with lower in-use environmental impacts, the extension of furniture lifetime is expected to reduce the demand for raw material extraction, reduce the need for new product production, and reduce the overall environmental impact of the furniture. In contrast to electronics and vehicles, however, there is no need to upgrade furniture and the structural complexity of furnishings tends to be simpler than the average personal vehicle or electronic device. Hence, potentially lower-cost lifetime-extension strategies such as self-repair are more accessible for non-experts. There are no legal constraints on the personal use of older furniture, as older furniture emits fewer volatile organic compounds (VOCs, as introduced in Section 1.2.2) than new products and there are no major safety concerns involved in using worn-down furnishings. Secondly, most home furnishing products may be considered "passive durable goods," meaning they are considered to have no environmental impact during the use phase (Kaddoura et al., 2019). Most of the products' environmental impact occurs at extraction, production, and end-of-life. As will be discussed in Section 3.3.2, this feature of furniture may also be the reason that furniture product longevity is relatively under-studied. However, this feature adds to the arguments in favor of condoning lifetime extension in the furniture category. There are clearly many positive reasons to explore circularity in furniture. In response to the need for more circular furniture consumption, furniture has become the focus of many endeavors in the burgeoning circular economy and will also provide the focus of this study. Efforts are being made at many levels of the supply chain and through different pathways in the CE (Ellen MacArthur Foundation, 2019). Some of these efforts are summarized in Table 1.1.

1.2.3. Defining and classifying furniture products

In the interests of clarifying the scope of this study moving forward, definitions of the furniture product category were investigated. The International Organization for Standardization (ISO, 2021) recognizes furniture as the scope of ISO Technical Committee 136, namely the

Pathway	Example	Source
Share	Furniture leasing	Schoonover et al. (2021)
Maintain/ Prolong	User strategies to prolong product lifetimes	Haase & Lythje (2022)
	Designs that adapt to user needs	Bosch et al. (2017)
Reuse/ Redistribute	Online secondhand furniture retailers	Hinojo et al. (2022)
Refurbish/ Remanufacture	Exploring the potential for reconditioned office furniture in as a product-service system in Sweden	Öhgren et al. (2019)
	History of and trends in furniture repair in the United States	Wilmering (2004)
Recycle	Designing furniture that uses recycled textiles	Wang et al. (2023)
	Designing furniture for recyclability	Bruno et al. (2022)
	Adding value to recycled wooden furniture products	Yang & Zhu (2021)

Table 1.1: Examples of household furniture in the circular economy, as shown in scientific literature.

"free-standing or built-in units which are used for storing, lying, sitting, working and eating." Similarly, Smardzewski (2015) defines furniture as the "objects of applied arts intended for mobile and permanent furnishing of residential interiors." Both definitions refer to furniture broadly as both movable and built into a structure. However, the US Consumer Product Safety Act ensures that US law only recognizes movable items as furniture. In the definitions for 16 CFR 1303.2 (Consumer Product Safety Commission, 2008), the furniture is defined as "those movable articles: (i) Used to support people or things; (ii) other functional or decorative furniture articles".

Further organization of products within this product category is necessary in enabling researchers to specify research scopes. In the literature, it was found that Wenker et al. (2018) divides office furnishings between those that function as "enclosed spaces" and "surfaces" to assess the environmental impacts of wooden furniture in Germany. Another assessment of environmental impacts of household furnishings by Wiprächtiger et al. (2022) utilized groupings based on the room in which the furniture is found, and then by dominant material type. Categorizations of furniture design by Smardzewski (2015) and those found in van Beijnum (2021), which is a modified version of the former study, were more granular. In the study by Smardzewski (2015), furniture is divided into classes based on the activities performed in the rooms in which the furniture is typically found, then on function, ultimately returning 36 household furniture categories. The modifications by van Beijnum (2021) were made due to additional findings in the literature and data availability. Grouping furniture products requires an understanding of the function of different rooms and items, and this can vary depending on the cultural context.

The factors of design, purchasing decisions, use, and decisions to dispose of furniture items by consumers highly depend on a society's material culture. Modern furniture retailers market furniture styles as a way to materialize their customers' ideal lifestyles. These aesthetic ideals are in turn guided by class position, as well the understandings of "privacy, morality, family, and care" (Hollows, 2008). A study by Grant (2012) has identified choices in home furnishings in urban Africa with trends in fashion, globalization, and the need for functional workspaces within the home. In all, consumer decisions in home furnishings are rooted in practical, social, and cultural factors (Chevalier, 2012) that should be considered per case study.

1.2.4. Quantifying materials in furniture to inform solutions

To inform decision-making in a transition toward the circularity of furniture products, material stock-taking, or quantification, must first be performed. Quantification will lead to (1) establishing a baseline against which new strategies toward sustainability can be evaluated, (2) developing projections for material supply and demand according to scenarios to aid in developing action plans, and (3) communicating status, progress, and challenges to one another using a shared language. In the same way that organizations monitor the flow of human and financial resources in the economy, data must be collected to track the efficiencies and inefficiencies of material use, as well as make informed decisions about future actions (The OECD, 2008). In the case of furniture, quantification will provide (1) an idea of the portion of complex materials in the furniture stock (i.e., particleboard, laminates, and other composite materials) and aid in calculating estimates of ease of recyclability, (2) expected outflow to landfill and circularity pathways, and (3) inform projections of the scale of environmental impact through production and material extraction (Cordella & Hidalgo, 2016). As globalization continues to develop international relations, unequal power relations between the wealthier and poorer nations continue due to the persistence of pre-existing divides. The digital divide gives rise to unequal access to digital technologies and skills; the innovation divide disadvantages countries with lower access to the knowledge needed for designing and producing advanced technologies; disparities in bargaining power; and inequity in access to capital toward circular development (Barrie et al., 2022). According to Barrie et al. (2022), one strategy to avoid a worsened divide in progress toward circularity (i.e., the “circularity divide”) is to increase international collaboration and coordination in planning for circularity. As the standard language for communicating circularity, data will be needed for all countries to participate in this collaboration. Therefore, standard frameworks for measuring material in products are a necessary step towards a global transition to a more circular economy. The methodological framework introduced in this report is an attempt to drive the efforts toward quantifying furniture and its materials at a national scale.

2
Literature Review

2.1. Material quantification of furniture in the literature

A literature review was conducted to assess the state of the art in stock-taking of materials in furniture. Over a thousand results with relevance to furniture material stocks and flows were returned with the use of keywords "furniture," and "material stock" or "material flow" Appendix A. However, only 19 results remained when the search was filtered to exclude studies of buildings, infrastructure and roads, production, and manufacturing. Manual analysis of these results found a further 12 could be eliminated due to their focus on material supply chains, as opposed to product categories, and quantification of environmental impact rather than material stock. Of the last eight results (Table 2.1), none exclusively studied materials in furniture, especially not at a global scale. Four articles presented studies that approached quantification from the perspective of a particular material category. These investigations tended to focus on forest biomass or wood. One study (Wiprächtiger et al., 2022) quantified material flows of furniture at the national scale in Switzerland and provides a methodological basis for this study.

The study done by Wiprächtiger et al. (2022) is a top-down investigation of case studies in household furniture and clothing. The research scope includes an environmental impact assessment of certain waste-prevention strategies, such as the repair of clothing and the reuse of clothing and household furniture.

2.2. Knowledge gap

From this literature review, there is only one study (with the geographical scope of Switzerland) that quantifies household furniture and its materials at a national or regional scale that has been published in the journals indexed by the Web of Science database. There are still many opportunities for research in the quantification of furniture that includes various material types in different product categories. This gap is also present for furniture on a global scale. In an attempt to close this knowledge gap, the aim of this study is three-fold. The first goal is to introduce strategies that can be used to quantify in-use household furniture when no such data is available from secondary sources. The second objective is to demonstrate this quantification method in a case study, which will aid in achieving the third aim, which is to analyze the quantified in-use stock and flows in the household furniture sector to inform future action toward reducing the impacts of this consumer product category. These three goals have been formalized into three main research questions that will guide the design of the current study.

2.3. Research questions

To address the knowledge gap found in the literature review, three main research questions have been formed and an attempt will be made to answer them in this study. Sub-questions have been formed in order to specify the research objectives for the first two questions.

1. What are the static and dynamic stocks and flows of furniture and its materials in households across the US?
   (a) How do the stocks and flows differ between income quintiles and area types?
   (b) What implications do these differences have on future decisions in material demand and waste management in a circular economy?
2. In what ways might the increase in the use of lifetime extension strategies for household furniture products affect future demand and outflows of materials in American household furniture?
3. How can the mass of materials in household furniture be quantified at the national scale?
   (a) What are the strengths and limitations of the quantification methodology used in determining the material stock and flows of American household furniture?
   (b) In what ways can the quantification methodology be used for other geographical locations on the national scale, and what are the limitations?

2.4. Scope definition

The geographic scope will be the United States, meaning the 50 official states as of 2023, excluding territories. The sampling will be performed at the level of counties and metropolitan areas. The temporal scope of the study is from 1971 to 2100, based on data available from the IMAGE model for SSP2 (Stehfest et al., 2014). This temporal scope enables the use of historical data and provides an opportunity to project the future stock of materials in household furniture. The products and materials of this study will be limited to the aggregated categories of materials found in common household furniture in homes across the US and the literature which report their material composition. More details are provided in Section 3.2 of this report. The definition of furniture for the current study will be limited to movable articles both indoors and outdoors that are used for storing, lying, sitting, and eating, as it is assumed that built-in furniture has lifetimes closer to that of a building than that of movable furnishings. Data collection on ownership, material use, product weight, and price will also be limited to movable articles. For purposes of exploring the generalizability of the model, certain large-scale indoor and outdoor recreational products (swing sets, basketball hoops, and recreational tables) will also be included in the scope of this study. Patio umbrellas, often an accompanying feature of outdoor eating and recreation, will also be included.

Table 2.1: Summary of the literature found most relevant to this study.

Author(s) (Year)	Description and scope	Exclusive or extensive study of materials in furniture?	Quantification of material stock?
Gonçalves et al. (2021)	Assesses of the stocks and flows of forest biomass in various product categories for Portugal in 2015. Circularity and resource efficiency is analyzed via the use of indicators.	No, the data is for various aggregated forest biomass product categories.	Yes, for forest biomass.
Stephan et al. (2020)	Analyzes the material flows of the Parkville Campus of the University of Melbourne in 2017 input-output analysis. The data was gathered from material procurement information and contact with the local waste management contractor.	No, it includes all material procurement at the university.	Yes, for the scope of the university campus.
Kayo et al. (2019)	Quantifies the environmental impacts and approximates impact reductions related to wood consumption in Japan from 1970 to 2013. Also, the study projects expected impacts based on multiple future scenarios to 2050.	No, the focus is on aggregated wood products categories, including paper and buildings.	Yes, for wood.
Suthar et al. (2016)	Investigates the role of stakeholders in the informal waste system in Dehradun, India through surveys and a material flow framework.	No, various aggregated product categories of waste are included.	Yes, for the informal waste sector.
Suter et al. (2017)	Measures material flows and stocks of wood in use in Switzerland. Environmental impacts are then assessed using life cycle analysis (LCA).	No, various aggregated product categories are included.	Yes, for wood.
Szichta et al. (2022)	Proposes a model for the prediction of timber volume recovery according to lifetimes of products in various sectors and historical domestic consumption of timber products as of 2019 in Germany.	No, various aggregated product categories are included.	Yes, for timber.
Wiprächtiger et al. (2022)	Proposes a method for assessing the environmental performance of waste prevention activities over the whole life cycle of products in Switzerland.	Yes, the furniture was divided into eight categories and environmental performance was assessed according to furniture type where possible.	Yes, the data collection for wooden and metallic furniture was performed through a short survey.

3 Methodology

3.1. Overview of the study design

Socio-metabolic material flows can be identified as the materials that are added to the materials used within the social system, taken from the natural environment through extraction (Haberl et al., 2019). Material flow analysis (MFA) is used to measure socio-metabolic flows and stocks that make up the in-use stocks or material stocks of society, usually in terms of mass within a defined period and geographical boundary (Lanau et al., 2019). MFAs do not generally include hibernating stocks, or those stocks are simply kept in storage (Müller et al., 2014), although there are studies that are now investigating these stocks (e.g., Wallsten et al., 2015). Material stocks leave via disposal as waste, emissions, or leachate into landfills or the environment at large (Haberl et al., 2019). MFAs studied by Augiseau and Barles (2017) were found to have four main purposes.

1. Forecasting and comparing future inputs and output flows to estimate the demand of materials and waste generation, thus giving warning to potential environmental problems (Müller et al., 2014).
2. Identifying the current material composition of the anthropogenic stock (i.e., the material stocks of society), and how they might evolve over time.
3. Estimating the composition of future material stocks.
4. Studying the urban metabolism and how it relates to that of rural areas, then use to inform legislation relating to industrial ecology.

Various MFA approaches have been developed toward achieving these aims, and those approaches can largely be categorized as "static bottom-up or top-down flow analysis; bottom-up stock analysis; dynamic retrospective or prospective flow analysis with flow-driven or stock-driven models; and top-down prospective or retrospective stock analysis using a flow-driven model" (Augiseau & Barles, 2017). The inputs required to conduct MFAs come from a variety of sources that are often highly variable in both quality and coverage (Augiseau & Barles, 2017). The data used to inform the investigation can dictate the type of analysis that is possible. Historically, the data acquired for top-down MFAs allows the modeler to estimate flows of materials in a system, resulting in flow-driven analyses (Lanau et al., 2019). For example, the Wiprächtiger et al. (2022) study of Swiss furniture stocks used a top-down approach, as national end-use data for wooden furniture was available. The total amount of furniture was then divided into estimates for different product types and compositions.

Bottom-up MFAs are developed by counting the objects that contain the materials of interest to the study, and then multiplying the number of objects with the "material intensity" of said material (Lanau et al., 2019). This method returns the estimation of a stock, which is used to develop a stock-driven approach for estimating flows. Bottom-up analyses are generally limited in geographic, temporal, and coverage of materials due to the need for large amounts of fine-resolution data. Widening the scope of bottom-up studies results in more limitations and uncertainty (Lanau et al., 2019). Indeed, in their review of MFA approaches, Augiseau and Barles (2017) found that approaches are often combined to account for uncertainty in the data. Due to the lack of quantification data in many product sectors, performing MFA strictly using one approach may be difficult and require the use of heightened uncertainties in the analysis. Household furniture is a product category that remains largely unquantified, as discussed in Chapter 2, thus this study will employ a combination of MFA methodologies.

An illustration of the overall study has been provided in Figure 3.1. The study will begin by developing the static model, then feeding the static results into the Dynamic Stock Model (Pauliuk & Mutel, 2014). The resulting dynamic furniture stocks and flows will be multiplied by the material intensities of the furniture to obtain the dynamic material stocks and flows.

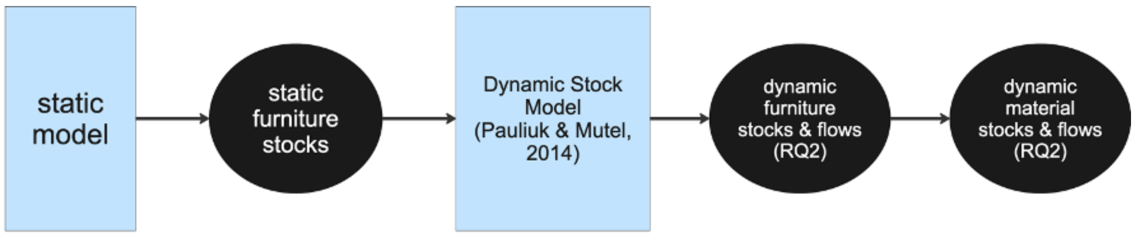


Figure 3.1: Flowchart of the overview of the study methodology and relevant outputs.

3.2. Modeling the static stocks of household furniture

Static material flow analysis (s-MFA) is a method that can be described as a method for quantifying the stocks and flows of physical materials in a "snapshot," often defined as one year (Fischer-Kowalski & Hüttler, 1998; Müller et al., 2014). The five main properties of a s-MFA to consider are the inflow, outflow, stocks, processes, and system boundary. Inflows are materials that cross into the scope of the study, represented by the system boundary. Examples can include material that enters a national economy via mining and/or import or material that enters the global economy through extraction (Fischer-Kowalski et al., 2011). The inflow encounters a process, through which it is transformed and possibly stored as stock over the course of the year or however long the temporal "snapshot" of the model is. The material then leaves that process as an outflow and becomes an inflow to another process or outflow from the entire system across the system boundary. Outflows can be in the form of emissions to the natural environment, exports from a country, or a product that is no longer within the scope of the study. An important consideration for s-MFAs is mass balance, which is the concept that the material input to a process is equal to the material that is in the stock of that process and its output (Pauliuk & Müller, 2014). When looking at a system as a black box consisting of various systems, the total input to the system should be equal to its total stock and outflow.

In this study, a bottom-up approach is used to estimate the in-use stock of American household furniture in 2020. This will be done by taking representative samples from households across the nation. This data will be aggregated in the top-down stage of the methodology to reflect average furniture unit intensities for each income quintile on the divisional level. The sample data will be multiplied with household data obtained by the US Census Bureau (USCB). A model in Python developed by Pauliuk and Mutel (2014) will be used to then calculate the inflow and outflow of materials in household furniture in 2020.

3.2.1. Clustering and sampling American residences

To collect data that represents all of the fifty states of the US, the sampling method in this study was based on the integrated national sampling design used by the USCB to survey housing units all over the country, including Puerto Rico (Demographic Statistical Methods Division, 2022). Primary sampling units (PSUs) are designated by the Census Bureau, usually counties and metropolitan areas. These sampling units are further aggregated into states, then nine divisions, and then finally into four regions (Figure 3.2). The sample design calls for the selection of two different properties that applies to every PSU and are relevant to the aim of the current study. These properties are then used to group the PSUs into clusters (the number of which is k), which have similar values along the two clustering properties. The clustering is done by a statistical test called K-means clustering and is performed in this study within each US division to allow for the samples to be taken from a relatively even distribution across the US. K-means clustering is used by the USCB and in many statistical studies as an "unsupervised machine learning algorithm" that identifies non-overlapping groups of samples, then identifies the center of each group to act as a representative for each group of samples (Zubair et al., 2022). In this study, K-means clustering was performed in order to account for any potential patterns in furniture ownership resulting from residential floorspace and urbanization. Therefore, clustering was done using the population density and the median floor space of each PSU. Median floor space data was not available for all American PSUs, so the clustering was performed with those sample areas that had median floor space data available. Data on other features of sample units within the US, such as land area, household size, and household composition, were merged into the same spreadsheet that contains floor space and population density in Supplementary Materials G-1. This data will be available as Supplementary Materials A-4 and A-5.

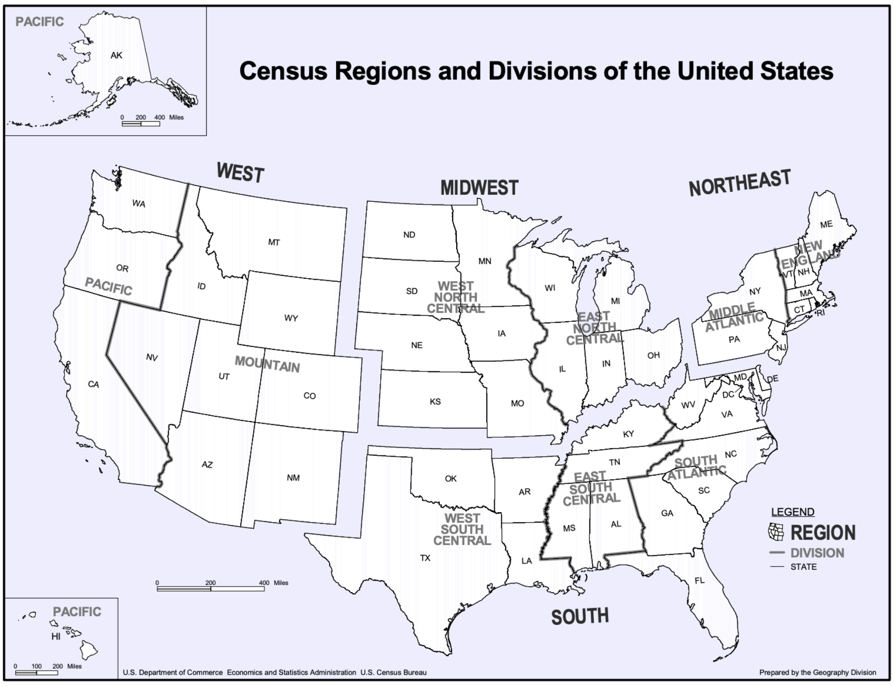


Figure 3.2: Map of the nine US Census Bureau divisions (Geography Division, 2023).

Because there were much fewer urban sampling units than rural sampling units, the urban PSUs were not clustered. The urban sample area that was chosen for each region has the median population density among the urban PSUs in each region. Ultimately, all urban areas for each division were treated as one cluster. As the sample selection process was being tested and developed, some additional PSUs were sampled. However, these samples were used to increase the sample size in the final analysis. Therefore, it should be noted that the real number of collected samples for some divisions is more than indicated by the steps of the methodology, which are summarized below.

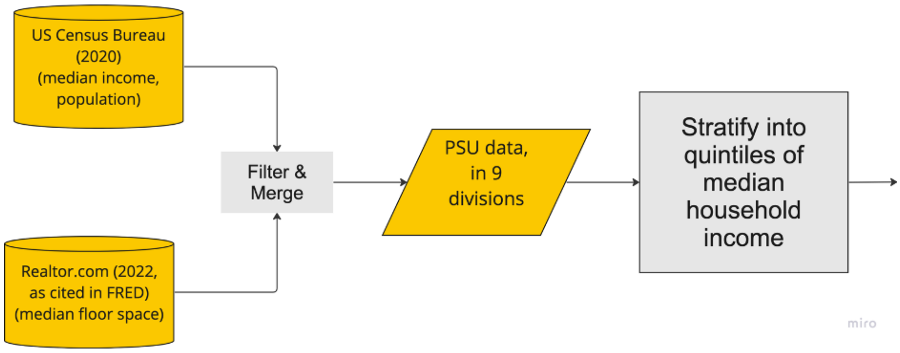


Figure 3.3: Flowchart illustrating data input for stratifying PSUs by median household income and census divisions.

1. After collecting and merging the data on the 3143 PSUs around the US (Figure 3.3), it was decided from the available data, which features of the data represent residential floor space and urbanization. These features will be used in grouping the samples.
2. The 50 US states were divided into nine USCB regional divisions (Geography Division, 2023) and into quintiles according to median household income in 2020 (Bureau of Labor Statistics, 2023) (Supplement A-1).
3. As differentiation between the urban and rural material intensities of furniture materials is desired for this study, the urban PSUs were separated from the non-urban, or rural, areas (Figure 3.4). Areas with over 1000 people/square mile were considered to be urban (UN Statistics Division, 2005).
4. For urban sample units:
   (a) One urban PSU with the median population density was selected from each division.
5. For rural sample units:
   (a) Median floor space and population density were chosen as the properties on which the PSUs will be clustered.
   (b) The population density and the median floor space for each rural PSU were scaled from zero to one, relative to its position from the maximum and minimum of the range of values for those properties.
   (c) With the elbow method through the KneeLocator method in the kneed package (Arvai, 2020) in Python, it was found that for most divisions (8 out of 9) five clusters were the most efficient number of clusters for which distinct groupings could be made.
   (d) K-means clustering was performed on the scaled population density and scaled median floor space (Figure 3.5). KMeans method from the SKLearn package (Pedregosa et al., 2011) was used in Python used to do the statistical calculation.

(e) One cluster center was located per cluster using the shortest Euclidean distance, along with the associated closest PSU, in terms of Euclidean distance. With five PSUs for each of the nine divisions, 45 total rural PSUs were selected for sampling.
(f) The furniture unit data was collected for urban areas and rural areas, with each data point labeled with the division name, the PSU Federal Information Processing Standard Publication 6-4 (FIPs code), floor space, and some additional information such as number of bedrooms and lot size that may be useful for future studies (Supplementary Material B-1).

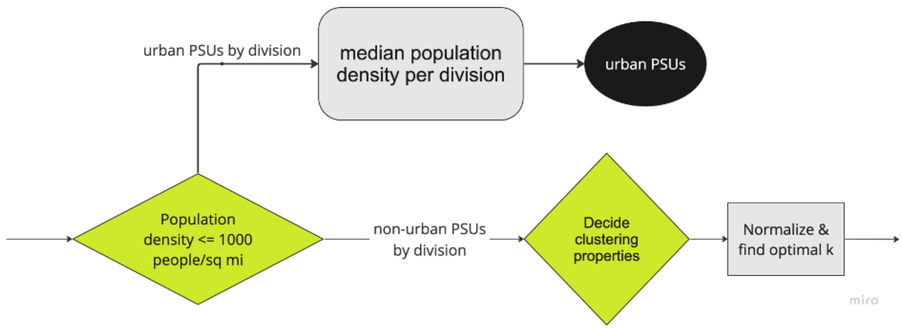


Figure 3.4: Flowchart illustrating the urban-rural division and setting up rural PSUs for K-means clustering.

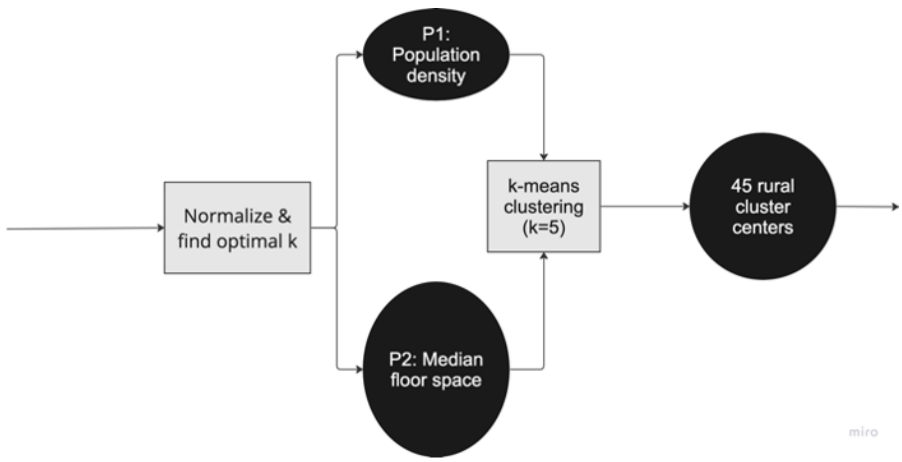


Figure 3.5: Flowchart illustrating the K-means clustering of PSUs per division.

