ENVIRONMENTAL PERFORMANCE OF CHAIR PRODUCTION AND DISTRIBUTION IN CONVENTIONAL AND ADDITIVE MANUFACTURING

Lappeenranta-Lahti University of Technology LUT

LUT School of Energy Systems

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ABSTRACT

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Environmental performance of chair production and distribution in conventional and additive manufacturing

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The growing availability of hobbyist- and industrial-scale 3D printers has started the transition toward mass customization achieved through distributed production. 3D printing-supported mass customization, as opposed to conventional mass production, shortens the lead time between design and demand, bringing about new supply chain models. In this life cycle assessment (LCA) study, a chair was selected as the basis of a process- and system-level comparison between an additive (AM) and conventional manufacturing (CM) system. The preliminary findings show that the environmental impacts of the 3D-printed chair are greater than that of the conventional chair on the process level. The result is the opposite for the system-level comparison between AM’s distributed production against CM’s centralized one. Furthermore, the AM chair has notably lower environmental impacts than the CM chair when compared by kilogram, not by chair. This infers that if the weight of the chairs were the same, then the AM chair would be the more sustainable option.

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SYMBOLS AND ABBREVIATIONS

Abbreviations

3D	Three-Dimensional
ABS	Acrylonitrile butadiene styrene
ADPe	Abiotic Depletion Potential (Elements)
ADPf	Abiotic Depletion Potential (Fossil)
AM	Additive manufacturing
ASTM	Additive Manufacturing Tech. Standards
CAD	Computer-aided design
CM	Conventional manufacturing
EE	Embodied Energy
EPD	Environmental Product Declaration
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
FGF	Fused Granular Fabrication
GHG	Greenhouse gas
GLT	Glued laminated timber
GWP	Global Warming Potential
GWP100	Global Warming Potential 100 Years
HDF	Hard-density fiberboard
HDPE	High-density polyethylene
ILCD	International Life Cycle Data
ISO	International Org. for Standardization

LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LDPE	Low-density polyethylene
LSAM	Large-scale additive manufacturing
LT	Layer thickness
LVL	Laminated veneer lumber
MDF	Medium-density fiberboard
MDP	Medium-density particleboard
OSB	Oriented strand board
PAS	Publicly Available Specification
PE	Polyethylene
PEF	Product Environmental Footprint
PET	Polyethylene terephthalate
PETG	Polyethylene terephthalate glycol-modified
PLA	Polylactic acid or Polylactide
PMMA	Polymethyl methacrylate
PP	Polypropylene
PS	Polystyrene
PU	Polyurethane
PV	Photovoltaic
PVC	Polyvinyl chloride

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1 INTRODUCTION

In today's economy, growing demands for product variety and customization pressure companies to invest in flexible production systems where processes "outlive the products they were originally built for" (Luft et al., 2019; Nicholls and Bumgardner, 2018). Industry 4.0 is seen as an enabler of such systems (Buer et al., 2018). First coined at the Hannover Messe trade fair in 2011, Industry 4.0 has become a buzzword for intelligent and interconnected factories of the future (Buer et al., 2018; Červený et al., 2022). Among its many definitions, it refers to the smart "networks of manufacturing resources...that are autonomous, self-configuring, knowledge-based, [and] sensor-equipped" (Buer et al., 2018). Technological trends of Industry 4.0 include but are not limited to additive manufacturing, augmented reality, big data, blockchain, cyber-physical systems (e.g., robotics and artificial intelligence), cybersecurity, and the Internet of Things (Buer et al., 2018; Cyplik and Zwolak, 2022; Hernandez Korner et al., 2020; Khorasani et al., 2022).

These technologies are increasingly crucial for companies to increase their manufacturing competitiveness as rapidly changing consumer needs give companies little time to react—making long-term company forecasts obsolete (Hernandez Korner et al., 2020; Luft et al., 2019). They allow for the autonomous collection and analysis of real-time data on process parameters and customer behavior (Khorasani et al., 2022). However, increasing product variety increases complexity within a product system, which is exceptionally resource-intensive (Buer et al., 2018). The flexibility provided by Industry 4.0 technologies not only supports the realization of mass customization but, most importantly, sets resource-efficient production as the new manufacturing standard (Khorasani et al., 2022).

Mass customization, an integral theme of Industry 4.0, is a paradigm shift in manufacturing from Industry 2.0's mass production, as illustrated in Figure 1 (Hernandez Korner et al., 2020; Nicholls and Bumgardner, 2018). Rather than the "design-make-sell" strategy prevalent in mass production, mass customization's "design-sell-make" strategy means the final product will only be manufactured if there is a demand for it (Nicholls and Bumgardner, 2018). Thus, by incorporating a customer's unique needs and preferences early in the production process, mass customization can minimize the costs of producing unsold products and holding inventory while maximizing a product's value for its customer (Hernandez Korner et al., 2020; Khorasani et al., 2022). To implement mass customization on a large scale, these custom-made products have to be, ironically, mass-produced while achieving cost and lead times comparable to those of mass-produced products (Cerdas et al., 2017; Khorasani et al., 2022; Nicholls and Bumgardner, 2018).

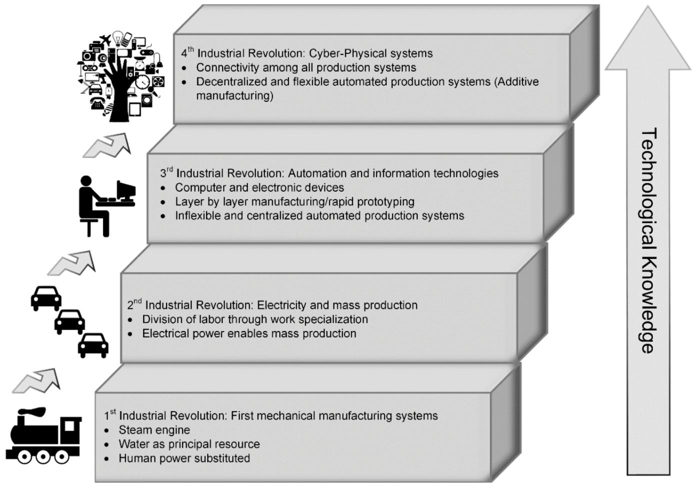

Figure 1: Industrial Revolutions 1.0 to 4.0 (Hernandez Korner et al., 2020)

Additive manufacturing (AM), or three-dimensional (3D) printing, is critical in transitioning from mass production to mass customization because it allows manufacturers to "reprogram rather than retool production lines" (Khorasani et al., 2022). Thus, achieving greater design and process flexibility and, ultimately, product variety (Nicholls and Bumgardner, 2018; Osama et al., 2019). Manually retooling production lines is the status quo in conventional manufacturing (CM), a broad category in which subtractive manufacturing, e.g., drilling or milling, and formative manufacturing, e.g., injection molding or casting, fall under (Khorasani et al., 2022; Saade et al., 2020). Creating individually customized products within a CM system would require specialized tools or molds for each product design iteration, which must be changed between batches. This added complexity increases production time and tooling costs. (Khorasani et al., 2022) In such inflexible production lines, it is riskier to offer a customized product catalog because the demand for some products could be as low as zero (Chen and Lin, 2017; Nicholls and Bumgardner, 2018).

In contrast, additive manufacturing translates 3D computer-aided design (CAD) models into a physical product, one layer at a time, without generating burrs, chips, shavings, and other wastes unavoidable in subtractive manufacturing (Garcia et al., 2018; Osama et al., 2019). It improves resource efficiency by using just the right amount of raw materials to build a product with the occasional use of supports to prevent overhangs from collapsing (Garcia et al., 2018). AM's improved machine flexibility eliminates the need for retooling and simplifies the number of production stages (Guessasma et al., 2015; Khorasani et al., 2022; Luft et al., 2019).

Shorter lead times and greater product variety and customization are some of the competitive priorities furniture manufacturers are now striving for, on top of meeting the standard market requirements of low prices and high product quality (Nicholls and Bumgardner, 2018; Osama et al., 2019). The furniture industry is currently operating at the Industry 2.0 level, mass-producing standardized furniture by assembling various wooden, plastic, and metal components through a make-to-stock or assemble-to-order supply chain strategy (Červený et al., 2022; European Commission. Joint Research Centre., 2017). Alternative strategies, such as built-to-order or design-to-order, would offer greater customization for customers (Nicholls and Bumgardner, 2018).

However, AM has a low adoption in the furniture industry—only 15% of the 144 furniture enterprises surveyed use a 3D printer (Červený et al., 2022; Khorasani et al., 2022). Integrating AM into their production lines would expand the possibilities of furniture design by 1) creating unique geometries and features not replicable in CM, 2) filling a component's interior in almost infinite ways, and 3) integrating multiple materials or working mechanisms into a single component (Khorasani et al., 2022; Oropallo and Piegl, 2016). This design freedom reduces the complexity of furniture parts production and assembly, potentially even designing out screws, hinges, or metal connectors depending on how the 3D printed part or product is re-imagined (Tomec et al., 2022; Yang and Du, 2022).

1.1 Research Objective

This thesis aims to address the research gap in life cycle assessment (LCA) studies comparing AM and CM systems by:

1. extending the study duration beyond a single service life of a product
2. scaling up production and distributing the products to multiple countries

This preliminary cradle-to-grave LCA study quantifies the environmental impacts of a chair produced through two different means: CM and AM. Scenarios A1 to A4 first compare the impacts of one conventional chair and one 3D-printed chair at the process level, gradually extending the time intervals. Scenarios B1 and B2 compare the impacts at a system level. A fictitious situation of delivering chairs to nine consumer locations worldwide examines the differences between CM's centralized and AM's distributed logistics.

The introduction highlights the interactions between Industry 4.0, mass customization, and AM and how the three trends drive society's transition towards responsible consumption and production, or sustainable development goal 12, as set by the United Nations (2023). The second chapter focuses on additive manufacturing: its technology classifications, common materials, and product life cycle. The next chapter reviews similar aspects of conventional furniture manufacturing. Literature reviews will be included in chapters two and three to understand how LCA has already been applied to both manufacturing methods—the functional units, system boundaries, and methodological reasoning behind each case study. The fourth chapter is about the LCA methodology, which includes defining the goal, scope, and data to be collected for the model. The experimental results of the GWP 100 Years (GWP100) and Abiotic Depletion Potential, Fossil (ADPf) impact categories are analyzed in chapter five. Based on the findings, conclusions are drawn, making note of the current study's limitations and future research areas.

2 ADDITIVE MANUFACTURING

AM technologies are classified based on the initial state of the material being fed into the 3D printer: solid, powder, and liquid, with filament, sometimes considered the fourth category (Cerdas et al., 2017; Hernandez Korner et al., 2020). Various other classifications are based on material type, material preparation, layer generation technique, and phase change phenomenon (Hernandez Korner et al., 2020; Osama et al., 2019). Still, the state of the material is the most commonly used classification (Hernandez Korner et al., 2020). It is also the one standardized by the Additive Manufacturing Technology Standards (ASTM) committee, which has defined seven main categories: 1) powder bed fusion, 2) direct energy deposition, 3) material extrusion, 4) vat photopolymerization, 5) binder jetting, 6) material jetting, and 7) sheet lamination (Cerdas et al., 2017; Saade et al., 2020).

