

Life Cycle Assessment of 3D Printed Products in a Distributed Manufacturing System

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Summary

Motivated by the rising costs of doing business overseas and the rise and implementation of digital technologies in production, new strategies are being explored to bring production and demand closer. While concepts like cloud computing, internet of things, and digital manufacturing increasingly gain relevance within the production activities of manufacturing companies, significant advances in three-dimensional (3D) printing technologies offer the possibility for companies to accelerate product development and to consider new supply chain models. Under this production scheme, material supply chains are redefined and energy consumption hotspots are relocated throughout the life cycle of a product. This implies a diversification of energy mixes and raw material sources that poses a risk of shifting problems between life cycle phases and areas of protection. This study compares a conventional mass scale centralized manufacturing system against a 3D printing-supported distributed manufacturing system on the basis of the production of one frame for eyeglasses using the life cycle assessment methodology. The study indicates clearly that the optimization potential is concentrated mainly in the energy consumption at the unit process level and exposes a close link to the printing material employed.

Introduction

The provision of goods to meet customer needs is one of the most important drivers for economic development worldwide. Manufacturing, as the activity through which material is transformed into usable products, contributes to a large portion of global employment. By 2014, manufacturing represented, on average, 15% of the gross domestic product (GDP) in Organization for Economic Cooperation and Development (OECD) members, 10% in non-OECD, and more than 30% for the case of China and Korea (World Bank 2016).

Manufacturing is responsible of a large share of the global environmental impacts as it requires energy and materials within its production processes and releases significant amounts of emissions and waste (Dufloy et al. 2012). As reported by Gutowski and colleagues (2013), the global amount of carbon emissions per capita from industry reached 900 kilograms (kg) of greenhouse gas (GHG) emissions per capita in 2010. Moreover, the international division of labor in manufacturing imposes global environmental challenges due to the amount of energy consumption and GHG emissions by the different transportation modes involved (e.g., truck, rail, air, or ship). Freight

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transportation was found to consume 45% of the total transport energy in 2009 (Edenhofer et al. 2014).

Manufacturing has focused, since the last century, on mass production models to raise productivity. Mass-produced goods are characterized by having low or no customer-specific attributes and components, which allow to assemble products faster therefore reducing production costs and increasing production rates.

The demand for a larger product variety coupled with a reduction of the product life cycles propelled the emergence of the mass customization manufacturing paradigm (Mourtzis and Doukas 2012). Mass customization regards the production of goods which considers the specific needs of customers while meeting large-scale production demands (Matt et al. 2015; Coletti and Aichner 2011).

Distributed Manufacturing Systems and Additive Manufacturing

Aiming at increasing the degree of personalization in production, the concept of distributed manufacturing can be seen as a conceptual shift away from the conventional mass production systems (Kohtala 2015). Distributed manufacturing systems (DMSs) are, in general, enthusiastically presented as implying several advantages compared to a conventional centralized manufacturing system (CMS). Research from Rauch and colleagues, for instance, presents a qualitative comparison between a CMS and a DMS (Rauch et al. 2016). As argued, DMS could potentially reduce pollution through the reduction of global transport whereas CMS is characterized by implying high global flows of goods and materials, which, in turn, results in “. . . high pollution and waste of energy” due to global transportation (Rauch et al. 2016, 131). DMSs place production closer to the point of sale and give the customer a higher freedom to influence the design and production process of the product (Rauch et al. 2016). In a DMS, the supply chain can be simplified and partly substituted by a regional pool of manufacturing resources working connected in a cloud-based manufacturing system (Wu et al. 2014; Rauch et al. 2016). Integrated in this cloud-based manufacturing system are also services like the product design process (Matt et al. 2015; Wu et al. 2014). In DMS, the unit process level and production line are predominantly supported by additive manufacturing (AM). AM is defined as “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining” (ASTM Standard 2012, 2). AM technologies produce parts by continuously forming layers of an object through depositing material (Gao et al. 2015). These technologies can be classified in three different categories defined by the condition of the material at the input side. These are powder based, solid based, and liquid based. This categorization has been already explained in detail in Gibson and colleagues (2015) and standardized by the Additive Manufacturing Technology Standards (ASTM) committee on AM, as reported by Mani and colleagues (Mani et al.

2014). The most frequently used additive processes are stereolithography, selective laser sintering (SLS), digital light processing, fused deposition modeling (FDM), and selective laser melting (SLM). These processes are also commonly referred to as three-dimensional (3D) printing. In this paper, the analysis is focused on FDM techniques. The development of inexpensive 3D printing hardware equipped the consumers with tools that allow them to influence product innovation and manufacturing processes. Open source and affordable commercial 3D printers supported by social media and crowd sourcing data networks increasingly blend enabling consumers to produce (Wittbrodt et al. 2013). In 2014, the total volume of the market for AM is estimated to be more than US\$4 billion (Wohlers and Caffrey 2015). However, with a forecast of rapid growth in the near future and the maturing technology, 3D printing will most probably account for a significant product output and thus also for a significant environmental impact. With the rise of AM, DMSs are expected to have an impact on environmental sustainability (Ford and Despeisse 2016; Kohtala 2015) as it not only redefines material supply logistics, but also implies the appearance of new business models (Rauch et al. 2016), product development processes, and production processes. Particularly if driven by AM processes, DMS will lead to a relocation of energy consumption hotspots throughout the life cycle of a product that would diversify the mix of energy being embodied in products. Moreover, as DMS allows a more active participation of consumers within the manufacturing process of products, drastic changes in quality can occur, which have effects on energy and material consumption. 3D printed products often require postprocessing operations (Gao et al. 2015). From a technical perspective, built-in support material (i.e., raft) must be separated from the object printed. Different processing steps, such as washing, scrubbing, peeling, and cutting, are usually performed for this matter (Gao et al. 2015). In addition, from an aesthetic point of view, several processing steps might be necessary to achieve a smooth surface finish. Polishing, sanding, chemical processing, and painting steps might follow the printing process, if necessary (Kietzmann et al. 2014). However, products can be found in the market where the surface quality shows that the product is produced with 3D printing and the relative low surface quality is used as an aesthetic element of the design. In this regard, the small batch size in 3D printing and the high degree of personalization of the product should be considered. However, the amount and type of postprocessing necessary to provide the object with a specific finish, dimension, look, or even material properties basically depends on the 3D printing technology used, the process parameters (Prasad et al. 2014), and the product’s purpose (Conner et al. 2014). For FDM, suitable postprocessing technologies can be divided into additive (e.g., adding a nano-filler to the surface [Gajdoš et al. 2015]), subtractive (e.g., computer numerical control [CNC] machining [Boschetto et al. 2016]), or chemical (e.g., treatment with acetone solution [Galantucci et al. 2009]) processes. The specific energy demand and environmental impact of postprocessing strongly depend on the utilized technologies.