3.2.2. Using real estate websites as a data source for in-use furniture

The steps for collecting the raw data on furniture units in each selected sample household are outlined below. The limitations of this method are discussed in Chapter 6 and Appendix E.

Five listings from movoto.com (Movoto, 2023) were selected for each non-urban PSU (selected through K-means clustering) and representative urban PSU. If there were insufficient options on movoto.com, realtor.com (National Association of Realtors & Move, 2023) or zillow.com (Zillow, 2023) were used. Below is an outline of the steps that were followed to find the sample listings on the real estate websites (Figure 3.6).

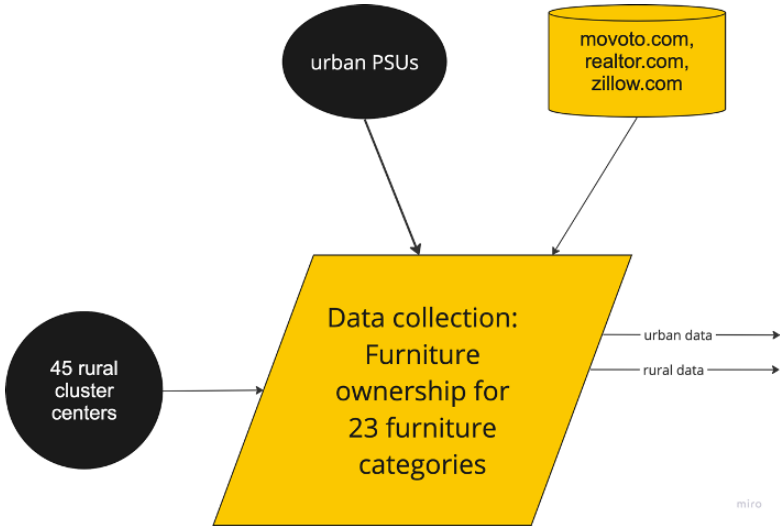


Figure 3.6: Flowchart illustrating the data inputs and outputs of the furniture ownership data collection stage.

1. Listings were filtered by the PSU being sampled. 5 random numbers, between 1 and the number of listings available for that PSU, were selected using a random number generator in Python.
2. Additionally, the researcher filtered for "existing homes" or homes that were older than 3 years old to avoid model homes and new-build listings, which were assumed to have no furniture or utilize model furnishings. Empty plots of land were also excluded from the selection of possible samples.
3. If rentals and homes for sale were available, both were selected. However, as the rentals listed on the site seldom had pictures of furniture, rental properties are mostly absent from the final data collection.

Once a viable listing is selected, a row in the furniture data unit spreadsheet (Supplementary Materials B-1) was filled. The guidelines for identifying viable listings have been provided below.

1. The displayed number of bedrooms and rooms other than the living room, garage, kitchen, and bathroom(s) total no less than one room fewer than the listed number of bedrooms. If the number of rooms is too few, the listing is assumed to have too many rooms excluded from the listing page to be counted as a sample.
2. Listings must have sufficient data about the property provided, such as floor space data and listing prices. For this study, lot size was not required to be considered a viable sample.
3. Model houses were considered not viable as samples in this study. As it was not always clear whether a listing used model rooms or not, some further guidelines have been developed to discern which listings used model home images. If the answer is "yes" for two or more of the questions below, the listing is considered not viable as a sample.

   (a) Are there full place settings on the dining tables (with silverware and plates)?
   (b) Is the home or are the closets completely free of clutter and clothing? Is there a lack of food in the pictures of pantries? (Fruit on the countertop is excluded.)
   (c) Is there a noticeable lack of furniture that may be used to store items, such as shelves and dressers?

4. In the case that a chosen sample is deemed not viable, an alternative sample must be found. The original number of listings is filtered for a $50,000 range around the originally chosen listing value (e.g., If a $125,000 is chosen, then filter for $100,000 to $150,000) and listings are evaluated until there is one that can be considered a usable sample.

3.2.3. Identifying and recording in-use household furniture using the photograph method

General categorizations of furniture, such as the Wenker et al. (2018) study's use of "enclosed spaces" and "surfaces" may be sufficient for studies that have access to the furniture being quantified (due to the ability to measure the size, etc. to gauge more granular observations,) to gauge material use. However, the photograph method used in this study relies on perceived size and use for classifying furniture, which then informs material use. For example, it may be seen quite clearly in an image that there are two "enclosed space"-type furniture units in a room. Since there is no way to measure the size or weight of this furniture, the study would need to rely on the average weight of all "enclosed space"-type furniture to gauge the quantity of materials. However, there is a large range in mass and typical material use between end tables (with a drawer) and wardrobes. Therefore, a more granular approach is preferred.

In this study, a combination of the classifications used by Smardzewski (2015) and van Beijnum (2021), as described in 1.2.3, was used with further modifications to better represent American furniture. Furniture frequently found in American homes for indoor and outdoor recreation was added to the roster and recorded. Seating furniture was distinguished by upholstery and backing features, resulting in distinct categories: couch, upholstered chair, ottoman, dining chair, and stool. Office chairs were separated from upholstered chairs and dining chairs due to the apparent use of mesh or leather textiles and the regular use of plastic. Similarly, plastic and metal storage were separated from other storage categories due to the prevalence of plastic and (ferrous) metals in their compositions, respectively. Coffee tables and consoles have been grouped into one category due to their similar structure and function. For ease of data collection, final decisions on furniture classification were made based on how American furniture store websites typically list offerings. Specifically, "dressers" and "chests of drawers" are cataloged as one product type (Ashley, 2023; IKEA, 2023a; Target, 2023; Wayfair LLC, 2023; Williams-Sonoma, 2023a). Children's play furniture or toys have not been counted unless it is indistinguishable from regular furniture in appearance or apparent use. Furniture units were categorized as listed in Appendix B, and counted as shown in Figures 3.7 and 3.8. A more detailed description of the furniture categories is provided in Supplementary Materials B-3.

Using the furniture categorizations and expectations established, data collection on in-use furniture was performed through movoto.com and other real estate sites (Movoto, 2023; National Association of Realtors & Move, 2023; Zillow, 2023). Figures 3.7 and 3.8 demonstrate how furniture was inventoried and identified through pictures. The images shown are from movoto.com (Movoto, 2023); However, the exact site and home address were not saved and will not be shared for privacy purposes. Note that the pictures were shown one at a time on the website and as much furniture was identified before moving on to the next image in the best interests of time. Upholstery/fabric patterns and other features of the furnishing were utilized to avoid double-counting pieces as much as possible. It may be observed from this example how it may be difficult to gauge sizes, such as "double" vs "single" bed frames, thus it is necessary to categorize the width of the beds in relation to the width of the pillows on the bed. There are also cases, as in Rooms 3 and 4, where the photograph cuts off a furniture piece and there are no additional images at different angles of the room and the furniture piece. In these cases, a "best guess" must be used in the context of the room type, visible features, and size relative to the other pieces in the image. Of course, this practice introduces some error in the quantification of furniture ownership. However, leaving entire pieces unaccounted for will certainly result in error, most likely at a wider margin than misidentifying a product.

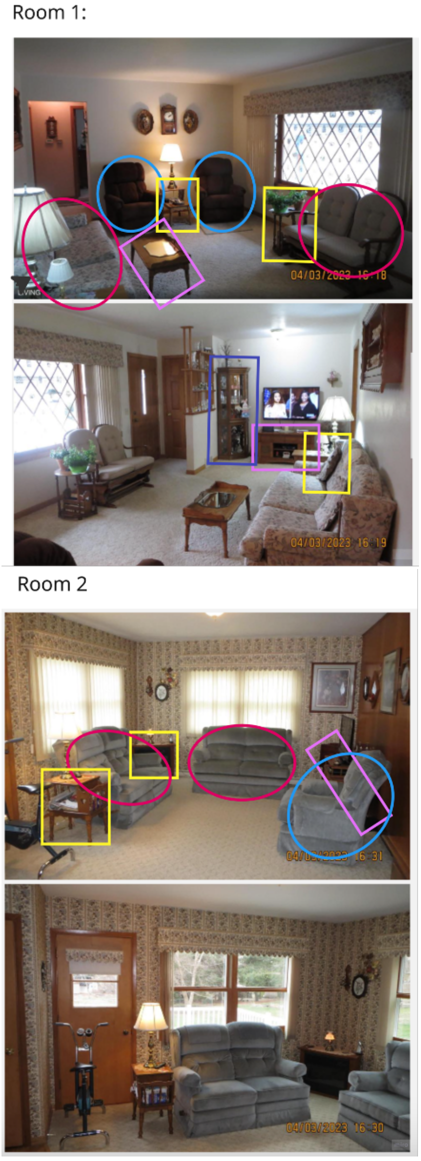


Figure 3.7: Demonstration of furniture identification and counting in Rooms 1 and 2.

- Magenta ovals: Upholstered chairs with more than one seat were counted as couches.
- Blue ovals: Upholstered chairs with one seat were counted as upholstered chairs.
- Yellow rectangles: Tables with a surface area of one seat or less, were counted as end tables.
- Pink rectangles: Tables with a larger surface area than an end table but around the same height were counted as coffee tables.
- Purple rectangle: Furniture units with more than three shelves and no front cover or a glass cover were counted as shelves.

- Yellow rectangles: End tables
- Magenta ovals: Couches
- Pink rectangle: Coffee table
- The bottom picture of Room 2 is a different angle of the same room. The couch shown in the middle of the bottom image is the same as the one on the left of the top image, as it is flanked by the same end tables. No new furniture units were found in the bottom image.

Figure 3.8: Demonstration of furniture identification and counting in Rooms 3 and 4.

- Purple oval: A bed with enough room for only one pillow (without overlapping). Counted as a single bed frame.
- Dark yellow rectangles: The middle unit is shown to be a dresser with more than three drawers stacked vertically. It is not clear what the unit at the bottom left corner of the top image is. However, there are no other angles of this object and the researcher used their "best guess" to conclude that it is also a dresser due to the shape of the front edge, which matches the other dresser, and the height of the unit.
- Purple rectangle: A furniture unit with more than two stacked shelves and a front glass covering was counted as a shelf.

- Dark yellow rectangle: Determined to be a dresser using "best guess" after observing the texture of the front of the unit.
- Blue rectangles: Units with the height of a dining table, but only accommodate one dining chair due to the pedestals at their sides.
- Pink oval: A seating unit with a leg-to-back ratio of a little over 1:1 and surface area for one seat.
- Yellow rectangle: A table with a surface area of around one seat. The presence of drawers or shelves is hidden, so "best guess" was used.

Movoto.com (Movoto, 2023) was chosen as the primary source of furniture unit data for several reasons. It is recommended that any future research using a similar method consider these features of a real estate website before using it as a data source. The first benefit is that the site is in collaboration with multiple real estate companies, for the sake of increased geographical coverage and increased diversity in listing values. Second, listings are available for the entire nation and most or all selected sample areas. Clear pictures of the rooms are provided, often with furniture in them. Ideally, there is a zoom-in feature enabled for the pictures. Next, the listing page structure generally includes readily listed prices, floor space, number of bedrooms, and any other data that is important to the current study. Finally, the overall site structure enables the user to search listings with equal numbers of listings on each page and filter for listings by PSU, price range, and listing type or age.

3.2.4. Speed of the photograph method for data collection

The average speed of performing the photograph method to collect data on in-use household furniture was calculated to inform any future researchers considering this method. After many initial rounds, the researcher was able to achieve a speed of around 2.08 minutes per 1,000 sq ft, or 1.4 s/m^2 with a standard deviation of 0.6 s/m^2. That scales to around 5.2 minutes (+/- 2.2 minutes) per median American single-family home sold in 2022 (221 m^2; US Census Bureau, 2023). Finding samples to perform the photograph method was actually the most time-consuming aspect of data collection, and the time spent on this step varied wildly depending on the availability of listings in the PSU and the norms for real estate listings in that area.

3.2.5. Modeling furniture ownership per floor space unit with linear regression

The furniture unit data was processed with Python using the Seaborn data visualization package (Waskom, 2021). Regression between furniture units and floor space (m^2) was assessed with the coefficient of determination (i.e., R-squared). This analysis was used to decide whether the relationship between floor space and furniture units was sufficient to use as the base model (Figure 3.9). To use a parallel term between the amount of furniture in a given area and the amount of material in a given volume (known as material intensity), the furniture/m^2 will be referred to as the "furniture intensity" at times for the remainder of this report. The furniture intensity of each furniture category is provided in Appendix C.

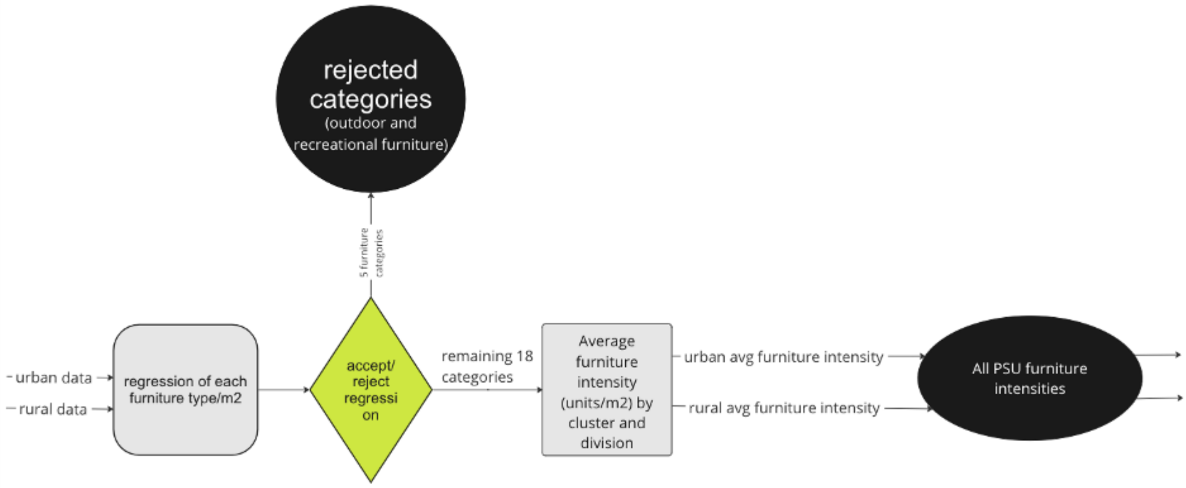


Figure 3.9: Flowchart illustrating regression and decision-making for modeling furniture/m^2.

Figure 3.10 displays a few examples of the regression plots that were used to evaluate the model and determine whether furniture units/floor space in squared meters should be used to calculate total stocks of American household furniture. All of the plots for the furniture categories that will be used in the model are available in Appendix D. The confidence interval (light green shading) around the regression line (dark green) on each plot in Figure 3.10 illustrates the range within which 95% of means would lie for furniture units at a corresponding floor space of any further samples taken, given the data provided to the model (Sim & Reid, 1999). It can be seen from the plots that the confidence interval widens as the floor space grows, meaning that the precision of the regression line for higher floor spaces and higher numbers of furniture units is decreased, relative to lower floor spaces and numbers of furniture units. The decrease in precision, illustrated notably in the plot for dining chair data (bottom left, Figure 3.10) may be due to higher variability of furniture intensity for larger homes or a lack of data for larger homes. This returns three possibilities concerning the relationship between furniture intensity and floor space. One is that the furniture intensity for smaller homes is less variable than for homes with larger total floor spaces. Secondly, more data concerning larger homes is required to increase the precision of mean furniture intensity in larger homes. Finally, it

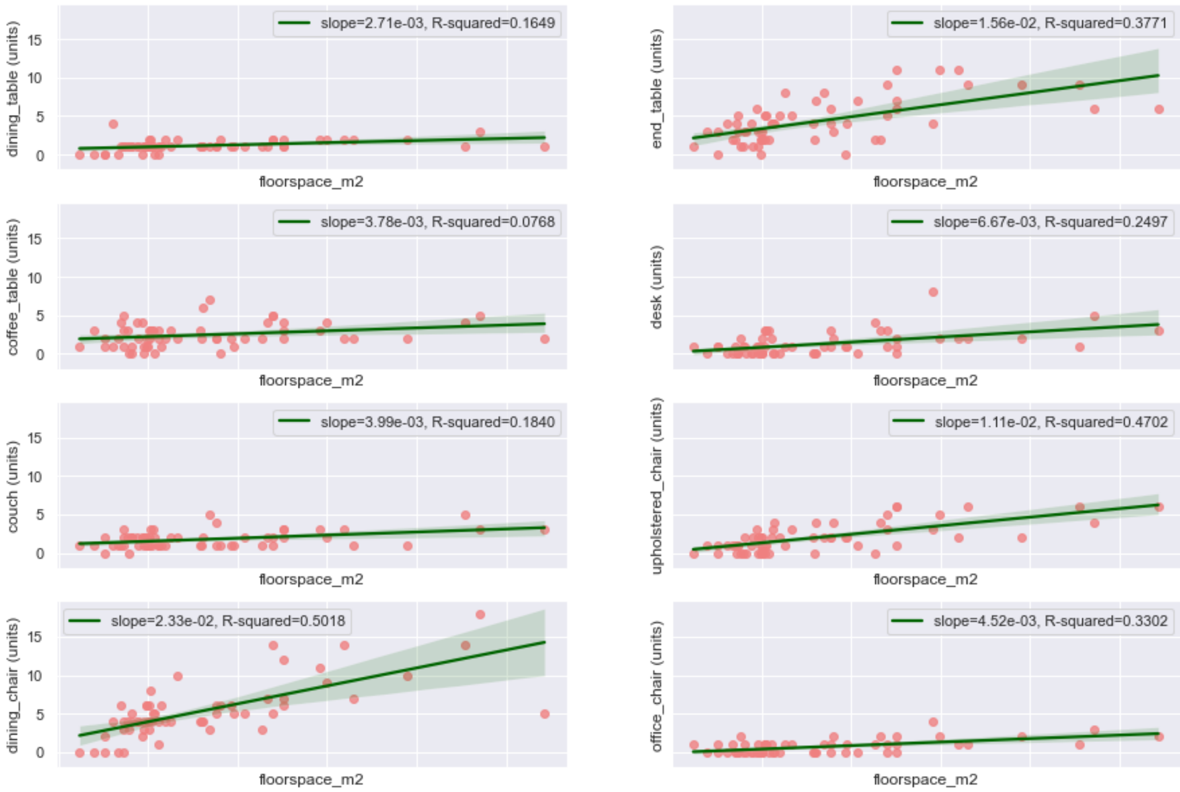


Figure 3.10: Example regression of furniture units/m2 of urban residential floor space sampled for each furniture category.

may be that there are other mediating factors that affect furniture ownership, especially for larger homes. R-squared is displayed in the regression plots to illustrate the extent to which the samples taken in the study show that floor space is a factor of furniture units or furniture ownership. The figures for R-squared can also be interpreted as the “percentage of correctness obtained by the regression” (Chicco et al., 2021). The R-squared values found in this study were all found to be relatively low, with the R-squared value for couches to be the highest at 0.2429 and the lowest being 0 for swing sets and trampolines. Only five of the furniture categories of the 26 scored above 0.1, these being indoor, non-recreational furniture categories. However, a low R-squared value was expected as several other factors are assumed to be factors of furniture ownership aside from floor space, such as income, life stage, and even cultural factors (e.g., minimalism). Thus, for the sake of simplifying the model, this study uses floor space as the single factor of furniture ownership, with no mediating factors for the base model.

Recreational furniture categories (i.e. recreational tables, trampolines, swingsets, and basketball hoops) will be excluded from the scope of this study moving forward due to the binary nature of furniture ownership in these categories and the finding that ownership of these pieces is not dependent on floor space. Following the convincing example of trampolines and swing sets, as well as the lack of material intensity or composition data, outdoor furniture categories (i.e., patio chairs, tables, and umbrellas; benches) will also be excluded from the scope of the remaining length of the study due to doubts about the relationship between indoor floor space and outdoor furniture. Based on a quick calculation using the weighted average mass of the cutoff furniture per m^2 compared to total furniture mass, the decision cuts off around 14% of the mass accounted for in the collected furniture unit data. Outdoor and recreational furniture will be discussed as counterexamples for this model in Chapter 6.

3.2.6. Putting it all together: Obtaining the static stock of American household furniture

Finally, multiplying the accepted linear regression models from Section 3.2.5 by the IMAGE SSP2 (Stehfest et al., 2014) data for floor space in American households in 2020, an estimate for the total number of furniture units in American households is calculated. Equation 3.1 represents this calculation, as F is the total estimated furniture units, P is the US population in a given year, f is the floor space per capita, and x_i is the furniture unit per m^2 for each furniture category. n is the number of furniture categories being considered in the study.

More about the IMAGE SSP2 scenario data can be found in Section 3.3.1. The actual static portion of the analysis will conclude here, as the input to the dynamic model will be the furniture stock, in units. The final "snapshot" results for material stocks in household furniture were obtained after conducting the dynamic stock analysis, from which the results for each year can be pulled.

$$F = \sum_{i=0}^{n} P * f * x_i \tag{3.1}$$

3.3. Modeling dynamic household furniture stocks and flows

When conducting a dynamic material flow analysis (d-MFA), the dimension of time is added to the analysis and allows for the study of system behaviors over time (Müller et al., 2014). The timestep, or the smallest unit of time considered for the investigation of the system, is usually one year (Müller et al., 2014), as it is in this study. The scope of d-MFAs can be largely distinguished as retrospective and prospective studies. Some studies, such as the current study, are a combination of both. Retrospective d-MFA analyzes past stocks using historic data, whereas prospective d-MFA extrapolates known data to project into the future. Referring back to the MFA types (Augiseau & Barles, 2017) introduced in 3.1, this study is also an example of a stock-driven model, as the minimum required stock is estimated with the static model and used to calculate the necessary inflows, accounting for any outflows that have occurred and any changes to the minimum stock requirements. To first estimate the stock and its changes over time requires the use of variables that are endogenous and exogenous to the model. Exogenous model variables affect the values of various endogenous variables without being changed, itself (Müller et al., 2014). The endogenous variables in this study are the inflows and outflows. Each inflow per year is an age cohort of the product that is input to the stock at one discrete timestep of the model (Pauliuk & Heeren, 2020). Each cohort may have its own characteristics, such as composition, lifetimes, and recycling rates. On the other end, dissipation is a concept used notably by (Ayers, 2002, as cited in Müller et al., 2014) to describe outflows, the tendency for materials in a stock to eventually be taken out of the in-use stock as irrecoverable waste, recycled, or reused. The rate of outflow is determined by the lifetime of products that make up the stock. In this section, each of these necessary inputs of the dynamic model, as well as the outputs, will be described.

3.3.1. Using floor space data to calculate dynamic household furniture stocks

The exogenous variable that will be used to drive the minimum required stock in this study is residential floorspace in the US over time. Data from IMAGE 3.0 (Stehfest et al., 2014), under the scenario labeled SSP2 was used to obtain estimates of the US population from 1970-2100, urbanization from 1971-2100, and floor space by income quintile and urban/rural areas from 1970-2100. The IMAGE data used in this study has been provided as Supplementary Material F.

Due to the limitations of d-MFA and the need to assign lifetimes to each cohort, assigning a positive stock at year 0 of the analysis will imply that all of the initial stock was input to the material stock in year 0 and that all of this stock has the same probability of dissipation at each timestep. However, it is likely that some of that stock came into the stock in previous cohorts, thus different parts of the stock have various probabilities of dissipation. To solve this issue, the floorspace per capita was extrapolated down to zero to 1900 (Müller et al., 2014), allowing for the initial stock within the scope of the study to be composed of various cohorts at different points in their lifetime, thus having different probabilities of dissipating in the next year.

The household furniture stock estimates that the Dynamic Stock Model (DSM) returned was multiplied and subsequently multiplied again by furniture intensity estimates as shown in Figure 3.11 to obtain the estimated number of total furniture units/year as an input to the DSM. This is similar to the calculation performed to obtain the static household furniture stock (Equation 3.1); However, the equation is performed for each year of the study. The total furniture units/year, also known as the minimum stock for each year, and the inflow of each year is calculated as the outflow from that year and any additional stock needed to meet the minimum stock amount. Any year within the study period can be specified in the Python file (Supplementary Materials G-3) to obtain static results, such as the plots displayed in Chapter 4. The historical data and projection provided by the IMAGE model contributed to the calculations made for the dynamic stocks of American household furniture.

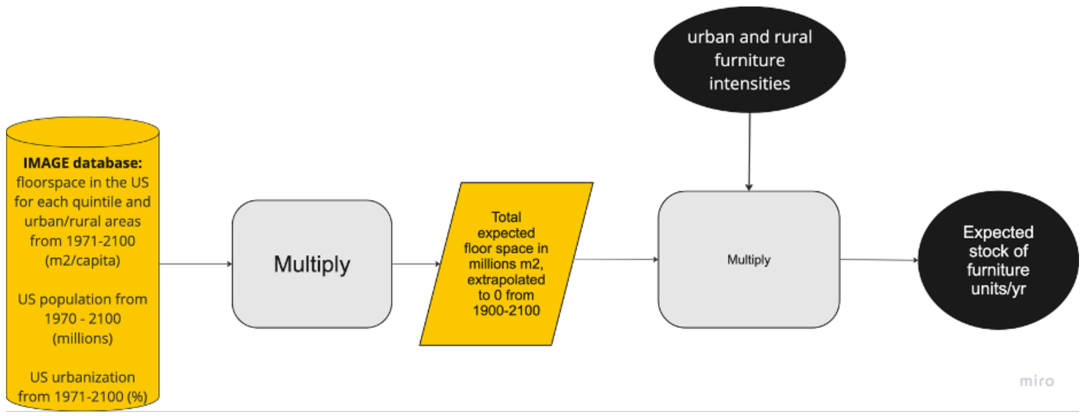


Figure 3.11: Flowchart illustrating the use of data from IMAGE 3.0 SSP2 to calculate the minimum furniture stock per year.