2.1 Filament-based vs. Pellet-based Feedstock in Large-Scale AM

Of the seven, material extrusion is one of the most frequently used AM technologies, largely because the affordability of 3D printers has made it accessible to consumers, not just companies (Cerdas et al., 2017; Pringle et al., 2018). In material extrusion AM, the material, oftentimes thermoplastics, is melted down and forced through a heated nozzle to create the 3D-printed product, layer by layer. Depending on whether the feedstock is in the form of filament or pellets, material extrusion can be further classified into Fused Filament Fabrication (FFF) or Fused Granular Fabrication (FGF). The trademarked version of FFF is called Fused Deposition Modeling (FDM) since it was introduced by Stratasys, whose co-founder Scott Crump developed and patented the process. Figure 2 shows how the FFF/FDM 3D printer (on the left) has a filament feeding system to unwind the filament from its spool, whereas the FGF 3D printer's screwing mechanism (on the right) is what ensures a consistent flow of pellets from the hopper. (Tagscherer et al., 2022)

Most hobbyist-scale desktop 3D printers are based on FFF/FDM technology since filaments are readily available. Manufacturers supply spools of 1.75 mm or 2.85 mm diameter filament, maintaining a consistent product quality for more reliable prints. Large-scale AM (LSAM), also known as large-format or industrial 3D printing, can print larger parts or entire products with build volumes ranging from 0.48 cubic meters like the German RepRap X1000 to 2.48 cubic meters like the Zilla3D Deltazilla. The Erector EB 2076 LX, with its 23.78 cubic meters build volume, is one of the largest FFF/FDM 3D printers. The same is true for the Big Area Additive Manufacturing printer by Cincinnati Lab (35.5 cubic meters) for FGF 3D printers. (Shah et al., 2019) For this thesis, a large-format 3D printer can build an item with a volume

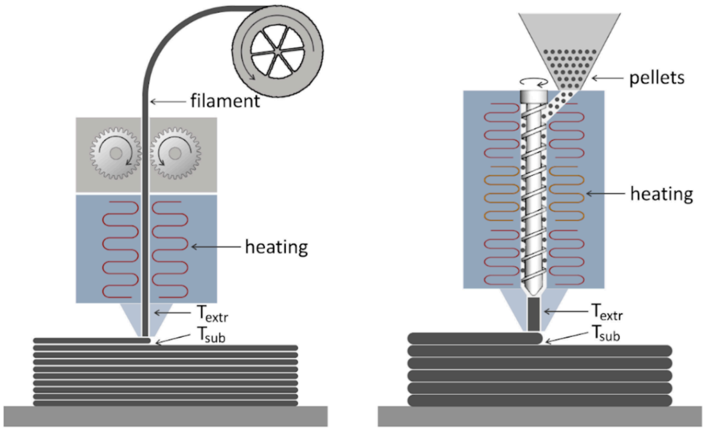

Figure 2: FFF/FDM (left) and FGF extrusion technologies (Tagscherer et al., 2022)

of one cubic meter, which is the most common size among commercial large-scale material extrusion 3D printers (Lehmann et al., 2022; Shah et al., 2019). Chairs, end tables, coffee tables, and other compact furniture pieces fall within these size dimensions.

FFF/FDM 3D printers have more limitations when printing on a larger scale than their FGF counterparts. Pellets are not as commercially available as filaments, but they make FGF printers more flexible regarding material use, opening up options for recycling misprints or creating custom-blended materials. FGF 3D printers are not restricted to just pellet-based feedstocks. With suitable modifications, they can extrude other material types, such as ceramic pastes, hydrogels, bio-inks, and composites. The larger the print, the greater the material required and the costlier it gets. Pellets are typically cheaper than pre-made filaments. (Tagscherer et al., 2022)

2.2 Overview of Existing LCA Studies in AM

Garcia et al. (2018) and Saade et al. (2020) laid the groundwork for providing a systematic literature review on the environmental performance of AM.

Saade et al. (2020) studied how LCA was applied to 3D printing, using the keywords ”LCA” or ”life cycle assessment” and ”3D” and ”print.” They categorized the papers based on their applicable industry sectors, AM technology, and LCA methodology. Out of the 52 papers they evaluated in detail, the majority (36 papers) were not industry-specific; a generic part was printed to focus more on the AM technology itself. The aircraft and automotive sector had ten papers, with the construction sector trailing at three papers. There was also one 3D printing LCA study for each of the following: a wind turbine, a gas turbine burner, and a printed circuit board. (Saade et al., 2020)

Material extrusion was the second most studied at 17 papers, only surpassed by powder bed fusion (23 papers). As for the LCA methodology, the functional unit was mainly the 3D-printed part (30 papers) rather than a mass-based one (10 papers). The most adopted system boundary was ”cradle-to-gate” (22 papers), with ”cradle-to-grave” studies and ”cradle-to-gate” + ”end of life” studies almost tied for second with 12 and 11 papers, respectively. Ecoinvent was the most common background database choice (24 papers), followed by literature-based data (13 papers). (Saade et al., 2020)

The 21 papers that offered an AM to CM comparison recorded Global Warming Potential (GWP) values more often than Embodied Energy (EE) values, almost twice as much, using the Recipe impact assessment method (13 papers) more often than CML (8 papers). A general trend of GWP values noted is that in CM, the materials acquisition and pre-processing life cycle stage contributes the most to the total GWP values, whereas in AM, it is the production stage that contributes the most, as high as 80%. (Saade et al., 2020)

Garcia et al. (2018) did a broader literature review of 43 papers using the similar keywords except they used ”sustainability” instead of ”life cycle assessment” specifically. They assessed 43 papers, categorizing them by AM technology, feedstock material, research goal, and the environmental aspects and impacts analyzed. Of the AM technologies, material extrusion and powder bed fusion had the most papers covering this topic, tied at 13 papers each. For the feedstock material, five of the material extrusion papers used acrylonitrile butadiene styrene (ABS) and four of them used polylactic acid or polylactide (PLA). For the other AM technologies, there were three papers for each of these materials: steel, titanium aluminum, metal alloy, and epoxy resin. (Garcia et al., 2018)

Garcia et al. (2018) found that energy consumption was the main environmental aspect discussed, covered by 87% of the papers. They compiled a range of energy consumption measurements for 12 of these papers. There were three papers related to PLA-based material extrusion, and they will be discussed further in the Energy Consumption subsection. (Garcia et al., 2018)

Neither Saade et al. (2020) nor Garcia et al. (2018) specified the size of the 3D-printed parts and the type of material extrusion technology used, but a closer look at some of the more relevant papers for this thesis revealed that the 3D-printed parts were produced from desktop 3D printers based on the FFF/FDM process.

2.3 Materials

One of the design guidelines for creating more recyclable furniture pieces is mono-materiality, which is the default for single-nozzle, single-extruder 3D printer setups in AM (Kelly, 2022;

Mirabella et al., 2014). Material extrusion 3D printers can utilize various plastics, including PLA, ABS, and polyethylene terephthalate glycol-modified (PETG) (Bremer et al., 2022).

For this thesis, PLA was selected as the material for the AM chair. This is primarily because not only is PLA one of the two most used feedstocks for material extrusion along with ABS, but it is also extensively investigated (Cerdas et al., 2017; Cosate de Andrade et al., 2016; Garcia et al., 2018). Furthermore, while PLA, ABS, and PETG are all recyclable, only PLA is biodegradable, which opens up composting as a possible end-of-life treatment option (Algarni and Ghazali, 2021).

2.3.1 PLA

PLA is a bio-based and biodegradable thermoplastic derived from renewable organic materials high in starch and can be either composted or recycled at the end of its life (Moretti et al., 2021; Pringle et al., 2018). It is seen as the greener alternative to petroleum-based polymers in terms of GHG emissions and, in some cases, it could be a good alternative to wood (Cosate de Andrade et al., 2016; Kreiger and Pearce, 2013). Its applications are expanding beyond biomedical sutures and implants to single-use items, packaging, textiles, injection-molded products, and 3D printing (Aryan et al., 2021; Cosate de Andrade et al., 2016). PLA has the lowest printing and printer bed temperature out of the three; it is 190-210°C and 25-80°C, respectively (Algarni and Ghazali, 2021).

2.3.2 ABS

ABS is the other popular material, along with PLA, used in FFF/FDM and FGF 3D printing (Cruz Sanchez et al., 2015). However, PLA and ABS have different 3D printing applications. PLA is more suitable for lightweight applications that will not be subjected to high mechanical stress. On the other hand, ABS is used for applications that require greater durability, strength, and impact resistance, making it the better choice for functional prototypes and parts for boats and computers, among others. (Algarni and Ghazali, 2021)

2.3.3 PETG

PETG has been used for CM processes like injection molding and is extending its applications into AM. PETG is seen as a potential greener alternative for ABS. While they are both petroleum-based thermoplastics, PETG emits less toxic fumes during 3D printing than ABS. PETG can be recycled with other PET plastics, whereas ABS and PETG must be sorted separately. The printing temperature for PETG (230-250°C) is similar to ABS' (220-260°C), but PETG requires a lower printer bed temperature, 60-80°C compared to ABS' 90-110°C. (Algarni and Ghazali, 2021)

2.4 AM Workflow and Process Parameters

AM's workflow can be split into three phases: the design, processing, and testing phases illustrated in Figure 3. While AM technologies may differ in the processing phase, the designing part of the pre-processing phase and the mechanical testing part of the post-processing phase are relatively similar across the field. (Osama et al., 2019)

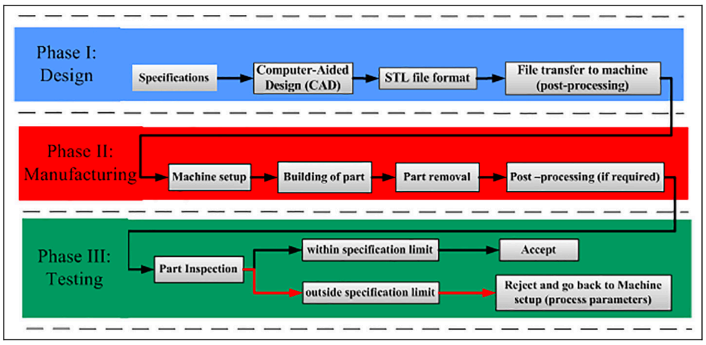

Figure 3: AM Workflow (Osama et al., 2019)

When designing the 3D model of the product, topology optimization is the underlying framework for achieving structurally sound 3D printed products out of the least amount of material. Topology optimization algorithms reduce the weight, improve the stiffness, and distribute the stress by redistributing the material in an iterative process. (Khorasani et al., 2022; Kreiger and Pearce, 2013)

During the processing phase, a 3D printer's performance is affected by a combination of the following factors:

- the interior structure of the printed object, as in how much of it is empty space (infill density), and at what angle is the interior filled (raster deposition angle).
- the height of the extruded layer (layer thickness). The thicker the layer, the faster the build time at the expense of a less smooth and detailed finish. (Cerdas et al., 2017; Vidakis et al., 2022)
- the printing speed, which depends on how fast the extruder moves and the user's desired print quality and accuracy of the final product.
- the right temperature for the nozzle to ensure that the material is properly deposited onto the printer bed and that the bed's temperature prevents the printed object from warping or shifting during the process. (Vidakis et al., 2022)

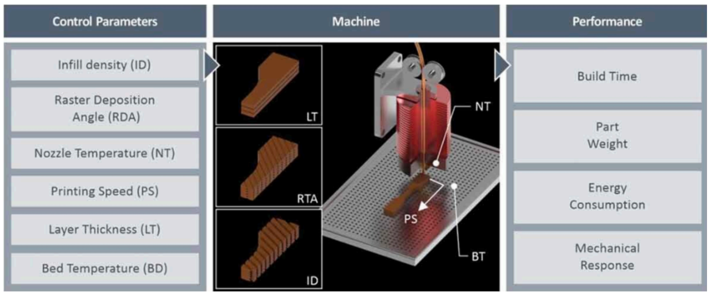

Figure 4: AM Printing Parameters (Vidakis et al., 2022)

These printing parameters and performance factors are summarized in Figure 4, and the following subsections highlight the ones contributing to either AM's strengths or weaknesses.

