Life Cycle Greenhouse Gas Implications of Multi Jet Fusion Additive Manufacturing

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ABSTRACT: This study fills a gap in additive manufacturing life cycle assessments by improving decision-making in plastic product manufacturing. This assessment investigated cradle-to-gate life cycle energy consumption and greenhouse gas (GHG) emissions of multi jet fusion (MJF) three-dimensional (3D) printing technology across production quantities ranging up to 100,000 plastic parts. Results for MJF 3D printing site energy consumption were 25% lower than the median reported value for selective laser sintering. Modeled GHG emissions for the MJF part manufacturing unit process increased linearly at a rate that would surpass emissions associated with injection molding plate production after approximately seven full build chamber print jobs, equivalent to 700 parts for the studied design. Major factors contributing to MJF's emissions were 3D printing electricity consumption and material yield. Sensitivity analyses showed that variations in manufacturing facility electricity generation source, post-processing time, raw material production life cycle inventory (LCI) data, and printing speed could alter MJF cradle-to-gate GHG emissions by over 20%. The LCI data, build configurations, and process variables explored in this study provide a basis for estimating MJF GHG emissions per kilogram of polyamide 12 (PA12) product for a given design. These findings can guide 3D printing product design and manufacturing decisions for reducing GHG emissions.

KEYWORDS: life cycle assessment, greenhouse gas emissions, additive manufacturing, 3D printing, multi jet fusion

INTRODUCTION

The rapid pace of growth in the additive manufacturing industry has not been matched by advances in sustainability evaluation.1 Some additive manufacturing technologies have had little or no assessment of their environmental impacts.2 Consequently, business leaders are left to consider manufacturing, procurement, and capital investment decisions without sufficient knowledge of sustainability tradeoffs.

Introduced in 2016, multi jet fusion (MJF) three-dimensional (3D) printing technology has received scarce environmental evaluation even as industry adoption of MJF is increasing.3 The technology is 5–10 times faster than other 3D printing technologies.4,5 The manufacturer states that MJF enables large-scale production, resulting in an economic breakeven point at 110,000 parts with injection molding and 65% lower cost than other additive manufacturing methods.6,7 As such, MJF presents a potential alternative to existing manufacturing methods for high-volume production of plastic products, which have been cost prohibitive for other additive manufacturing processes such as selective laser sintering (SLS) and fused deposition modeling (FDM).8,9

Multi Jet Fusion. MJF is a powder-bed fusion (PBF) process technology, which ISO/ASTM 52900 defines as an "additive manufacturing process in which thermal energy selectively fuses regions of a powder bed."10 MJF builds parts layer-by-layer over the working area of a build platform inside a build unit, depositing chemical agents onto select areas of each powder layer, and fusing those areas with infrared radiation.11

Figure 1 presents an overview of the MJF 3D printing process. The only publicly available life cycle assessment (LCA) of MJF indicates that MJF generates less environmental burden than SLS and FDM.12 Tagliaferri et al.12 used the Eco-Indicator 99 method in SimaPro v7.1 software for life cycle impact modeling and comparison of MJF, SLS, and FDM printing systems to arrive at their conclusion that MJF presented the lowest environmental impact potential. However, the description of methods, data sources, and assumptions in this study, including the system boundary, process flow, life cycle inventory (LCI), and material yield, lack sufficient detail to thoroughly probe the results and facilitate their replication. Moreover, Tagliaferri et al.12 do not provide unit process LCI data for MJF or discuss the technology's
environmental impact in the context of high-volume production or conventional manufacturing methods. Considering SLS and MJF are both powder-bed fusion technologies and use similar plastic powder materials, existing literature on SLS serves as the basis for evaluating MJF in this paper. A review of available SLS studies shows a median specific energy consumption (SEC) value of 130.75 MJ/kg, which is the site energy consumed by the machine for manufacturing of 1 kg of product (see Table S1 in the Supporting Information). These values indicate that SLS energy efficiency is superior to FDM and comparable to stereolithography (SLA). In contrast, LCI data for injection molding reflect SEC values between 12.6 and 19.6 MJ/kg, significantly less than reported SLS SEC values. Previous studies have shown that injection molding consumes less energy than the additive manufacturing processes in high-volume production scenarios, despite the initial production burden of injection mold tooling.