3.3.2. Estimating furniture product lifetimes

Lifetime is a characteristic of a product that defines the probability that the product will be taken out of the stock as outflow as it ages. Models often use distribution functions, which are used to estimate the portion of an inflow cohort that remains in the in-use stock at any point in time. Depending on the shape of this distribution (e.g., normal, Weibull distribution, and so forth), there may be more or less of the cohort leaving the in-use stock when that cohort reaches a certain age. For example, if the lifetime of dining chairs has a normal distribution with a mean of 15 years, it is likely that most dining chairs will be disposed of (i.e., leave the material stock) after around 15 years of use. Some chairs may survive until the age of 20, but some chairs may also only survive 5 years or less.

The lifetimes used in this study have been referenced in Supplementary Materials C-2 and are summarized in Table 3.1. The lifetime of the products used to assess material intensity and lifetime were all found in scientific and grey literature for life cycle analyses (LCAs) on furniture, then averaged. To conduct the LCAs, practitioners are required to identify the service lifetime of the product in question (Guinée et al., 2002). However, in the case of furniture, the economic lifetimes assigned to many assessments are assumptions or are sometimes omitted from the study (Cordella & Hidalgo, 2016). By averaging the lifetimes, it is also assumed that the variations of products within each furniture category occur at equal frequencies. Based on an estimation made by Hebrok (2016), most furniture has a lifetime of 2-30 years. For this study, that conclusion was assumed to mean that approximately 95% of furniture has a lifetime that falls around the mean. The distribution was assumed to be a folded normal distribution to avoid any negative lifetime values, with a mean of 15 years and a standard deviation of 7.5 years.

Table 3.1: Description of indoor furniture categories.

Furniture category	Average lifetime used	Sources
Dining table	15	Alonso (2022c); Breedveld (2022c)
End table	15	Breedveld (2020d)
Coffee table	15	Breedveld (2020d, 2021d); Hoxha & Jusselme (2017); Sessa (2018)
Desk	22.5	Alonso (2022b), Sessa (2022b); Spitzley et al. (2006); Wang et al.(2016)
Couch	15	Breedveld (2021b); Hoxha & Jusselme (2017); Wang et al. (2016)
Upholstered chair	13.4	Bianco et al. (2021); Breedveld (2021b); Prunel (2021)
Dining chair	15	Breedveld (2020b, 2020a, 2021e, 2023e, 2023a, 2023b, 2023d)
Office chair	18	Alonso (2022a); Breedveld (2023b); Linkosalmi et al. (2016b); Spitzley et al. (2006)
Stool	15	Breedveld (2019, 2021a)
Ottoman	15	Breedveld (2020b, 2021d)
Single bedframe	15	Coloma-Jiménez et al. (2022); González-García et al. (2011); Sessa (2022a)
Double bedframe	15	Hoxha & Jusselme(2017) ; Sessa (2022a)
**Shelf	12	Linkosalmi et al. (2016)
Dresser	15	Sessa (2022b)
Wardrobe	10	Alonso (2022d); Iritani et al.(2015) ; Medeiros et al.(2016); Wang et al. (2016)
Plastic storage	5	**Researcher estimate
Metal storage	15	Alonso (2021); Ecovibes (2021)
Folding table	15	**Researcher estimate

*** Indicates that the estimates for the furniture category contains calculations made by the researcher. See Supplementary Materials C-2 for more information and calculation*

3.3.3. Estimating the material intensity of furniture products

Material intensity is the amount of a type of material, as defined by the modeler, within one unit of good or product. This is necessary to calculate the stocks of these materials from the total amount of product. In this study, the mass of materials will be described in kilograms per unit of furniture, and each type of furniture will have different material intensities. Table 3.2 shows the categorization of material types following a survey of LCAs in scientific literature and industry data (Supplementary Materials C-2). The average material intensity in kilograms of each material category per furniture unit (Table 3.3) was weighted by the corresponding furniture intensity of each product type for urban areas (Supplementary Materials B-2). A majority of the LCAs that informed the material intensities used in this study were accessed from the Environdec database (Alonso, 2021, 2022a, 2022b, 2022c, 2022d; Breedveld, 2019, 2020a, 2020b, 2020c, 2021a, 2021b, 2021c, 2021d, 2023a, 2023b, 2023c; EcoVibes, 2021; Prunel, 2021; Sessa, 2018, 2022a, 2022b). Other studies were pulled from scientific literature (Bianco et al., 2021; Coloma et al., 2022; González-García et al., 2011; Hoxha & Jusselme, 2017; Iritani et al., 2015; Linkosalmi et al., 2016; Medeiros et al., 2017; Spitzley et al., 2006; S. Wang et al., 2016). Material intensity results for plastic storage, one of the two shelf products, and the folding table were calculated by the researcher from product specifications accessed through ULINE.com (ULINE, 2023a, 2023b, 2023c, 2023d, 2023e). The "tables and desks" category includes dining, coffee, end, and folding tables, as well as desks. "Upholstered chairs" refers to couches, upholstered chairs, office chairs, and ottomans. "Un-upholstered chairs" represent dining chairs and stools. Single and double bedframes are both included in the "beds" category. Shelves, dressers, wardrobes, plastic storage, and metal storage are all represented under the "storage units" umbrella.

3.3.4. Differentiating the mass of furniture between income quintiles

A survey of furniture products sampled revealed that furniture at different price points tends to have different scales of mass. In order to reflect this phenomenon in the model, further data was collected on sample products from each furniture category to estimate a weighting factor for three different representative furniture product categories (dining tables, upholstered chairs, and double bedframes, as categorized in this study (Table B.1). Five furniture retailers with the highest US brick-and-mortar and online sales (Statista Research Department, 2022b, 2022c) with a national distribution network were chosen from each of which five products at different price points spaced across the total price range in each representative furniture category. These retailers are listed below.

- Target (Target, 2023): A representative of discount furniture retailers, especially known for ubiquitous distribution and online sales.
- Williams-Sonoma (Williams-Sonoma, 2023a): A representative of high-end furniture, one of the highest-grossing furniture retailers in the country (Statista Research Department, 2022c).
- IKEA (IKEA, 2023a): A representative of discount furniture retailers, known for transforming the market with flatpack distribution and self-assembly (IKEA, 2023b).
- Ashley Furniture Store (Ashley, 2023): A representative of mid-tier furniture retailers and one of the highest-grossing furniture retailers in the US (Statista Research Department, 2022c).
- Wayfair (Wayfair LLC, 2023): A representative of online furniture retailers and one of the highest-grossing furniture retailers in the online category (Furniture Today, 2020). They provide a selection of furniture at wholesale to high-end prices.

Table 3.2: Categorization of material labels that were found in the literature used to inform material intensities.

Material category	Material labels, as seen in the literature			
Solid wood	Solid wood	Beech	Camphorwood	White oak
	Wood (if indicated as solid	Birch	Padauk	Rubber wood
	Solid timber	Pine	Cherry	Hardwood
Wood layers	Wood	Painted wood	Backing material	Other wood/paper
	Ply(wood)	Veneer (birch)		
Particleboard	Particleboard	Laminate	MDF	Wood wool
	Laminated board	HDF	MPD	Chipboard
Paper	Paper	Carton	Cardboard	Paperboard
Metals	Non-ferrous metals	ZAMAK	Copper	Zinc alloy
	Metal (pieces), screws, staples,	Aluminium	Brass	Other metals: Aluminium,
		Aluminium & other non-	Alloy (Cu, Zn, Al)	
Ferrous metal	Steel	Stainless steel		
	Iron	Steel parts		
Plastic	Plastics (pieces)	Extrude polystyrene	Polypropylene parts	POM
	ABS (polymer)	PE film	PP GF30	Polyester (fibre, cloth)
	PU/PUR/polyurethane (base)	PE/polyethylene	PA6	Powder coating
	PU (flexible) foam	LDPE	PA6 GB30	Recycled foam
	Polystyrene foam slab	PP/polypropylene	PA6 GF30	PVC tape
		PP/glass fibre	Nylon (zipper)	TPE
Other polymers	Polymer	Isocyanate	Epoxy – polyester resin	Other polymers
Concrete	Concrete			
Glass	Glass			
Rubber	Rubber			
Paints	Paints and varnishes	Sealant	Acrylic varnish	Finish
	Paints	Acrylic lacquer	Tint	Master
	Alkyd paint			
Adhesive	Glues and adhesives	PVAs	Hot-melt adhesive	Adhesives and plastics
	Glue (UF)	PVAc	Spraying glue	Adhesives and finishes
Textiles	Textiles	Fabric	Textiles (upholstering)	Wool
	Textile thread	(Woven) cotton	(Sheep) leather	Felt
	Natural fibre			
Other substances	Silicone	Oil	Lead	

Table 3.3: Weighted average material intensities for major furniture categories, kg/furniture unit.

Material	Furniture category				
	Tables and desks	Upholstered chairs	Unupholstered chairs	Beds	**Storage units
solid wood	13.3264	16.9113	4.043	1.3499	8.3509
layer wood	0.8119	0.0009	1.2282	0.392	0.3392
particle-board	8.0748	0	0	15.4728	40.7831
paper	0.1711	0.0003	0	0	0.4008
metals	0.6363	0.0002	0.0344	0.2482	0.5358
ferrous metal	4.4531	0.0013	4.3935	0.0907	10.2415
plastic	0.4752	0.0018	1.0445	0.1244	3.0695
concrete	0.8401	0	0	0	0
glass	2.0096	0	0	0	0
rubber	0.0004	0	0.0001	0	0
paints	0.0704	0.0001	0.0876	0	0.1502
adhesive	0.0891	0	0.2775	0.0006	0.0737
textiles	0.0096	0.0021	0.3126	0	0.0019
other polymers	0.0422	0.0002	0.5279	0	0.0188
other substances	0.1398	0	0.0312	0	0.0024
Category sources	Alonso (2022a, 2022b); Breedveld (2020d, 2021d); Hoxha & Jusselme (2017); Sessa (2018, 2022); Spitzley et al. (2006); Wang et al. (2016).	Alonso (2022a); Bianco et al. (2021); Breedveld (2020c, 2021f, 2021c, 2023c); Hoxha & Jusselme (2017); Linkosalmi et al. (2016c); Prunel (2021b); Spitzley (2006); Wang et al. (2016).	Breedveld (2019, 2020a, 2020c, 2021a, 2021e, 2023a, 2023c, 2023d, 2023e).	Coloma-Jiménez et al. (2022); González-García et al. (2011); Hoxha & Jusselme (2017); Sessa (2022a).	Alonso (2021, 2022d); EcoVibes (2021); Iritani et al. (2015); Linkosalmi et al. (2016); Mederios et al. (2017); Sessa (2018); Wang et al. (2016).

*** Indicates that the estimates for the furniture category contains calculations made by the researcher. See Supplementary Materials C-2 for more information and calculation methodology.*

Figure 3.12: Flowchart illustrating the process for finding quintile weighting factors, using the example of Quintile 3.

Where there was an inadequate selection for certain furniture categories from any given retailer, other stores providing a wider selection in that category was used. For this study, La-Z-Boy's (La-Z-Boy Incorporated, 2023) online retail platform was also used to supplement the representation of high-end upholstered chairs. For each retailer and each furniture category, the products were sorted using the sorting filter "Price: Low to High". The number of products was then divided into quartiles and a representative product from the end points of each price range was chosen (usually a product with the price at the demarcation line for each quartile) for a total of five products. In the case of retailers where too many products existed in the category to list (as was the case with Wayfair), the visible number of pages was divided in this manner and products were chosen. In the case of some furniture categories, researcher discretion was practiced for filtering products that fit into the specific furniture category within the retailer site but did not fit into the description of the furniture, as described in Section 3.2.2; for instance, sofa covers in IKEA's online sofa selection.

As shown in Figure 3.12, the weight for each representative product was sorted according to the original retail price. The sample products for each category were then divided into quintiles, and the mass per functional unit of the furniture units was averaged for each quintile and then divided by the average of all masses per functional unit to obtain the quintile weighting factor (Equation 3.2). Q_n for each quintile was then divided the average $\bar{x}_{Q_n}$ for all quintiles $\bar{(y)}_Q$ to find the quintile weighting factor. The sources and equations for all products and weighting factors can be found in (Supplementary material D-1).

$$Q_n = \frac{\bar{x}_{Q_n}}{\bar{y}_Q} \tag{3.2}$$

3.3.5. Differentiating the wood types used in furniture between income quintiles

A survey of furniture products sampled for Section 3.3.4 revealed that furniture at different price points tends to use different types of wood-based materials. In order to reflect this phenomenon in the model, further data was collected on sample products from each furniture category to estimate the percent contribution of each wood type (particleboard, layer wood, and solid wood, as categorized in this study (Table 3.2) to the wood mass of the American furniture stock for each income quintile. In addition to the stores listed in Section 3.3.4, five stores that are all known to have national distribution and high sales column for furniture online and/or in store (Statista Research Department, 2022b, 2022c) provided additional data: Amazon.com (2023) for office chairs and single bedframes; West Elm (Williams-Sonoma, 2023b) for single bedframes, shelves, and wardrobes; MattressFirm.com (2023) for single bedframes; Big Lots (2023) for single bedframes; and Home Depot (2023) for wardrobes. Data was first collected from representative furniture product listings in the first, third, and fifth price quintiles of each website to see what types of wood the furniture in each quintile contained. To decrease the need for further sampling, it was necessary to create aggregate categories of the furniture types. Surface- and panel-type furniture were distinguished from furniture types that used a frame (frame-types) to support upholstery or padding. This was done because it seemed that as the price of the product went up, the wood used in panel and surface types was more prominent in the design of the product, whereas the composition of upholstery materials was given more attention in the design of furniture in frame-type categories.

For every wood type within each aggregated furniture category and price quintile, a "score" was determined to indicate the prevalence of that wood type. A 1.0 was given to the wood type if the furniture listing is shown to only contain that wood type. If a furniture product has multiple types of wood in it, it is assumed (unless otherwise stated on the product site) that there is an even amount of each listed type of wood in the product (by mass). This was done to decrease the error that would result from detailed calculations on furniture parts and wrongly hypothesizing their wood compositions. Most listings did not provide enough information to accurately inform the researcher which type of wood was in which part of the furniture. The assumed percentage for each type of wood is then added to its total "score" for the furniture category for that quintile. For example, if a dining chair in Quintile 5 is described as containing solid wood and particleboard, 0.5 is added to the solid wood score for dining chairs in Quintile 5 and 0.5 is added to the particleboard score for dining chairs in Quintile 5. If the next chair listed has only solid wood, then a 1 is added to the score for solid wood, Quinitle 5. This brings the score for solid wood in dining chair, Quintile 5 to 1.5. This only pertains to the wood that is contained in a given furniture product, so if the product contains no wood, then nothing is added to any of the wood scores. After the final score for each wood type in each category and price quintile is added, the scores are normalized as a percentage of the sum of scores for solid wood, layer wood, and particleboard. More details on the data and formulas used for this process can be found in Supplementary Materials C-2.

The estimates for each category are listed in Table 3.4. For panel-type furniture (i.e., dining tables, end tables, coffee tables, desks, shelves, dressers, and wardrobes), the lowest price quintile is dominated by products made primarily of particleboard. By the highest-price quintile, the products are estimated to be comprised of mostly solid wood. On the other hand, frame-type furniture (single and double bed frames, couches, upholstered (arm)chairs, dining chairs, office chairs, stools, and ottomans) contained more layer wood at the lower price quintiles. Solid wood and particleboard are estimated to be present in similar quantities. At the highest quintile, frame-type furniture contains about half solid wood and particleboard becomes slightly more common as well, while layer wood is less dominant.

Finally, the average material intensities, quintile weighting factors, and the wood composition by price quintile were multiplied to find the material intensity for each furniture category and each income quintile (Supplementary Materials C-1).

3.3.6. Running the model with Python

The Dynamic Stock Model by Pauliuk and Mutel (2014) was handled as a black box in this method to estimate the stocks and flows of home furnishings over time. The model was used within a Python file created for this study (Supplementary Material G-3), with the inputs of the expected furniture stock obtained in Section 3.3.1, along with the mean and standard deviation of lifetimes for each furniture category (Section 3.3.2). The outputs of the Dynamic Stock Model are the stock and outflow of furniture units in millions per year by cohort, and the inflow of

quintile	wood type	Estimated composition of wood parts for panel- and surface-type furnishings	Estimated composition of wood parts for frame type furnishings
1	solid wood	0.01	0.2
	layer wood	0.09	0.6
	particleboard	0.9	0.2
2	solid wood	0.18	0.4
	layer wood	0.095	0.4
	particleboard	0.725	0.2
3	solid wood	0.35	0.6
	layer wood	0.1	0.2
	particleboard	0.55	0.2
4	solid wood	0.475	0.575
	layer wood	0.15	0.2
	particleboard	0.375	0.225
5	solid wood	0.6	0.55
	layer wood	0.2	0.2
	particleboard	0.2	0.25

Table 3.4: Estimates for the composition of wood types within the wood mass in household furniture at different price quintiles. The compositions are assumed to be different between two categories, those categories being panel- and surface-types (all tables, shelves, dressers, and wardrobes), and frame-types (couches, upholstered (arm)chairs, dining chairs, office chairs, stools, ottomans, and single and double bed frames.)

furniture units in millions per year.

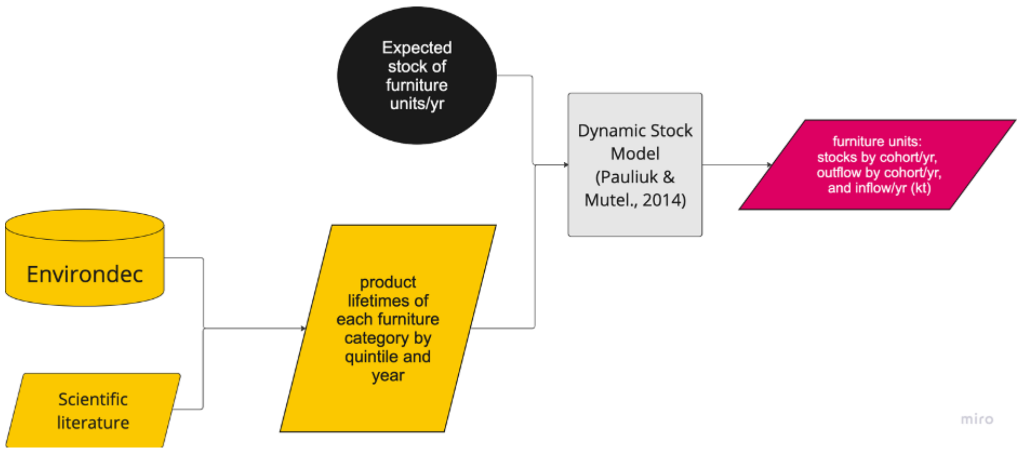


Figure 3.13: Flowchart illustrating the inputs to the Dynamic Stock Model and the outputs of dynamic furniture stock, outflow, and inflow.

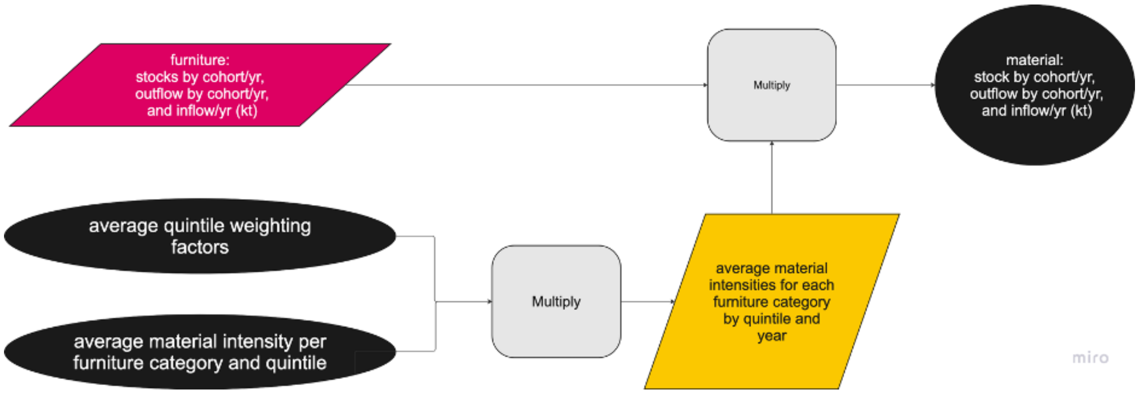


Figure 3.14: Flowchart illustrating inputs and processes needed to obtain material stocks for the dynamic base model.

The model_runner Python file (Supplementary Materials G-3) used in this study functions as a loop through which the furniture stock estimator (Supplementary Materials G-2) and the Dynamic Stock Model are run for each value of the dimensions (area type, quintile, and furniture category), as specified by the user. The file outputs a dataframe, saved to an Excel spreadsheet (Supplementary Materials H), that gives the results of the model for each dimension value specified. The same Python file also outputs the visual representations of the results, as shown in Chapter 4.

4 Base Model Results

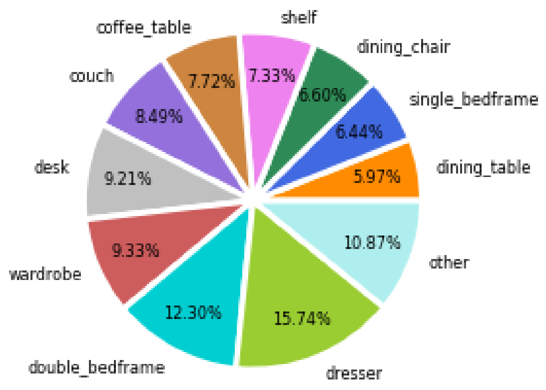
In this chapter, the results of the base model will be displayed. The design of the base model is as described in Chapter 3, with no further adjustments made to the model parameters. The material intensities and the furniture intensities are assumed not to have changed over time. Scenarios with changes to the model parameters are tested in Chapter 5. Limitations and implications of the base case results and scenarios are discussed in detail in Chapter 6.

4.1. The results for static stocks of material in American household furniture

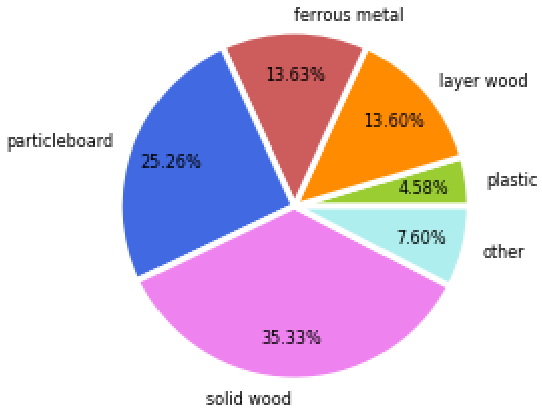
Using the basic version of the model developed as described in Chapter 3, 146 kt of household furniture was estimated to be in use within the US in 2020. A snapshot of the composition of the American household furniture stock in terms of mass of each furniture type in 2020 is provided in Figure 4.1a. Double bedframes (darker teal) and dressers (light green) each represent more than 10% of the material stock and are the top contributors to American household furnishings in terms of mass. Again, the "other" category represents the aggregate of any furniture types that make up less than 4% of the stock estimated in the base model (light teal).

The base case returns an estimation (Figure 4.1b) that demonstrates that wood-based materials – solid wood (pink), layer wood (orange), and particleboard (dark blue) – together comprise about 74% of the total material stock for American household furniture. Of the wood-based materials, solid wood is the most dominant wood material represented in the furniture stock at 35% and particleboard is second at 25%, in terms of mass. Ferrous metals also represent a large portion of the material stock in American household furniture, at 13%. Plastic represents about 4.5%, a relatively minor, but still notable portion of the material stock in household furniture in 2020. The "other" category in Figure 4.1b is an aggregate representation for all material categories that did not include more than 4% of the mass in the material stock of American furniture. These categories include non-ferrous metals, other polymers, paints and varnishes, textiles, adhesives, glass, concrete, rubber, and other (miscellaneous) substances.

When the composition of material stocks is compared between the highest and lower American income quintiles, there is a clear change. The mass used in furniture and used by the lowest quintile (Figure 4.2a) is largely composed of particleboard (dark blue) and also of layer wood (orange). In contrast, the Americans earning higher incomes (Figure 4.2b) use furniture that is composed primarily of solid wood (pink), according to the results of the base model. All three of the topmost prominent materials in the furniture stock for Americans in Income Quintile 5 are wood-based. The large percentage of biomass (i.e., wood) in the American furniture stock suggests that there are opportunities to use the stock as carbon storage. However, applications of household furniture toward carbon storage may be complicated when there is a large amount of particleboard in the material stock. These opportunities will be discussed in more detail in Chapter 6.

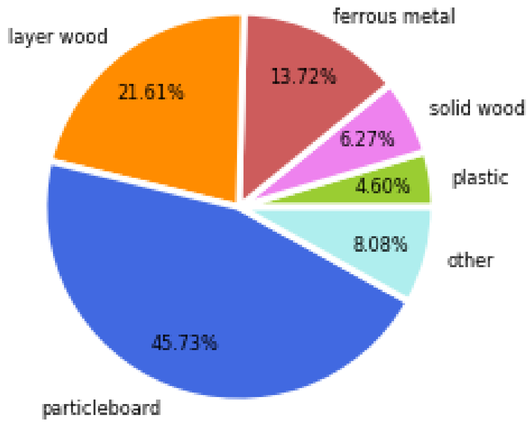


(a) The percentage of mass by furniture category in 2020.

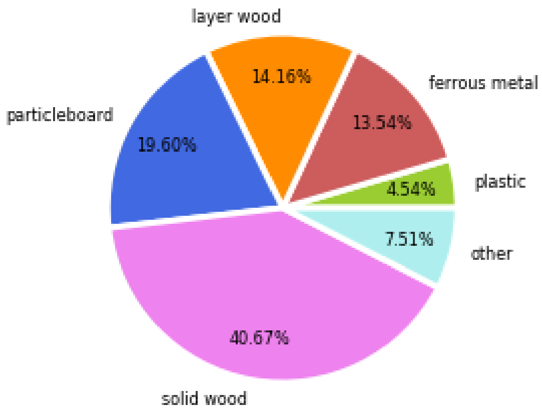


(b) The percentage of mass by material type in 2020.