2.4.1 Infill Density

One of AM's advantages over CM is its ability to adjust the patterns and percentage of the printed product's infill, which is one aspect of topology optimization. The infill of a 3D printed product can range from 0% to 100%, with the latter only required for specific design criteria, such as a watertight item (Kreiger and Pearce, 2013). An infill of 0% is fine if its structural integrity is intact. The higher the infill percentage, the higher the printing quality, but the build time, material usage, and energy demand are also greater (Cerdas et al., 2017). For products that do not require significant mechanical stress, an infill of 79% or less is easily achievable with average small-scale 3D printers. Typical 3D prints are done with an infill of 25%, the majority with an infill of 15%. (Kreiger and Pearce, 2013)

2.4.2 Energy Consumption

Figuring out the lowest possible infill density a 3D-printed product requires to be still structurally sound for its intended application is important because it affects the build time of a product (Kreiger and Pearce, 2013, p. 1515). Build time is the primary driver of the energy consumption of a 3D-printed product. Energy consumption consistently remains the main contributor to AM's environmental impacts. (Cerdas et al., 2017) This topic has been intensively studied, resulting in energy consumption values for FFF/FDM processes using PLA filament ranging from 0.007 - 0.03 kWh/piece (Griffiths et al., 2016), 0.1 - 0.52 kWh/piece (Kreiger and Pearce, 2013), and 0.5 - 1.25 kWh/piece (MOGNOL et al. 2006) as reported by Garcia et al. (2018). Cerdas et al. (2017) compared AM's and CM's energy consumption values, finding that injection molding processes required 0.11 to 5.82 kWh/kg, whereas depending on the 3D printer and its printing parameters and the printed object, values vary greatly from 23 kWh/kg to even 346.4 kWh/kg.

2.5 End-of-Life Treatment Options for PLA

Out of PLA's end-of-life treatment options, mechanical or chemical recycling is more favorable than composting, incineration, and landfill from an environmental standpoint (Aryan et al., 2021; Zhao et al., 2018). Mechanical recycling was selected over chemical recycling for this LCA model since it was the prevalent method of recycling 3D prints among hobbyists and filament vendors. Mechanical recycling's widespread use can be attributed to the availability of open-source extruders called recyclebots that can make commercial-quality filament from plastic waste. (Woern et al., 2018)

2.5.1 Composting

PLA is certified as compostable. It is possible for it to biodegrade in industrial composting facilities where the process would look similar to Figure 5. (Moretti et al., 2021)

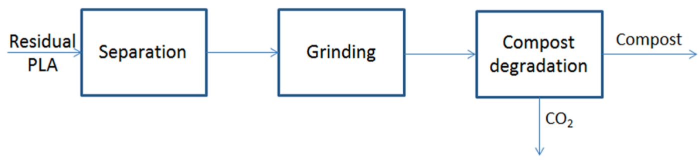

Figure 5: PLA Composting (Cosate de Andrade et al., 2016)

However, most facilities do not provide the optimal conditions for PLA to achieve satisfactory biodegradation. PLA takes up to ten weeks to fully biodegrade, but these facilities typically operate on a short-term batch process of three to five weeks. Even if PLA were to biodegrade fully, PLA does not contain nutrients that can enhance the quality of the fertilizers made from compost. Composting PLA does not partially displace fertilizer production like how incinerating or recycling PLA would for energy and virgin plastic production, respectively. (Cosate de Andrade et al., 2016; Moretti et al., 2021)

2.5.2 Mechanical Recycling

Mechanical recycling is more beneficial than chemical recycling regarding human health, ecosystem quality, and efficient use of resources. The tradeoff is that mechanically recycled PLA is of lower quality than its virgin counterpart and chemically recycled PLA due to several factors. During the mechanical recycling process illustrated in Figure 6, residual PLA is heated and cooled several times as it undergoes the grinding, washing, drying, extrusion, and cooling steps. (Aryan et al., 2021; Cosate de Andrade et al., 2016)

Prolonged exposure to high temperatures, especially during the extrusion step, leads to thermal degradation (Pringle et al., 2018). As the polymer chains break down, their molecular

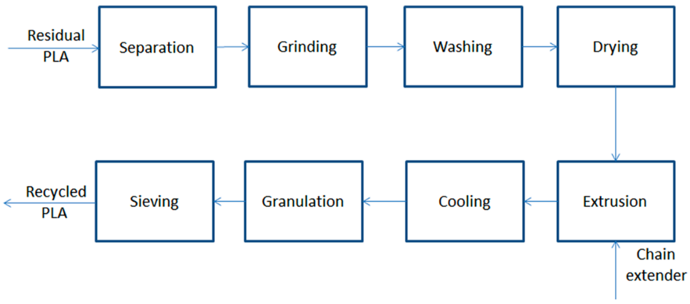

Figure 6: PLA Mechanical Recycling (Cosate de Andrade et al., 2016)

weight is reduced, affecting their mechanical strength, flexibility, and other physical properties (Cruz Sanchez et al., 2015). Pringle et al. (2018) noted that PLA should not be exposed to temperatures over 210°C for a long period to minimize its thermal degradation.

There is a finite number of times a specific batch of PLA can be recycled and reprinted before its properties deteriorate enough to prevent its usage, but studies have been inconclusive as to what that number is (Bremer et al., 2022). PLA has been determined to no longer be 3D-printable, too brittle and stiff after two extrusions (Zhao et al., 2018), five extrusions (Cruz Sanchez et al., 2015), or ten extrusions (Żenkiewicz et al., 2009). Adding some virgin PLA to the mechanical recycling process helps improve the properties of the recycled PLA (Cosate de Andrade et al., 2016; Zhao et al. 2018). Another way is to add a chain extender during the PLA extrusion step (see Figure 6) to maintain its properties (Cosate de Andrade et al., 2016).

The separation and washing steps (see Figure 6) are important for preventing contaminants and impurities from being introduced into the process, which would further affect the quality of the recycled PLA (Cosate de Andrade et al., 2016). Different types of plastics cross-contaminate each other's recycling processes, so even though PLA recycling is technically feasible, it has not been integrated into the existing recycling facilities. The challenge that has yet to be addressed is that PLA cannot be easily sorted by sight from mixed plastics waste streams collected in large-scale recycling facilities, and it cannot be efficiently separated based on its density alone either. Near-infrared sensors would have to be used to separate PLA from conventional plastics effectively, but those are expensive. Currently, most recycling facilities do not have this technology already and are unlikely to make that investment soon. (Carné Sánchez and Collinson, 2011; Moretti et al., 2021)

3 THE FURNITURE INDUSTRY

Furniture is ubiquitous in everyday life. Some furniture pieces are a space to store, hang, or place items, while others serve as a place to work, eat, sit, or sleep (Wenker et al., 2018). Many different materials and designs make up the broad definition of furniture. Given the variety of furniture products available, there are many environmental labeling instruments, each with its own metrics for defining how sustainable a piece of furniture is. Environmental product declarations (EPDs) are only one of them. EPDs are LCA-based reports published by some manufacturers to provide transparent and third-party verified information about their product's environmental impacts. (Cordella and Hidalgo, 2016)

3.1 An Overview of the Existing LCA Studies on Furniture

Wenker et al. (2018) categorized furniture by its four main functions: storage furniture with either enclosed space (e.g., wardrobes and sideboards) or surface area (e.g., shelves and tables), seating furniture (e.g., chairs and stools), and furniture for lying down (e.g., beds). The LCA furniture case studies listed in Table 1 are categorized into these four functions. Furniture can be further organized into residential and commercial furniture, as the materials used also have a lot to do with the function of the furniture piece. Wood-based materials make up a significant portion of storage furniture with enclosed space, whereas metals are more prominently present in storage furniture with surface area commonly found in office furniture. (Wenker et al., 2018)

Cordella and Hidalgo (2016) conducted a systematic literature review of 82 papers and EPDs related to LCA case studies on the environmental performance and life cycle hotspots of a broad range of furniture items, examining eight papers that met their research criteria in greater detail. They observed three general approaches for deciding the functional unit in these studies: 1) by its function and service life, 2) by a single unit of furniture and its service life, and 3) by its mass or a single unit but without accounting for its service life. The second approach, where the functional unit is determined to be one unit of furniture, is often used for EPDs so potential customers can compare the environmental impacts of different furniture pieces. (Cordella and Hidalgo, 2016)

As for the system boundaries of these studies, the ”cradle-to-grave” scope was the most adopted (6 out of 8 papers and 28 EPDs), followed by ”cradle-to-use” (20 EPDs) and then ”cradle-to-gate” (1 paper and 1 EPD). It is important to note that of the 54 ”cradle-to-grave” and ”cradle-to-use” assessments, less than half of them (2 papers and 17 EPDs, the ones

Table 1: Furniture LCA studies (adapted from Cordella and Hidalgo, 2016; Iritani et al., 2015)

Seating	**Lying**	**Storage (surface)**	**Storage (enclosed)**	Reference
Office chair, visitor chair				Askam et al., 2012
Wooden chair				Skaar and Jorgensen, 2012
Office chair				Babarenda Gamage et al., 2008
Student chair, office chair, public space chair		Student desk, office desk	Office cabinet, kitchen cabinet	Linkosalmi et al., 2016
	Convertible cot/bed	Study desk, bedside table		González-García et al., 2012
	Convertible cot/bed	Office table	Kitchen cabinet	González-García et al., 2011b
		School desk		Mirabella et al., 2014
		Wooden table		Gustafsson and Börjesson, 2007
		Office table and desk		Spitzley et al., 2006
		Unspecified storage (surface)	Unspecified storage (enclosed)	Wenker et al., 2018
			Wooden wardrobe	Iritani et al., 2015

from the Norwegian Foundation scheme) modeled the use phase. All 48 consulted EPDs and 6 papers considered the following five impact categories: acidification, climate change, eutrophication, ozone depletion, and photochemical ozone formation. As for the two remaining papers, one assessed the impacts of climate change and acidification, and the other assessed only climate change. Different versions of the CML method were used to characterize these impact categories, except for one paper, which used the TRACI method. (Cordella and Hidalgo, 2016)

From their literature review, Cordella and Hidalgo (2016) concluded that materials are the biggest contributor to furniture's environmental performance, supporting Saade et al.'s (2020) findings in their AM to CM comparison. Linkosalmi et al. (2016) also found that materials play a substantial role in greenhouse gas (GHG) emissions in the eight furniture manufacturing processes they assessed, contributing 38% to 90% of the impact. Processing and assembling ranged from 8% to 58% whereas packaging and transportation were seen as more negligible, from 1% to 8% (Linkosalmi et al., 2016). Yang (2023) also noted the following trend of environmental hotspots across various types of furniture (from highest to lowest impact): materials, production, distribution/disposal, with the use stage contributing the least.

3.2 Materials

Since wood has the best environmental profile out of the other materials, the EU Ecolabel criteria previously recommended that the material content be at least 90% by weight of wood or wood-based and no more than 3% of other materials. However, stakeholder feedback, including two European furniture associations, mentioned that only a small fraction of the furniture market satisfied that criteria. (European Commission. Joint Research Centre., 2017) For most furniture pieces, wood—even if it is the most common material—would not be able to replace the other materials entirely (Cordella and Hidalgo, 2016). In 2016, the revised EU Ecolabel for furniture dropped the material weight limits and expanded its product scope to include plastics, metals, glass, textiles, and other non-wood-based materials (European Commission. Joint Research Centre., 2017).