Environmental Aspects of Three-Dimensional Printed Products in a Distributed Manufacturing System

Much of the research done toward understanding how AM can contribute to a more sustainable development departs from three arguments, as discussed by Ford and Despeisse (Ford and Despeisse 2016): (1) It provides opportunities to improve resource efficiency allowing the redesign of both products and processes to minimize in-house waste; (2) it extends product life cycle through technical approaches and a stronger person-product relationship; and (3) it simplifies value chains by reducing logistic complexity and placing production closer to the consumer. Work from Gebler and colleagues found that the implementation of AM might allow reducing energy and carbon dioxide (CO₂) emissions intensities on about 5% by 2025 (Gebler et al. 2014). The implications on the environment of AM technologies from a unit process perspective is usually analyzed by three different indicators: material yield, direct energy consumption, and emissions. Research from Stephens and colleagues found FDM 3D printers to emit ultra-fine particles to their direct environment (Stephens et al. 2013), suggesting that the type and volume of emissions are directly linked to the employed build material. As they found, polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) can be classified as being high “emitters,” although ABS thermoplastic presented a much higher rate of emissions compared to PLA. Research from Baumers and colleagues (2011, 2013) proposes a methodology to consistently measure energy consumption in additive manufacturing processes. Research by Kellens and colleagues (2014) provides a model to estimate the environmental impact of SLS processes based on different design features of products. Research from Chen and colleagues (2015) and Huang and colleagues (2015) presented a comparison of direct digital manufacturing processes against several traditional manufacturing systems. Research by Yoon and colleagues (2014) presents a comprehensive comparison of specific energy consumption for bulk forming subtractive and additive processes. As summarized in their research, while the specific energy consumption in injection molding processes ranges within the literature between 0.11 and 5.82 kilowatt-hours (kWh)/kg, AM processes (specifically FDM processes) have been reported to have a specific energy consumption ranging between 23 kWh/kg up to very high values of even 346.4 kWh/kg as referring to research by Luo and colleagues (1999). As argued by Chen and colleagues (2015), while 3D printing technologies demand, in general, less power than conventional manufacturing processes (e.g., injection molding), energy consumption is primarily driven by the processing time resulting in a higher product energy embodiment. In their research, they provided an analysis of energy use and material yield for different additive processes. Particularly in the field of AM, life cycle assessment (LCA) studies are still scarce. The research from Kreiger and colleagues (Kreiger et al. 2014; Kreiger and Pearce 2013) present an LCA-based comparison of different 3D printed and mass-scale produced plastic products and an LCA analysis for the recycling of

postconsumer plastic to produce AM filament. Research from Serres and colleagues (2011) compares the environmental impact of AM processes through the application of an LCA against a traditional milling process performed by a CNC machine. Meteyer and colleagues (2014) provide a model to assess the amount of energy and material consumed at a unit process level for a binder-jetting process. A similar research presents a predictive model to estimate consumption of resources during the printing phase (Le Bourhis et al. 2014). Other research from Faludi and colleagues (2015) present an LCA-based comparison of AM and CNC machining for prototyping purposes. Applying the LCA methodology, they compared the production of two parts made of ABS using three different technologies (CNC and two AM machines). Applying each of the technologies, they analyzed the impact of producing two different parts, one with a higher degree of complexity (including some curvatures) and one simpler part using traditional machining. They found that the consumption of electricity is always the main driver of environmental impacts in the AM processes. As they conclude, the environmental impacts of prototyping activities are, not surprisingly, decreased with higher utilization rates for both technologies. In their study, they identified the FDM machine to be the one with the lowest environmental impact per job for (both for high and low utilization rates). Regarding the application of AM for the decentralization of production activities, Khajavi and colleagues present a technical evaluation of the potential impact of introducing AM within a supply-chain configuration for spare parts (Khajavi et al. 2014). Some approaches exist to evaluate technically and economically the effect of applying AM to decentralize manufacturing activities (Durão et al. 2016; Khajavi et al. 2014). However, no comprehensive study trying to assess the environmental impacts of a product manufactured in a decentralized manufacturing system employing AM compared to its centralized counterpart exists. To contribute to the knowledge regarding the environmental dimension of DMS, this paper aims at comparing the environmental impact of one 3D printed product produced under a DMS and a conventional equivalent product manufactured in a CMS.

Method

The LCA methodology was used to estimate the potential environmental implication of the systems under study. In our study, a cradle-to-grave attributional LCA was performed. The goal of the study is to assess the potential environmental impact of a good manufactured in a DMS compared to a product produced in a CMS.

The study uses eyeglasses frames (figure 1) as the exemplary product as eyeglasses are very common and widespread goods highly influenced by fashion trends, so the demand for each specific frame design is low in quantity, which makes it suitable to be manufactured in a DMS. The functional unit of this study is the provision of one eyeglass frame at the point of sale. Printing parameters were investigated to achieve an equivalent