In view of MJF’s potential for high-volume production applications, this study seeks to improve upon existing additive manufacturing sustainability literature by providing modeled unit process LCI data for MJF and an impact assessment of the technology’s use on climate change. Furthermore, this study provides sensitivity analyses to depict potential variance in life cycle impact outcomes from changes in MJF process parameters and modeling assumptions. The primary goal of this study is to improve decision-making in plastic product manufacturing by identifying climate change implications of MJF 3D printing across various production volumes. Toward this goal, this study applies LCA methods to evaluate the HP MJF 4210 3D Printing system.

**METHODS**

This LCA utilizes process-based methods in accordance with the ISO 14040 standard to evaluate the cradle-to-gate life cycle primary energy consumption and greenhouse gas (GHG) emissions of additive manufacturing with the HP Jet Fusion 4210 3D printing system. LCIs are calculated for raw materials, transportation, and manufacturing unit processes based on reference mass flows of 1 kg using secondary data from several sources. Data for raw material production and parameters for the MJF part manufacturing process originate from MJF technical documents and communications with HP representatives. Other sources for the LCIs in this report include: previous process LCAs and LCIs; ecoinvent 3.5; and Argonne National Laboratory’s Greenhouse Gases, Regulation Emissions, and Energy Use in Transportation (GREET) 2019 model. Process parameters, inputs, and outputs are modeled using SimaPro 9.0.0.48 LCA software and Microsoft Excel spreadsheets.

**Process Flow and System Boundary.** The MJF 3D printing process flow and system boundary are shown in Figure 2. The product...
material inputs to the MJF process under investigation in this LCA are polyamide 12 (PA12, also referred to as Nylon-12), fusing agent, and detailing agent. Other ancillary material inputs that amortize over the production of multiple print jobs, such as the 3D printer’s cleaning roll, maintenance kits, packaging, and part cleaning materials, are excluded from this study with the expectation that these inputs contribute less than 1% of the cradle-to-gate life cycle impact. Other product system components that amortize over their respective lifespans, such as the 3D printer, the processing station, and manufacturing facility infrastructure, are also excluded from this LCA.28 Maintenance of equipment, storage, and disposal of process waste fall outside the scope of this LCA.

Geography. This study models a manufacturing facility in Michigan as the destination for all input materials to the part manufacturing process. This manufacturing facility uniquely hosts both injection molding and MJF printing services under one roof, presenting an equitable decision-making scenario for additive versus conventional manufacturing.29 The production location of PA12 raw materials is Marl, Germany, which is the location of Evonik’s PA12 production plants. Evonik is the dominant supplier of PA12 powder for additive manufacturing, including SLS and MJF, and also produces PA12 pellets for injection molding.30–33 Fusing agent and detailing agents were modeled with HP’s 3D Open Platform Materials and Applications Lab in Oregon as the origin due to the lack of U.S. manufacturer location data.24

MJF Part Manufacturing Process. Figure 3 shows the process flow within the MJF part manufacturing process. The part manufacturing process involves five primary steps: powder mixing and loading, MJF 3D printing, cooling, unpacking, and post-processing. Descriptions of each step are provided in the Supporting Information.

Functional Unit. The functional unit of the product system is 1 kg of PA12 product, modeled with the manufacturing of 33 LCD controller front cover parts (Figure 4). This part appropriately simulates a product that could be manufactured with MJF because it represents a typical plastic enclosure. Many industries require manufacturing of similar enclosures, from automobiles to consumer electronics and medical devices, across a variety of volumes.34,35 This part could be realistically considered for either additive or conventional manufacturing, depending on the application and quantity required. This study assumes that the LCD controller front cover can be additively manufactured with MJF technology based on the features of the part. The 3D computer-aided design (CAD) file for the LCD controller front cover originates from Thingiverse, a website that hosts user-submitted 3D models.36

Assessment Metrics. This study measures cradle-to-gate life cycle energy consumption in units of megajoules [MJ] based on the primary energy of input material feedstocks, process fuels, process electricity consumption, and electricity grid generation mix. Cradle-to-gate life cycle GHG emissions are measured in kilograms of carbon dioxide equivalent [kg CO2 equivalent] on a 100 year global warming potential time horizon using the values recommended by the Intergovernmental Panel on Climate Change Fifth Assessment Report.37 The life cycle impact assessment considers these measures across volumes ranging from 1 to 3032 kg PA12 product (33–100 000 LCD controller front cover parts).