3.2.1 Wood

Wood is considered the main material used in furniture, especially here in Finland (Cordella and Hidalgo, 2016; Linkosalmi et al., 2016). A 2011 market report found that wood-based materials comprised 56% of the furniture manufactured in the EU 27, corresponding to 56% of the production value (European Commission. Joint Research Centre., 2017). Wood often appears as wooden panels and boards in finished products (Cordella and Hidalgo, 2016).

The two main types of wood panels are solid wood and reconstituted wood, which differ in composition and manufacturing methods. Solid wood has only been mechanically processed. Plywood, laminated veneer lumber (LVL), and glued laminated timber (GLT) fall under this category. Reconstituted wood, otherwise known as engineered wood or composite wood, is created by combining wood fibers, particles, or veneers with adhesives and binders. Common reconstituted wood products include medium-density particleboard (MDP) or particleboard in short, medium-density fiberboard (MDF), hard-density fiberboard (HDF), and oriented strand board (OSB). (Iritani et al., 2015)

From the environmental perspective, wood is also widely regarded as the best available option, provided that wood is procured from certified sustainable sources (European Commission. Joint Research Centre., 2017). Wood-based materials have a relatively low contribution to the total greenhouse gas (GHG) emissions of a piece of furniture, ranging from 8% to 54% (Linkosalmi et al., 2016). Its main sources of environmental impacts are its embodied energy and the chemical additives, such as resins, in its manufacturing process (Cordella and Hidalgo, 2016). Wood-based materials are generally less durable, so the chemical additives and treatment help extend the use stage of its product life cycle (Cordella and Hidalgo, 2016). Nowadays, low formaldehyde emission resins and adhesives are required for wood-based panels, further lowering one of its main sources of environmental impacts (European Commission. Joint Research Centre., 2017). The environmental impacts arising from the energy-intensive sawing and drying of wooden boards can be mitigated using energy from wood residues at the production site (Cordella and Hidalgo, 2016; Linkosalmi et al., 2016).

3.2.2 Metals

Aluminum, steel, and other metals are the second most commonly used material after wood. They account for 12% of the furniture manufactured and 17% of the production value. (European Commission. Joint Research Centre., 2017) Metals, especially primary aluminum, have higher environmental impacts per weight than wood, largely because of their energy-intensive production processes (Cordella and Hidalgo, 2016). Depending on the furniture piece, they can contribute up to 70% of the total GHG emissions, but recycling the metal at the end of the product's life can help lower their environmental impact (Linkosalmi et al., 2016).

3.2.3 Plastics

Plastics are also present in furniture pieces, with their significance increasing in non-domestic applications, representing 6% of the furniture manufactured and 1% of the production value. The most common plastics used include high- and low-density polyethylene (HDPE and LDPE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polymethyl methacrylate (PMMA), and nylon-6,6. (European Commission. Joint Research Centre., 2017) The majority are derived from petroleum, thus considerably impacting GHG emissions, up to 37% in one furniture study. Compared to wood and metals, plastics have a high emission-to-mass ratio. (Linkosalmi et al., 2016)

3.3 Production Flow Chart

Due to the variety of materials used, the furniture manufacturing process is complex, and the specific steps at a production facility depend on how much of the work is already done on the purchased semi-finished products (Wenker et al., 2018). Figure 7 depicts the value chain of a generic furniture product, with the headings of each category closely aligned with the life cycle stages mentioned in the ISO 14040 standards: material acquisition and pre-processing, production, distribution and storage, use, and end-of-life (Cordella and Hidalgo, 2016).

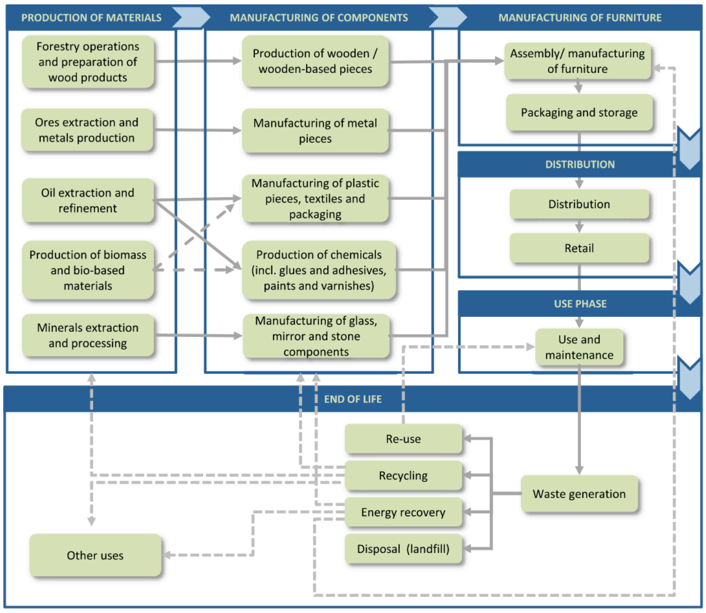

Figure 7: Value Chain of a Generic Furniture Product (Cordella and Hidalgo, 2016)

Woodworking industries cover various activities related to the processing and manufacturing of wood-based furniture. The manufacturing process of a woodworking plant can be divided into four phases: panel production, woodworking, painting, and metal parts processing. In the first phase, wood is cut into planks or boards before it undergoes pressing, gluing, laminating, or other processes to produce different wood-based panels like plywood or particleboard. The woodworking phase is where wooden components are cut, shaped, and assembled. During assembling, joinery techniques can be applied to connect the wooden components together without using nails or screws. (Mirabella et al., 2014) The third phase involves applying paint or coatings to the wood surfaces through surface preparation, priming, or vanishing processes (Wenker et al., 2018). Finally, steel, aluminum, iron, or other metal parts are cut, welded, or undergo surface treatment before being incorporated into the wooden product (Mirabella et al., 2014).

3.4 End-of-Life Treatment Options for Furniture

The easier a furniture piece is to assemble, the easier it will be to repair and eventually disassemble for material reuse and recycling (European Commission. Joint Research Centre., 2017; Hernandez Korner et al., 2020). Current mass-produced furniture pieces are not designed with recyclability in mind—the different materials, paints, glue, veneer, varnish, and other protective and decorative coatings complicate the process and potentially contaminate the recycled material, making the endeavor more costly (Wenker et al., 2018). While 83% of metals are recycled after use at various recycling rates, glass used in furniture cannot be recycled with post-consumer glass containers and will contaminate the entire batch if incorrectly disposed of (European Commission. Joint Research Centre., 2017; Linkosalmi et al., 2016). In 2018, only 0.33% of the 12 million tons of furniture waste generated in the United States alone was recycled. The majority, approximately 80%, was disposed of in landfills, and the remaining 20% was incinerated for energy recovery. (US EPA, 2022)

4 Methodology

LCA is an environmental management tool that can evaluate the environmental impacts of a product throughout its life cycle, identifying the hotspots to improve upon. LCAs also provide supporting evidence for green advertising claims and help with decision-making at the company, industry, or government level. The thesis' LCA modeling approach will be primarily based on ISO standards, but other guidelines are available. These include the International Life Cycle Data (ILCD) Handbook, Product Environmental Footprint (PEF) Guide, GHG Protocol Product Standard, and Publicly Available Specification (PAS) 2050. According to the ISO 14040:2006 and ISO 144044:2006 standards, LCA consists of four phases: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation. (Schrijvers et al., 2016b, 2016a)

Defining the goal and scope of a product system starts with quantifying how much of a product is needed to perform a specific function, also known as the functional unit. The reference flow can then be determined to calculate the input and output data of the unit processes. The system boundary can include any or all of these life cycle stages: material acquisition and pre-processing, production, distribution, and storage, use, and end-of-life. An allocation procedure is also selected for multifunctional processes, including recycling, reuse, energy recovery, or co-production. (Schrijvers et al., 2016b, 2016a)

4.1 Goal and Scope Definition

This LCA study was performed using *LCA for Experts (GaBi)* software. The environmental impacts of two chairs—one manufactured through conventional means and the other through large-scale FGF 3D printing—were compared in six different scenarios:

- Scenarios A1 to A4 compare the environmental impacts of CM and AM's chair production process and end-of-life treatment over a 15-, 30-, 45-, and 60-year period, respectively. 15-year intervals were chosen because the EPDs that have been consulted stated that as the expected service life of their products. The 3D-printed PLA chairs are assumed to have the same minimum service life.
- The remaining two scenarios, B1 and B2, were designed based on Cerdas et al. (2017)'s research methodology of comparing not just CM and AM's process but also CM's centralized system versus AM's distributed one. This was modeled using a fictitious situation in which the CM chairs were produced in a centralized location and had to be distributed to eight other consumer locations in different countries over a 15- and

30-year period for Scenarios B1 and B2, respectively. Alternatively, the AM chairs were produced at each of the nine consumer locations.

4.1.1 Functional Unit and Reference Flow

For the CM system, a chair was designed by combining the LCA information from Linkosalmi et al.'s paper (2016) and the design information from several EPDs and furniture retailer websites to work with common furniture materials already in the GaBi database (Ondaretta, 2023). Table 2 breaks down the material type and quantity used for different chair parts.

As for the AM system, the measurements of a chair created from a large-scale 3D printer were all taken from Dr. D-Flo's Large Format 3D Printer Build Series on YouTube (see Table 2). The chair is made entirely out of PLA, and it is assumed that the quality and structural integrity of the 3D-printed chair would be comparable to the mass-produced one.

Table 2: The bill of materials for the two chairs

	Conventional Chair (Linkosalmi et al., 2016; Ondarreta, 2023)	**3D-Printed Chair** (Florian, 2022)
		
Product Components		
Backrest	Plywood: 3.323 kg	PLA: 17.85 kg
Seat cushion	Polyurethane: 0.441 kg	
Seat	Upholstery: 0.217 kg, Plywood	
Frame (incl. Base/Legs)	Powder paint: 0.191 kg, Steel: 3.3 kg	
Excluded Materials	Chemicals: 0.608 kg	Plastic colorant: 1.79 kg
Product Specifications		
Dimensions [width x depth x height x seat height]	47.5 x 55 x 81.5 x 46 cm	Assumption: same as CM's
Mass	7.54 kg	17.85 kg
Weight capacity	Assumption: same as AM's	Over 77 kg
Service life	15 years	15 years

The reference flow in each of the six scenarios is the same: a single chair that has a 15-year service life, which is in line with the information given on consulted EPDs (Ondarreta, 2023). The functional unit used varies between scenarios. In Scenario A1, the functional unit is the provision of indoor seating for one customer over 15 years; it is the equivalent of one reference flow. The functional units of Scenarios A2, A3, and A4 equal two, three, and four reference flows, respectively. This means they provide indoor seating for 30 (A2), 45 (A3), and 60 years (A4). The provision of indoor seating is either a 7.54 kg chair conventionally manufactured from metal, plastic, textile, and wooden components or a 17.85 kg 3D-printed chair made from 100% PLA. The dimensions of the 3D-printed chair were not specifically mentioned in the video, so it is assumed to be the same as the conventional chair's, which is 47.5 x 55 x 81.5 x 46 cm (width x depth x height x seat height).

Scenarios B1 and B2 have the same reference flow as the others, but their functional units are the provision of indoor seating for 476 customers over 15 (B1) and 30 years (B2) in each of the nine countries. The number of customers, 476, was selected by first calculating this specific large-format FGF 3D printer's maximum annual production capacity. Since each chair takes approximately 18 hours to print, there would be 486 chairs produced in a year. Thus, the functional units for Scenarios B1 and B2 are set to 476 chairs to leave some buffer time for changeovers between print jobs, printing errors, and print failures.