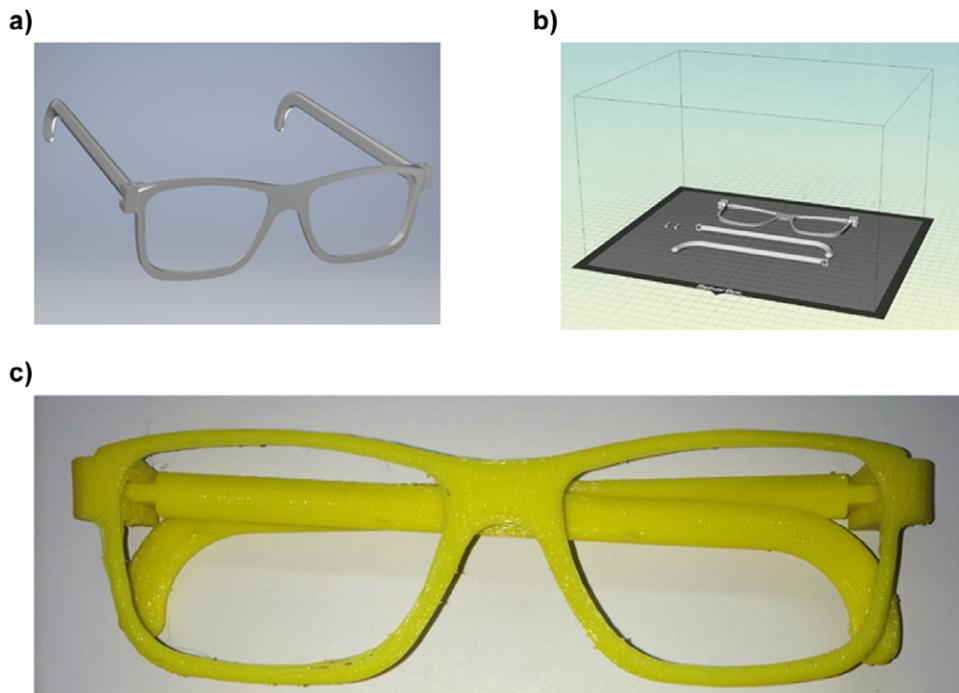


Figure 1 Printed product. (a) Assembly perspective. (b) Makerbot printing model. (c) Printed eyeglass frames.

product quality, and therefore we assume that a typical eyeglass frame is used for around 3 years in both cases. A sensitivity analysis to assess the influence of different printing qualities was performed in order to investigate the effect of differences in the printing process specifically on the life cycle environmental impact of the 3D printed product.

The study considers eight different environmental impact categories: climate change (GWP); acidification potential (APO); depletion of abiotic resources potential (ADP); marine aquatic eco-toxicity potential (MAETP); human toxicity potential (HTP); eutrophication potential, freshwater aquatic eco-toxicity potential (FAETP); and terrestrial eco-toxicity potential (TEP). The characterization of elementary flows was done using the methodology CML 2001 (Guinée 2002). ecoinvent 3.0 (ecoinvent Center 2015) was used as the database for the background data. The systems were modeled in the software Umberto (ifu Hamburg GmbH 2015).

Systems Definition and Life Cycle Inventory

A summary of the life cycle inventory as well as a product tree diagram with the respective system boundaries are included in the supporting information S1 available on the Journal's website. Six locations are considered set in different regions of the world where the product is sold to the customer. These locations are India, Australia, Russia, the United States, Japan, and Mexico. Figure 2 shows a description of the fictitious scenarios modeled for this study. Each of the scenarios was modeled by considering local electricity mixes and transportation distances, and we assumed that the production process is the same in every different location.

For the CMS, one production site placed in the City of Guangzhou, P.R. China was modeled. From this factory, the conventional eyeglass frames are delivered to the points of sale (as indicated in figure 1). The process chain includes raw material production, product manufacturing, distribution (whole sale), and the customer (use phase). The frame itself consists of a cellulose acetate and two stainless steel screws connecting the front piece with the temples. We modeled the production of cellulose acetate based on two patents patent (Kuo and Bogan 1997; Frank and Malthaner 1994) as shown in supporting information S1 on the Web. The amount of acetic anhydride and acetic acid required was varied and included in the sensitivity analysis as they were found to vary between the different formulations in the patents. After the production of the cellulose fibers from different raw materials, these cellulose acetate fibers are extruded to make cellulose acetate sheets of desired thickness (we have assumed 4 millimeters [mm] for this case study). Cradle-to-gate energy required to produce cellulose acetate sheets has been reported to range between 23.5 and 26 kWh/kg (Granta Design Limited 2013). These sheets are injection molded and after machined to make the frame front and two end pieces of the specified dimensions. The rest of the cellulose sheet is discarded. The waste was estimated to be 25.2 grams (g). Energy for injection molding for cellulose acetate is reported to range between 5.15 and 5.6 kWh/kg (Granta Design Limited 2013). We have performed measurements using the injection molding machine model Victory Spex 120 from the manufacturer Engel and found that approximately after 50 parts the energy consumed converged to 7 kWh/kg. This dimension is also supported by Spiering and colleagues (2015), further stating that the specific energy for the injection

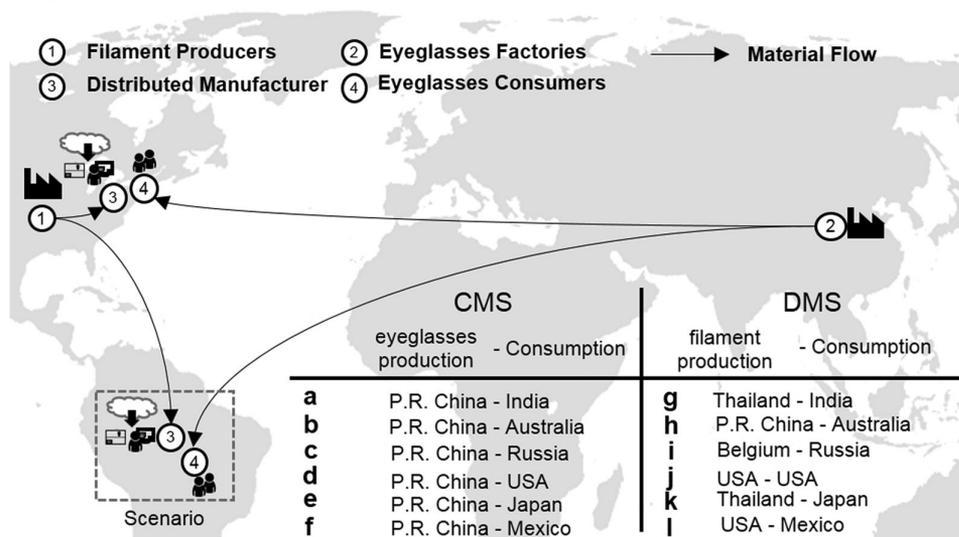


Figure 2 Description of the scenarios considered. In the figure, a, b, c, d, e, and f are the scenarios for the conventional manufacturing system and g, h, i, j, k, and l are the scenarios for the distributed manufacturing system. In the study, analogous systems are directly compared for example a vs. g represents a scenario where a pair of eyeglass frames is to be used in India. CMS = centralized manufacturing system; DMS = distributed manufacturing system.