Figure 4.1: Composition of the total material stock of American household furniture in 2020.



(a) The percentage of mass by material type for the lowest income quintile (Q1) in the US, 2020.



(b) The percentage of mass by material type for the highest income quintile (Q5) in the US, 2020.

Figure 4.2: Composition of the material stock owned by Income Quintiles 1 and 5, respectively, 2020.

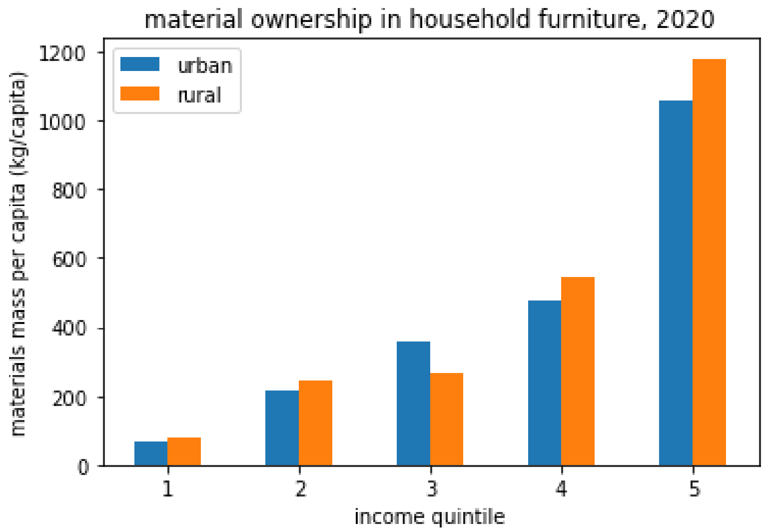


Figure 4.3: Estimated material ownership per capita by area type and quintile in 2020, base case.

Figure 4.3 shows the static furniture ownership in kg per capita for 2020 by income quintile and area type in the US. The blue bars show the results for urban areas, whereas the orange bars show the results for rural areas. Income Quintile 1 represents the fifth of the adult US population with the lowest incomes, and Income Quintile 5 represents those with the highest incomes. The general pattern shown in the figure illustrates that consumers at higher income levels tend to have higher masses of in-use stocks of furniture per capita in comparison to consumers at lower income levels. The mass per capita in household furniture owned by the highest income quintile surpasses the mass of material stock per capita of the lowest income quintile by a scale of 12. The highest income group also seems to have about twice the mass in material ownership than the next highest (fourth) income group. Given the initial assumption that higher-quality items have higher mass and the finding during model development that confirmed this assumption (Supplementary Materials D-1), the added weight of materials contributes to the scaled-up material ownership. After a sensitivity analysis comparing a run of the base case model with no quintile weighting factor and a run with the use of the quintile weighting factor, the sensitivity of the material stock of Quintiles 1 and 5 are -0.32 and 0.59, respectively.

The base model results also show that the rural areas tend to have slightly more mass per capita in furniture than their income counterparts, except for in the third income quintile. One explanation for this is that there is more floor space per capita in rural areas (Mazur, 2016; Moura et al., 2015). Thus, there is less furniture per unit of floor space, but more furniture per capita than in urban areas. Upon reviewing the furniture intensities (Supplementary Materials B-2) of the third quintile in each area type, it appears that most furniture categories included in the results occur at a higher rate over floor space in urban spaces than in rural areas. The exceptions were stools, single bedframes, shelves, dressers, and metal storage units B). Both urban and rural areas display an upward trend in material ownership in household furniture as income increases. It seems that the income disparities of material ownership may be similar whether one lives in the city or the country.

4.2. The dynamic stocks and flows of materials in American household furniture

4.2.1. Overall dynamic base case results

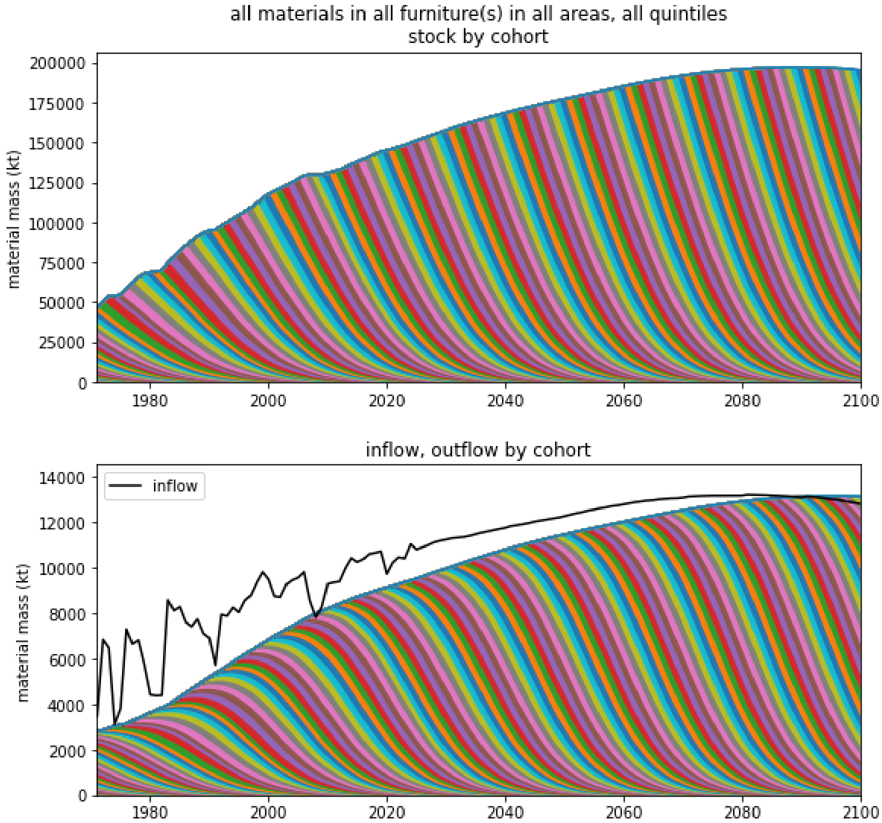


Figure 4.4: Total stock of materials in household furniture (kt) by cohort, outflow by cohort, and inflow for the base case, 1971-2100 for all areas, quintiles, furniture categories, and material types.

Figure 4.4 shows the dynamic results of the stock-driven model of the material mass in furniture in all areas, quintiles, and for all furniture types. The stock of American household furniture over time is illustrated in the top plot. The outline of the area plot (area plot outlined in blue) represents the total stock over the years. The stock is expected to keep growing until around 2080 when the minimum demand for furniture plateaus and may even start to decrease. Each stripe on the plot area represents a cohort of the material input to the stock. As the products of each cohort reach the end of their functional lifetime over time, the cohort stripe tapers until it is no longer represented in the total stock. Because the average lifetime for most of the furniture categories was specified to be 15 years, with some categories ranging from 5 to 22.5 years, and a standard deviation of 50% of the average lifetime, the stripes span around 30 years from the beginning until it is no longer visible.

The bottom plot shows the inflows (black line) and the outflows of the materials in household furniture by cohort (area plot outlined in blue). The results of the dynamic model for the base case shows that the inflow, or the demand of new furniture materials, is expected to reach saturation towards the last decade of this century when the inflow of household furniture materials meets the American minimum demand for household furniture materials. After saturation is reached, base model projects that the outflow from the American stock of household furniture will be larger than the inflow. Until then, however, the capacity of the current furniture stock is expected to be overwhelmed by the need for new materials. Even with furniture recycled at 100% into new furniture, new materials will need to be added until the minimum demand for furnishings plateaus in the distant future.

4.2.2. Dynamic base case results by area type

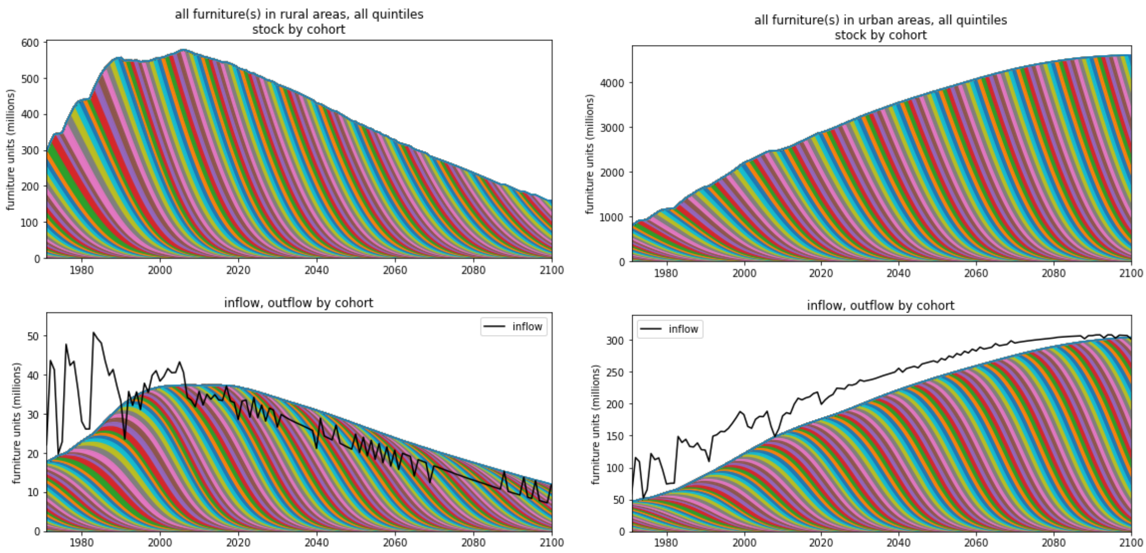


Figure 4.5: Rural (left) and urban (right) inflows and outflows of materials in household furniture, base case, 1971-2100.

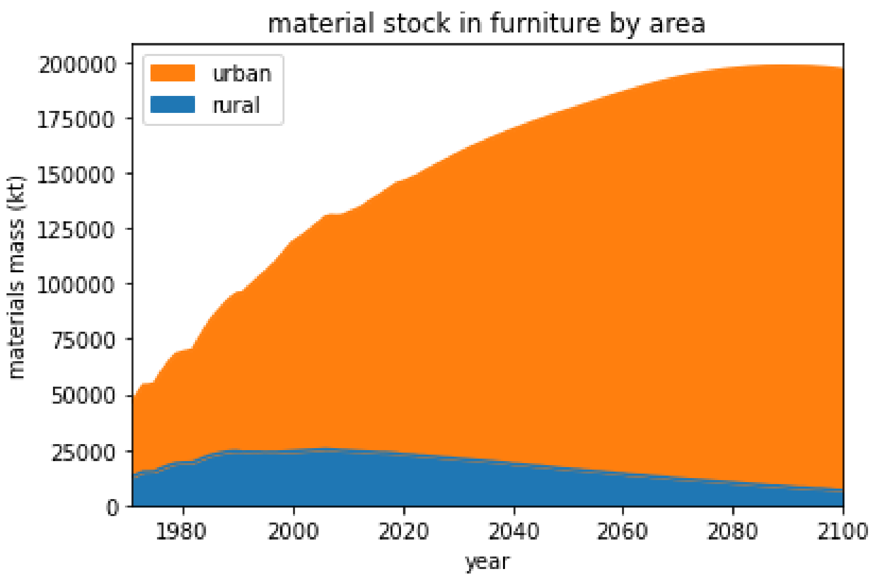


Figure 4.6: Material ownership by area type, base case, 1971-2100.

Figure 4.5 shows the dynamic results after separating the base case results by area type. It is clear that the rural and urban areas of the US are experiencing very different trends when it comes to materials in household furniture. Rural demand for furniture material has been decreasing steadily since the late 2010s, and this trend is expected to continue throughout the century. On the other hand, the material stock in urban household furniture has been increasing from the start of the study period, and the rate of growth in the stock is expected to slow only at the end of the study period, or the end of the century. In the rural results, the cohort sizes are larger when stock in rural areas increases at higher rates from 1980 to the mid-1990s, and the cohort sizes decrease when there is a slowing or decreasing demand for materials in rural areas. While the demand for new materials decreases, the dissipation of material from the accumulated stock continues, resulting in an outflow that is larger than the inflow of household furniture materials in rural areas of the US. Demand for household furniture materials in American urban areas is expected to act very differently, with demand outpacing outflows until the end of the century, with both inflow (the demand) and outflow increasing until the last decade of the study period.

The scale of furniture ownership in rural areas is minor compared to that of urban areas (Figure 4.6). By far, urban areas are hotspots for material ownership and with increasing urbanization, the composition of rural ownership becomes smaller, even as the overall material ownership plateaus. In 2020, consumers in urban America are estimated to have owned 84% of the material stock in household furnishings. In 2050, that portion increases to 91% and then finally to 97% in 2100. These results highlight the increasing importance of the effect of urbanization on future American household furniture stocks.

4.2.3. Dynamic base case results by income quintile

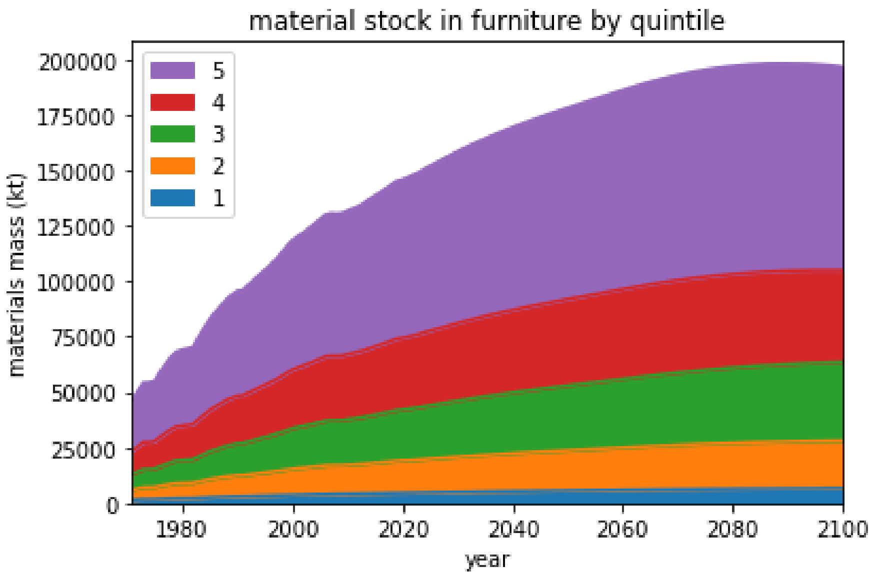


Figure 4.7: Material ownership by quintile, base case, 1971-2100.

Figure 4.7 shows the stock of materials in American household furniture over time. According to the results of the base model, consumers in the highest income quintile (i.e., Quintile 5, shown in purple) is estimated to have 48%, about half, of the total material stock in American household furnishings in 2020. The quintile with the lowest income, Quintile 1, is estimated to own a mere 3% of the mass in household furnishings. In the base case, those material inequalities are expected to remain between the highest and lowest earners in the country. The projected inequalities are a result of a combination of the finding and subsequent input to the model that more expensive furniture tended to weigh more, and the IMAGE SSP2 projection for floor space per capita according to income quintile (Stehfest et al., 2014).

5
Modelling Lifetime Extension Scenarios

5.1. Lifetime extension as a circularity strategy for durable products

As expressed in Section 1.2.2 of the Introduction, furniture is a product category that is an ideal candidate for circular economic (CE) strategies, particularly lifetime extension, even when compared to other durable product categories. Therefore, it is imperative to develop strategies to implement lifetime extension of household furniture and understand the effects of possible lifetime extension scenarios.

A survey of the scientific literature on the lifetime extension of furniture and durable goods was performed on the Web of Science and Google Scholar databases, as well as Google Search for grey literature. In the first section, a summary of those findings will be provided to contextualize the following section, in which the development of scenarios for the repair and reuse of furniture on a large scale will be discussed (Section 5.2). The following results will investigate the effects of repair and reuse lifetime extension strategies on the flows of materials for American household furniture (Section 5.4).

5.2. Understanding lifetime extension strategies

An additional literature review was performed to establish a basic understanding of lifetime extension and the terms used to describe related concepts. The findings of this review were also used to inform the assumptions used to complete an analysis of lifetime extension scenarios.

5.2.1. Defining repair and reuse

The United Nations Environmental Programme (IRP, 2018) illustrates the distinction between lifetime extension strategies, as understood by the United Nations, in a graphic (Figure 5.1). End-of-use (EOU) is defined as the time at which the consumer no longer wants the product and seeks ways of removing the product from their possession. The product is still functional but may require some repair or maintenance. This may also be understood as the durability of the product. End-of-life (EOL) signals the time at which the product fails to be functional, can no longer be used by the consumer, and is beyond repair (IRP, 2018). Through this graphic, the International Resource Panel categorizes repair as a value-retention process, where the product experiences a longer service lifetime until EOU than in the reuse strategy, as the product deteriorates to a point past immediate reuse. The consumer is then able to use the product to its actual end-of-life stage.

In a conference paper written to establish a repairability indicator of electronic goods in the non-commercial context, Flipsen et al. (2016) defines repair as “the correction of specific faults

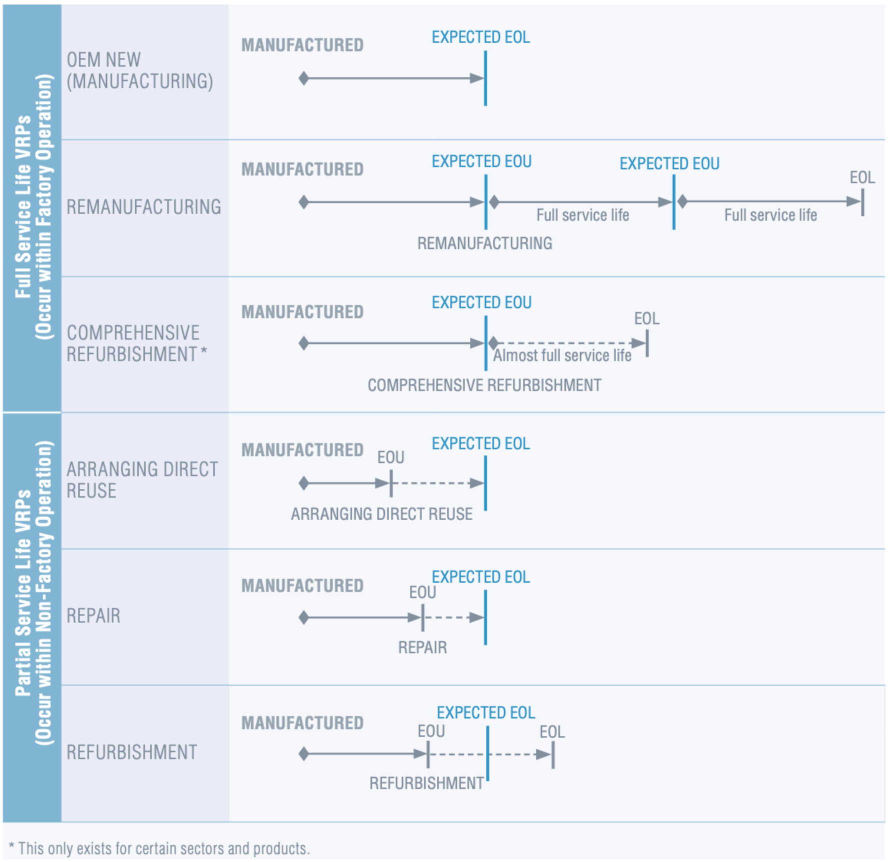


Figure 5.1: A summary of different value retention process compared to the end-of-use (EOU) of new products and end-of-life (EOL) (IRP, 2018)

in a product, bringing the product back to working condition". This definition of repair will also be used for the scenario analyses in this study.

5.2.2. A brief and qualitative state of the art for furniture repair

The decision to repair sits at a cross-section between self-empowerment, structural empowerment, and design. A study by Hebrok (2016) that factors beyond novelty-seeking contribute to consumer decisions to repair. Rather, it is an issue of cultural norms. Jaeger-Erben et al. (2021) concluded that repair had a non-significant role in increasing product lifetimes, but also attests to the possibility that repair was not sufficiently represented in their sample. The authors postulate that consumers currently exist in a "culture of non-repair". These results call for a deeper study on the lifetime extension of furniture repair. The barriers to repair identified in the study were primarily financial and behavioral costs for products with short innovation cycles. These conclusions highlight the importance of social, regulatory/structural, and design factors that will enable and encourage users to repair. An example of financial and behavioral costs to repair is the consideration between Do-It-Yourself (DIY) and expert or commercial repair. While DIY may be less costly and possibly more satisfying, the extent of damage and need for extensive repair time, special skills, and knowledge may require expert aid (Svensson-Hoglund et al., 2022). Users must balance these factors, as well as their own personal confidence and valuation of the broken product in question before making the decision to repair. The furniture product category has an advantage, in that there is a relative lack of technical complexity in the structure of furniture pieces (e.g., in comparison to electronics or automobiles) (Manoochehri et al., 2022). Therefore, educating and enabling most consumers to perform some furniture repair is viable.

The consumers' willingness to repair also depends on the consumer needs to desire extended ownership of the product in the first place. This may be due to the initial durability of the price (profitability of repair), emotional attachment (context of acquisition and history of ownership), and culture (i.e., life phases, design, and trends) (Svensson-Hoglund et al., 2022). Additional structural factors may contribute to the ease and ability of consumers to dispose of or refurbish/repair their furnishings (Hebrok, 2016). According to a study by Hebrok (2016), furniture is most often disposed of due to reasons other than a decline in performance, but rather due to other more cosmetic "flaws". According to the definition of different lengths of product lifetimes in Section 5.2.1, this means that the service lifetime of furniture is often only until end-of-use and not end-of-life. These conclusions highlight the importance of social, regulatory/structural, and design considerations that will empower and encourage users to repair.

5.3. Quantifying and modeling repair and reuse scenarios

The scientific body of knowledge was very limited on the quantified effects of repair on the lifetime extension of furniture products. However, the literature was a bit more extensive on the lifetime extension of other durable goods, specifically on goods that required energy consumption in their use phase such as household appliances. Cooper et al. (2021) and Linkosalmi et al. (2016) both write that the quantified lifetime of furniture may be understudied due to this "passive" feature of furniture. Therefore, modeling lifetime extension scenarios requires the use of some assumptions and proxies adapted from European efforts in increasing the instances of repair in their economy. The analysis requires inputs on the timeline of the repair scenario, expected life extension after repair, a projected amount of furniture taken in and repaired as a percentage of the total furniture stock, and an estimated addition of mass needed for repair.

5.3.1. Identifying the inputs to lifetime extension scenarios

A study by Russell et al. (2023) in value retention of wooden furniture through reuse, repair, and refurbishing of wooden chairs found that all three CE methods required the use of "significantly less" new materials and had reduced environmental impacts across all categories compared to the production of a new chair. Wooden parts were observed to require the highest amount of additional materials by weight for non-upholstered chairs. In the case of the upholstered chair, an additional major category of new materials required to regain functionality were upholstery materials (i.e., polyurethane foam, polyester fabric). Across the chairs that were tested in the study, about 20% of additional mass was required to perform the repair. The model will use 20% added mass for all furniture that is repaired. Reuse does not require any additional mass.

The expected lifetime extension of furniture is extremely variable, since the quality of repair, the initial state of the product, and consumer behavior/decisions all contribute to the length of lifetime extension. According to the International Resource Panel (IRP, 2018) and a study by van Stijn et al. (2021), the lifetime extension usually does not exceed the original expected lifetime of the product (what is the original EOL). To reduce overall error in the scenario analyses, 50% of the EOU was chosen to split the difference between the extreme that no lifetime was added due to repair and the other extreme, which is that the product lasts twice as long as its original service life, due to repair. The original expected lifetime will be the same as the base case. On the other hand, a furniture product that is reused may surpass the length of time for which it was initially used (EOU). In the study that included an investigation into furniture reuse by Wiprächtiger et al. (2022), the service lifetime of furniture was doubled. Similarly, 100% was chosen to represent lifetime extension due to reuse for this study.

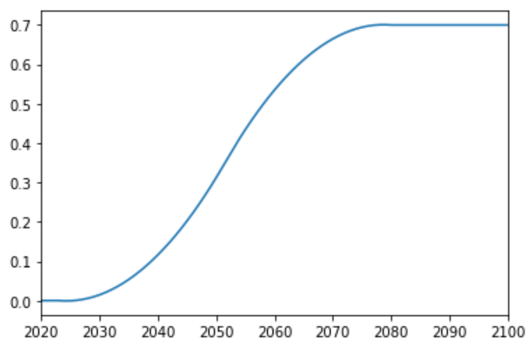


Figure 5.2: The S-curve used to simulate the adoption of the lifetime extension strategies from 2025 to 2070.

To define the timeline and goals of the repair and reuse scenarios, federal US government websites were searched in an attempt to find plans or goals relating to the repair and lifetime extension of durable goods or furniture. Unfortunately, none were found, and the Dutch goal of 100% circularity by 2050 was used as a loose guide to developing the timeline of the scenarios. 2025 has been chosen as the start date. The Dutch circularity target was set in 2016 (Ministerie van Infrastructuur en Waterstaat, 2022), meaning the timeline is about 34 years long. For the US, that would mean that 2059 is the target year. However, due to the difference in scale of the economy and area, relative dispersion of the population, and persisting political divisions, the end year was pushed to 2070 in the scenarios. The end goal of 100% circularity as set by the Dutch Ministerie van Infrastructuur en Waterstaat (2022) was an inspiration to aim for an optimistic scenario in this analysis. However, there are no repair goals to further inform the lifetime extension scenarios (Morseletto, 2020), and some furniture products will not be repairable due to damage beyond repair or other material/structural features that make it economically or physically unfeasible to repair. Therefore, 70% was set as the end goal for the proportion of furniture in the stock to undergo repair or reuse. The rate at which furniture repair increases will occur on an S-curve (Figure 5.2), which simulates a system transition (Rogers, 2010), such as one that is required for the repair and reuse of furniture to become the norm.

The values of the properties defining mass added, lifetime extension, adoption timeline, and extent of adoption were combined in different configurations to give rise to five scenarios, as seen in Table 5.1.