Figure 3. MJF part manufacturing process flow.

Figure 4. LCD controller front cover. Key characteristics: mass, 30.32 g; volume, 30.02 cm3; bounding box length, 108.6 mm; bounding box width, 95.4 mm; and bounding box height, 16.1 mm.
Multi Jet Fusion Life Cycle Inventory. Raw Materials—PA12. The most commonly used material among powder-bed fusion technologies, including MJF, is PA12. Since peer-reviewed LCI data for PA12 are not publicly available, previous LCAs on SLS used LCI data for polyamide 6 (PA6) as modeling inputs for raw materials.\(^4\)\(^\text{29,43}\) However, an eco-profile report by Arkema, one of the main manufacturers of PA12, indicates that cradle-to-gate energy consumption for the production of PA12 is over 1.5 times higher than PA6.\(^4\)\(^\text{51}\) EarthShift Global provided PA12 LCI data showing approximately 2.67 times higher cradle-to-gate energy consumption and 2.3 times higher GHG emissions than PA6.\(^4\)\(^\text{2,43}\) As a conservative approach, this study uses the EarthShift Global data for modeling, and sensitivity analyses explore the variance in LCA results when using PA6 data. Table S2 in the Supporting Information lists LCI data for PA6 and PA12 used in this study.

Raw Materials—Fusing and Detailing Agents. Material Safety Data Sheets (MSDS) for HP’s fusing and detailing agents inform LCI data calculations. The main ingredients for the fusing agent are water, 2-pyrrolidone, and triethylene glycol.\(^4\)\(^\text{44}\) The associated patent refers to these agents as ink-type formulations; therefore, this study modeled the manufacturing of the agents based on printing ink production LCI data from the ecoinvent 3.5 database in SimaPro.\(^4\)\(^\text{46}\) This study made assumptions shown in Table S3 of the Supporting Information regarding the percentage of each ingredient, which were conservatively chosen near the upper bounds of the percentages identified in the respective MSDS.

Transportation. This study used the distance & time tool on Searates.com and Google Maps to calculate the trucking and ocean freight distance required to transport PA12 and the fusing and detailing agents from their respective production facilities to the part manufacturing facility in Michigan. LCI data and assumptions for trucking and ocean freight transportation are shown in Table S4 of the Supporting Information.

Part Manufacturing—Multi Jet Fusion 3D Printing. LCI data for the MJF part manufacturing process depict electricity consumption and associated indirect GHG emissions from generation and transmission; data for direct emissions from MJF equipment are not available but are assumed negligible for modeling purposes. Tables S7 and S8 in the Supporting Information show the characteristics of MJF equipment and modeling assumptions used for this unit process.

This study used Autodesk Netfabb 2019 to prepare the build platform CAD file, packing parts inside the build chamber with the software’s automated 3D packing—Monte Carlo tool (see Figure S1 in the Supporting Information). Assuming a scrap rate of 5%, 35 parts are required to produce the functional unit, resulting in a build chamber filled to 31% of volume capacity and a packing density of 8.2%. The maximum number of parts that could be packed in the chamber is 108. Sensitivity analyses explore the variance in LCA results from a scenario with a 100% full build chamber and another scenario with more densely packed parts based on the recommended packing density range of 8–12%.\(^4\)\(^\text{7}\) Part production quantities greater than 108 were calculated by determining the number of maximum builds that could be completed and allocating remaining parts to a partial build. Tables S5 and S6 in the Supporting Information provide additional details associated with selected part production quantities from 33 to 100,000 parts.

Powder Mixing and Loading. Energy consumption for the powder mixing and loading step is calculated based on idle time, idle power, mixing and loading time, and processing station power.