molding process is linked to the product weight per cycle. Once all the primary components, that is, frame front with hinges, end pieces with hinges, and screws are ready, the eyeglasses frame is assembled manually. The final weight of the eyeglass frame, including hinges and screws, goes to about 30 g out of which approximately 0.045 g is the weight of the hinges and the screw and the rest is the cellulose acetate. For this system, the study does not consider the production and disposal of the infrastructure required for the production. Explicitly, the analysis did not include production of machines nor their transportation and maintenance. Research by Telenko and colleagues (Telenko and Seepersad 1997) compared the energy use of injection molding and SLS. The energy used to manufacture the tooling required (e.g., molds) for injection molding was found to represent a significant share of the energy embodied to a part. As they estimated, the production of the steel mold required for the injection molding process accounted for over 75% of the energy required to manufacture a batch of 50 parts using SLS. For this paper, however, we did not consider the production of the tooling as we assume the lifetime of the mold to be long enough to diminish the effect on a per-part basis. As reported in Ullmer (2014), mold life cycles range from 500,000 to 2 million cycles. Within the described system, the frame is not produced to order, but sent to a retail store where a part of the stock remains unsold. As reported by Shen and Li (2015), in the case of the fashion industry, retailers may hold between 25% and 40% of unsold products at the end of the selling season. Although it can be argued that the unsold product might find a market after the main selling season is over, we consider, however, that this market does not influence the demand of the new model. Regarding the end-of-life (EoL) phase, we assumed that there is no difference in the type of treatment independently of whether the unsold product finds a new market or is directly disposed for

incineration. We assume that, in the case the unsold products find a new market after the selling season, the product would be sooner or later discarded, but this does not affect the type of EoL treatment modeled. A sensitivity analysis was performed to investigate the contribution of unsold eyeglass frames to the environmental impact of a sold pair as this has been often identified as one of the main advantages of a DMS compared to a CMS. We varied the amount of unsold product from 10% to 50% and reported the results as a best- and worst-case scenario.

For the DMS, we modeled the AM process from a desktop 3D printer directly placed at the points of sale. PLA filament was selected as the material to be deposited. Different studies have analyzed the environmental impact of the production of PLA on a cradle-to-gate perspective. Vink and colleagues (2003) and more recently Guo and Crittenden (2011) estimated the energy required to produce 1 kg of PLA granules to move around 14 to 17 kWh/kg. The work from Vink and colleagues refers to data from the NatureWorks[®] manufacturing plant, which served to create the data set for the production of PLA inecoinvent. The synthesis of raw PLA, and the subsequent transformation into filament, was included into the analysis. PLA granules are converted into filament through an extrusion process using filament extruders. Commercial extrusion machines have a capacity ranging from 3 to 15 kg of filament per hour with a power rating of 11 kilowatts (Stieben 2015). In our study, we assumed a production of 15 kg per hour and calculated a total of 1 kWh per kg of filament. We have assumed that there is no material waste during the extrusion process as the scrap from an extrusion process is normally reinserted in the process. Once made, the filament is rolled on a spool, which consists of different material and comes in various sizes according to the machines they are to be used in. We consider the reel that holds the filament to be made of polypropylene (PP) by injection molding and made

Table 1 Experimental results for frame printing

| No. | Printing parameters | | Product properties | | | |
|-----|---------------------|------------|--------------------|--------------------------|---------------------|------------------------------|
| | Layer height [mm] | Infill [%] | Weight [g] | Energy consumption [kWh] | Printing time [min] | Sufficient strength [yes/no] |
| 1 | 0.1 | 55 | 16.6 | 0.289 | 271 | Yes |
| 2 | 0.3 | 10 | 12.2 | 0.118 | 101 | No |
| 3 | 0.2 | 10 | 12.7 | 0.147 | 137 | No |
| 4 | 0.2 | 55 | 14.5 | 0.164 | 165 | Yes |
| 5 | 0.1 | 10 | 13.6 | 0.241 | 228 | No |
| 6 | 0.1 | 100 | 19.7 | 0.327 | 307 | Yes |
| 7 | 0.3 | 100 | 17.2 | 0.132 | 124 | No |
| 8 | 0.2 | 100 | 17.7 | 0.169 | 164 | Yes |
| 9 | 0.2 | 55 | 14.5 | 0.162 | 166 | Yes |
| 10 | 0.2 | 55 | 14.5 | 0.164 | 157 | Yes |
| 11 | 0.2 | 55 | 14.5 | 0.167 | 171 | Yes |
| 12 | 0.3 | 55 | 14.3 | 0.132 | 107 | No |
| 13 | 0.2 | 55 | 14.4 | 0.165 | 166 | Yes |

Note: mm = millimeters; g = grams; kWh = kilowatt-hours.

at the same site where the filament is being extruded. Cradle-to-gate energy required to produce PP has been estimated to be range around 17 to 22 kWh (Guo and Crittenden 2011; Vink et al. 2003). The weight of an average reel that carries around 900 g of filament is approximately 200 g. For the production of the filament, five different production sites were modeled considering the current global filament industrial production hubs, namely Escanaffles (Belgium), Nebraska (USA), Rayong (Thailand), and Taizhou (P.R. China). The transportation of the filament to the place of printing was defined based on proximity, that is, we assumed that the filament is imported from the closest factory and other factors like price or market presence were not considered. All prints were performed on a Replicator 5th Generation FDM 3D printer by MakerBot Industries, LLC. As summarized in table 1, for the characterization of the printing process, we performed several experimental prints to find technically complying printing parameters for the product. We varied the layer height and infill and measured energy and material consumed. The layer height describes the resolution of the print in vertical direction in millimeters. A smaller layer height results in higher print resolution and better product quality, but increases printing time and energy consumption. The power demand of the Replicator 3D printer depends on the state of the machine. For the different machine states, we measured an average power demand of 12 watts (W) for idle state, 72 W for set-up state, 75 W in warm-up state, and 71 W in build state. The utilized desktop 3D printer is on the lower end of power demand in the wide range of FDM printers available on the market. Industrial-grade FDM printers have a much higher power demand while being faster in production and producing higher-quality parts. In Yoon and colleagues (2014), a Dimension 768 SST by Stratasys Ltd. was found to have a power demand more than ten times higher than one of our desktop Replicator printers. The energy values given in table 1 are representative for the modeled DMS with desktop 3D printers and can change significantly if other FDM machines are used.