5.3.2. Implementing the lifetime extension scenarios in the model

The scenario analysis was performed using Python by combining the assumptions summarized in Figure 5.1 with the inputs of the base case scenario. Since the dynamic model (Pauliuk & Mutel, 2014) was treated as a black box in this study, only the minimum required stock and the lifetime of the household furniture products were changed to simulate the scenario conditions, as these are the two inputs to the Dynamic Stock Model. Therefore, calculations for the inflow and outflow were not modified. This prevents the model from returning very nuanced results in terms of the timing of the inflow of materials needed for repair and materials discarded due to repair, which will be discussed in more detail in Section 6.3.5. However, this simplified scenario analysis (Figure 5.3) can still be used to compare the overall effect of different strategies against the base case. Suggestions for incorporating more realistic inflows and outflows to the stock due to repair will be discussed in Section 6.3.5.

The average lifetime of each furniture product category was found using Equation 5.1, which considers the percentage of products upon which a lifetime extension strategy is used. This percentage changes over the course of the scenario analysis timeline along the S-curve to simulate lifetime extension scenario adoption (Figure 5.2). It is assumed that the furniture

Scenario name	Scenario description
Base case	0% adoption, 0% lifetime extension, 0% mass added for repair
Repair	70% adoption from 2023 - 2070, 50% lifetime extension, 20% mass added for repair
Delayed start	70% adoption scenario starts at 2035 and the goal is achieved in 2080
Q5 repair	Only Quintile 5 accepts the control scenario
Reuse	70% adoption 100% lifetime extension 0% mass added for repair
Reuse and repair	70% adoption 150% lifetime extension 20% mass added for repair

Table 5.1: A summary of the lifetime extension scenario assumptions.

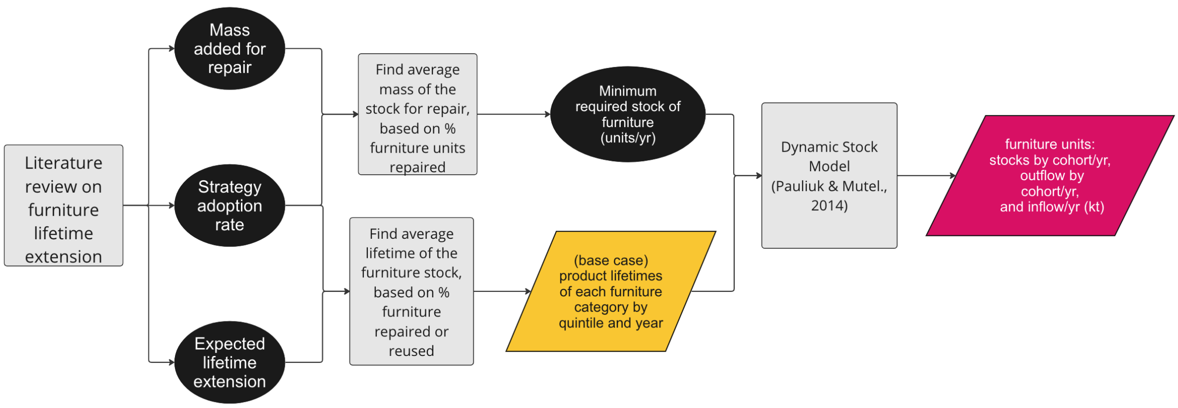


Figure 5.3: Flowchart illustrating the implementation of assumptions to analyze lifetime extension scenarios in household furniture.

products that are not affected by lifetime extension strategies still have the average lifetime that was used in the base case. Finally, the total average lifetime of the product category for each year L can be found by adding the product of the base case lifetime l_o and the percentage of unaffected furniture units to the product of the extended lifetime l_e and the percentage of furniture that is repaired or reused r. It is assumed that the lifetime distribution for each product remains on a folded normal distribution with a standard deviation of 50% of the mean lifetime, as it is in the base case.

$$L = l_o(1 - r) + l_n(r) \tag{5.1}$$

While there is no added mass required to reuse household furniture products, an added mass must be calculated to analyze repair scenarios. In this study, the added mass required to repair each furniture product category per year was calculated in a similar manner to the extended lifetime calculation. The average mass of the whole furniture product category in each year M was found by multiplying the average mass used in the base case m_o and the percent of products not repaired, then summing this with the product of the mass of repaired products and the percent of furniture that has been repaired r. a is used in Equation 5.2 to represent the mass of additional material that is needed for the repairs as a percentage of the original mass of the furniture product.

$$M = m_o(1 - r) + m_o r(1 + a) \tag{5.2}$$

5.4. Comparing the results of lifetime extension scenarios in American household furniture

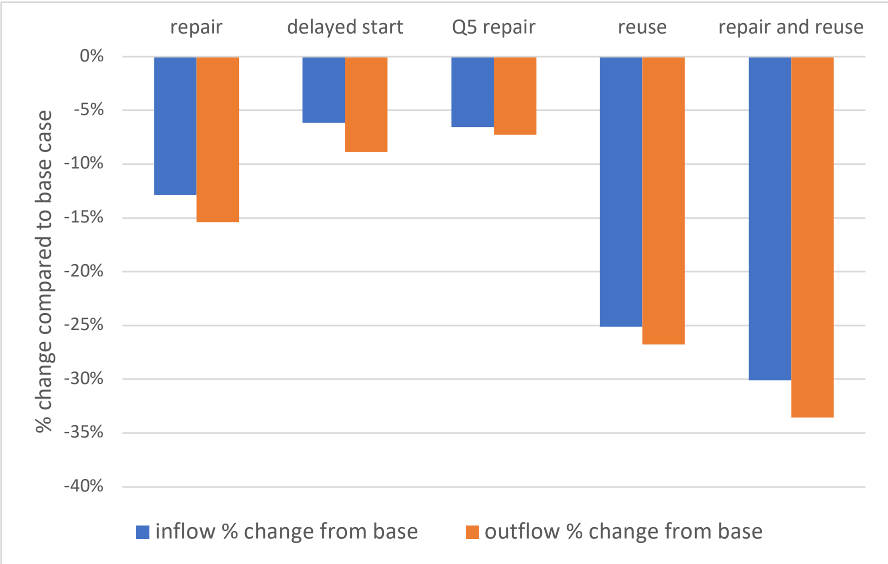


Figure 5.4: Percent differences in inflow (blue) and outflow (orange), compared to the base case, which is at 0%.

Figure 5.4 displays the results of the model for each scenario, as described in Section 5.3.1. The plot depicts the average percent difference in inflow and outflow between the base case and each scenario from 2058 to 2062, which is a five-year range around 2060. This year was shown to represent the results of the scenario analysis, as it is a little over twice the average lifetime of most of the furniture categories modeled in the base case, and it is also within the period on the strategy adoption timeline before the rate of adoption starts to slow. According to the results of the model and in comparison to the base case, repair and reuse strategies are expected to reduce the inflows and outflows of materials to the American household furniture stock in all scenarios. In all scenarios, the model returns the projection that outflows will be reduced by a larger amount than the inflow, although this is likely an artefact of the modeling method since the mass is added to the material stock for the repair. No mass is modeled to leave the stock due to repair; rather, it stays in the stock and eventually leaves when the entire furniture product reaches EOL.

Additionally, it can be seen that the reuse strategy, under the same adoption conditions as the repair case, incurs a larger effect on material inflows and outflows in the years around 2060 than the repair scenario. This is because there is no need for additional materials in reuse, avoiding the dampening effect on reductions in material demands that would otherwise occur with repair because additional mass is required for repair. In the scenario that explored the combination of repair and reuse strategies, repair seems to incur a relatively marginal reduction to the material demand and outflow, in comparison to the effect it has on its own. This phenomenon will have to be investigated with further work.

Thirdly, the impact of the adoption of the repair strategy by just the highest-income quintile (Q5 in Figure 5.4) was modeled. When compared to the repair scenario in which all quintiles adopt the strategy, Quintile 5 seems to account for about half of the reductions. While this is not surprising considering the expected dominance of the quintile in furniture ownership in the base model (Section 4.2.3), this result further emphasizes the importance of the participation of the richest Americans in circular strategies for furniture, such as repair.

Finally, a scenario was developed to inquire into the effects of a delayed start to the repair scenario by 10 years and the achievement of the repair goal (70% furniture repaired) by 10 years, as well. Compared to the repair scenario that starts in 2025 and ends in 2070, the repair strategies are expected to have a lower effect on the inflows and outflows to the material stock of American household furniture around 2060 when the strategies are launched later. While this is to be expected, the dampening effect of this late start decreases the demand and outflow reductions by about a third. This demonstrates the urgency of establishing lifetime extension strategies such as repair for household furniture, and how detrimental delays can be to the effectiveness of these strategies.

6 Discussion

In this chapter, the results of the base model and scenarios will be interpreted. An evaluation of the methodology introduced in this study will also be performed. This will provide context and background to the answers to each research question, the summarized answers to which will be provided in Chapter 7.

6.1. Implications of the base case and lifetime extension scenario results

This section will start with an analysis of the base case results to establish a "baseline" of the stock and flows of American household furniture. A discussion of the scenario analyses will follow to inform possible strategies to improve circularity for household furniture used within the US.

From stock-taking American household furniture, the furniture categories that are dominant in terms of the total mass of stock, such as double bedframes, dressers, and shelves (Figure 4.1a) have high compositions of wood-based materials (Table 3.3). This result was demonstrated in Figure 4.1b, which demonstrated that about 74% of the mass in American household furniture was wood-based and 14% consists of ferrous metals (i.e., steel and iron). These results corroborate the estimates made in the top-down study for household furniture in Switzerland by Wiprächtiger et al., which used a composition of 70% wood and 13% steel for their analysis on Swiss household furnishings (Hofer et al., 2019; Swiss Federal Customers Administration FCA, 2020, as cited in Wiprächtiger et al., 2022).

In the dynamic results of rural areas, the decrease in minimum material demand for furniture causes the outflow of furniture materials to dip below the demand for new materials, indicating the need for a strategy to retain the value of used furniture in these rural areas. Because the IMAGE data projects a steady increase in urban floor space in the US (Stehfest et al., 2014), the expected minimum demand for furniture materials in urban areas increases through the end of the century. The base model results show that the demand for new materials seems to exceed the outflow of material throughout the modeling period, signaling the need for circularity strategies to manage resource demand in urban areas into the future. Capturing the flow of disposed furniture from rural communities for recycling may be a way to satisfy the demands for household furniture in urban areas to a small extent. Indeed, the scale difference between the rural and urban stocks is so large that the rural outflows will not be able to match the furniture demands of urban residents. Clearly, any strategies aimed at resource management and circularity of furniture products need to prioritize urban areas to maximize effectiveness.

Should the average composition of furniture remain similar over time and demand for furnishings continue to increase as the base case shows, there will be an increase in demand for wood-based materials. The dominant presence of wood products in the material stock presents the opportunity for the furniture stock to act as carbon storage; Yet, differences in the quality of the wood used in furniture affect its ability to store atmospheric carbon. Engineered wood is prominent in low-quality furniture products that rely on particleboard and other engineered wood materials to meet costs. From the survey of high-end furniture in this study, it was also found that engineered wood (high-durability and otherwise) also features heavily in the more expensive furnishings. Wood products like particleboard that are made with low-value materials such as wood chips and fibers may have low durability, especially when affected by water damage and stress. In order to act as carbon storage, wood products must have long service lifetimes. Otherwise, wood that is discarded will be incinerated or decompose, releasing the greenhouse gases that should ideally be stored (Brunet-Navarro et al., 2016). Durability can be increased with the increased use of binders, such as urea-formaldehyde (Pedzik et al., 2022). However, the use of such chemicals presents risks to human health in the use phase (Skaar & Jørgensen, 2013) and increases harm to the environment in the manufacturing and disposal phases (Peischel, 2022). Trading chemical safety for durability towards increasing carbon storage capabilities is not a desirable compromise.

Recycling processes also compromise the structural integrity of engineered wood and require additional energy and material inputs. Recycling processes may increase the complexity of wood materials, making them difficult to re-integrate into a closed-loop system (Zimmer & Angie Lunelli Bachmann, 2023). Solutions to recycle wood products contaminated with adhesives and preservatives, such as medium-density fiberboard and high-density fiberboard, two types of particleboard, are currently at laboratory scale (Besserer et al., 2021). Strategies to reduce demand for new furniture materials overall would perhaps be a more effective way of helping the furniture demands to reach saturation earlier and prevent further need for harmful extraction of materials. The circularity approaches that can be used toward this object are, for example, lifetime extension strategies: repair, refurbish, and reuse.

To achieve a higher level of circularity in the household furniture sector, various lifetime extension strategies must be evaluated to increase the value retention of products and materials that comprise the furniture. It is clear from the results of the scenario analysis that reuse is preferred over repair to reduce the inflow of new materials that are necessary to satisfy the minimum demand for household furniture stocks over time, as well as to reduce outflows from the furniture stock. This is because reuse does not require additional materials in order to be carried out, whereas repair is assumed to require an additional 20% of the original mass of each furniture piece being repaired. However, both reuse and repair have been shown to reduce inflows and outflows of household furniture materials and may be used together to improve the circularity of household furnishings. To increase the reuse of furniture products, furniture must be built for durability. This depends highly on the materials from which the furniture is made, and the design of the products.

Of course, given that furniture ownership is contingent on cultural norms, product design and the consumer's use of the product is also a deciding factor in the longevity of furniture products within the household. Any strategies aiming at circularity in household furnishings must account for the social and cultural aspects of furniture use and willingness to participate in circularity strategies. In this regard, increasing urbanization can present an opportunity for circularity, as urbanization necessitates higher densities of people and their belongings. Having furniture in higher concentrations can mean that local reuse and repair is more viable since there is a larger pool of people in the area to share (repair) skills and tools and a larger customer base for professionals to pull from. One barrier presented by urbanization against circularity is establishing the infrastructure necessary to set up collection hubs and transportation networks to enable circularity efforts at a larger scale may be more difficult in cities where space is tight (Nicolini, 2022). For example, obtaining a warehouse for storing furniture collected for reuse may be difficult and more expensive in a city.

6.2. Main model assumptions

The major assumptions used in developing the base model and base results are summarized in Table 6.1. The necessity to make most of the assumptions arose due to a lack of material intensity, furniture lifetimes, and furniture ownership data in scientific literature, highlighting the need for additional studies of these data inputs.

6.3. Strengths, limitations, and potential improvements of the methodology

This section contains an analysis of the methodology introduced in the current study. Due to the nature of bottom-up material flow analysis (MFA), data collection and the initial phases of quantifying American household furnishings were highly time- and data-consuming. However, because there was very little data available on which to base a top-down analysis for household furniture, introducing methods for bottom-up data collection contributes to the possibilities in future research methods on this product category. Household furniture is especially difficult to quantify, as there are no public records of purchase and manufacture, and cannot be seen from the outside via satellite or drones, as is the case with buildings. The photograph method for collecting furniture data is novel and provides insight into furniture ownership across many geographical regions and demographic groups, without the need for having a personal network in all of these groups or spending resources on travel.

6.3.1. Limitations and strengths of the sampling and data collection method

The method introduced in this study does not cluster urban areas depending on population density or median floor space. Rather, urban PSUs in each division were treated as one cluster. The PSU with the median household income was chosen to represent all urban PSUs in its division, therefore only one furniture intensity per division for calculated for all quintiles in the urban areas. This limits opportunities to study any nuance in furniture ownership per quintile in terms of furniture units. Future research may cluster urban PSUs as well in order to capture the nuances in furniture ownership in urban regions.

One barrier to taking more samples in urban areas was the unavailability of data compared to rural PSUs. Rural homes were often shown with in-use furniture on real estate websites, whereas urban listings were often bare, utilized model furnishings, or did not provide pictures of the inside of the property. While this may be due to the significantly higher prevalence of renting in American urban areas (US Census Bureau, 2023), renters may be required to remove their belongings before listings are placed and landlords can also use images from when the property was unoccupied. There are also limitations in ensuring that all furniture in all rooms is accounted for, as the researcher is limited to accessing the furniture units shown at certain angles in the real estate listings. If not all furniture units can be seen in the photos, the researcher will underestimate the stock of furniture in the houses. The availability of property images to the researcher is an important consideration for this method.

On the other hand, the photography method allows researchers to access furniture ownership data without necessarily having a strong network in the geographical region or socio-economic community of study. It is also a low-cost and anonymous and relatively quick method of surveying homes. The data collection also relies on the researcher's perception and the appearance of the furniture as it is shown in the listing pictures, the description of each furniture category is dependent on its size and appearance relative to other furniture pieces in the picture. This method may introduce some error from the distortion of the cameras or

Methodology section	Assumption	Source of assumption
Scope selection S 2.4	Furniture lifetimes are significantly different between movable and built-in furnishing types due to built-in nature and lower turnover of ownership (i.e. reselling is a precursor to reuse).	Research assumption
Sampling, static model S 3.2.1	Clustering features were chosen to be population density and median floorspace, as they had the largest range of the population features available from the extracted data. The extracted data was chosen due to assumed influence of household size, composition, and income, floorspace, and population density on furniture ownership.	Researcher assumptions
Sampling, static model S 3.2.1	All urban units were placed into the same cluster, under the assumption that median floorspace and population density was adequately representative of those features in urban areas.	Researcher assumption
Data collection, static model S 3.2.2	The photos listed for each property on the real estate websites, given they match the criteria set by the researcher for "valid" samples," provides a sufficient representation of furniture ownership of that household.	Researcher assumption
Lifetime, dynamic model S 3.3.2	The aggregated lifetimes used in the LCAs were considered end-of-use for the model, and the point at which furniture is discarded.	Research estimates, with aggregations of data in literature (See Table 3-5)
Lifetime, dynamic model S 3.3.2	The lifetimes were averaged, assuming the variation of products represented in the material intensity data collection are equally present in the total population.	Researcher assumption
Lifetime, dynamic model S 3.3.2	Standard deviation of lifetime is 50% of the mean, interpreted from a study that reports that most furniture approaches end-of-use at 2-30 years, translating to a mean of 15 years with a standard deviation of 7.5.	Interpreted from Hebrok (2016)
Material intensity by quintile, dynamic model S 3.3.4	It is assumed that consumers in higher income levels tend to buy higher-priced furniture.	Researcher assumption
Material intensity by quintile, dynamic model S 3.3.4	The overall material composition of each furniture category remains the same between product price ranges.	Researcher assumption

Table 6.1: A summary of the main assumptions used in this study.

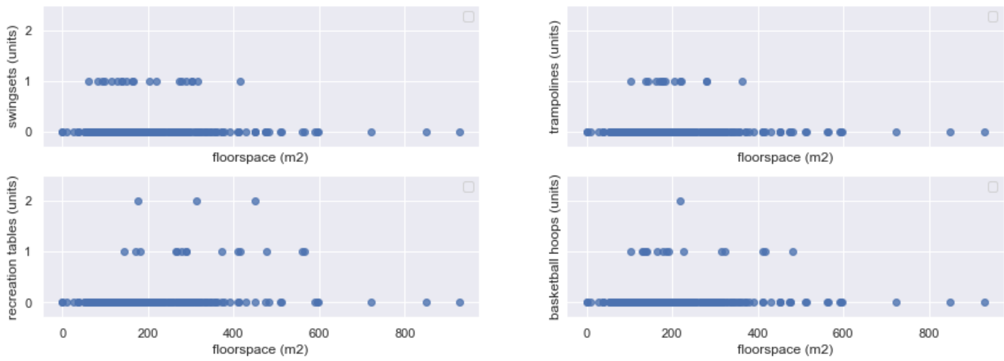


Figure 6.1: Scatter plots of furniture in outdoor and recreational furniture categories counted at rural residences, in furniture units/m^2

photographic settings used by real estate companies, such as the wide-angle lens (Hometrack, 2023). However, having one person or a trained team collect data using a consistent definition of furniture categories may provide more a scientifically robust data output.

6.3.2. Limitations of the linear regression model for furniture intensity

The floor space-driven model does not work well for outdoor furniture, as outdoor furniture may not depend on indoor floor space and may work for recreational furniture, by the same logic. Recreational product categories such as basketball hoops, swing sets, and trampolines did not work with this model due to the tendency to be present in binaries, regardless of floor space or lot size. The linear fit of the model as assessed with R-squared ranged widely for outdoor furniture, as demonstrated between patio chairs and patio tables in Figure 6.1. The outdoor furniture was cut from the scope of the study as a category due to this variability. However, data on lot size for each property (when it was available) has been recorded in Supplementary Materials B-1 and may be used to evaluate the effect of lot size on the outdoor category in future research. Likewise, the driving main driving factor(s) for large-scale recreational product ownership may lie in explanations other than floor space and should be the focus of further investigation. It is estimated that 14% of the total household furniture stock was unaccounted for after cutting out outdoor and recreational furnishings. This mass could not simply be re-incorporated into the overall analysis using indoor furniture intensities because their material compositions tend to be significantly different than indoor furniture products (i.e. more metal and plastic than wood). Further research may be done to estimate the size and composition of the cut-off categories, to be reincorporated into the results of this study.

Most furniture categories also did not have high regression with floor space (Appendix D), but due to the limitations in the model to consider one main driver of furniture stock, floor space continued to be used in the model. There may be other mediating factors involved in indoor household furniture ownership that should be investigated in future research, as this is another gap in the scientific literature.

Another limitation of the data introduced to the model is that material intensities did not use a stricter product-service unit, such as m2 of seating or m3 of enclosed space. Because the nature of the data collection on in-use furniture through the photographs made it impossible to measure accurate sizes/volume, it did not seem logical to multiply a kg/m^2 or kg/m^3 material intensity by the number of furniture units. However, future studies may get around this by finding an average size of furniture (possibly by quintile) and multiplying this average by the furniture units before finding material composition.

6.3.3. Limitations and research suggestions on material intensities of household furniture

Much of the data in the literature and industry literature provides aggregated material data. Thus, it was especially difficult to categorize non-ferrous metals. There was also no way to check if the materials labeled "metal" in some cases were ferrous or non-ferrous, as in the data for the OVO table collection from Environdec. Details for plastics were also wide-ranging, from accounts of different types of plastics to accounts for general "plastic" or "plastic pieces" categories

Due to the lack of data in the literature for products explicitly sold in the US, the material intensities were largely taken from European manufacturers that submitted information on their designs for Environmental Product Declarations (EPDs) from third parties. Some material intensity data was also found for products made in China, the US, and Brazil (e.g., Iritani et al., 2015; Spitzley et al., 2006; S. Wang et al., 2016). This does not reflect the makeup of the furniture supply and stock in the United States today. It was estimated that in 2019, the country imported 35% of domestically sold upholstered furniture, mostly from China, and 78% of wooden household furniture is said to be imported, mostly from Vietnam (Luppold & Bumgardner, 2021). Because European-made furniture is known to be primarily bio-based (Renada et al., 2015, as cited in Coloma et al., 2022), the results of this study may have over-estimated the composition of wood in American household furniture stock.

There is also no data in the literature on the difference in the material composition of household furniture across different income groups. To fill this gap in the data weighting factors were used in the study to differentiate the mass of the furniture units in each quintile, and samples of representative product listings were used to estimate differences in the wood types used between price quintiles. However, the material compositions per quintile were only estimated for wood. More information is needed on material intensity on other material types to understand how composition differs for plastic and metal, especially in the case of furniture frames. In particular, the prevalence of steel in lieu of wood was notable for the lowest price quintiles of bedframes. There is also further nuance in the durability of products that use particleboard between quintiles, as there is a large range of density in particleboard, which has a large effect on its durability and longevity. Higher-density particle- and fiberboard tend to be more durable and more expensive (Alibaba.com, 2023a, 2023b). The current study does not categorize materials in a way that supports an investigation into this nuance. However, this does not change the concern for the recyclability and repairability of particleboard, which has proven to make up a large portion of the material stock of American household furniture. Specific research into the types of materials used for furniture at different price levels will increase the accuracy of material intensity estimations for wood and other materials.

Future studies with improved material intensities may require research of the percent domestic product and the percent of imported furniture to estimate furniture material intensities that reflect the stock in the U.S. The study by Wiprächtiger, et al. (2022) utilized assumptions of the percent domestic product in Swiss furniture, and a similar assumption could be made for future studies after consulting with industry experts or trade data.

Additionally, more research can be done with the model using variable material intensities over time. In the current study, the material intensity of each product category remained the same. However, the effects of changes in legislation or norms for furniture design may be explored by altering the percentage of materials (e.g., replacing plastic with metals). The effects of using higher-density or simply more material to increase the durability of products can be investigated (i.e. replacing particleboard with solid wood).

6.3.4. Limitations and suggestions for research on household furniture lifetime

Lifetime estimates for household furniture are difficult to find in scientific literature and industry reports. Two theories are offered in the literature to explain the lack of furniture lifetime data. As stated in Section 1.2.2, furniture has an advantage in the circular economic transition because it tends not to require energy in the use phase. However, this feature also means the use phase of furniture is unattractive for researchers, particularly for life cycle analysis (LCA) practitioners. In other words, furniture manufacture and disposal are generally the focus of environmental impact studies than its total lifetime (Cooper et al., 2021; Linkosalmi et al., 2016). Therefore, the length of furniture lifetimes is difficult to define in LCA studies. The second explanation is that the actual lifetime of durable goods not only depends on the intention of the design or producer (expected lifetime) but relies heavily on the end consumer behavior and consumer understanding of the expected lifetime (Nishijima & Oguchi, 2023).

The assumed lifetime for many furniture categories is the assumed minimum end-of-use found for the LCA of that product, not based on tested end-of-life or expected lifetime of the product, which is an estimate by the designer. In this study, an aggregation of these minimum end-of-use lifetimes and some researcher assumptions were used as end-of-use in the base study case and changed for the scenario case to reflect efforts in increasing furniture lifetime. Therefore, the model treats end-of-use as the point at which the furniture is disposed of – or would be disposed of – unless a lifetime extension strategy is implemented. The full expected lifetime of furniture (end-of-life) may be longer, and repair is expected to occur at any point between end-of-use and end-of-life, so the frequency of repair and thus inflow to supply repairs may be overestimated in the repair scenarios.

The additional suggested nuance in furniture lifetime is that upholstered furniture is replaced at higher rates than non-upholstered goods such as dining tables (Cooper, 2012), which is not adequately reflected in the lifetimes for the base model. All literature found on lifetimes for these furniture categories was relatively similar, especially in the service lifetimes provided in the LCAs from Environdec, which assumes a minimum lifetime of 15 years. Future research may choose to divide furniture categories into upholstered and non-upholstered groups to reflect this difference if sufficient lifetime data exists to corroborate the assumption.