MJF 3D Printing. Energy consumption for 3D printing is calculated based on idle time, idle power, build volume, printing speed, and printing power. Energy intensity is expected to vary over the duration of a print job based on packing density, printing speed, and other printer parameters. The energy profile of the 3D printer was not available, but based on communications with the manufacturer, this study models the power consumption for the 3D printer using a constant 0.3 kW for idle status and constant 8.525 kW.\(^4\)\(^\text{48}\) Considering the typical power consumption of 9–11 kW for the 3D printer stated on the equipment datasheet, sensitivity analyses explore the variance in LCA results when using 11 kW for power consumption.

Cooling and Unpacking. Due to the lack of power profile data for the processing station, electricity consumption data for cooling and unpacking were assumed to be the same as powder loading and mixing. Based on discussions with the manufacturer, this study assumed that the processing station recovers 97.6% of excess powder during unpacking.\(^4\)\(^\text{48}\) The remaining powder is unusable and requires post-processing for removal, typically amounting to 10% of the part mass.\(^4\)\(^\text{39}\) Telenko and Seepersad\(^4\)\(^\text{40}\) also report a 10% excess powder loss in the equivalent step of the SLS process. The modeled part scrap rate and power loss assumptions result in a projected PA12 material yield of 85.8% for the MJF process.

Post-Processing. This study assumed 1 min of compressed air bead blasting per LCD controller front cover for post-processing based on a case study by PostProcess Technologies Inc., resulting in 0.166 kWh of electricity consumption per part using the parameters and equation shown in Section S4.4 of the Supporting Information.\(^4\)\(^\text{50}\)

RESULTS AND DISCUSSION

Cradle-to-Gate Impact. Modeled MJF production of 1 kg of PA12 LCD controller front covers results in a potential cradle-to-gate life cycle impact of 803 MJ and 46 kg CO\(_2\) equivalent emissions. The modeled site energy consumption of the MJF part manufacturing life cycle unit process, including post-processing, was 177 MJ/kg. However, previous studies of specific energy consumption (SEC) for SLS did not account...
for energy consumed during cooling, unpacking, and post-processing. Excluding these steps for the MJF process results in a modeled SEC of 98.7 MJ/kg, which is slightly lower than the range of SLS SECs noted in previous studies and 25% lower than the median reported value. Table S9 in the Supporting Information provides additional data on the SEC value for each step of the MJF part manufacturing process.

Figure 5 shows the relative contribution of each life cycle unit process to cradle-to-gate GHG emissions. The dominant impact for the MJF process is the part manufacturing process. Powder loading and mixing, MJF 3D printing, fast cooling, unpacking, and post-processing account for 59.8% of the cradle-to-gate GHG emissions for the system. In particular, electricity consumption from MJF 3D printing is responsible for 33% of total cradle-to-gate GHG emissions. The second highest contribution to GHG emissions for the MJF process results from PA12 production with 39.3% of the overall impact. Together, the fusing and detailing agent production and transportation, and PA12 transportation accounted for less than 1% of the overall product system GHG emissions.

The relative contributions of each life cycle unit process to the overall cradle-to-gate primary energy consumption differ slightly from their contributions to cradle-to-gate GHG emissions. PA12 production is the dominant contributor to cradle-to-gate primary energy consumption, accounting for 50.1% of the energy consumed. MJF part manufacturing accounts for 49.0% of cradle-to-gate energy consumption. The higher impact of PA12 production to energy consumption is likely the result of PA12 material feedstock energy. For example, feedstock energy contributes approximately 30% to the cradle-to-gate primary energy consumption for PA6 production. Additional data depicting the cradle-to-gate primary energy consumption for PA12 product during the PA12 production unit process, resulting in higher amounts of indirect GHG emissions from increased PA12 production requirements for SLS. Although MJF requires a fusing agent and detailing agent not used in SLS, PA12 production requirements for SLS. Although MJF requires a fusing agent and detailing agent not used in SLS, the estimated embodied energy for PA12 is slightly lower than SLS.2,52 Furthermore, the projected 85.8% PA12 material yield suggests a higher resource efficiency for MJF in comparison to SLS.39 Considering the 45% powder waste material rate from Kellens et al. and a conservative estimate for PA12 embodied energy of 129.1 MJ/kg, SLS would consume 84 MJ more energy than MJF per kg of PA12 product during the PA12 production unit process, resulting in higher amounts of indirect GHG emissions from increased PA12 production requirements for SLS. Although MJF requires a fusing agent and detailing agent not used in SLS, these consumables only amount to 5.8 MJ per kg of the final product. These modeled energy and resource efficiency results indicate that the overall GHG emission burden of MJF is lower than SLS.