The percentage of material inside the product structure is set by the parameter infill. The higher the infill, the more material is used inside the outer shells of the work piece and thus the printing quality increases as do printing time, material usage, and energy demand. The number of outer shells was set to the value of 3 and infill pattern to hexagonal for all prints. Each set of printing parameters has a strong influence on the build time whereas the time for the idle state (before and after the print), warm-up state, and set-up state (which divides the warm-up state in first and final heating) are printer-specific constants with the total values of 208 seconds (s), 216s and 65s, respectively.

Out of the brief analysis presented in table 1, we defined a best and worst scenario (number 6 and number 4, respectively) which were afterward included in our sensitivity analysis. Although many of the stores offering this service provide the customer with digital images of the eyewear and are able to measure exactly the size in which the frames are required to be printed, some of these companies accept free returns. Nevertheless, as the frames are produced to orders, it was assumed that there is no product that remains unsold. While we understand that this assumption might be biased in favor of the DMS, we made this assumption as our aim is to evaluate both of the systems considering the main characteristics that have been presented in the literature as an environmental advantage when compared against a CMS. The production of supporting material (i.e., raft) was modeled in order to assess the production of plastic waste as a part of the printing process.

The generated waste of the printing process measured ranged from 7.7 g to less than 1 g depending on printing parameters and supporting structures. In the model, waste generation was given a value of 9.2 g per print as this was the value reported after measurements by Protohaus, a FabLab in braunschweig offering professional 3D printing services. Experienced users are found to create less waste than unexperienced users by optimizing the printing parameters according to their gained knowledge. To

gain realistic insights valid for a wide range of experience levels, the modeled value of maximum waste generation is set 20% above the measured value. It was also assumed that no post-processing, such as washing, scrubbing, cutting, or chemical processing, is required after the printing process. On this point, while we do agree that the quality of the product does not really reveal to have a good finishing quality, this seems, however, to be part of a trend among emerging businesses. A fast search on the online catalogues of the companies offering this service was done. In the catalogues, it is common to see eyeglasses frames in which the quality of the surface does not really differ from the product that we were able to print with prices rounding the US\$50 per part. This is not to argue that a “low finishing quality” will be a rule between the different models, but rather to discuss that even without a nice/smooth surface those products seem to have found a market. It is possible to find eyewear glasses with a higher-quality finishing, that is, adding more printing layers of which prices are around US\$300 to US\$500 (Pqeyewear 2017; Protos eyewear 2016; framelapp printed eyewear 2017; Optoid eyewear 2016). For both the DMS and the CMS, an incineration scenario for the discarded unsold eyeglass frames and the postconsumer wasted eyeglass frames was modeled. No EoL credits were accounted for any of the systems, which might be a conservative assumption considering the fact that the amount of waste produced by the CMS is larger than the DMS. The disposal phase of both systems, however, was calculated to have a negligible portion of all the life cycle impact and therefore this was not studied in detail. The routing applications of open street maps (OpenStreetMap 2015) and sea-distances (Sea-distances.org 2015) were used to calculate transportation distances in both the DMS and the CMS. For comparison, the lenses are not included in the modeling as these differ in material, quality, and cost depending on the consumer's specific needs and are not necessarily driven by fashion or a trend. This assumption is discussed further in the paper.

Results and Discussion

This section presents the potential environmental impacts associated to the production of a pair of eyeglasses frame for both of the systems under study. The contribution of each of the life cycle phases to the eight impact categories is presented in figure 2a. The most important processes contributing to the different impact categories are shown in figure 2b. The sensitivity factors identified in the previous section were varied and their influence is represented in figure 3 in terms of best- and worst-case scenarios. The absolute values for each impact categories are included in the supporting information S2 on the Web.

Contribution Analysis and Absolute Impacts

Figure 3 presents the contribution of each of the product life cycle phases defined to the eight impact categories studied and for each of the six scenarios modeled for both of systems.

Figure 4 shows the contribution of the processes to the impact categories being studied for one of the scenarios. The environmental impact in the CMS for all the impact categories is predominantly driven by the production of acetic acid and acetic anhydride represented in the figure in green hues. The production of acetic anhydride, acetic acid, and cellulose is responsible for over 35% of the GWP emissions whereas the production of the frame contributes to around 30% of the emissions. The other seven impact categories are driven mainly by the production of acetic anhydride. It is important to notice that the overall contribution of the transportation phase is relatively small, under 5% in all the categories researched. For the DMS, the total environmental impact is split into two big hotspots. While the printing process contributes to around 60% to 75% of the total impacts for the categories GWP, APO, ADP, MAETP, and HTP, the production of PLA granules is responsible for most of the impacts caused in categories such as eutrophication potential (EP), FAETP, and TEP. As discussed in the section *Systems Definition and Life Cycle Inventory*, the impact of the printing process can be even higher if industry-size production FDM machines are used for the making of the products. While being faster and producing higher-quality parts, the specific energy demand of a Dimension 768 SST is, with 191.3 kWh/kg (Yoon et al. 2014), 15 times higher than the average of 12.71 kWh/kg for the measured desktop 3D printer for the production of one frame with sufficient strength.

Best- and worst-case scenarios for both systems were considered and indicated as upper and lower extremes in the box plot. As described before, in the best-case scenario for the CMS, only 10% of the products remain unsold whereas in the worst-case scenario 50% of the products remain unsold. Particularly sensitive in this regard are FAETP, terrestrial eco-toxicity potential (TETP), and HTP impact categories, which are mainly driven by the production of products such as acid anhydride and acid acetic.

In the DMS, the best- and worst-case scenarios were defined in table 1 (case 4 and 6, respectively) with the calculation results showing significant differences in most of the impact categories. Particularly for GWP, APO, and ADP, changes on the amount of energy demanded during the printing process can imply a duplication of the total environmental impact. For categories driven by the amount of material used like EP, FAETP, and TETP, small differences in the product weight contributed to significant increments on life cycle impacts.