6.3.5. Limitations and suggestions for future research in scenario analyses

The Dynamic Stock Model (Pauliuk & Mutel, 2014) was a black box in this study and the scenario conditions (i.e., changes to lifetime and mass of furniture) were used to change the lifetime and minimum stock that were input to the model. Consequently, this meant that the model represented a system where any material that was unusable following the repair of a furniture unit was kept within the system until the entire furniture product was disposed of. This does not reflect reality, where one can expect any broken scrap pieces to immediately exit the in-use stock as waste or to be used for other purposes. Future endeavors to assess the impacts of lifetime extension strategies such as repair may be able to model repaired furniture in a similar way to recycled materials in furniture. A percentage of the outflow furnishings (whole units and parts of repaired furniture) will go to disposal. The rest will re-enter the stock as "repaired furniture" with lifetimes that are 50% of the original expected income. An added demand of 20% of the mass of the repaired furniture will be input into the material stock to represent the mass needed to repair the furniture. This mass will have the same lifetime as the repaired furniture.

6.4. Generalizability of the model and method for other countries

While some limitations certainly exist and knowledge in the form of cultural context is needed to inform the categorization and identification of furniture materials/products, the method can be generalized with some adaptations.

6.4.1. Generalizability of the sampling and furniture unit data collection method

The method introduced in this study was used for the US, which is the third largest country in the world by land mass and population, including territories (CIA.gov, 2023a, 2023b). Therefore, the approach attempts to encompass a wide geographical range and diversity in demographic areas. Divisions may not be necessary for smaller countries but will be important for larger countries with a high degree of range in median floor space, population density, income, or lifestyle between regions.

Secondly, an extensive network and knowledge of the language for in-person or online surveys is not necessary for the photograph method. However, the photograph method requires that the researcher have access to an abundance of photographic data that represents homes all over the region. Furniture ownership data collection as shown in this study may be difficult for countries that do not show listings with in-use furniture normally (e.g., Japan). This is especially true in areas of high population density where renting apartments or flats is more common.

Lastly, some knowledge of the cultural context of furniture pieces in the homes of the study area is recommended for the researcher to identify products more common in some regions than others, such as variations of beds, tables, and chairs. This is important in decisions of finding “viable” sample real estate listings and in deciding which products are counted as furniture. For example, traditional Japanese beds are often thick mats or “futon” that are laid on the floor at night. The mats are folded and stored in closets every morning, and therefore likely not visible to the researcher in any pictures. The same could be said for homes that primarily use Murphy beds or fold-out beds. It would be critical then for the researcher to recognize this practice if there are no traditionally Western beds (i.e., an open-faced bedframe that holds a mattress) shown in the pictures. Other hints would need to be used to distinguish between listings that do and do not show sufficient representation of the furniture in use in each household.

6.4.2. Generalizability of the furniture intensity model

The use of the model for furniture intensities found during this study will likely not be generalizable to other geographical areas of study. This is especially true for countries in which household composition varies greatly from that of the US, such as having multiple generations or extended families in one home. This is based on the assumption that households tend to share some furniture items such as dining tables and couches/sofas; Therefore, furniture per capita and furniture per square meter may differ with varying cultural practices.

As with furniture unit data collection, some cultural knowledge is recommended for effective categorization and recognition of materials and furniture in different regions of the world. Material categories may differ depending on cultural norms. Taking the example of bamboo or rattan, the material may not be considered wood (for biological, manufacturing, or environmental impact purposes) and new categories may need to be added to the analysis. Furniture categories may be different depending on cultural needs from furnishings, for example, floor cushions instead of chairs and futons instead of bedframes. The accessibility or priorities placed on private outdoor and indoor recreation was demonstrated in the first portion of the methodology. However, as shown in Section 6.3.2, these categories proved not to be driven by residential floor space. Whether to count those items as furniture in the scope of the study and how best to estimate their numbers in residential households needs to be decided by the researcher. While this does not help to generalize the furniture intensity model to other countries, the issue of having different furniture categories may be solved by using an aggregated furniture intensity model, although it would still have to be explicitly stated which types of furnishing products are counted as "furniture".

7 Conclusion

To summarize, this study sought to understand how household furniture stocks and flows can be quantified at a national scale, and how the results of the model can inform action towards circularity strategies that aim to reduce the harmful environmental and social impacts of household furniture consumption. An attempt was made to quantify household furniture stocks by introducing new strategies for collecting data and modeling furniture ownership within homes with a hybrid top-down and bottom-up approach. For the purposes of demonstrating this methodology and performing meaning analysis on the results of the model, the US was chosen as the case study for this research. Furthermore, a scenario analysis of two lifetime extension strategies – repair and reuse – was done to assess the scale of the potential impacts of these strategies on the demand and disposal of household furniture materials. Finally, the research questions initially posed in Chapter 2 have been answered through this research. The answers are summarized below.

7.1. Summarizing the research findings

7.1.1. Answering Research Question 1: Reviewing the static and dynamic model results

The first aim of this study was to attempt the quantification of household furniture and its materials, using the US as a case study. Therefore, **Research Question 1 asked:** ***What are the static and dynamic stocks and flows of furniture and its materials in households across the US?***

Representative samples of in-use furniture stocks were taken from homes across the US. This data, along with data on furnishings on the market and findings in the literature were then used to model the material stocks and flows of materials in the household furniture. In doing so, it was found that 74% of the mass of in-use furniture stocks in 2020 were wood-based, and about half of that was solid wood. An estimated 14% was comprised of ferrous metals and plastic contributed to about 4.5% of the mass. Although no change in furniture material composition was assessed in this study, the dynamic results revealed a demand for new materials in furniture that outpaced outflows from the disposal of furniture products until the end of the 21st century. At that point in time, saturation of the demand for materials in household furnishings is expected to be reached in the US and outflows may start to exceed demand.

Sub-research question 1A addresses this study's focus on the static representation of the American household furniture stock: ***How do the stocks and flows (of furniture and its materials in households across the US) differ between income quintiles and area types?*** Most of the household furniture stock in mass belonged to urban residents, although rural residents tend to have more furniture materials in kg per capita. The current model, which uses residential floorspace as the main driver of furniture ownership, projects urban residents to own increasingly higher shares of the total household furniture stock. Meanwhile, the absolute minimum demand for household furniture in rural areas is expected to decrease as urbanization continues. As for differences between income quintiles, the fifth of Americans with the highest incomes were estimated to use about twice the mass per capita in furniture within their homes than the next-highest earning fifth of Americans. In the base case (i.e., business-as-usual), the quintile of lowest-earning Americans own only 3% of the material stock in household furniture, while the highest-earning quintile claims half of the total material stock. The discrepancies extend to the compositions of furniture products, as well. Research for the current study found that Americans that can afford more expensive furnishing may own products with a much higher composition of solid wood than Americans that can only purchase cheaper goods. However, US consumers across all quintiles own products with large amounts of engineered wood products.

Next, a prospective dimension to the investigation of Research Question 1A is considered to answer **Research Question 1B:** ***What implications do the differences in household furniture stocks and flows between income quintiles and area types have on future decisions in material demand and waste management in a circular economy?***

The dominance of urban and high-earning Americans in the makeup of the US household furniture stock means that they should be the groups to focus on when planning efforts towards circularity in the home furnishing sector. Urban demand for furniture is not expected to dip below outflows of furniture materials until the very end of the 21st century, whereas outflows from rural areas have been and are expected to continue to outpace demand for materials in household furniture. This indicates the possibility of transporting used furniture products from rural to urban areas to help meet demand, although the scale difference between the rural outflows and the urban demand means that the rural outflows will be able to match only a fraction of the demand in American cities.

Additionally, the high prevalence of particleboard and other engineered wood in cheaper furniture compared to more expensive furniture indicates a nuance between the required waste treatment of wood from furniture at different price ranges. Engineered wood is much more difficult to recycle and contains higher quantities of contaminants than solid wood. The absolute outflow of particleboard will also increase with the growth of the total American household furniture stock. This means that scaled-up solutions to recycling engineered wood is urgently needed and limitations on using engineered wood for furniture products needs to be considered.

7.1.2. Answering Research Question 2: Reviewing implications of the results on lifetime extension of household furniture

Research Question 2 goes on to prompt discussion on the actions that can be taken to alleviate environmental pressures by reducing the demand and disposal of household furniture: ***In what ways might the increase in the use of lifetime extension strategies for household furniture products affect future demand and outflows of materials in American household furniture?***

In the base case results, it was shown that wealthier Americans own more furniture, and furniture with higher amounts of solid wood, than American in lower income quintiles. Solid wood is more durable and easily repaired compared to many engineered wood types such as particleboard. In the scenario results, the wealthiest Americans were also shown to cause the greatest reductions in demand and disposal of materials after adopting the repair strategy. Therefore, the onus for the adoption of lifetime extension strategies should mostly fall on wealthier consumers that can afford to have higher-quality products and pay to have them repaired. Legislation can be focused on enabling the transition toward normalizing and enabling lifetime extension, as well as discouraging fast furniture trends. To prevent the over-consumption of furniture by Americans in the higher income brackets, the repair and maintenance of furniture need to be incentivized through not only economic means but emotional and social means, as well.

The greatest reductions in demand and disposal of materials in household furniture were achieved when consumers in all income quintiles were able to adopt the repair and reuse strategies. Legislation and entrepreneurial efforts can be made toward encouraging business models that expand access to higher-quality furniture and its repair to lower-income consumers. Currently, lower-income consumers are marketed low-quality product offerings that make it difficult to enact lifetime extension strategies and which prevent them from participating in circularity initiatives. Implementing the improved distribution of secondhand, high-quality furniture may offer a solution. The high concentration of furniture stock in urban areas may provide an important opportunity for local reuse, repair, and recycling initiatives with many participants in small and easily-traveled areas. Additionally, reducing up-front costs to low-income consumers by way of furniture leasing and providing free repairs can help to increase the service lifetimes of furniture products while improving the affordability of more durable furnishings.

On a legislative level, urbanization presents opportunities that are in favor of dematerialization in furniture ownership, since urban residents own less furniture material per capita than rural residents. Higher concentrations of people and furnishing may present opportunities for more locally-available circularity solutions, such as local secondhand shops and repair businesses. This reduces the effect of barriers such as transportation to use circularity strategies for household furniture. However, the highly-planned and population-dense nature of cities can also present its own challenges against making space for the infrastructure needed to carry out circularity strategies on a large scale (Nicolini, 2022).

7.1.3. Answering Research Question 3: Reviewing the strengths and limitations of the study methdology

Research Question 3 required a critical assessment of the methodology that was performed while carrying out the research and after analyzing the results. In return, the limitations and strengths of the methodology, as well as its potential benefit to future research projects, were identified. To reiterate, **Question 3 was:** ***How can the mass of materials in household furniture be quantified at the national scale?***

In the current study, the answer to this question was a bottom-up collection of furniture ownership data, stratified by income quintile and further divided by area type. Representative samples were taken across the US using the statistical grouping method K-means clustering, which was performed for each of the nine US Census Bureau divisions. Furniture ownership data was collected by looking at photographs of property listings online and tallying furniture units by product category. Furniture units per m^2 were then calculated as a linear regression model. The model was applied to the national scale using top-down data on median floor space from IMAGE SSP2 (Stehfest et al., 2014).

The introduction of the current methodology requires not only a summary of its benefits but also a transparent review of its limitations. Identifying the most significant of these may be useful in improving the method for future research endeavors. Towards this end, **Research Question 3A asks:** ***What are the strengths and limitations of the quantification methodology used in determining the material stock and flows of American household furniture?***

While an in-depth discussion on the limitations of the methodology can be seen in Chapter 6, the main limitations stem from the nature of bottom-up material flow analyses (MFAs). Bottom-up MFAs require high amounts of data, which in turn is time-consuming to gather and analyze. This limits the number of samples that can be taken, forcing the use of representative sampling. Although efforts were made to group the sample population in meaningful ways through

K-means clustering, well-photographed listings were much more available for owner-occupied homes, which are more common in rural areas. Therefore, bias toward owner-occupied homes in rural areas may have resulted. On the other hand, using the bottom-up data collection method to build an understanding of the American household furniture stock was necessary, as no quantified data was available for household furniture in terms of product units or mass. The method introduced in this study presents a low-cost and unintrusive method for collecting data on in-use furniture in homes from across the country and from all income quintiles.

Lastly, because one aim of this study was to introduce new approaches to quantifying in-use home furnishings at the national scale, it is important to understand the generalizability of the method in quantifying in-use furniture stocks for other geographical scopes. **Question 3B asks:** ***In what ways can the quantification methodology be used for other geographical locations on the national scale, and what are the limitations?***

Because the approach does not require personally connecting with the residents of the homes being sampled in the data collection, the method in this study is generalizable for researchers that are not highly integrated into the communities that they are researching. However, it is still recommended to have a basic understanding of the furniture types and functions that are typical to any given culture that is being studied. It is important to understand what objects are and are not considered to be furniture before making the decision to count them one way or the other for the data collection.

It is not recommended to use the linear regression models found in this study to quantify furniture in other geographic locations. This is especially true for areas that commonly follow lifestyles that are very different to that of many Americans, since lifestyle and culture are determinants of material consumption, especially in the home (Chevalier, 2012).

7.2. Concluding remarks

Ultimately, American consumers, business owners, designers, and other entities along the furniture supply chain need to be more aware of their potential role in enabling circularity and lifetime extension of their furnishings. Any furniture material outflow that is burned or decomposed will only release the carbon back into the air, along with any additional toxic compounds in the furniture products. Continued increases in demand for materials will also maintain pressure on regions such as Oceania and central Africa to continue deforestation. The threat of slow violence (Nixon, 2011, as cited in Davies, 2022) caused by the extraction of resources to satisfy the demands of wealthier countries will also continue to affect residents of those areas. US consumers must be better educated on where their timber and other materials for their consumer goods comes from and why it is important to exercise lifetime extension strategies such as repair. Designers and furniture manufacturers should continue to, and escalate, their considerations for the source of their materials, the durability and repairability of their products, and the impacts of their eventual disposal in terms of the environment and health of stakeholder communities. While the scale and distance from the impact of the purchase and disposal of their products on communities and ecosystems around the world make these issues hard to grasp for many, there are real and viable strategies that can be carried out at local levels within the US. This is true for many different product categories, but furniture is a passive durable product that can be designed to last a lifetime or even longer and generally has uncomplicated structures that are more easily understood than, for example, consumer electronics or automobiles. Therefore, furniture is a very good candidate for implementing material circularity strategies such as repair that is accessible and achievable to communities at all income levels.

In order to reach a "culture of repair and reuse," social transitions must take place. This will require legislative support for systems that enable easy access to both expert repair and the opportunity to learn Do-It-Yourself repair. Economic incentives for lifetime extension and deterrents for further purchases of new goods must be in place to help consumers decide to extend the service lifetime of their household furniture. Finally, it must be emphasized that the wealthiest Americans are most ideally poised to adopt lifetime extension strategies due to the higher quality of their furniture and because they own a larger portion of the material mass of household furniture than any other quintile. However, strategies for increasing the repair and reuse of furniture must be approached both inclusively and adapt to consumers at different income levels. A true shift in the system of furniture consumption cannot occur without including all those living in the US.

References

Addo-Fordjour, P., Afram, I. S., & Oppong, J. (2022). Selective and clear-cut logging have varied imprints on tree community structure in a moist semi-deciduous forest in Ghana. *Heliyon*, *8*(11), e11393. https://doi.org/10.1016/j.heliyon.2022.e11393

Alejandre, C., Akizu-Gardoki, O., & Lizundia, E. (2022). Optimum operational lifespan of household appliances considering manufacturing and use stage improvements via life cycle assessment. *Sustainable Production and Consumption*, *32*, 52–65. https://doi.org/10.1016/j.spc.2022.04.007

Alibaba.com. (2023a). HDF Melamine faced HDF Board Carb P2 4 8ft panel 9mm 11mm 12mm 14mm 15mm 17mm 18mm 25mm Wood Materials Furniture Vietnam Timber. Retrieved August 8, 2023, from https://www.alibaba.com/product-detail/HDF-Melamine-Faced-HDF-Board-Carb_1600900986653.html?spm=a2700.7735675.0.0.22bddGF7dGF7DE&s=p

Alibaba.com. (2023b). Wholesale White MDF Waterproof Melamine Mdf Board 9mm 12mm 15mm 18mm Melamine MDF. Retrieved August 8, 2023, from https://www.alibaba.com/product-detail/Wholesale-White-MDF-Waterproof-Melamine-Mdf_1600272969707.html?spm=a2700.7735675.0.0.7328VmzBVmzB6A&s=p

Alonso, G. B. (2021). *Environmental Product Declaration in accordance with ISO 14025 for Implicit mobile pedestal (9U) from Steelcase* (tech. rep. S-P-03829). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/896e3a93-b10b-4b42-e5e4-08da53492d7b/Data

Alonso, G. B. (2022a). *Environmental Product Declaration in accordance with ISO 14025 for DO Chair from Steelcase* (tech. rep. S-P-02981). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/1f0d2513-292c-4db5-e5e6-08da53492d7b/Data

Alonso, G. B. (2022b). *Environmental Product Declaration in accordance with ISO 14025 for Lares desk (1800x800 mm) with wooden legs from Steelcase* (tech. rep. S-P-07397). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/c8c4ed6b-07fd-44b7-5110-08dafd38c942/Data

Alonso, G. B. (2022c). *Environmental Product Declaration in accordance with ISO 14025 for: Lares Meeting circular table (Ø 1000 mm) with wooden legs from Steelcase* (tech. rep. S-P-07398). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/7352bba5-b3f3-4d12-b15c-08daf25c9c72/Data

Alonso, G. B. (2022d). *Environmental Product Declaration in accordance with ISO 14025 Universal cupboard with laminated hinged doors (1980x1000mm) from Steelcase* (tech. rep. S-P-02684). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/4862c1af-d4d7-4211-e5f1-08da53492d7b/Data

Amazon.com, I. (2023). Furniture. Retrieved July 9, 2023, from https://www.amazon.com/gp/browse.html?node=1063306&ref_=nav_em__furn_0_2_17_7

Arvai, K. (2020). KneeLocator. Retrieved July 9, 2023, from https://kneed.readthedocs.io/en/stable/api.html#kneed.knee_locator.KneeLocator

Ashley Global Retail, L. (2023). Furniture. Retrieved July 9, 2023, from https://www.ashleyfurniture.com/c/furniture/

Augiseau, V., & Barles, S. (2017). Studying construction materials flows and stock: A review. *Resources, Conservation and Recycling*, *123*, 153–164. https://doi.org/10.1016/j.resconrec.2016.09.002

Austin, K. G., Schwantes, A., Gu, Y., & Kasibhatla, P. S. (2019). What causes deforestation in Indonesia? *Environmental Research Letters*, *14*(2), 024007. https://doi.org/10.1088/1748-9326/aaf6db

Baptista, A. I., & Perovich, A. (2019). *U.S. Municipal Solid Waste Incinerators: An Industry in Decline* (tech. rep.). Tishman Environment and Design Center. https://www.no-burn.org/wp-content/uploads/2021/03/CR_GaiaReportFinal_05.21-1.pdf#page=15

Barrie, J., Anantharaman, M., Oyinlola, M., & Schröder, P. (2022). The circularity divide: What is it? And how do we avoid it? *Resources, Conservation and Recycling*, *180*. https://doi.org/10.1016/j.resconrec.2022.106208

Becerril-Piña, R., & Mastachi-Loza, C. A. (2020). Desertification: Causes and Countermeasures. https://doi.org/10.1007/978-3-319-71065-5{_}81-1

Besserer, A., Troilo, S., Girods, P., Rogaume, Y., & Brosse, N. (2021). Cascading Recycling of Wood Waste: A Review. *Polymers*, *13*(11), 1752. https://doi.org/10.3390/polym13111752

Bianco, I., Thiebat, F., Carbonaro, C., Pagliolico, S. L., Blengini, G. A., & Comino, E. (2021). Life Cycle Assessment (LCA)-based tools for the eco-design of wooden furniture. *Journal of Cleaner Production*, *324*, 129249. https://doi.org/10.1016/j.jclepro.2021.129249

Bieser, J. C., Blumer, Y., Burkhalter, L., Itten, R., Jobin, M., & Hilty, L. M. (2022). Consumer-oriented interventions to extend smartphones' service lifetime. *Cleaner and Responsible Consumption*, *7*, 100074. https://doi.org/10.1016/j.clrc.2022.100074

Big Lots Stores LLC. (2023). FURNITURE. Retrieved July 9, 2023, from https://www.biglots.com/c/furniture/_/N-3063694192

Bradshaw, C. J. A., Sodhi, N. S., Peh, K. S.-H., & Brook, B. W. (2007). Global evidence that deforestation amplifies flood risk and severity in the developing world. *Global Change Biology*, *13*(11), 2379–2395. https://doi.org/10.1111/j.1365-2486.2007.01446.x

Breedveld, L. (2019). *Environmental Product Declaration for Babar from Arper* (tech. rep. S-P-01668). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/3570e509-48f1-4b25-8acb-9b67e39a3664/Data

Breedveld, L. (2020a). *Environmental Product Declaration in accordance with ISO 14025 for OVO Armchair from Benchmark* (tech. rep. S-P-01958). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/086cfe1e-c4e8-4df2-fbfc-08d92980ffe1/Data

Breedveld, L. (2020b). *Environmental Product Declaration in accordance with ISO 14025 for OVO Bench collection from Benchmark* (tech. rep. S-P-01955). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/8a46693f-023f-4327-9550-b170271e8360/Data

Breedveld, L. (2020c). *Environmental Product Declaration in accordance with ISO 14025 for: OVO Table Collection from Benchmark* (tech. rep. S-P-01957). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/3df62b72-9434-44d9-b06f-be26f3afe342/Data

Breedveld, L. (2021a). *Environmental Product Declaration in accordance with ISO 14025 for Arris: table from MARK* (tech. rep. S-P-04306). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/c6cd87a6-d63d-41f6-8065-08d941d5f1c9/Data

Breedveld, L. (2021b). *Environmental Product Declaration in accordance with ISO 14025 for Type: benches from MARK* (tech. rep. S-P-03305). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/c31c629f-9254-46aa-805d-08d941d5f1c9/Data

Breedveld, L. (2021c). *Environmental Product Declaration in accordance with ISO 14025 for: Alf: stools and chairs from MARK* (tech. rep. S-P-03293). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/8a0141b7-1143-4aab-8064-08d941d5f1c9/Data

Breedveld, L. (2021d). *Environmental Product Declaration in accordance with ISO 14025 for: Arris: chair, sofa from MARK* (tech. rep. S-P-003307). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/2cd29745-6080-4841-8059-08d941d5f1c9/Data

Breedveld, L. (2023a). *Environmental Product Declaration for CATIFA 53 from Arper* (tech. rep. S-P-08425). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/12617f1b-bde7-4389-0cb0-08db3c2e10fb/Data

Breedveld, L. (2023b). *Environmental Product Declaration in accordance with 14025:2006 for Hari Chair from Ondarreta* (tech. rep. S-P-08979). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/3585e601-a31f-458e-c3bc-08db39c762ee/Data

Breedveld, L. (2023c). *Environmental Product Declaration in accordance with ISO 14025 for AAVA Wood from Arper* (tech. rep. S-P-02424). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/046995e5-e930-44bc-a2be-08db196e9a1c/Data

Brunet-Navarro, P., Jochheim, H., & Muys, B. (2016). Modelling carbon stocks and fluxes in the wood product sector: a comparative review. *Global Change Biology*, *22*(7), 2555–2569. https://doi.org/10.1111/gcb.13235

Bureau of Labor Statistics. (2023). Unemployment. Retrieved July 2, 2023, from https://data.ers.usda.gov/reports.aspx?ID=17828

Chevalier, S. (2012). Material Cultures of Home. In *International encyclopedia of housing and home* (pp. 222–230). Elsevier. https://doi.org/10.1016/B978-0-08-047163-1.00365-9

Chicco, D., Warrens, M. J., & Jurman, G. (2021). The coefficient of determination R-squared is more informative than SMAPE, MAE, MAPE, MSE and RMSE in regression analysis evaluation. *PeerJ Computer Science*, *7*, e623. https://doi.org/10.7717/peerj-cs.623

CIA.gov. (2023a). Country Comparisons - Area. https://www.cia.gov/the-world-factbook/field/area/country-comparison/

CIA.gov. (2023b). Country Comparisons - Populations. Retrieved July 19, 2023, from https://www.cia.gov/the-world-factbook/field/population/country-comparison/
Circle Economy. (2023). National Circularity Gap Metric - Circularity Gap Reporting Initiative. Retrieved July 9, 2023, from https://www.circularity-gap.world/countries
Coloma, M., Akizu-Gardoki, O., & Lizundia, E. (2022). Beyond ecodesign, internationalized markets enhance the global warming potential in the wood furniture sector. *Journal of Cleaner Production*, *379*, 134795. https://doi.org/10.1016/j.jclepro.2022.134795
Consumer Product Safety Commission. (2008). Definitions.
Cooper, T. (2020). Slower Cycles: An Essential Characteristic of the Circular Economy. In S. Eisenriegler (Ed.), *The circular economy in the european union* (pp. 99–116). Springer International Publishing. https://doi.org/10.1007/978-3-030-50239-3{_}9
Cooper, T., Kaner, J., Furmston, K., & Cutts, A. (2021). Furniture lifetimes in a circular economy: a state of the art review. *4th PLATE 2021 Virtual Conference*.
Cordella, M., & Hidalgo, C. (2016). Analysis of key environmental areas in the design and labelling of furniture products: Application of a screening approach based on a literature review of LCA studies. *Sustainable Production and Consumption*, *8*, 64–77. https://doi.org/10.1016/j.spc.2016.07.002
Cox, J., Griffith, S., Giorgi, S., & King, G. (2013). Consumer understanding of product lifetimes. *Resources, Conservation and Recycling*, *79*, 21–29. https://doi.org/10.1016/j.resconrec.2013.05.003
Davies, T. (2022). Slow violence and toxic geographies: 'Out of sight' to whom? *Environment and Planning C: Politics and Space*, *40*(2), 409–427. https://doi.org/10.1177/2399654419841063
Demographic Statistical Methods Division. (2022). 2021 AHS Integrated National Sample: Sample Design, Weighting, and Error Estimation.
Duku, C., & Hein, L. (2021). The impact of deforestation on rainfall in Africa: a data-driven assessment. *Environmental Research Letters*, *16*(6), 064044. https://doi.org/10.1088/1748-9326/abfcfb
Dunlap, A., & Riquito, M. (2023). Social warfare for lithium extraction? Open-pit lithium mining, counterinsurgency tactics and enforcing green extractivism in northern Portugal. *Energy Research & Social Science*, *95*, 102912. https://doi.org/10.1016/j.erss.2022.102912
EcoVibes. (2021). *Environmental Product Declaration in accordance with ISO 14024 for Metallic Bookcase (low version) from DROMEAS S.A.* (tech. rep. S-P-02949). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/072bda23-f1cf-44f7-4056-08d8d0dbc8ee/Data
Ellen MacArthur Foundation. (2019). The butterfly diagram: visualising the circular economy. Retrieved July 9, 2023, from https://ellenmacarthurfoundation.org/circular-economy-diagram
Ellen MacArthur Foundation. (2023). The technical cycle of the butterfly diagram. Retrieved July 9, 2023, from https://ellenmacarthurfoundation.org/articles/the-technical-cycle-of-the-butterfly-diagram

EPA Office of Resource Conservation and Recovery. (2022). *Building a Circular Economy for All: Progress Toward Transformative Change* (tech. rep.). US EPA.