Environmental Performance Relative to Conventional Manufacturing. The modeled primary energy consumption and GHG emissions for the MJF process differ significantly from high-volume production conventional manufacturing methods for plastics, such as injection molding. For example, existing literature reports that the injection molding unit process results in an electricity consumption of 1.79 kWh/kg, which is equivalent to 1 kg CO₂ equivalent emissions per kg of the plastic product based on conversion with the GREET 2019 RFC grid mix, 2020 simulation.18,24 In contrast, the modeled GHG emissions for the MJF part manufacturing unit process were 27.4 kg CO₂ equivalent emissions per kg of PA12 product. Moreover, injection molding demonstrates a material yield of 96.7%, requiring 11.3% less PA12 material to produce the same part mass as modeled for MJF in this study. However, the injection
molding process requires the production of tooling specific to the plastic product. Mold plate production for injection molding of the LCD controller front cover design could result in 244–460 kg CO₂ equivalent emissions, depending on the use of aluminum or steel tooling.²⁸ MJF part manufacturing unit process GHG emissions would break even with mold plate production emissions after approximately 4–7 print jobs, or 12–21 kg of PA12 (400–700 LCD controller front cover parts), as shown in Figure S5 in the Supporting Information. This relatively low-quantity break even point is consistent with previous studies that compared SLS to injection molding.²⁰,²¹ Other aspects of an injection molding product system could increase this GHG emission break even point further, such as the emission burdens from mold plate transportation and machining of the mold. However, a comparative LCA of the injection molding process for the LCD controller front cover part design is beyond the scope of this study.

Variable Sensitivity Implications. Results from the sensitivity analyses show that changes to several parameters can significantly influence MJF GHG emissions. These parameters provide a basis for estimating GHG emissions per kilogram of PA12 product for a given design, packing density, and build height. Based on the sensitivity analyses, comparisons between MJF and other forms of manufacturing could vary significantly based on the source of electricity for the manufacturing facility, the amount of time spent air/bead blasting, the LCI data used for PA12 production, and the printing speed. These four variables set to the optimum condition for MJF could potentially shift the cradle-to-gate GHG emissions of the functional unit to 8.29 kg CO₂ equivalent.

Implications on Manufacturing and Part Design Decisions. The results of this study demonstrate that the environmental impact of manufacturing with MJF depends on the application and production volume scenario. If a product requires additive manufacturing with MJF or SLS due to design features and properties afforded by powder-bed fusion technologies, MJF will likely result in lower GHG emissions than SLS. In the case that other additive manufacturing methods could be suitable for the product, further analyses would be required to account for the differences in technology processes, material types, and product systems. In cases where MJF is applied to an injection molding-capable part, MJF may result in lower GHG emissions for low production volumes of parts. However, MJF is very likely to cause significantly more indirect GHG emissions than injection molding for large production volumes, unless carbon-free electricity is used for MJF.

Smaller parts and a higher packing density could potentially result in lower emissions per kilogram of PA12 product for MJF, which might extend the GHG emission break even point with injection molding to quantities ranging into the thousands.²¹,²⁸ Different part designs change the outcome of the GHG emissions based on their ability to be packed into the build chamber with a lower or higher packing density. Part designs that allow nesting could increase the packing density and result in a lower ratio of energy consumption to parts produced, and vice versa.²¹ However, the emission burdens of mold plate production, transportation, and machining for injection molding are unlikely to accommodate tens or hundreds of thousands of parts produced by MJF at a lower emission impact. This finding implies that the mass production of injection molding-capable parts with MJF runs counter to climate change mitigation efforts.