4.1.2 System Boundaries

The system boundaries for the six scenarios are all cradle-to-grave, with the distribution stage in Scenarios B1 and B2 on a global scale. As with many of the LCA studies done on furniture or 3D-printed products, environmental impacts from the use stage were assumed to be the same. Otherwise, the usage of water, soap, vacuum cleaner, and other cleaning agents for product maintenance would vary greatly depending on consumer behavior (Cordella and Hidalgo, 2016). The following system boundary diagrams illustrate the use stage only for indicating the different consumer locations, which becomes especially relevant for Scenarios B1 and B2 with the centralized and distributed manufacturing system comparison.

Scenario A1: 15-year Period, Process-Level

Scenario A1 is illustrated in Figure 8 where a single chair of both types is manufactured and used for the entirety of its 15-year service life.

CM's system boundary for this chair starts from procuring the semi-finished products: 1) plywood panels, 2) steel tubing, 3) polyurethane rigid and flexible foam, 4) powder paint for the steel, and 5) cotton fabric for the upholstery (Linkosalmi et al., 2016; Ondarreta, 2023). These components are joined together with the help of screws, staples, and clips during the furniture assembly process (Linkosalmi et al., 2016). Incineration was selected as the end-of-life option for the conventionally manufactured chair.

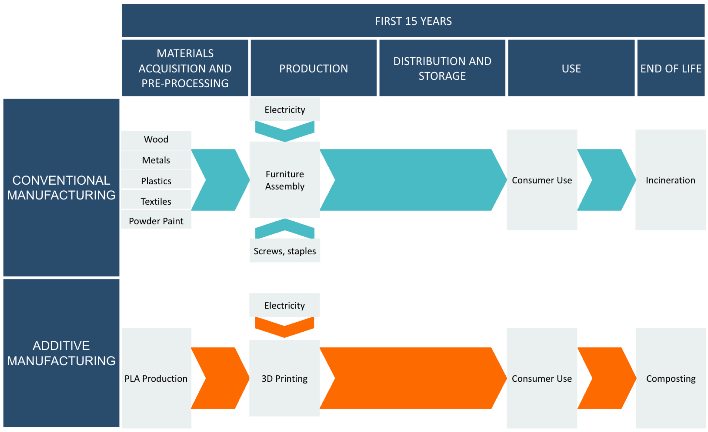

Figure 8: CM and AM systems in Scenario A1

In Scenario A1, AM's product system begins with the production of PLA, which is then 3D-printed into a chair before ending up as compost (see Figure 8). Assuming no washing, sanding, cutting, or chemical treatments are needed for the 3D-printed chair, the post-processing step after the 3D printing was also excluded from the system boundary (Cerdas et al., 2017). If it were FFF/FDM 3D printing, the production of filament and the spool reel holding the filament would have been considered before the 3D printing process.

Scenario A2: 30-year Period, Process-Level

In the 30 years of Scenario A2 (see Figure 9), after both types of chairs reach the end of the first 15-year service life, the CM chair is incinerated, and a new one is manufactured in the same method as depicted in Scenario A1 (see Figure 8).

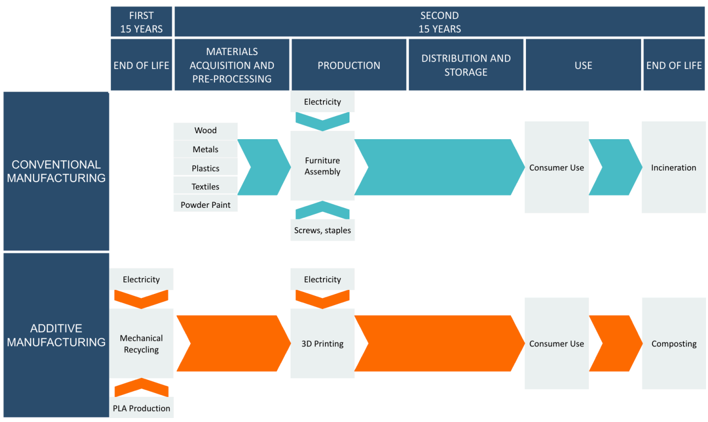

Figure 9: CM and AM systems in Scenario A2

In contrast, the AM's product system is different between Figure 8 and Figure 9. This is because the PLA used to create the 3D-printed chair in the first 15-year period is not composted. Instead, the PLA is kept in a closed loop by being mechanically recycled once and 3D-printed again for the second 15-year period (see Figure 9). It is assumed that the mechanical recycling of PLA produces granules small enough not to clog the pellet extruder, avoiding the need for a pellet production step.

Scenarios A3 and A4: 45- and 60-year Periods, Process-Level

Starting from Scenario A2, for every 15-year interval, the number of conventional chairs produced increases by one, whereas the 3D-printed chair goes on to its next generation since the PLA is kept in a closed loop. Scenarios A3 and A4's graphs for CM and AM are identical to Figure 9.

Scenarios B1 and B2: 15- and 30-year Periods, System-level

For Scenarios B1 and B2, transportation distances between the furniture manufacturer(s) and the consumers were added to both models. Figure 10 illustrates the centralized manufacturing approach in turquoise and the distributed approach in orange for these fictitious scenarios where the location markers represent the manufacturer's location and the simple dots represent the consumer's. In AM's distributed manufacturing system, the 3D-printed chairs were locally made, as seen by how there are only location markers in Figure 10. In contrast, the conventional chairs were all made in the same location (indicated by a single location marker in Figure 10) before being delivered across the globe to the consumer locations marked with a simple dot.

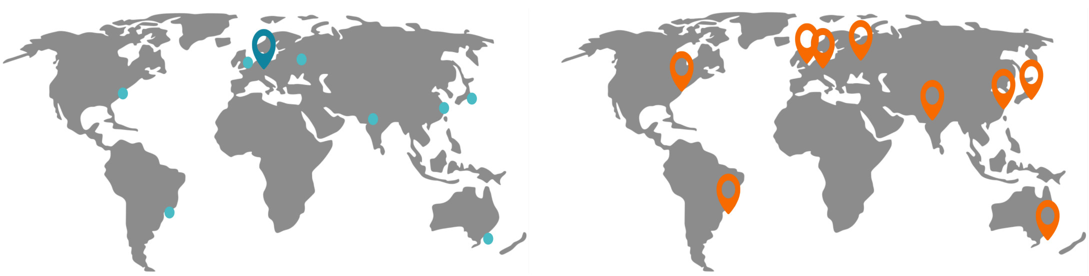

Figure 10: CM's centralized (left) vs. AM's distributed (right) approach in Scenarios 3 and 4

The nine consumer locations, including Zbaszynek, Poland as the baseline, were chosen among the most populated cities, with no more than one city representing each country. The nine cities for the consumer locations are Tokyo, Japan; Delhi, India; Shanghai, China; Moscow, Russia; London, United Kingdom; New York City, United States; São Paulo, Brazil; and Sydney, Australia. Initially, Lagos, located in Nigeria, and some other cities were on the list to have at least one city representing each of the six inhabited continents, but there was a lack of electricity and diesel data for these countries in GaBi.

In the CM product system, the location of the centralized manufacturer was set to Zbaszynek, Poland, since that is home to furniture giant IKEA's largest production unit (Bräck, 2021). This centralized manufacturer will deliver chairs to the nine consumer locations (see Figure 11).

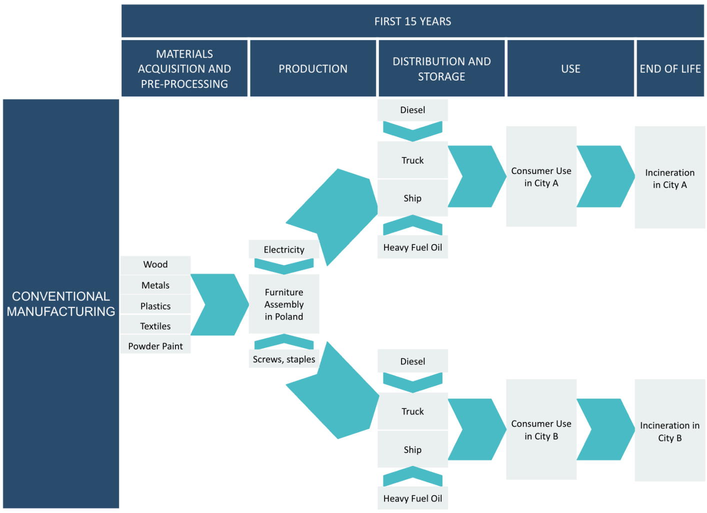

Figure 11: The abridged (2 out of 9 consumer locations) CM system in Scenarios B1 and B2

On the other hand, the AM system will have nine distributed manufacturers for the nine consumer locations, each responsible for delivering chairs to their local area (see Figure 12). The distributed manufacturers are assumed to have the same 3D printing, mechanical recycling, and composting processes, although the electricity and diesel mixes have been adjusted according to the country.

Packaging of the chairs is excluded from both product systems by assuming that the same amount of corrugated cardboard and polyethylene film would be used for both chairs since they are of the same dimensions.

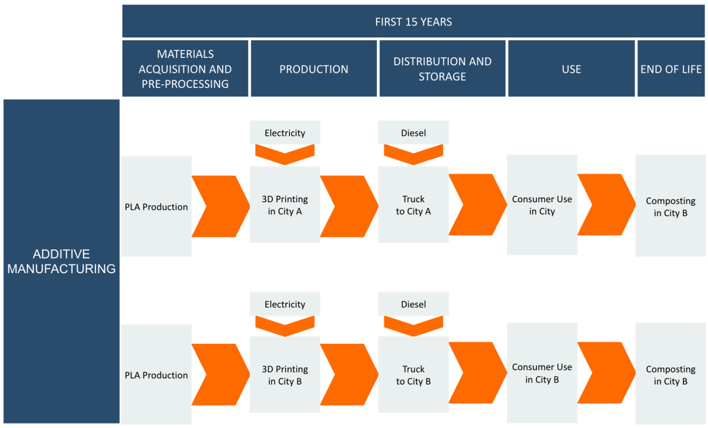

Figure 12: The abridged (2 out of 9 consumer locations) AM system in Scenario B1

4.2 Life Cycle Inventory Analysis

LCA's second phase, the life cycle inventory (LCI) analysis, is where data related to environmental aspects is collected for each unit process. The data could include energy, raw material, and ancillary inputs as well as outputs like products, co-products, waste, and releases to air, water, and soil. This LCA study uses databases last updated in 2021 including Sphera, ecoinvent, PlasticsEurope, and worldsteel, and data taken from literature for background processes. The specific LCI sources for each process can be found in Table 12 in Table A.

4.2.1 LCI for AM

The unit processes for the AM product system are the production, 3D printing, mechanical recycling, and composting of PLA. The inputs and outputs of AM's LCI are compiled in Table 11 in Table A.

PLA Production

The process data for first-generation PLA production is based on Vink et al.'s cradle-to-gate analysis of the NatureWorks manufacturing plant; the data set is available on the ecoinvent database (Cerdas et al., 2017). It accounts for the following steps: 1) growing, harvesting, and drying the corn, 2) transporting it to the corn wet mill, 3) hydrolyzing the corn starch into dextrose using enzymes, 4) fermenting the dextrose into lactic acid, 5) polymerizing the lactic acid to form long chains of polylactic acid, or PLA (Vink et al., 2003; Cosate de Andrade et al., 2016). For every kilogram of PLA produced by NatureWorks LLC requires 54 MJ of fossil fuels, and the company plans to bring down the requirement to 7 MJ/kg PLA within the next eight years (Vink et al., 2003).