European Commission. (2023). Circular economy action plan. Retrieved July 11, 2023, from https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., Moriguchi, Y., Schütz, H., Schandl, H., & Weisz, H. (2011). Methodology and Indicators of Economy-wide Material Flow Accounting: State of the Art and Reliability Across Sources. *Journal of Industrial Ecology*, *15*(6), 855–876. https://doi.org/10.1111/j.1530-9290.2011.00366.x

Fischer-Kowalski, M., & Hüttler, W. (1998). Society's Metabolism. *Journal of Industrial Ecology*, *2*(4), 107–136. https://doi.org/10.1162/jiec.1998.2.4.107

Flipsen, B., Bakker, C., & van Bohemen, G. (2016). Developing a reparability indicator for electronic products. *2016 Electronics Goes Green 2016+ (EGG)*, 1–9. https://doi.org/10.1109/EGG.2016.7829855

Fraser, M. (2022). PIONEERS OF THE FUTURE: THE COUNTRIES LEADING THE WAY WITH CIRCULAR ECONOMY POLICY. Retrieved July 9, 2023, from https://www.circle-economy.com/blogs/the-circular-economy-who-is-leading-the-way

Fuller, T. L., Narins, T. P., Nackoney, J., Bonebrake, T. C., Sesink Clee, P., Morgan, K., Tróchez, A., Bocuma Meñe, D., Bongwele, E., Njabo, K. Y., Anthony, N. M., Gonder, M. K., Kahn, M., Allen, W. R., & Smith, T. B. (2019). Assessing the impact of China's timber industry on Congo Basin land use change. *Area*, *51*(2), 340–349. https://doi.org/10.1111/area.12469

Furniture Today. (2020). Market share of the leading online furniture retailers in the United States as of 2019. Retrieved July 11, 2023, from https://www.statista.com/statistics/1136122/market-share-of-online-furniture-retailers-us/

Geist, H. J., & Lambin, E. F. (2002). Proximate Causes and Underlying Driving Forces of Tropical Deforestation: Tropical forests are disappearing as the result of many pressures, both local and regional, acting in various combinations in different geographical locations. *BioScience*, *52*(2), 143–150. https://doi.org/https://doi.org/10.1641/0006-3568(2002)052[0143:PCAUDF]2.0.CO;2

Geography Division. (2023). Census Regions and Divisions of the United States. Retrieved July 2, 2023, from https://www2.census.gov/geo/pdfs/maps-data/maps/reference/us_regdiv.pdf

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11–32. https://doi.org/10.1016/J.JCLEPRO.2015.09.007

Goe, M., & Gaustad, G. (2014). Strengthening the case for recycling photovoltaics: An energy payback analysis. *Applied Energy*, *120*, 41–48. https://doi.org/10.1016/j.apenergy.2014.01.036

Gonçalves, M., Freire, F., & Garcia, R. (2021). Material flow analysis of forest biomass in Portugal to support a circular bioeconomy. *Resources, Conservation and Recycling*, *169*, 105507. https://doi.org/10.1016/j.resconrec.2021.105507

González-García, S., Gasol, C. M., Lozano, R. L., Feijoo, G., Gabarrell, X., & Pons, J. (2011). Assessing the global warming potential of wooden products from the furniture sector to improve their ecodesign. *Science of The Total Environment*, *410-411*, 16–25. https://doi.org/10.1016/j.scitotenv.2011.09.059

Graedel, T. E., Harper, E. M., Nassar, N. T., Nuss, P., & Reck, B. K. (2015). Criticality of metals and metalloids. *Proceedings of the National Academy of Sciences*, *112*(14), 4257–4262. https://doi.org/10.1073/pnas.1500415112

Grant, R. (2012). Material Cultures of Domestic Interiors. In *International encyclopedia of housing and home* (pp. 200–205). Elsevier. https://doi.org/10.1016/B978-0-08-047163-1.00360-X

Guinée, J., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., Koning, A. d., Oers, L. v., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H., Bruijn, H. d., Duin, R. v., & Huijbregts, M. (2002). *Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background* (Vol. 7). Kluwer Academic Publishers, ISBN 1-4020-0228-9.

Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D. B., & Fischer-Kowalski, M. (2019). Contributions of sociometabolic research to sustainability science. *Nature Sustainability*, *2*(3), 173–184. https://doi.org/10.1038/s41893-019-0225-2

Hartini, S., Wicaksono, P. A., Prastawa, H., Hadyan, A. F., & Sriyanto. (2019). The Environmental Impact Assessment of Furniture Production Process Using the Life Cycle Assessment. *IOP Conference Series: Materials Science and Engineering*, *598*(1), 012078. https://doi.org/10.1088/1757-899X/598/1/012078

Hebrok, M. (2016). Where Furniture Goes to Die. Designing for Sustainable Behaviour in a Practice Perspective. *Techniques & culture*. https://doi.org/10.4000/tc.7855

Hischier, R., Reale, F., Castellani, V., & Sala, S. (2020). Environmental impacts of household appliances in Europe and scenarios for their impact reduction. *Journal of Cleaner Production*, *267*, 121952. https://doi.org/10.1016/j.jclepro.2020.121952

Hollows, J. (2008). Home-Making: Domestic and Material Culture. In *Domestic cultures* (pp. 74–94). Open University Press.

Home Depot. (2023). Armoires & Wardrobes. Retrieved August 11, 2023, from https://www.homedepot.com/b/Furniture-Bedroom-Furniture-Armoires-Wardrobes/N-5yc1vZc7om

Hometrack. (2023). The Do's and Don'ts of Real Estate Photography. Retrieved July 8, 2023, from https://www.hometrack.net/blog/the-dos-and-donts-of-real-estate-photography

Hoxha, E., & Jusselme, T. (2017). On the necessity of improving the environmental impacts of furniture and appliances in net-zero energy buildings. *Science of The Total Environment*, *596-597*, 405–416. https://doi.org/10.1016/j.scitotenv.2017.03.107

Inter IKEA Systems B.V. (2022). Year in Review. Retrieved October 25, 2022, from https://about.ikea.com/en/about-us/year-in-review

Inter IKEA Systems B.V. (2023a). Furniture. Retrieved July 9, 2023, from https://www.ikea.com/us/en/cat/furniture-fu001/

Inter IKEA Systems B.V. (2023b). The story of IKEA flatpacks. Retrieved July 8, 2023, from https://www.ikea.com/ph/en/this-is-ikea/about-us/the-story-of-ikea-flatpacks-puba710ccb0

International Organization for Standardization. (2021). ISO/TC 136 - Furniture. Retrieved July 11, 2023, from https://www.iso.org/committee/52448.html

Iritani, D. R., Silva, D. A. L., Saavedra, Y. M. B., Grael, P. F. F., & Ometto, A. R. (2015). Sustainable strategies analysis through Life Cycle Assessment: a case study in a furniture industry. *Journal of Cleaner Production*, *96*, 308–318. https://doi.org/10.1016/j.jclepro.2014.05.029

IRP. (2018). *Re-defining Value: The Manufacturing Revolution. Remanufacturing, Refurbishment, Repair and Direct Reuse in the Circular Economy* (N. Nasr, J. Russell, S. Bringezu, S. Hellweg, B. Hilton, C. Kreiss, & N. v. Gries, Eds.). A Report of the International Resource Panel. United Nations Environment Programme.

Jaeger-Erben, M., Frick, V., & Hipp, T. (2021). Why do users (not) repair their devices? A study of the predictors of repair practices. *Journal of Cleaner Production*, *286*, 125382. https://doi.org/10.1016/j.jclepro.2020.125382

Kaddoura, M., Kambanou, M. L., Tillman, A.-M., & Sakao, T. (2019). Is Prolonging the Lifetime of Passive Durable Products a Low-Hanging Fruit of a Circular Economy? A Multiple Case Study. *Sustainability*, *11*(18), 4819. https://doi.org/10.3390/su11184819

Kagawa, S., Nansai, K., Kondo, Y., Hubacek, K., Suh, S., Minx, J., Kudoh, Y., Tasaki, T., & Nakamura, S. (2011). Role of Motor Vehicle Lifetime Extension in Climate Change Policy. *Environmental Science & Technology*, *45*(4), 1184–1191. https://doi.org/10.1021/es1034552

Kamin, D. (2022). 'Fast Furniture' Is Cheap. And Americans Are Throwing It in the Trash.

Karamage, F., Shao, H., Chen, X., Ndayisaba, F., Nahayo, L., Kayiranga, A., Omifolaji, J., Liu, T., & Zhang, C. (2016). Deforestation Effects on Soil Erosion in the Lake Kivu Basin, D.R. Congo-Rwanda. *Forests*, *7*(12), 281. https://doi.org/10.3390/f7110281

Kaufman, J. D., & Hajat, A. (2021). Confronting Environmental Racism. *Environmental Health Perspectives*, *129*(5). https://doi.org/10.1289/EHP9511

Kayo, C., Dente, S. M., Aoki-Suzuki, C., Tanaka, D., Murakami, S., & Hashimoto, S. (2019). Environmental Impact Assessment of Wood Use in Japan through 2050 Using Material Flow Analysis and Life Cycle Assessment. *Journal of Industrial Ecology*, *23*(3), 635–648. https://doi.org/10.1111/jiec.12766

Kaza, S., Yao, L. C., Bhada-Tata, P., & Van Woerden, F. (2018). Trends in Solid Waste Management. Retrieved July 2, 2023, from https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html

Khan, M. A., Mittal, S., West, S., & Wuest, T. (2018). Review on upgradability – A product lifetime extension strategy in the context of product service systems. *Journal of Cleaner Production*, *204*, 1154–1168. https://doi.org/10.1016/j.jclepro.2018.08.329

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kwak, M. (2016). Assessing the Greenness of Product Lifetime Extension. *ICIC Express Letters*, *7*(2), 491–496.

Lanau, M., Liu, G., Kral, U., Wiedenhofer, D., Keijzer, E., Yu, C., & Ehlert, C. (2019). Taking Stock of Built Environment Stock Studies: Progress and Prospects. *Environmental Science & Technology*, *53*(15), 8499–8515. https://doi.org/10.1021/acs.est.8b06652

La-Z-Boy Incorporated. (2023). La-Z-Boy. Retrieved July 9, 2023, from https://www.la-z-boy.com/

Li, S., Linn, J., & Spiller, E. (2013). Evaluating "Cash-for-Clunkers": Program effects on auto sales and the environment. *Journal of Environmental Economics and Management*, *65*(2), 175–193. https://doi.org/10.1016/j.jeem.2012.07.004

Linkosalmi, L., Husgafvel, R., Fomkin, A., Junnikkala, H., Witikkala, T., Kairi, M., & Dahl, O. (2016). Main factors influencing greenhouse gas emissions of wood-based furniture industry in Finland. *Journal of Cleaner Production*, *113*, 596–605. https://doi.org/10.1016/j.jclepro.2015.11.091

Luppold, W. G., & Bumgardner, M. S. (2021). Analyzing changes in the U.S. wood furniture industry from 1997 to 2019: Production, net imports, and consumption. *BioResources*, *17*(1), 939–951. https://doi.org/10.15376/biores.17.1.939-951

Magrach, A., Senior, R. A., Rogers, A., Nurdin, D., Benedick, S., Laurance, W. F., Santamaria, L., & Edwards, D. P. (2016). Selective logging in tropical forests decreases the robustness of liana–tree interaction networks to the loss of host tree species. *Proceedings of the Royal Society B: Biological Sciences*, *283*(1826), 20153008. https://doi.org/10.1098/rspb.2015.3008

Manoochehri, S., Schluep, M., Dams, Y., Mehlhart, G., Bekkevold Lingås, D., Marin, G., Nicolau, M., & Colgan, S. (2022). *An overview of Europe's repair sector* (tech. rep.). European Environmental Agency. Retrieved August 9, 2023, from https://circulareconomy.europa.eu/platform/sites/default/files/2022-12/Repair%20sector.pdf

Martuzzi, M., Mitis, F., & Forastiere, F. (2010). Inequalities, inequities, environmental justice in waste management and health. *The European Journal of Public Health*, *20*(1), 21–26. https://doi.org/10.1093/eurpub/ckp216

MattressFirm.com. (2023). Furniture & More. https://www.mattressfirm.com/furniture-and-more/5637147577.c

Mazur, C. (2016). Homes on the Range: Homeownership Rates Are Higher in Rural America. Retrieved July 12, 2023, from https://www.census.gov/newsroom/blogs/random-samplings/2016/12/homes_on_the_range.html

Medeiros, D. L., Tavares, A. O. D. C., Rapôso, Á., & Kiperstok, A. (2017). Life cycle assessment in the furniture industry: the case study of an office cabinet. *International Journal of Life Cycle Assessment*, *22*(11), 1823–1836. https://doi.org/10.1007/s11367-017-1370-3

Ministerie van Infrastructuur en Waterstaat. (2022). Circular Dutch economy by 2050. Retrieved July 19, 2023, from https://www.government.nl/topics/circular-economy/circular-dutch-economy-by-2050

Morseletto, P. (2020). Targets for a circular economy. *Resources, Conservation and Recycling*, *153*, 104553. https://doi.org/10.1016/j.resconrec.2019.104553

Moura, M. C. P., Smith, S. J., & Belzer, D. B. (2015). 120 Years of U.S. Residential Housing Stock and Floor Space [Supplementary Materials]. *PLOS ONE*, *10*(8), e0134135. https://doi.org/10.1371/journal.pone.0134135

Movoto Real Estate. (2023). Real Estate, Homes for Sale, MLS Listings | Movoto. Retrieved July 9, 2023, from https://www.movoto.com/

Müller, E., Hilty, L. M., Widmer, R., Schluep, M., & Faulstich, M. (2014). Modeling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods. *Environmental Science & Technology*, *48*(4), 2102–2113. https://doi.org/10.1021/es403506a

National Association of Realtors & Move, I. (2023). realtor.com | Homes for Sale, Apartments & Houses for Rent. https://www.realtor.com/

Nicolini, E. (2022). The Circularity of MSW in Urban Landscapes: An Evaluation Method for a Sustainable System Implementation. *Sustainability*, *14*(12), 7358. https://doi.org/10.3390/su14127358

Nishijima, D., & Oguchi, M. (2023). Measuring product lifetime extension potential by increasing the expected product lifetime: Methodology and case study. *Business Strategy and the Environment*, *32*(4), 1218–1231. https://doi.org/10.1002/bse.3183

Observatory of Economic Complexity. (2021). Wood Products. Retrieved August 9, 2023, from https://oec.world/en/profile/hs/wood-products

Organisation for Economic Co-operation and Development. (2008). *Measuring Material Flows and Resource Productivity* (tech. rep.). OECD. https://www.oecd.org/environment/indicators-modelling-outlooks/MFA-Guide.pdf

Organisation for Economic Co-operation and Development. (2013). *Material Resources, Productivity and the Environment: Key Findings* (tech. rep.). OECD. https://www.oecd.org/greengrowth/MATERIAL%20RESOURCES,%20PRODUCTIVITY%20AND%20THE%20ENVIRONMENT_key%20findings.pdf

Organisation for Economic Co-operation and Development. (2022). Plastic pollution is growing relentlessly as waste management and recycling fall short, says oecd. Retrieved August 30, 2023, from https://www.oecd.org/environment/plastic-pollution-is-growing-relentlessly-as-waste-management-and-recycling-fall-short.htm#:~:text=Only%209%25%20of%20plastic%20waste,is%20disposed%20of%20as%20residues).

Pauliuk, S., & Heeren, N. (2020). ODYM—An open software framework for studying dynamic material systems: Principles, implementation, and data structures. *Journal of Industrial Ecology*, *24*(3), 446–458. https://doi.org/10.1111/jiec.12952

Pauliuk, S., & Müller, D. B. (2014). The role of in-use stocks in the social metabolism and in climate change mitigation. *Global Environmental Change*, *24*, 132–142. https://doi.org/10.1016/j.gloenvcha.2013.11.006

Pauliuk, S., & Mutel, C. (2014). dynamic_stock_model. https://github.com/stefanpauliuk/dynamic_stock_model/tree/master

Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., Blondel, M., Prettenhofer, P., Weiss, R., Dubourg, V., Vanderplas, J., Passos, A., Cournapeau, D., Brucher, M., Perrot, M., & Duchesnay, E. (2011). Sckikit-learn: Machine Learning in Python. *Journal of Machine Learning Research*, *12*, 2825–2830. https://scikit-learn.org/stable/about.html#citing-scikit-learn

Pedzik, M., Auriga, R., Kristak, L., Antov, P., & Rogoziński, T. (2022). Physical and Mechanical Properties of Particleboard Produced with Addition of Walnut (Juglans regia L.) Wood Residues. *Materials*, *15*(4), 1280. https://doi.org/10.3390/ma15041280

Peischel, W. (2022). Is It Time to Stop Burning Our Garbage? Retrieved August 9, 2023, from https://www.bloomberg.com/news/articles/2022-05-23/environmental-concerns-grow-over-incinerators-in-u-s

Population Division. (2022). World Population Prospects 2022. Retrieved July 2, 2023, from https://population.un.org/wpp/Graphs/Probabilistic/POP/TOT/900

Prunel, D. (2021). *Environmental Product Declaration in accordance with ISO 14025 for LAIME Armchairs from Noma* (tech. rep. S-P-03871). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/f970a49a-52da-43fb-fc05-08d92980ffe1/Data

Rogers, E. (2010). *Diffusion of Innovations*. Simon; Schuster.

Romer, C., & Carroll, C. (2010). Did 'Cash-for-Clunkers' work as intended? Retrieved July 26, 2023, from https://obamawhitehouse.archives.gov/blog/2010/04/05/did-cash-clunkers-work-intended

Russell, J. D., Huff, K., & Haviarova, E. (2023). Evaluating the cascading-use of wood furniture: How value-retention processes can contribute to material efficiency and circularity. *Journal of Industrial Ecology*, *27*(3), 856–867. https://doi.org/10.1111/jiec.13284

Sanford, T., Boucher, D., Elias, P., Lininger, K., May-Tobin, C. C., Roquemore, S., Saxon, E., Martin, J. I., & Mulik, K. (2011). The drivers of tropical deforestation: a comprehensive review. *AGU Fall Meeting Abstracts*. https://www.researchgate.net/publication/258470823_The_drivers_of_tropical_deforestation_a_comprehensive_review

Sessa, F. (2018). *Environmental Product Declaration in accordance with ISO 14025 for CADDY from Bisley* (tech. rep. S-P-01612). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/a59d0834-df3d-47c1-945d-25b3859938de/Data

Sessa, F. (2022a). *Environmental Product Declaration* (tech. rep. S-P-05032). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/967e89d6-3854-4276-65e9-08d9d9f76d3d/Data

Sessa, F. (2022b). *Environmental Product Declaration in accordance with ISO 14025 for Desks & Drawers from Living by Bisley* (tech. rep. S-P-05033). The International EPD System. https://api.environdec.com/api/v1/EPDLibrary/Files/8a5f6a03-af9a-4379-65ea-08d9d9f76d3d/Data

Sim, J., & Reid, N. (1999). Statistical Inference by Confidence Intervals: Issues of Interpretation and Utilization. *Physical Therapy*, *79*(2), 186–195. https://doi.org/10.1093/ptj/79.2.186

Skaar, C., & Jørgensen, R. B. (2013). Integrating human health impact from indoor emissions into an LCA: a case study evaluating the significance of the use stage. *The International Journal of Life Cycle Assessment*, *18*(3), 636–646. https://doi.org/10.1007/s11367-012-0506-8

Smardzewski, J. (2015). Classification and Characteristics of Furniture. In *Furniture design* (pp. 47–95). Springer International Publishing. https://doi.org/10.1007/978-3-319-19533-9

Spitzley, D. V., Dietz, B. A., & Keoleian. (2006). *Life-Cycle Assessment of Office Furniture Products* (tech. rep. CSS06-11). Regents of the University of Michigan. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=00dca3830875d753ac87cf8f97de7ff4100a3e9a

Statista Research Department. (2022a). Value of the furniture market worldwide from 2020 to 2027.

Statista Research Department. (2022b). Furniture: market share of online retailers in the United States as of 2019.

Statista Research Department. (2022c). Sales of leading furniture stores in the United States in 2019. Retrieved July 2, 2023, from https://www.statista.com/statistics/514614/sales-of-the-leading-10-furniture-stores-in-the-us/

Stehfest, E., van Vuuren, D., Bouwman, L., & Kram, T. (2014). Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications.

Stephan, A., Muñoz, S., Healey, G., & Alcorn, J. (2020). Analysing material and embodied environmental flows of an Australian university — Towards a more circular economy. *Resources, Conservation and Recycling*, *155*, 104632. https://doi.org/10.1016/j.resconrec.2019.104632

Suckling, J., & Lee, J. (2015). Redefining scope: the true environmental impact of smartphones? *The International Journal of Life Cycle Assessment*, *20*(8), 1181–1196. https://doi.org/10.1007/s11367-015-0909-4

Suter, F., Steubing, B., & Hellweg, S. (2017). Life Cycle Impacts and Benefits of Wood along the Value Chain: The Case of Switzerland. *Journal of Industrial Ecology*, *21*(4), 874–886. https://doi.org/10.1111/jiec.12486

Suthar, S., Rayal, P., & Ahada, C. P. (2016). Role of different stakeholders in trading of reusable/recyclable urban solid waste materials: A case study. *Sustainable Cities and Society*, *22*, 104–115. https://doi.org/10.1016/j.scs.2016.01.013

Svensson-Hoglund, S., Russell, J. D., & Richter, J. L. (2022). A Process Approach to Product Repair from the Perspective of the Individual. *Circular Economy and Sustainability*. https://doi.org/10.1007/s43615-022-00226-1

Szichta, P., Risse, M., Weber-Blaschke, G., & Richter, K. (2022). Potentials for wood cascading: A model for the prediction of the recovery of timber in Germany. *Resources, Conservation and Recycling*, *178*. https://doi.org/10.1016/j.resconrec.2021.106101

Target Brands, I. (2023). Furniture Store: Target. Retrieved July 9, 2023, from https://www.target.com/c/furniture/-/N-5xtnr

The White House. (2022). FACT SHEET: Biden-Harris Administration Makes Historic Investment in America's National Labs, Announces Net-Zero Game Changers Initiative. Retrieved July 9, 2023, from https://www.whitehouse.gov/briefing-room/statements-releases/2022/11/04/fact-sheet-biden-harris-administration-makes-historic-investment-in-americas-national-labs-announces-net-zero-game-changers-initiative/

The White House. (2023). Readout of the White House Circular Economy Innovation Roundtable. Retrieved July 9, 2023, from https://www.whitehouse.gov/ostp/news-updates/2023/02/22/readout-of-the-white-house-circular-economy-innovation-roundtable/

The World Bank. (2022). Solid Waste Management. Retrieved July 2, 2023, from https://www.worldbank.org/en/understanding-poverty

ULINE. (2023a). 3-Drawer Cart - 15 x 22 x 24. Retrieved July 11, 2023, from https://www.uline.com/Product/Detail/S-19903/Sterilite-Storage-Boxes/3-Drawer-Cart-15-x-22-x-24

ULINE. (2023b). Economy Folding Table - 48 x 24. Retrieved July 11, 2023, from https://www.uline.com/Product/Detail/H-4208FOL-W/Folding-Tables-and-Chairs/Economy-Folding-Table-48-x-24-White?model=H-4208FOL-W&RootChecked=yes

ULINE. (2023c). H-10310 3-Shelf Open Bookcase. Retrieved July 11, 2023, from https://www.uline.com/PDF/IH-10310-SPFR.PDF

ULINE. (2023d). Metro Bookcase - 3-Shelf, Walnut H-10310 - Uline. https://www.uline.com/Product/Detail/H-10310/File-Cabinets-and-Bookcases/Metro-Bookcase-3-Shelf-Walnut

ULINE. (2023e). Vented Plastic Shelving - 36 x 18 x 74. Retrieved July 11, 2023, from https://www.uline.com/Product/Detail/H-6205/Industrial-Wire-Shelving/Vented-Plastic-Shelving-36-x-18-x-74

UN Statistics Division. (2005). *Demographic Yearbook 2005, Table 6: Definition of "urban"* (tech. rep.). United Nations.

US Census Bureau. (2021). Historical Population Change Data (1910-2020). Retrieved July 2, 2023, from https://www.census.gov/data/tables/time-series/dec/popchange-data-text.html

US Census Bureau. (2023). Highlights of 2022 Characteristics of New Housing. Retrieved July 2, 2023, from https://www.census.gov/construction/chars/highlights.html

US Environmental Protection Agency. (2023a). Fact Sheet about the National Recycling Goal: 50 percent by 2030. Retrieved July 9, 2023, from https://www.epa.gov/circulareconomy/fact-sheet-about-national-recycling-goal-50-percent-2030

US EPA. (2015). *National Recycling Strategy: Part One of a Series on Building a Circular Economy for All* (tech. rep.). US EPA. https://www.epa.gov/system/files/documents/2021-11/final-national-recycling-strategy.pdf

US EPA. (2021). Durable Goods: Product-Specific Data.