Although the mass production of injection molding-capable parts with MJF may produce significantly higher GHG emissions than injection molding, the design capabilities of MJF and other additive manufacturing technologies permit the production of parts that could not otherwise be manufactured with injection molding. In such cases, no GHG emission break even point may exist unless an alternate injection molding-capable design (perhaps comprising several injection-moldable components) could be substituted for the original part design. However, a substitute injection molding-capable design may still be warranted for mass production from an environmental perspective, given the relatively high energy and material consumption associated with MJF. For example, emissions from the post-processing step of 5000 LCD controller front covers would exceed the emissions from the production of injection molding tooling. For MJF to outperform injection molding from a cradle-to-gate GHG emission standpoint in a mass production setting, the environmental benefits of the part—designed specifically for additive manufacturing—must counter the excess energy and material consumption of the MJF part manufacturing process relative to the injection molding unit process. This requirement could potentially be met by the greater design freedom associated with additive manufacturing, which may facilitate part light-weighting, improved product performance, or consolidation of multiple components into a single part.²⁴

Limitations. This study did not validate part quality or processing times based on the simulated parameters for the MJF process. The electricity and material consumption data and assumptions used in this study for MJF were also not experimentally confirmed. Similarly, direct process emissions for the MJF process were not investigated.

Recommendations for Future Research. The difference between PA6 and PA12 LCI data results in disparate outcomes for MJF cradle-to-gate GHG emissions. Considering the prominent use of PA12 material in additive manufacturing and the rapid growth of the industry, LCI data for PA12 production should be made publicly available. An accurate electricity consumption profile for both the MJF printer and processing station should be described to provide an understanding of energy use fluctuations over the course of powder loading and mixing, printing, fast cooling, and unpacking. Likewise, the material yield of the MJF process should be validated across different part designs and volumes. Direct emissions of the MJF process should also be examined. Finally, future research should investigate the environmental impact of different post-processing methods applied to a variety of part designs. Although most additively manufactured parts require some form of post-processing, no LCI data exist on these processes.²⁴,²⁵

CONCLUSIONS

This study provided a cradle-to-gate life cycle assessment of primary energy consumption and GHG emissions for MJF. The LCI data, build configuration, and process variables explored in this study provide a basis for estimating MJF energy consumption and GHG emissions per kilogram of PA12 product for a given design. Based on the 3D printing parameter settings applied in this study, the modeled SEC for MJF is lower than the median reported SEC value for SLS. Moreover, the modeled powder loss and scrap rate resulted in
a material yield much higher than SLS, indicating that MJF generates an overall lower environmental burden than its peer technology.

This LCA also identified that MJF may consume less energy and result in fewer GHG emissions than injection molding for low production volumes until reaching a GHG emission breakeven point associated with the environmental burden of mold plate production, transportation, and machining. This breakeven point could fluctuate significantly based on the electricity generation source, post-processing time, PA12 production emission intensity, and printing speed. Beyond this breakeven point, MJF would result in significantly higher indirect GHG emissions than injection molding.

Based on this study, the positive or negative impact of MJF’s increasing adoption depends on how the technology is applied within the plastic product manufacturing industry. Use of MJF for high-volume product manufacturing where injection molding is possible will likely be detrimental to climate change mitigation efforts until electricity systems are decarbonized. In contrast, the application of MJF based on required product design features and properties as an alternative to SLS will likely result in a net-positive impact for climate change mitigation by reducing GHG emission generation and material consumption. Still, the energy consumption associated with MJF would result in significantly higher GHG emissions per kilogram of plastic products manufactured relative to emissions caused by injection molding. In such cases where additive manufacturing and high-volume production is required, sustainability benefits of additive manufacturing across the life cycle, such as part consolidation or light-weighting, should be emphasized in the product design stage to reduce GHG emissions.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.0c04845.

• Literature review data; LCI data, assumptions, and calculation methods for each life cycle unit process; descriptions of MJF part manufacturing steps; and additional LCA results data

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Author Contributions

The manuscript was written through the contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare the following competing financial interest(s): Mr. London worked at HP Inc. in the summer of 2019, prior to conducting this research and authoring this paper, and will return to work for the company in July 2020. Dr. Lewis and Dr. Keoleian declare no competing financial interest.

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ABBREVIATIONS USED

LCA, life cycle assessment; LCI, life cycle inventory; GHG, greenhouse gas emissions; MJF, multi jet fusion

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