Cradle-to-grave environmental impacts are presented for both production systems in figure 5, and absolute values are provided in the supporting information S2 on the Web. GWP results of the eyeglass frames in the DMS range from 0.18 to 0.62 carbon dioxide equivalent (kg CO₂-eq) throughout the scenarios whereas in the CMS system the amount of emissions ranges from 0.33 to 0.60 kg CO₂-eq. In the case of APO and ADP, the results compared similar as these two categories resulted to be mainly driven by the energy demanded during the printing process. GWP values for the worst-case scenario in the DMS were estimated to range between 0.35 and 0.45 kg CO₂-eq for products printed in Mexico, the United States, Russia,

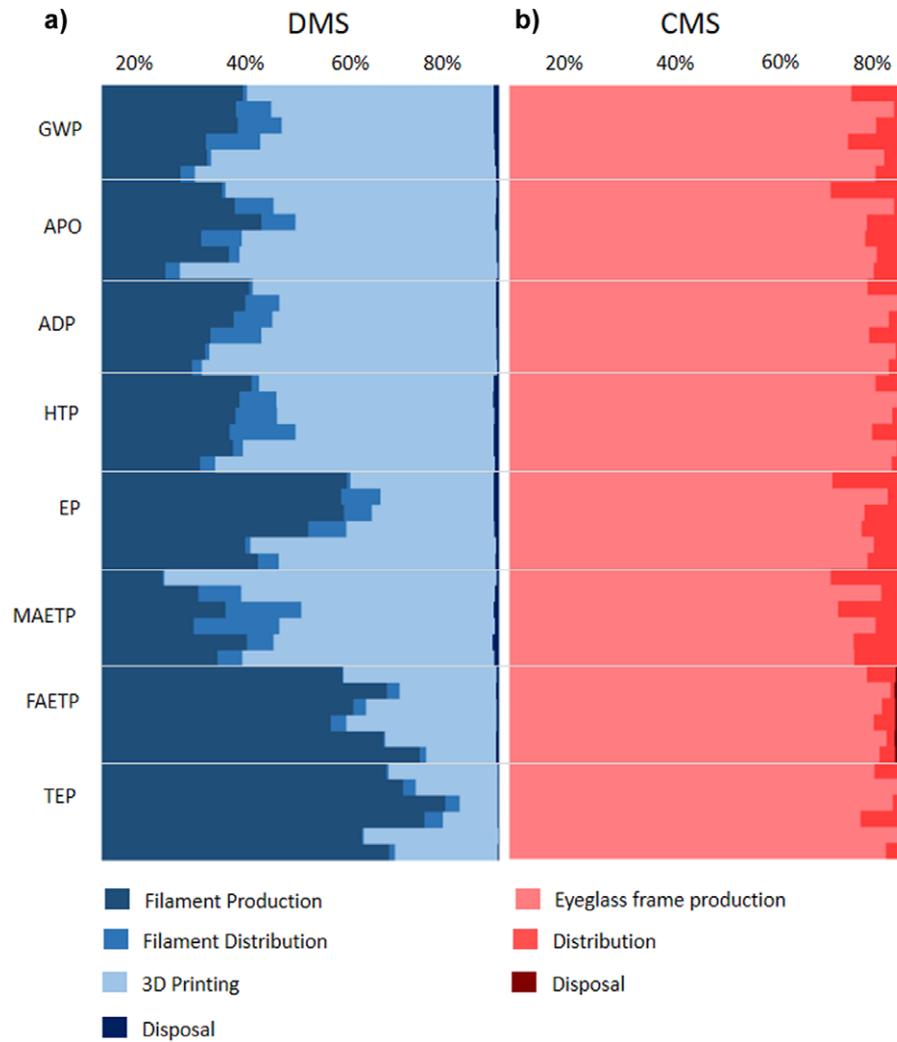


Figure 3 Contribution analysis by phases (a) distributed manufacturing system (DMS) and (b) centralized manufacturing system (CMS). Note: Impact categories: climate change (GWP), acidification potential (APO), depletion of abiotic resources (ADP), marine aquatic eco-toxicity potential (MAETP), human toxicity potential (HTP), eutrophication potential, freshwater aquatic eco-toxicity potential (FAETP), and terrestrial eco-toxicity potential (TEP). 3D = three-dimensional; GWP = global warming potential.

and Japan. For countries like India and Australia, the amount of GHG emissions varies between around 0.30 and 0.65 kg CO₂-eq.

Discussion

In this paper, we aimed at analyzing the environmental impacts of a product manufactured under a distributed manufacturing system. We compared the results against an equivalent product manufactured under a conventional manufacturing system with the assumption that the quality of the printed product would meet that of the mass-produced one. The study shows that CMS and DMS are strongly influenced by the production processes, the amount of material used, and the nature of the material. In a DMS, the production processes, that is, the electricity used during 3D printing, and the amount of material used drive the environmental impact. In the CMS, the

impact is driven by the material. While from the results it cannot be stated whether a DMS presents environmental advantages against a CMS or not, we identified the environmental impact of 3D printed products to depend basically on the following aspects and derived the potential and necessary strategies for beneficial implementation of DMS:

- a. *Energy efficiency*: As seen in figure 2a, printing electricity accounts for around 70% of the overall life cycle GWP, APO, and ADP impact. Improving printing efficiency, that is, minimizing printing time per product while maintaining printing resolution, is, in this regard, relevant. In our case study, to print a pair of eyeglass frames with similar quality than a wearable pair of eyeglasses (number 6 in table 1) we required 5 hours and 7 minutes. As the overhead energy demand for nonvalue creating production times is very low in 3D printing compared