3D Printing of PLA

The 1120 x 1120 x 1100 mm 3D printer began by outlining the side profile of the chair on the XY-axis as shown in Figure 13. The pellet extruder with a 5 mm nozzle diameter was ramped up to achieve an extrusion width of 9.87 mm (Florian, 2022). The 70°C heated borosilicate glass printer bed ensured proper adhesion of the first layer before more PLA was deposited, one 3 mm layer at a time in the Z-axis direction (Florian, 2022). Continuous spiral prints like this chair have an infill of 0% and do not need supporting structures; hence, the PLA waste generated during printing is minimal. Generally speaking, waste generated during the printing process varies between 9.2 g to less than 1 g, depending on how experienced the user is with optimizing printing parameters and minimizing the use of support structures (Cerdas et al., 2017). PLA is assumed to be zero during this step because the scraps can be directly re-fed back into the pellet extruder (Cerdas et al., 2017).

Figure 13: 3D printing a chair (Florian, 2022)

Table 3 summarizes the printing parameters for this chair. A steady stream of translucent PLA pellets was supplied to the extruder that was printing at 20 mm/s. This print speed is at the lower end of the suggested range. However, the pellet extruder's wide nozzle diameter compensated for that by reaching a volumetric output of approximately 1.1 kg/hr, going 25% over its recommended output. (Florian, 2022) The exact printing temperature was not explicitly mentioned in the video, but it is assumed to be in the range of 190-210°C (Algarni and Ghazali, 2021).

The total electricity consumption of the 3D printer during the build process was 23.7 kWh because the printer bed was 16.5 kWh, and the pellet extruder and motors were 7.2 kWh combined. Overall, it took approximately 18 hours to print a sturdy PLA-based chair that has a tested weight capacity of at least 77 kg with no sign of deformation. (Florian, 2022)

Table 3: 3D Printing a Chair from PLA Pellets (Florian, 2022)

Printing Parameters	Measurements
Volumetric output	approx. 1.1 kg/hr
Print speed	20 mm/s
Print time	18 hrs
Nozzle diameter	5 mm
Extrusion width x height	9.87 x 3 mm
Printing temperature	190–210°C
Printer bed temperature	70°C

PLA Mechanical Recycling

Cosate et al.'s end-of-life comparative study on PLA forms the basis of the process data collected for mechanical recycling and composting. Both processes' detailed inputs and outputs are listed in Table 11 in Table A.

In this scenario where the fictitious additive manufacturer has their own take-back scheme, the 3D-printed chairs are collected separately from the other plastic waste streams. The chairs are ground into small pieces of residual PLA, then washed and dried before extruded into filament. Even with adding a chain extender to offset the thermal degradation during extrusion, 0.04 kg of virgin PLA must be added for every kg of residual PLA to maintain its mass and mechanical properties. The newly extruded PLA filament is then cooled, broken into pieces through the granulation step, and sieved for size control, ready to be used again for 3D printing. (Cosate de Andrade et al., 2016)

PLA Composting

Composting was selected as the end-of-life option once the same batch of PLA was no longer suitable for mechanical recycling. It is the most conservative scenario compared to downcycling or incineration, where the material or energy is partially recovered. Landfill as an end-of-life option was not considered in this scenario where the fictitious additive manufacturer is responsible for taking back their chairs. In composting, the 3D-printed chairs are first ground into small pieces along with other compostable wastes. The mixture is then placed in windrows, degrading under controlled aerobic composting conditions following the ISO 14855-2:2018 guidelines. Every kg of residual PLA composted yields 0.33 kg of compost. It takes about 52 days for the PLA residual in the compost mixture to achieve satisfactory disintegration. The carbon dioxide released from the biodegradation of PLA is considered of biogenic origin, meaning that the amount of carbon dioxide absorbed during the corn-derived PLA's photosynthesis process equals the amount emitted during its degradation. In other words, the composting of PLA is a net-zero carbon process. (Cosate de Andrade et al., 2016)

4.2.2 LCI for CM

The unit processes for the CM product system include the acquisition of different materials, furniture assembly, and incineration. The inputs and outputs of AM's LCI are compiled Table 10 in Table A.

Materials Acquisition

The material composition and mass balance of the conventionally made chair (see Table 2) are based on one of the public space chairs documented by Linkosalmi et al. (2016). The following modifications were made to this wooden and steel-based chair with powder coating for this LCA model:

- 0.608 kg of chemicals, including acrylic lacquer and different types of glue (urea-formaldehyde adhesive, contact adhesive, and polyurethane reactive adhesive), were excluded due to difficulties installing the VTT/KCL-eco and CPM LCA databases. These missing chemicals account for 7.47% of the chair's original mass of 8.143 kg. To keep the same ratios for the other materials, the functional unit for this LCA's CM model was set to a chair weighing 7.535 kg, which is the value obtained after subtracting the missing chemicals (Linkosalmi et al., 2016).
- The wood-based material of the chair was originally a wood composite of 90% birch veneer and 10% plywood (Linkosalmi et al., 2016). However, since the birch veneer dataset was from the VTT/KCL-eco database, the wood-based material was adjusted to 100% plywood, similar to other EPDs (Ondarreta, 2023).
- The fabric for the upholstery was changed from a wool-polyamide blend to 100% cotton to work with the existing datasets in GaBi (Linkosalmi et al., 2016).
- The plastic components were not specified for this chair, but the combined inventory of the eight different furniture manufacturing processes listed PP, polyethylene (PE), polyurethane (PU), ABS, and ethylene vinyl acetate as possible candidates (Linkosalmi et al., 2016). PU foam was selected through consulting EPDs (Ondarreta, 2023).

Furniture Assembly

The environmental impacts of the chemicals are not accounted for from the material standpoint, but they are included from the energy standpoint since the energy consumption data for this chair is process-specific—18.58 kWh per chair (Linkosalmi et al., 2016). This is considered a bottom-up approach for data collection, whereas the top-down approach would divide the number of furniture pieces produced by the mill's average (Wenker et al., 2018). The environmental impacts of using screws, staples, and clips to assemble the furniture pieces are categorized under the production life cycle stage instead of materials acquisition and pre-processing. This is to highlight one of the advantages of AM is that screws, staples, and clips are not needed at all in AM's production stage.

Incineration

Ideally, the incineration data should also be country-dependent. However, since there were not enough datasets in GaBi to make that distinction, only one process, EU-28: Incineration domestic waste, was selected to represent all nine countries.

4.2.3 Including the Distribution Stage in Scenarios B1 and B2

For the CM system, Table 4 presents the land and sea transport distances for delivering the chairs from the centralized manufacturer in Zbaszynek, Poland, to the eight consumer locations. The Port of Gdańsk was chosen as the departure port from Poland, and the arrival ports selected for each of the eight countries were the ones closest to the consumer locations. These routes and distances were calculated using Google Maps and sea-distances (Google Maps, n.d.; sea-distances.org, 2019).

Table 4: Transport distances from manufacturer to consumer for CM's centralized system

Consumer location	By land, to port [km]	By sea [km]	By land, to consumer [km]
Zbaszynek, Poland	—	—	40
Tokyo, Japan	402	22,241	22
Delhi, India	402	13,218	1,466
Shanghai, China	402	21,005	5
Moscow, Russia	402	1,046	703
London, UK	402	1,659	150
NYC, USA	402	7,299	10
Sao Paulo, Brazil	402	11,569	85
Sydney, Australia	402	22,941	11

The diesel mixes for the trucks are country-dependent, whereas the heavy fuel oil for the cargo ships is from the EU-28. GaBi's utilization parameter in trucks and capacity utilization parameter in ships are calculated using the following equation:

$$\text{Utilization} = \frac{\text{Actual load}}{\text{Payload}} \tag{4.1}$$

where $Actual\ load$ is the total mass of chairs being transported and $Payload$ is the maximum vehicle load capacity (Sphera, 2022). Each of the eight ships transporting 476 chairs to their consumer location has a payload of 43,000 tons, resulting in a capacity utilization value of 0.0083%. From the arrival port to each of the consumer locations, the 476 chairs are delivered by a truck with a payload of 5 tons. The capacity utilization of the truck is 71.73%. These capacity utilization values do not change between Scenarios 3 and 4 because although the production of chairs doubles from 4,284 to 8,568 between the 15- and 30-year period, only 4,284 chairs are produced and distributed at a time. Since the 3D-printed chairs are manufactured at each consumer location, there are no sea transport distances to account for in AM's distributed system as shown in Table 5.

Table 5: Transport distances from manufacturer to consumer for AM's distributed system

Consumer location	**By land, to consumer [km]**
Zbaszynek, Poland	40
Tokyo, Japan	40
Delhi, India	40
Shanghai, China	40
Moscow, Russia	40
London, UK	40
NYC, USA	40
Sao Paulo, Brazil	40
Sydney, Australia	40

The land transport distance from the manufacturer to the consumer within the same city is assumed to be 40 km. This value is on the higher end of the average distance from one end to the other in these nine cities for a more conservative estimate. Using Equation 4.1, the capacity utilization of trucks with a 9.3 tons payload is 91.36%.

5 RESULTS AND DISCUSSION

This section focuses on the last two phases of the LCA methodology: life cycle impact assessment (LCIA) and interpretation. LCIA involves choosing relevant impact categories and their corresponding category midpoint or endpoint indicators (Saade et al., 2020). The interpretation phase discusses the conclusions and limitations of the results, checking for completeness, sensitivity, and consistency (ISO 14044, 2006). This LCA study considers two different impact categories: GWP100 and ADPf, when comparing the AM and CM product systems of a chair.

5.1 Global Warming Potential 100 Years

The GWP100 impact category measures the impacts of different greenhouse gases on global warming in terms of kg CO2 eq. It is the most common metric for comparison used in AM and furniture LCA studies. (Cordella and Hidalgo, 2016; Saade et al., 2020)

5.1.1 Scenarios A1 to A4: Process-Level

In Scenerios A1 to A4, Figure 14 shows that the GWP100 values of the AM and CM chair are closely tied, with the AM chair gradually emitting more greenhouse gases despite the majority of the PLA being recycled and re-printed into another chair with every passing 15-year period.

This trend holds when the GHG emission values are divided per chair as shown in Table 6. Since the conventional chair is manufactured the same way with the same amount of materials and energy in every scenario, CM's GWP100 values remain constant at 31.73 kg CO2 eq. On the other hand, AM's values slowly inch upwards, starting from 32.08 kg CO2 eq. in Scenario A1 to 33.03 kg CO2 eq. in Scenario A4. AM and CM's GHG emissions per chair are similar to the value of 32.83 kg CO2 eq. that Linkosalmi et al. (2016) obtained for their wooden public space chair with a powder-coated steel base, denoted as 3A in their paper. This was the study on which this LCA's conventional chair model was based. Linkosalmi et al. (2016) and CM's GWP100 values are similar, although CM's values are expected to increase when the excluded materials (acrylic lacquer and adhesives) are added to the LCA model in the next iteration.