US EPA. (2023b). Understanding Global Warming Potentials. Retrieved August 9, 2023, from https://www.epa.gov/ghgemissions/understanding-global-warming-potentials#:~:text=Methane%20(CH4)%20is%20estimated,less%20time%20than%20CO2.

van den Brink, S., Kleijn, R., Sprecher, B., & Tukker, A. (2020). Identifying supply risks by mapping the cobalt supply chain. *Resources, Conservation and Recycling*, *156*, 104743. https://doi.org/10.1016/j.resconrec.2020.104743

van Beijnum, B. (2021). *The cost of comfort: waking up to furniture waste [Unpublished master's thesis]* (Doctoral dissertation). University of Leiden, TU Delft.

van Stijn, A., Malabi Eberhardt, L., Wouterszoon Jansen, B., & Meijer, A. (2021). A Circular Economy Life Cycle Assessment (CE-LCA) model for building components. *Resources, Conservation and Recycling*, *174*, 105683. https://doi.org/10.1016/j.resconrec.2021.105683

Wallsten, B., Magnusson, D., Andersson, S., & Krook, J. (2015). The economic conditions for urban infrastructure mining: Using GIS to prospect hibernating copper stocks. *Resources, Conservation and Recycling*, *103*, 85–97. https://doi.org/10.1016/j.resconrec.2015.07.025

Wang, P., Ryberg, M., Yang, Y., Feng, K., Kara, S., Hauschild, M., & Chen, W.-Q. (2021). Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts. *Nature Communications*, *12*(1), 2066. https://doi.org/10.1038/s41467-021-22245-6

Wang, S., Su, D., & Zhu, S. (2016). A Comparative Study on Life Cycle Assessment of Typical Wood base Furniture. *Advances in Engineering Research*, *63*, 634–640. https://doi.org/10.2991/icseee-16.2016.115

Waskom, M. (2021). seaborn: statistical data visualization. *Journal of Open Source Software*, *6*(60), 3021. https://doi.org/10.21105/joss.03021

Wayfair Inc. (2021). Wayfair Announces Fourth Quarter and Full Year 2020 Results.

Wayfair Inc. (2023). Wayfair Announces Fourth Quarter and Full Year 2022 Results.

Wayfair LLC. (2023). Wayfair.com. https://www.wayfair.com

Wenker, J. L., Richter, K., & Rüter, S. (2018). A Methodical Approach for Systematic Life Cycle Assessment of Wood-Based Furniture. *Journal of Industrial Ecology*, *22*(4), 671–685. https://doi.org/10.1111/jiec.12581

Wicaksono, P. A., & Kadafi, C. A. (2020). The Improvement of Production Process Impact in Furniture Industry Toward Circular Economy. *E3S Web of Conferences*, *202*, 07052. https://doi.org/10.1051/e3sconf/202020207052

Wiedmann, T., Lenzen, M., Keyßer, L. T., & Steinberger, J. K. (2020). Scientists' warning on affluence. *Nature Communications*, *11*(1), 3107. https://doi.org/10.1038/s41467-020-16941-y

Wieser, H., & Tröger, N. (2018). Exploring the inner loops of the circular economy: Replacement, repair, and reuse of mobile phones in Austria. *Journal of Cleaner Production*, *172*, 3042–3055. https://doi.org/10.1016/j.jclepro.2017.11.106

Williams-Sonoma, I. (2023a). Williams-Sonoma Home. Retrieved July 9, 2023, from https://www.williams-sonoma.com/pages/williams-sonoma-home/?cm_type=gnav

Williams-Sonoma Inc. (2023b). Furniture. Retrieved July 9, 2023, from https://www.westelm.com/shop/furniture/

Wilson, D. C. (2015). Solid waste management. In *Global waste management outlook* (pp. 274–275). https://www.unep.org/resources/report/global-waste-management-outlook

Wiprächtiger, M., Rapp, M., Hellweg, S., Shinde, R., & Haupt, M. (2022). Turning trash into treasure: An approach to the environmental assessment of waste prevention and its application to clothing and furniture in Switzerland. *Journal of Industrial Ecology*, *26*(4), 1389–1405. https://doi.org/10.1111/jiec.13275

Zillow. (2023). Zillow: Real Estate, Apartments, Mortgages & Home Values. Retrieved July 8, 2023, from https://www.zillow.com/

Zimmer, A., & Angie Lunelli Bachmann, S. (2023). Challenges for recycling medium-density fiberboard (MDF). *Results in Engineering*, 101277. https://doi.org/10.1016/j.rineng.2023.101277

Zubair, M., Iqbal, M. A., Shil, A., Chowdhury, M. J. M., Moni, M. A., & Sarker, I. H. (2022). An Improved K-means Clustering Algorithm Towards an Efficient Data-Driven Modeling. *Annals of Data Science*. https://doi.org/10.1007/s40745-022-00428-2

A
Flowchart of literature review keywords and findings

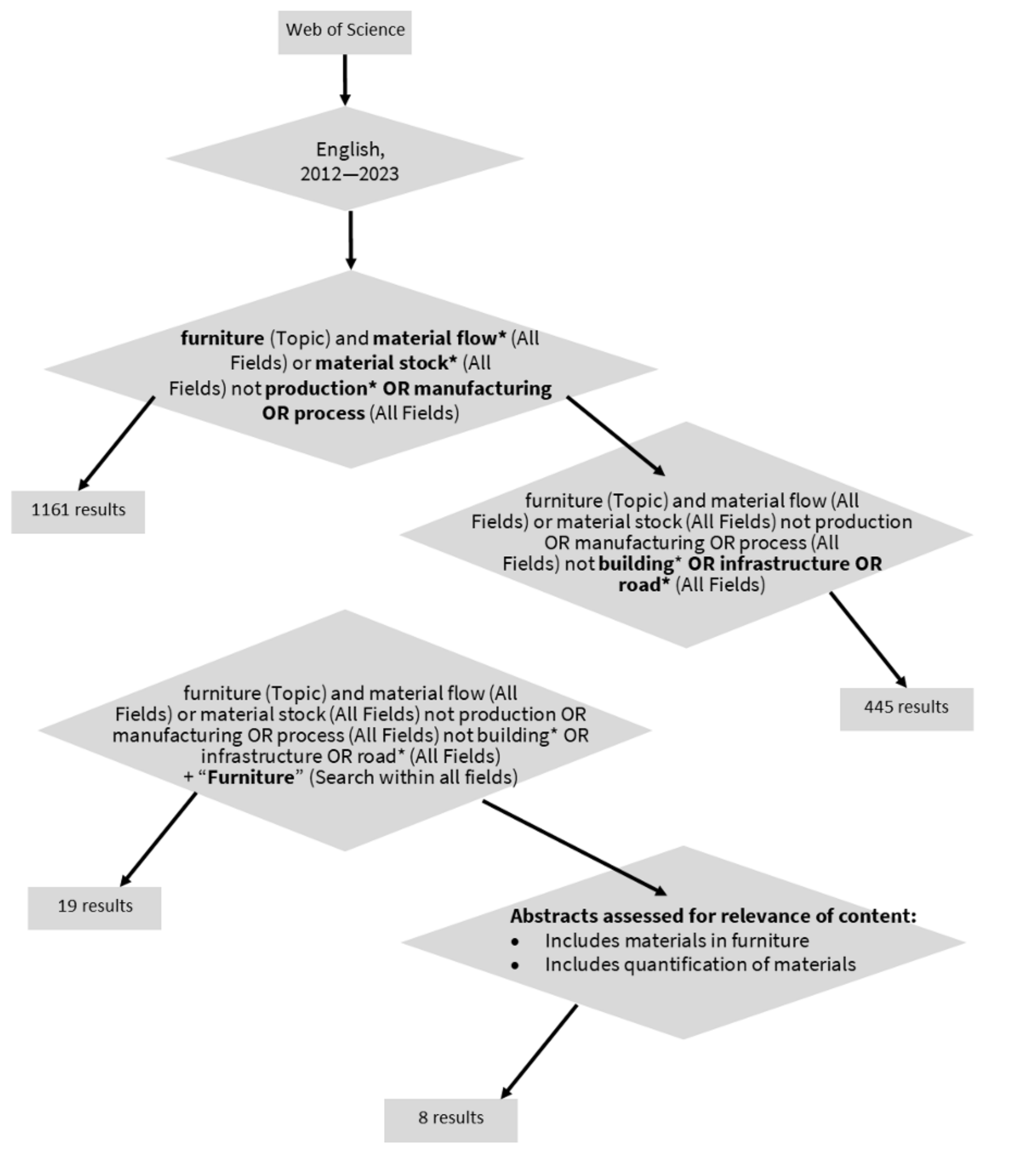


Figure A.1: Flowchart of keywords used and the number of results returned by the Web of Science database for the literature review.

B Furniture categorizations

Table B.1: Description of indoor furniture categories.

Furniture category	Description
Dining table	Any flat surface with non-foldable legs, leg(s) taller than the seat of a dining chair, and has the circumference/edge length to accommodate more than one dining chair
End table	Although some end tables are sold with more than two shelves or drawers, this size was chosen for consistency. (around the surface area of one dining chair seat).
Coffee table	Same height requirements as an end table, with the additional width requirement of less than two adjacent drawers or shelves. The surface is larger than that of an end table.
Desk	Same height requirement of a dining table but accommodates only one chair (due to leg arrangement, placement in room, additional drawers or other accessories, etc.).
Couch	An upholstered chair with more than two seats adjacent to one another and with back support. Also known as a sofa.
Upholstered chair	A chair with upholstery on the back and seat, with a leg-to-back ratio of around 1:1. These chairs only have the width for one seat.
Dining chair	A chair with a back and leg(s) that have slightly larger leg-to-back ratio than an "upholstered chair". The chair can be upholstered or not upholstered.
Office chair	A chair with a back and it leg(s) on wheels.
Stool	A chair with or without a back, and a leg-to-cushion height ratio of more than 1.
Ottoman	An upholstered seat without a back and with any seat dimensions, but a leg-to-cushion height ratio less than one.
Single bed frame	A bed frame that seems to have a width that accommodate less than two adjacent full-sized pillows. This includes cribs.
Double bed frame	A bed frame that seems to have a width that accommodates more than two adjacent full-sized pillows.
Shelf	A structure with no front covering or a glass covering that has more than two shelves, either in the horizontal or vertical dimensions. This can be any height.
Dresser	A structure with two or more drawers that can be pulled out, either in the horizontal or vertical dimensions. Its height may be at or below average human height.
Wardrobe	A structure that seems to be at or above average human height that is fully covered with a material other than glass or fabric. It may have some drawers.
Plastic storage unit	Any shelving or drawers, the main composition of which seems to be plastic.
Metal storage unit	Any shelving or drawers, the main composition of which seems to be metal.
Folding table	A table that is larger than an end table, whose legs appear to be foldable.

Table B.2: Description of outdoor and recreational furniture categories.

Furniture category	Description
Patio chair	Any chair with or without a back and the width of a single seat that is not considered a lawn chair.
Patio table	Any table of any size that is placed outside the home or in a sunroom or solarium. The surface must be solid (i.e., not upholstered).
Patio umbrella	An umbrella that stands by itself or is placed on top of a patio table, outdoors.
Bench	Any chair that has the width of more than one seat and is placed outdoors.
Swing set	A structure that is placed outdoors than accommodates more than one swing. (For example, a swing tied to a tree does not count as a swing set. However, a structure with one swing and a slide would.)
Trampoline	A trampoline that should accommodate more than one person.
Recreational table	Any table that seems to be used primarily for recreation. (e.g., It has handles and figures for foosball, or felt for pool.)
Basketball hoop	Any basketball with a stand and weighed-down or buried base.

C
Furniture intensities

For most household furniture categories, homes in urban areas have more units per meter squared. The exceptions are metal storage units, wardrobes, dressers, single bedframes, and stools.

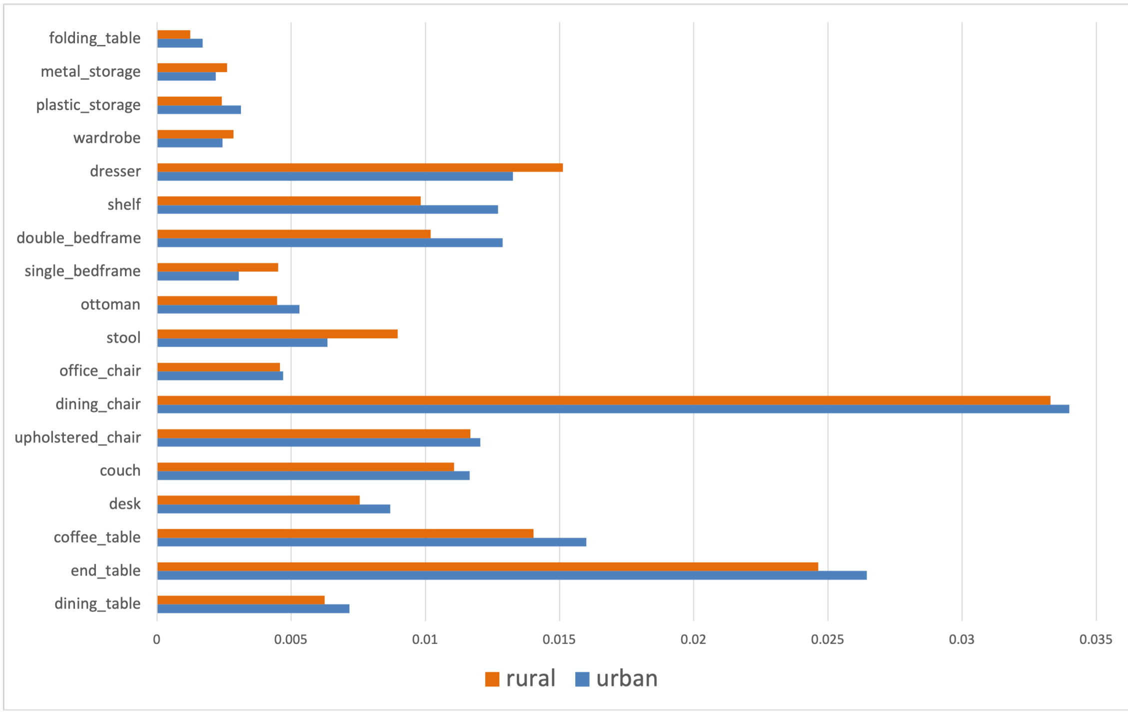


Figure C.1: Bar chart showing the furniture units/m^2, categorized by furniture category and area type.

D
Linear regression plots for all indoor furniture categories

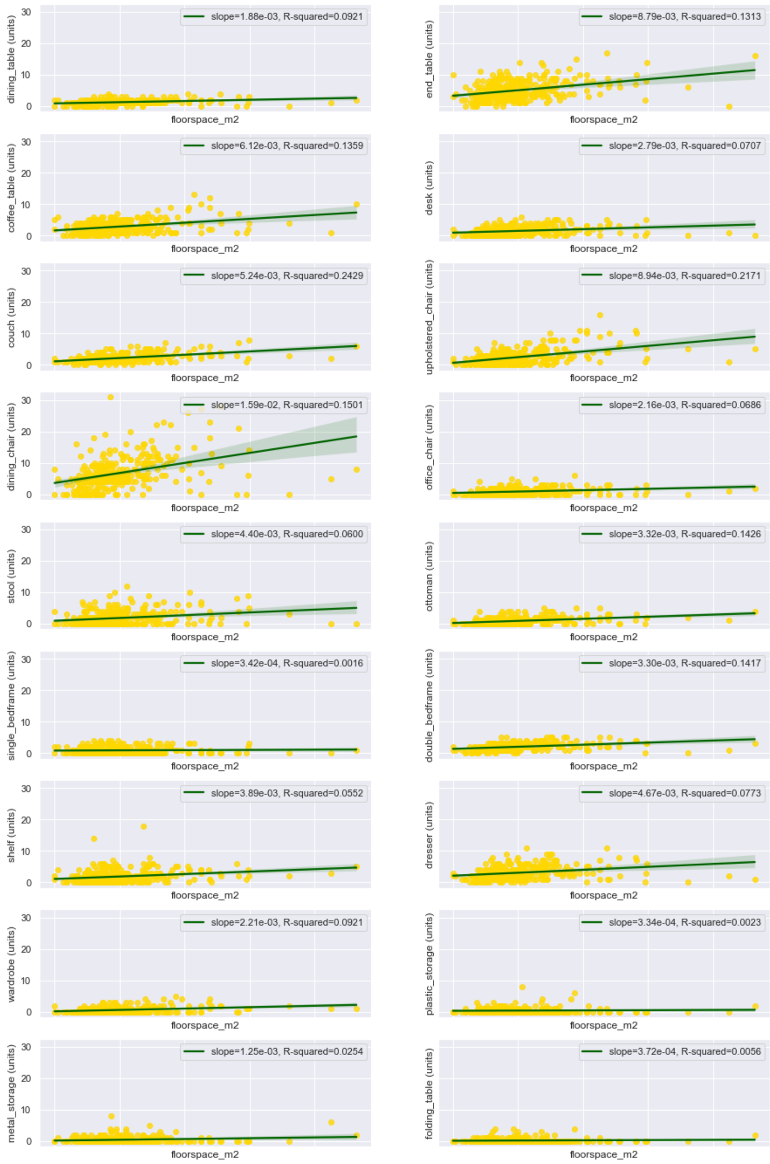


Figure D.1: Linear regression plots for the furniture intensity (units/m^2) of indoor furniture categories in rural areas.

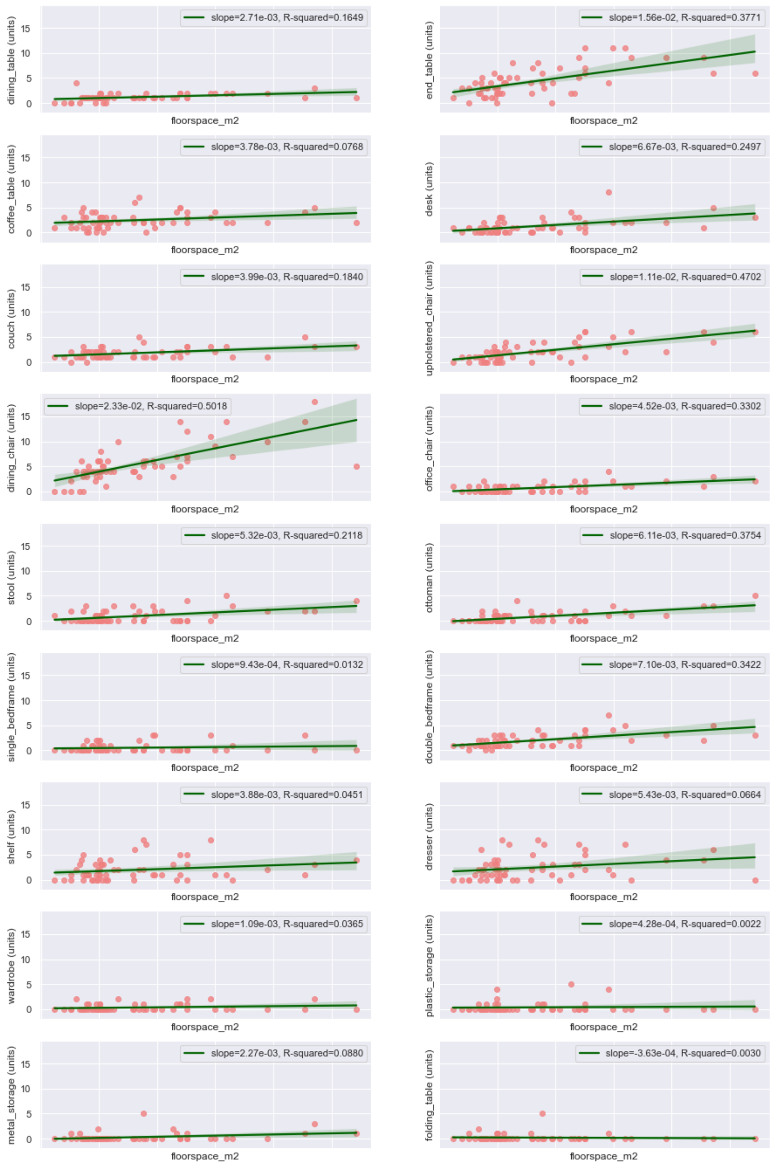


Figure D.2: Linear regression plots for the furniture intensity (units/m^2) of indoor furniture categories in urban areas

E
Unabridged discussion of limitations of the clustering method

There were several limitations found to exist in the methodology, which is thought to affect the representativeness of the data. First, the methodology does not call for clustering of the urban areas. The model would have provided more high-resolution results on urban areas in terms of the different furniture intensities between quintiles if the urban areas were also clustered along two properties (i.e., population density and median floor space) instead of being placed in one group. As it is, putting all urban areas of a division into one group means that all urban primary sampling units (PSUs) are given the same furniture intensity. This is because the method places emphasis on rural PSUs, which are higher in number than urban PSUs. Understanding the nuance of furniture ownership within urban populations is important in addressing the demand for materials for furniture, based on Figure 4.6, and will be increasingly important in the future. For better representation of urban areas, the methodology needs to prioritize sampling urban areas, possibly taking more samples for each urban PSUs than for rural PSUs.

Second, any primary sampling units that were not clustered before the data collection step was assumed to have the median average furniture intensity of all clusters in each division. This means that un-clustered PSUs in each division have the same furniture intensity regardless of income (i.e., a median furniture intensity per division is used) unless there were samples taken for that specific PSU or it was included in the sample population for clustering. Clustered PSUs inherit the median furniture intensity for its cluster within its division. This may be remedied in a couple of ways. First, the clustering may be done on median income and population density (floor space is accounted for later in the model, therefore representation of that dimension is not completely lost in the model). This provides a greater pool of sample PSUs to choose from, as the data found contained median income and population density data for all PSUs. This allows every PSU to be clustered and reduces the error inherent in assigning un-clustered sample areas with a median value for the entire division. However, the one disadvantage to having more sample units to cluster is the amount of computing power required to perform the clustering. In the case of the US, performing this method of sampling will increase the clustered PSUs from under 300 to over 3000 sampling units.

Clustering for all PSUs may also have been possible with the use of US Census Bureau population data multiplied by floor space per capita from the IMAGE database (Stehfest et al., 2014), instead of the database attained through the Federal Reserve Bank of St. Louis (Realtor.com, 2022). While this may provide a lower error in calculating floor space per PSU, the model loses all distinction between geographical regions and sampling units for floor space per capita. The current model returns aggregated that accounts for potential differences in furniture intensity by region. For studies that will consider the potential diversity of furniture intensity between regions, this may be an important feature to seek in the data collection stage of the method.

F
Supplementary materials

The Supplementary Materials list is provided as a PDF with links to each file in a compressed folder provided by the thesis writer.

(A) PSU data

1. 'county_data.xlsx' contains data concerning PSU names, populations, and median household income. References included.
2. 'floorspace_value.xlsx' contains data concerning median floorspace per PSU. References included.
3. 'division_floorspaces.xlsx' contains data concerning median floorspace per division to supplement data gaps in floorspace_value.xlsx. References included.
4. 'LND01.xls' (not used for the final version of the model) contains the land area of each PSU in square miles.
5. 'NHGIS_edited.xlsx' (not used for the final version of the model) contains data on estimates for household composition, household income and occupant status. More detailed information on the type of data available can be seen in the "headings" sheet within the file.

(B) Furniture unit data

1. 'furniture_unit_data.xlsx' contains raw furniture unit data collected from movoto.com, zillow.com, and realtor.com. Links to realtor sites included.
2. 'furniture_intensities.xlsx' contains output from Supplementary Material F-1 that contains the furniture unit per m2 for each PSU.
3. 'furniture_examples.docx' contains pictures of furniture to exemplify different furniture categories assessed in this study. Links to products included.
4. 'furniture_lifetimes.xlsx' contains the aggregated (averaged) lifetimes for each furniture category. The data structure allows for the modeler to change lifetimes across income quintiles and time. References and unaggregated data are in Supplementary Material C-2.

(C) Material intensities

1. 'material_intensities.xlsx' contains the average data from Supplementary Material C-2 and provides a data structure that allows the modeler to change material intensities across income quintiles and time.
2. 'material_intensities_dev.xlsx' contains the data that was used to calculate average material intensity and lifetime for each furniture category. Also contains the reference products used to estimate different composition of wood types for each quintile in panel- and frame-type furniture categories. References for material intensities and lifetimes included.

(D) Weighting factors

1. 'weighting_factors.xlsx' contains the calculations for developing the income quintile weighting factors and calculations for estimating the percentage of wood types used in household furniture per income quintile. Links to products included.

(E) IMAGE SSP2 data

1. 'floorspace_extract.xlsx' contains IMAGE SSP2 (Stehfest et al., 2014) estimates for floorspace in the US from 1971-2100 for different quintiles and different area types (urban and rural).
2. 'main.POPa.xlsx' contains IMAGE SSP2 estimates for total population in the US from 1970-2100.
3. 'main.URBPOP.xlsx' contains IMAGE SSP2 estimates for the percent urbanization of the US from 1971-2100.

(F) Python files

1. 'data_merger.py' accepts various spreadsheets for data on different properties of a country and performs k-means clustering on two chosen properties. The k-means clustering function outputs cluster center names to aid in data collection, then accepts the furniture unit data collected to aggregate the data to average furniture/m2 per sampling unit.
2. 'get_furniture_stocks.py' is an object that contains functions to use the population and floorspace data from IMAGE, multiply them with furniture intensity from Supplementary Material B-2, and output a static representation of furniture stocks.
3. 'model_runner.py' will accept (and clean) IMAGE data, accept user input for dimension values of interest, and run the static model (Supplementary Material F-2) and the Dynamic Stock Model (Pauliuk & Mutel, 2014) in a loop for each dimension value. The outputs are an Excel sheet with the dynamic stock and flow data (Supplementary Material G-1) and various visualizations of the results, if desired.

(G) Model results

1. 'total_base_results.xlsx' is the output file from Supplementary Material F-3, which contains the dynamic stock and flow results of the base model.