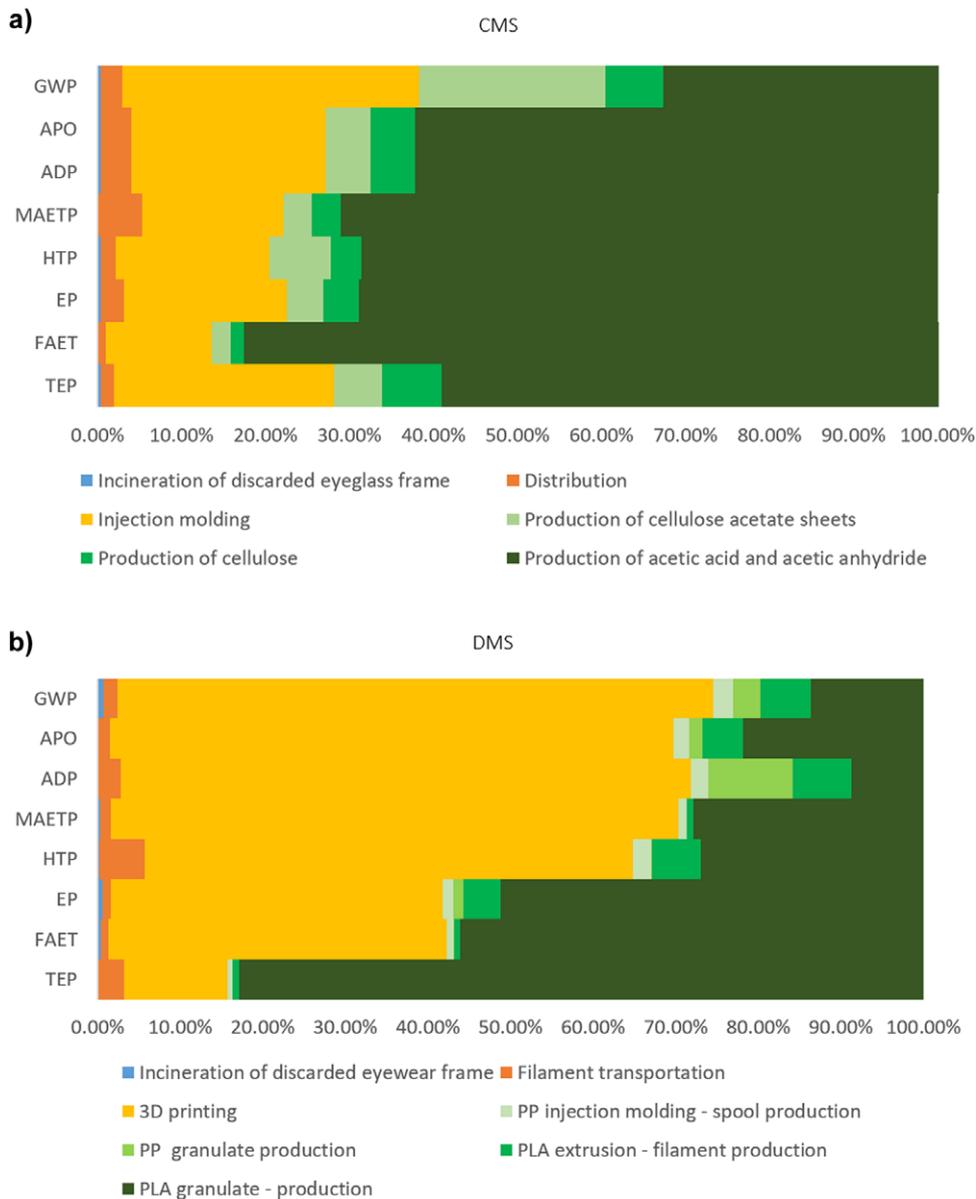


Figure 4 Contribution analysis by processes (a) distributed manufacturing system (DMS) and (b) centralized manufacturing system (CMS). Note: Impact categories: climate change (GWP), acidification potential (APO), depletion of abiotic resources (ADP), marine aquatic eco-toxicity potential (MAETP), human toxicity potential (HTP), eutrophication potential, freshwater aquatic eco-toxicity potential (FAETP), and terrestrial eco-toxicity potential (TEP). GWP = global warming potential.

to conventional manufacturing processes, this technology is generally suitable for low-volume production in DMS. Consequentially, additive manufacturing processes need to become significantly faster through technological improvements. Raising energy efficiency is also an improvement measure in CMS to lower the environmental impact of the production system. As mentioned in the discussion of the energy consumption values for injection molding Spiering and colleagues (2015) suggest measures to raise the energy efficiency of this process. With a lower volume per frame design, the impact of the mold in the CMS is stronger. In this case, the influence of making the

mold should be further investigated, which also includes making the molds with AM technology. For 3D printing and the case of the DMS, the current efficiency potential is expected to be much higher because the AM technology is relatively new and under rapid development.

- b. *The regional electricity mix where the product is printed:* The resulting emissions and consequently the impact categories GWP, APO, and ADP highly depend on the regional electricity mix. Within a CMS, it is a common strategy to place energy-intensive manufacturing at locations where energy is cheap and in the best case comes with a relative low carbon intensity per kWh; for

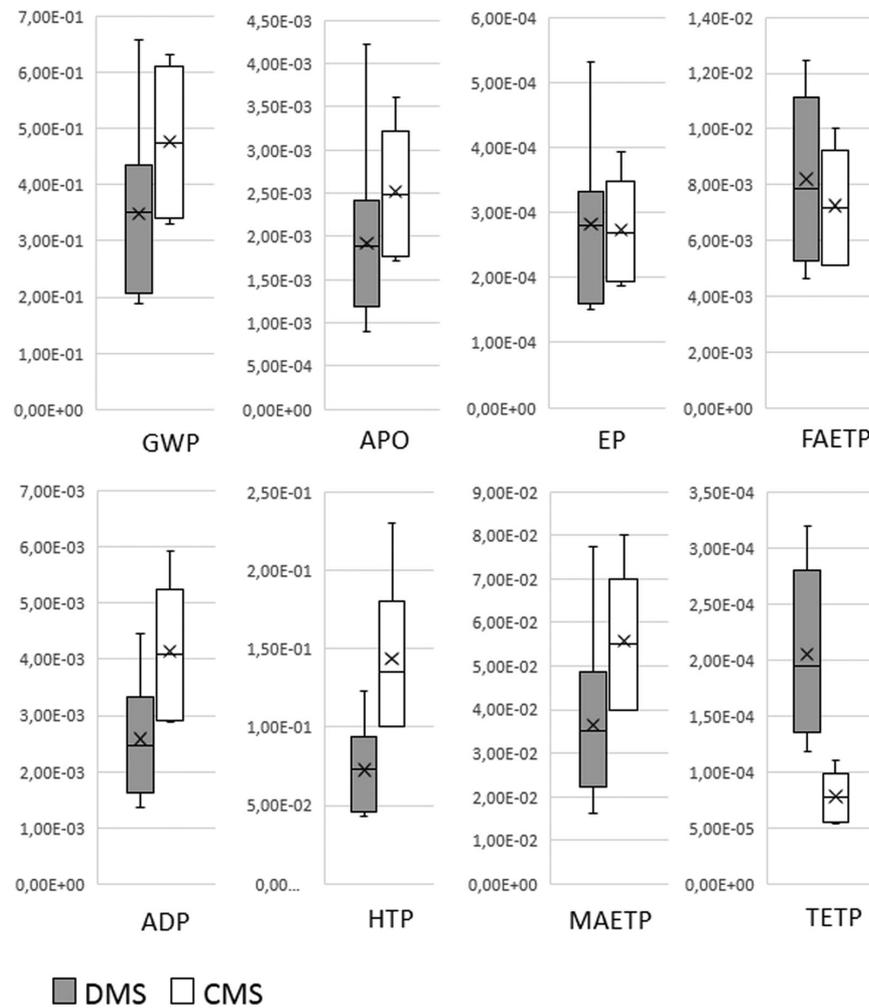


Figure 5 Cradle to Grave Environmental Impacts best/worst case analysis.