While AM and CM's GHG emission values per chair are similar, the mass of the 3D-printed chair (17.85 kg) was over twice as much as the mass of the conventional chair (7.54 kg). As a result, contrary to the conclusions drawn when interpreting Figure 14, the 3D-printed chair

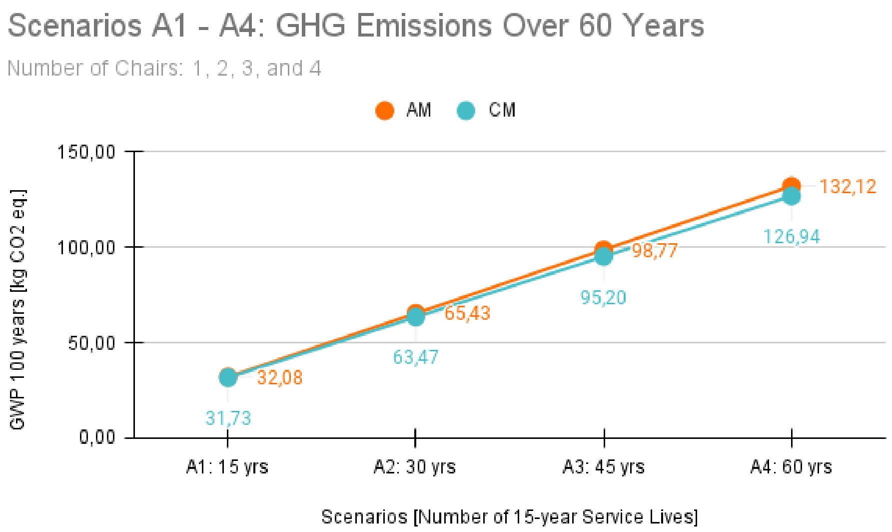

Figure 14: Scenarios A1 - A4: GWP 100 Years

Table 6: All Scenarios: GHG Emissions [kg CO2 eq.] per Chair and per Kilogram

	A1: 15 yr	A2: 30 yr	A3: 45 yr	A4: 60 yr	B1: 15 yr	B2: 30 yr
Per chair						
AM	32.08	32.71	32.92	33.03	26.32	25.31
CM	31.73	31.73	31.73	31.73	5.96e3	5.96e3
Per kg						
AM	1.80	1.80	1.80	1.80	1.47	1.42
CM	4.21	4.21	4.21	4.21	790.69	760.69

emits lower greenhouse gases per kilogram (1.80 kg CO2 eq.) compared to the conventional chair, which emits 4.21 kg CO2 eq. per kilogram (see Table 6). In the study by Linkosalmi et al. (2016), the public space chair 3A used plywood and steel tubing in almost equal amounts, each 44% of the overall weight of the chair. The GHG emission per kilogram of this chair is 4.03 kg CO2 eq., which is comparable with CM's 4.21 kg CO2 eq. value.

AM's 1.08 kg CO2 eq. value is more comparable with a different public space chair that Linkosalmi et al. (2016) examined. It was a 4.05 kg chair comprised of 80% wood with no steel. This wooden chair, denoted as 4B in their paper, has the lowest GWP100 value per chair (6.31 kg CO2 eq.) and per kilogram (1.56 kg CO2 eq.) of the four public space chair variations examined. (Linkosalmi et al., 2016) It is important to note that the 3D-printed chair's GHG emission per kg value is similar to the wooden chair's despite it being over four times its weight.

GHG emissions results for both chairs are presented in Table 7 and analyzed by their life cycle stages to identify the environmental hotspots. Based on the literature review, a common consensus among the AM and CM comparative studies was that CM's environmental hotspot is the materials acquisition and pre-processing phase, and AM's is the production phase (Saade et al., 2020). The results of this LCA study show that the environmental hotspot was the same for manufacturing the conventional and 3D-printed chair in Scenarios A1 to A4. The production stage has the biggest impact on overall GHG emissions. It is responsible for an average of 64% of AM's GHG emissions and 54% of CM's.

Table 7: All Scenarios: GHG Emissions [kg CO2 eq.] by Life Cycle Stage

	Materials	Production	Distribution	End of Life	TOTAL
AM					
A1	11.07	21.01	—	0.00	32.08
A2	11.51	42.02	—	11.89	65.43
A3	11.95	63.03	—	23.79	98.77
A4	12.40	84.05	—	35.68	132.12
B1	4.74e4	6.51e4	230.59	0.00	1.13e5
B2	4.93e4	1.30e5	460.39	3.69e4	2.17e5
CM					
A1	7.60	17.06	—	7.08	31.73
A2	15.20	34.11	—	14.15	63.47
A3	22.80	51.17	—	21.23	95.20
A4	30.40	68.23	—	28.31	126.94
B1	3.26e4	7.29e4	2.54e7	3.03e4	2.55e7
B2	6.51e4	1.46e5	5.08e7	6.06e4	5.10e7

As shown in Table 7, the contributions of each life cycle stage in CM remain constant throughout Scenarios A1 to A4. The production stage in AM exhibits a similar trend, but its materials and end-of-life stages of inversely correlated. Materials initially represent 35% of the total GHG emissions in Scenario A1 but only 9% in Scenario A4. Conversely, end-of-life covers 0% in Scenario A1 due to composting and increases to 27% in Scenario A4 after three rounds of mechanical recycling. This is because the amount of virgin PLA marginally increases throughout the four scenarios while PLA undergoes mechanical recycling at the end of every service life starting from Scenario A2.

5.1.2 Scenarios B1 and B2: System-Level

Once the distribution stage is expanded to include nine consumer locations in different countries for Scenarios B1 and B2, CM's GHG emissions values are substantially greater than AM's as shown in Figure 15. When scaling up the production and distribution of chairs, the GHG emissions per 3D-printed chair and per kilogram are further reduced compared to their counterparts in Scenarios A1 and A2 (see Table 6). In fact, the 3D-printed chair in Scenarios B1 and B2 has a lower environmental impact (1.47 and 1.42 kg CO2 eq. per kg, respectively) than the wooden chair studied by Linkosalmi et al. (2016), which was 1.56 kg CO2 eq. per kg. Comparing the GHG emissions per kilogram widens the difference between AM and CM significantly.

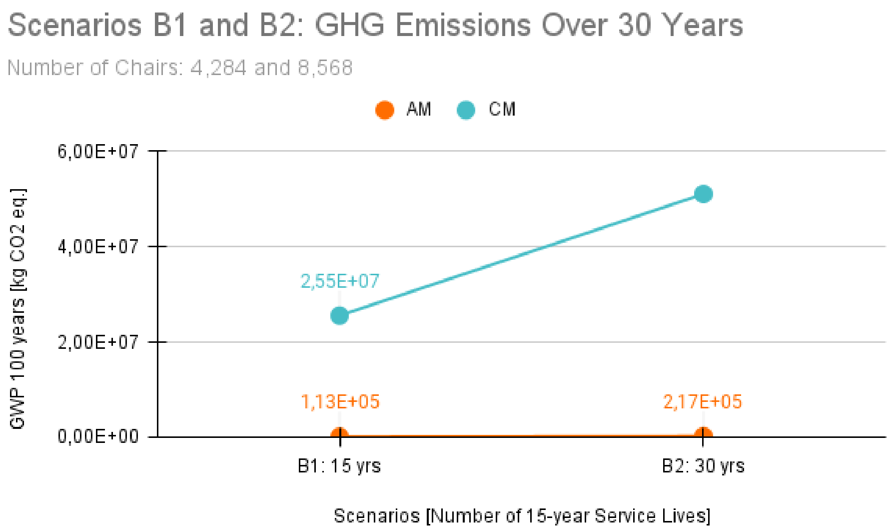

Figure 15: Scenarios B1 and B2: GWP 100 Years

Distribution in AM accounted for less than 1% in Scenarios B1 and B2, with production representing over half of the environmental impact because the 3D-printed chairs are manufactured locally at the nine consumer locations (see Table 7). In stark contrast, distribution in CM is responsible for 99% of the GHG emissions, 87% of which comes from the ship and 12% from the heavy fuel oil supplied to the ship.

It is difficult to find a direct GHG emissions comparison of the distribution stage with other studies because these values depend on many factors, including the weight and number of the products being transported, the manufacturer and consumer locations, and the delivery routes. Cerdas et al. (2017) conducted a comparative study where the centralized manufacturer was located in Guangzhou, China, and the eyeglasses frames were distributed to six other countries (India, Australia, Russia, USA, Japan, and Mexico). They found that AM's distribution contributed to less than 5% of the studied GHG impact category, which aligns with the findings for this LCA model. One of the figures in their paper illustrates that CM's distribution accounts for less than 30% of the GWP values in each of the six countries. (Cerdas et al., 2017)

5.2 Abiotic Depletion Potential (Fossil)

ADPf refers to the over-extraction of fossil fuels, expressed in terms of the amount burned. ADPf is not one of the five impact categories frequently reported in furniture EPDs (Cordella and Hidalgo, 2016). The one furniture case study that mentioned it was referring to ADP, elements (ADPe) instead (González-García et al., 2012). On the additive manufacturing side, Cerdas et al.(2017) reported ADPe values for their distributed AM and centralized CM comparison. The values of ADPe turned out to be negligible in this study, especially in Scenarios B1 and B2. Thus, ADPf was selected as a basis for comparison instead.

The ADPf values follow the same trend as the GWP100 values, where AM has the greater environmental impact in Scenarios A1 to A4, but as production and distribution are scaled, CM's fossil fuel requirement environmental impacts end up surpassing AM's in Scenarios B1 and B2 (see Figure 16).

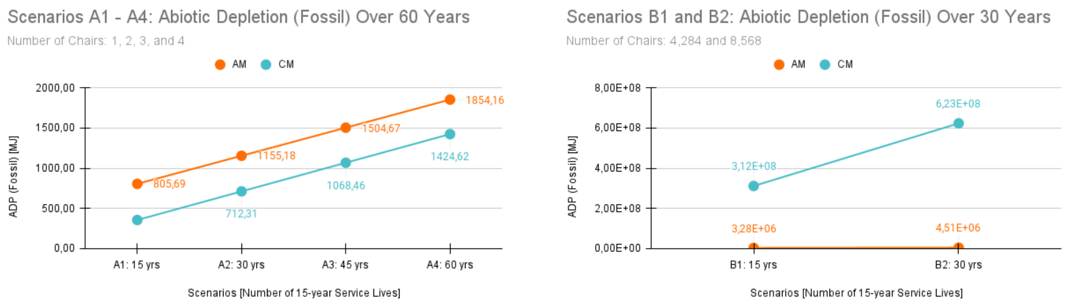

Figure 16: Scenarios A1 to A4 (left) and Scenarios B1 and B2 (right): ADP (Fossil)

When analyzing each life cycle stage's contribution to the overall amount of fossil fuels burned (see Table 8), materials are the leading factor in Scenarios A1 to A4 for both AM and CM. For manufacturing the conventional chair, materials contribute 52% of the total ADPf value, followed by production, which contributes 47%. These ratios are consistent across Scenarios A1 to A4. As for the 3D-printed chair, materials start as the main contributor in Scenario A1, accounting for 74% of the total fossil fuel requirement since it takes 54 MJ to produce one kg of PLA (Vink et al., 2003). For AM, the contributions of the materials and end-of-life stages are inversely related, as seen with the GHG emissions. Scenario A4 is where production in AM becomes the leading contributor at 45%.

At the system level, materials still contribute the most to the overall fossil fuel requirements for producing and distributing 3D-printed chairs, comprising 78% of the total in Scenario B1 and 59% in B2 (see Table 8). Following the pattern observed in the GWP100 impact category,

Table 8: All Scenarios: Abiotic Depletion Potential (Fossil) [MJ] by Life Cycle Stage

	Materials	Production	Distribution	End of Life	TOTAL
AM					
A1	597.79	207.90	—	0.00	805.69
A2	621.70	415.80	—	117.68	1.16e3
A3	645.61	623.71	—	235.36	1.50e3
A4	669.52	831.61	—	353.03	1.85e3
B1	2.56e6	7.15e5	3.13e3	0.00	3.28e6
B2	2.66e6	1.43e6	6.26e3	4.05e5	4.51e6
CM					
A1	184.23	168.62	—	3.30	356.15
A2	368.46	337.25	—	6.60	712.31
A3	552.69	505.87	—	9.90	1.07e3
A4	736.92	674.50	—	13.19	1.42e3
B1	7.92e5	7.22e5	3.10e8	1.41e4	3.12e8
B2	1.58e6	1.44e6	6.20e8	2.83e4	6.23e8

distribution in AM makes up less than 1% while distribution in CM makes up 99.5%, which comes entirely from heavy fuel oil. The ADPf values of the ship and truck processes are zero.

Table 9: All Scenarios: Abiotic Depletion Potential (Fossil) [MJ] per Chair and per Kilogram

	A1: 15 yr	A2: 30 yr	A3: 45 yr	A4: 60 yr	B1: 15 yr	B2: 30 yr
Per chair						
AM	805.69	577.59	501.56	463.54	765.50	525.82
CM	356.15	356.15	356.15	356.15	7.28e4	7.28e4
Per kg						
AM	45.14	32.36	28.10	25.97	42.89	29.46
CM	47.27	47.27	47.27	47.27	9.66e3	9.66e3

Table 9 presents the fossil fuel requirements per chair and per kilogram. Instances in which the 3D-printed chair has a better environmental profile than the conventional one are when the comparison is made per kilogram in all Scenarios or when the comparison is made per chair at the system level (B1 and B2). The ADPf impact category exhibits the same trends as the GWP100 one, except for a more noticeable difference between the ADPf values per chair relative to the GWP100 values per chair in Table 6.

5.3 Limitations

The environmental impacts of logistics in the materials acquisition and pre-processing stage were not included in this LCA model for several reasons. Previous LCA studies on furniture and EPDs found that logistics generally had a minor impact on overall GHG emissions (Cerdas et al., 2017; Linkosalmi et al., 2016). The study conducted by Linkosalmi et al. (2016) found that even with conventional furniture's wide-ranging supplier network, transportation contributed to less than 5% of the overall GHG emissions.

The logistics within the distribution stage in Scenarios 3 and 4 can still be improved upon. Referring back to Table 4, the land transport distances were combined into the same truck to simplify this LCA model. The next iteration of the CM product system should include two additional trucks that transport the 4,824 chairs from the manufacturer to the departure port. These trucks would each have a payload of 17.3 tons and a capacity utilization of 82.93%.

As for the AM product system, the current LCA model does not factor in how AM's significantly longer printing time would affect logistics. Unlike the CM system, the AM system, with only one large-scale 3D printer, would not be able to manufacture and distribute 476 chairs all at once. Hence the truck's capacity utilization of 71.73% is an oversimplification of the system. The next iteration should assume that if it takes 18 hours to 3D print a chair, eight chairs will be manufactured every six days. This means at least 60 trips will be needed to deliver 476 chairs to a consumer location, eight chairs per 40 km trip. The utilization becomes 5.29% instead, and after updating Table 4, the cumulative land transport distance of eight chairs per trip is 2,400 km at each consumer location. Delivering eight chairs at a time in a truck is also more feasible since the 3D-printed chairs are not as easily stackable as conventional chairs. The 3D-printed chair can only be delivered fully assembled, and the conventional chair is assumed to be delivered the same way. Iritani et al. (2015) noted that transporting fully assembled furniture results in fewer furniture pieces per delivery and more trips, significantly affecting GHG emissions.

The current LCA model did not demonstrate AM's advantage of enabling on-demand or just-in-time manufacturing. Cerdas et al. (2017) factored this in by performing a sensitivity analysis. They examined how the percentage of unsold eyeglass frames conventionally manufactured (from 10% to 50%) would influence the environmental impact of the ones sold. As the 3D-printed eyeglass frames were produced to order, it was assumed there would be no unsold pairs. (Cerdas et al., 2017) A similar sensitivity analysis will be considered for the next iteration.

6 FUTURE RECOMMENDATIONS

Given that AM applications in furniture are relatively new manufacturing models compared to CM, AM has a greater potential for improvement across many stages in a 3D-printed product's life cycle (Kreiger and Pearce, 2013). Future LCA studies comparing AM to CM can go in one or several of these directions.

6.1 Material Acquisition: Second-generation Feedstock

PLA is currently produced from first-generation feedstock, edible crops like corn and sugarcane that compete with food and feed production. Second-generation feedstocks such as corn stover, bagasse (sugarcane residue), straw, and other non-edible or waste biomass offer a food-secure option, further reducing the environmental impacts of future commercial PLA production. (Aryan et al., 2021)

6.2 Production: Renewable Energy

Kreiger and Pearce (2013) found that the cumulative energy demand of 3D printing PLA and ABS-based products can be lowered by 10% to 14% by powering a desktop 3D printer with a solar photovoltaic (PV) system. Lowering electricity consumption means reducing GHG emissions, and solar PV integration is something that distributed AM is better positioned to take advantage of. The large scale, high energy requirements, and lack of long-term energy storage are some of the technical challenges of incorporating solar PV that CM has to address to keep pace with its mass production.

While AM also has to address these challenges, it is not to the same extent (Kreiger and Pearce, 2013). There is a lower investment barrier for smaller, decentralized power generation units that can be integrated with 3D printers, although Cerdas et al. (2017) pointed out that the return on investment for these might also be lower. Furthermore, the energy efficiency of 3D printers and recyclebots will continue to improve, making it easier to pair with solar PV. PV-powered 3D printers have yet to be investigated extensively, but besides their potential to reduce AM's environmental impacts, they may be pertinent for off-grid communities and applications (Kreiger and Pearce, 2013).

6.3 End of Life: Distributed Recycling

Large-scale AM demands a greater amount of feedstock but there is still a limited production capacity of PLA (Zhao et al., 2018). Two-thirds of the global commercial PLA supply comes from corn grown in the United States and then processed by NatureWorks LLC, a joint venture between Cargill and Dow Chemical Company (Moretti et al., 2021; Vink et al., 2003). The remaining one-third is produced by Total Corbion from sugarcane grown in Thailand (Moretti et al., 2021). Equipping AM labs and workshops with recyclebots can address potential shortages of PLA feedstock while hastening the transition toward distributed recycling. Conventionally, the low recycling rates of plastics can be attributed to difficulties in collecting and transporting them because of their high volume-to-weight ratio and minimal net economic benefit. Distributed recycling via 3D printing manufacturers not only increases the number of smaller-scale plastic waste collection points but enables these waste plastics to be transformed into high-value products. (Cruz Sanchez et al., 2015) If a 3D printing manufacturer were to be responsible for taking back their products at the end of their life cycle and recycling it back at their site, the supplier transport distance during the materials stage would be zero for the next generation of products made from recycled plastic, further reducing the environmental impacts of AM.

7 CONCLUSIONS

AM supports not only the realization of mass customization in Industry 4.0 but also more sustainable production practices, including mono-materiality, dematerialization, and material reuse and recycling (Khorasani et al., 2022; Saade et al., 2020). Despite these advantages, studies remain inconclusive about AM's environmental impacts in relation to CM's. This thesis investigates whether AM's improved environmental performance would become more noticeable if the LCA model conducted were to:

- extend its system boundary to include several service lives of a product, drawing attention to how AM can take advantage of open-source plastic recycling extruders to produce several generations of products primarily from the same batch of material.
- expand its logistics to a global scale in the distribution stage, highlighting how AM enables decentralized and distributed production.

An LCA model comparing a 3D-printed chair with a conventional chair over the course of several service lives and across nine different consumer locations was conducted. The results indicate that the 3D-printed chair is the more environmentally friendly option in terms of Global Warming Potential 100 Years and Abiotic Depletion Potential (fossil) when the impacts are compared per kilogram. When the basis of the comparison is per chair, at the process level, the 3D-printed chair has similar GHG emissions as the conventional chair, but it requires substantially more fossil fuels. At the system level where AM's distributed logistics and CM's centralized logistics are factored in, the 3D-printed chair emerges as the more sustainable option in both impact categories.

The fact that the 3D-printed chair's GHG emissions and fossil fuel requirements per kilogram are either comparable or lower than the conventional chair's signifies that if the chairs were of equal weight, the 3D-printed chair would have at least the same environmental performance or better. The 3D-printed chair modeled in this LCA study weighed twice as much as the conventional chair. AM's design freedom and topology optimization by adjusting parameters like infill density could help with dematerialization. The environmental performance of AM can be further improved by using second-generation PLA feedstock, powering the 3D printer with solar PV, and taking advantage of AM's distributed recycling.

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A APPENDIX: LIFE CYCLE INVENTORIES

Table 10: LCI for the CM Product System (reference flow is 1 kg of the modeled chair)

MATERIALS ACQUISITION INPUT	(Linkosalmi et al., 2016)
Plywood	0.441 kg
Steel parts	0.438 kg
Plastic parts	0.002 kg
Expanded plastics	0.057 kg
Powder paint, steel	0.0253 kg
Textile (cotton)	0.0288 kg
FURNITURE ASSEMBLING Input	(Linkosalmi et al., 2016)
Screws, staples, clips	0.0084
Electricity	2.47 kWh

Table 11: LCI for the AM Product System (reference flow is 1 kg of PLA)

3D PRINTING **INPUT**	(Florian, 2022)
PLA Electricity	1 1.3 kWh
MECHANICAL RECYCLING **Input**	(Cosate de Andrade et al., 2016)
Residual PLA Virgin PLA Chemicals organic (chain extender) Electricity Water Lime Aluminum sulfate	1 0.04 kg 6.04 g 2649 kJ 0.169 kg 0.0017 kg 0.00205 kg
Output	
Recycled PLA Residual PLA waste Heat, waste	1 0.04 kg 286.6 kJ
COMPOSTING **Input**	(Cosate de Andrade et al., 2016)
Residual PLA Occupation, dump site	1 0.117 m^2
Output	
Compost Electricity Carbon dioxide, biogenic	0.33 kg 39.7 kJ 1.2 kg

Table 12: Inventory source of different materials, products, and processes

Material/Component	Data	LCI Source
AM		
PLA	US: Ingeo Polylactide (PLA) biopolymer	NatureWorks
Transportation (road)	GLO: Truck, Euro 0 - 6 mix, 12 - 14t gross weight / 9.3t payload capacity	Sphera
CM		
Plywood	EU/28: Plywood board (EN15804 A1-A3)	Sphera
Screws, staples, clips	EU-28: Fixing material screws galvanized (EN15804 A1-A3)	Sphera
Steel	GLO: Steel welded pipe	worldsteel
Plastic parts	RER: Polyurethane rigid foam (PU)	PlasticsEurope
Expanded plastics	EU-28: Polyurethane flexible foam (PU) - TDI-based, no flame retardant, low density	EUROPUR
Powder paint, steel	DE: Coating powder (industry; inside; white)	Sphera
Textile mill	GLO: Textile Manufacturing - Woven Fabric	CottonInc
Textile (cotton)	EU-28: Cotton raw conventional (EN15804 A1-A3)	Sphera
Transportation (road)	GLO: Truck, Euro 0 - 6 mix, 7.5 t - 12t gross weight / 5t payload capacity	Sphera
Fuel for Transportation (water)	EU-28: Heavy fuel oil at refinery (1.0wt.% S)	Sphera
Transportation (water)	GLO: Container ship, 5,000 to 200,000 dwt payload capacity, ocean going	Sphera
Incineration	EU-28: Incineration domestic waste (EN15804 C3)	Sphera
BOTH	*** means country-specific	
Electricity Production	***Electricity Grid Mix	Sphera
Fuel for Transportation (road)	***Diesel mix at filling station (100% fossil) C3)	Sphera