Note: GWP = global warming potential, climate change (kg CO₂-eq); APO = acidification potential (kg SO₂-eq); EP = eutrophication potential (kg PO₄-eq); FAETP = freshwater aquatic eco-toxicity potential (kg 1,4-DCB-eq); ADP = depletion of abiotic resources (kg Sb-eq); HTP = human toxicity potential (kg 1,4-DCB-eq); MAETP = marine aquatic eco-toxicity potential (1,4-DCB-eq); TETP = terrestrial eco-toxicity potential (1,4-DCB-eq). kg CO₂-eq = kilograms carbon dioxide equivalent; kg SO₂-eq = kilograms sulfur dioxide equivalent; kg PO₄-eq = kilograms phosphate equivalent; kg 1,4-DCB-eq = kilograms 1,4-dichlorobenzene equivalent; kg Sb-eq = kilograms antimony equivalent.

example, locating a carbon fiber line close to a hydro power plant (SGL Group 2016). Within a DMS, the products are produced close to the customer, hindering the strategy above. As a consequence, the same product produced at different locations could have a significantly different environmental impact. DMSs could allow and foster the development of on-side or close-to-side renewable energy generation using small units (e.g., photovoltaic, wind turbines) as discussed, for example, in Dahlgren and colleagues (2013). Powering DMSs with renewable energy sources offers therefore a possibility to further decrease the amount of environmental impact embodied in a printed product. The applicability of a less environmental intense electricity supply might be simpler to implement in a DMS because investment barriers

are lower for small, decentralized power generation units, although these might be lower in return on investment over their lifetime.

- c. *The material used:* We have only used PLA for the 3D printed model, which is one of the most commonly used FDM 3D printing material while still gaining popularity due to its easy-workable properties. PLA has been already benchmarked by other studies in the context of additive manufacturing (Vink et al. 2003; Kreiger and Pearce 2013) and is known to cause stress in toxicity-related categories, but having a reduced GWP, ozone depletion potential, and ADP impact. In our study, we found that the main driver for impact categories such as EP, FAETP, and TEP in the DMS investigated is the PLA material. Distributed recycling offers in this regard

opportunities toward reducing the impact associated with the raw materials in production. More and more research and development is done in the area of recycling aiming to produce filament out of postproduction as well as postconsumer waste. A decentralized recycling system in connection with a DMS would allow to reduce the environmental impacts caused by the material (e.g., Juraschek et al. 2016).

- d. *The experience of the user/quality of the printed product:* Printing resolution defines the amount of energy and material used during production. While it was possible to print wearable frames with different qualities, this difference resulted to influence strongly the environmental life cycle impact. Assuming that an inexperienced user would use more material and need longer printing times, the impact in categories like GWP, APO, and ADP emissions can easily double. So, for example, a product printed in Mexico by an experienced user would produce around 0.2 kg CO₂-eq; the “same” product printed by a more inexperienced user could produce almost 0.4 kg CO₂-eq. Printing quality is also important as it defines the lifetime of the product. CMSs are likely to operate in a more or less efficient state due to long learning time for the usually trained operators. DMSs are more likely to be operated in a worst-case scenario by inexperienced users. A high potential for decreasing the environmental impact of the manufacturing process in a DMS is the enhancement of process quality for inexperienced users. Training of the operators and designers can also help to raise the “buy to fly ratio” for the 3D printed products. The ratio of the material ending up in the final product from the input material into the printing process was measured with 68% at the lowest value. With proper design and process operation, FDM 3D printing can be utilized in production with almost no waste creation.
- e. *Avoid rebound effect:* The risk that additive manufacturing triggers consumption is high. As process efficiency tends to increase, both the cost of 3D printers and the printing process decrease and thus enabling 3D printing to become mainstream technology. Furthermore, the technical advantages that AM might bring, such as the flexibility of producing products everywhere and supply demand fast and at any time, implies the risk of an overall increase in consumption. Especially in the investigated case of fashionable products, as eyeglass frame customers could demand a new frame style far more often than before if these are easier and cheaper to manufacture. The assumed one-to-one replacement in this paper is then a rather optimistic assumption for the DMS as it is very likely that companies might aim at increasing consumption by offering higher degrees of personalization in very short times, putting the product just a click away from the point of sale and thereby causing that more products will be printed thus multiplying the environmental impact. Comparing, for instance, the DMS scenario with the lower GWP impact (~0.19 kg CO₂-eq) against the

CMS scenario with the largest GWP impact (~0.6 kg CO₂-eq) while assuming a lifetime of 3 years for both of the products, it might be simple to argue that the eyeglass frame from the DMS could reduce the impact to one third. If, in turn, the lifetime of the DMS eyeglass frames was 1 year, then the DMS eyeglass frame would not present any environmental advantage after 3 years. Moreover, if a user were to print a pair of eyeglass frames per month, the potential GWP impact caused by the DMS eyeglass frame can be even 10 times larger than the impact of the CMS eyeglass frames.

Limitations and Future Work

This is a study limited to compare the environmental impact of one product manufactured under two different production systems. Although this study followed an extensive procedure to highlight the potential environmental impacts of a transition toward a localized production by means of AM, the approach followed is nevertheless based on several assumptions and future work is necessary to understand the environmental implications of 3D printed products in a DMS.

A broader understanding can be reached by: (1) expanding the boundaries of the systems, that is, considering the respective infrastructure, the production, and lifetime of additive production hardware. While the infrastructure used on the conventional manufacturing system is more robust and engineered to have a long operation lifetime, this might not be the case with desktop 3D printers, which can have shorter lifetimes, a fact that could influence the environmental impact of the printed product. In this study, the environmental impacts of the processes and materials outside the system boundary for creating a pair of glasses, that is, the making of the lenses, are not extensively compared to the processes under investigation. Lenses are usually produced from allyl di-glycol carbonate, which embodied energy reaches relatively high values ranging from 43 to 47 kWh/kg (Granta Design Limited 2013). Considering this, it can be argued the production of the lenses drives the environmental impact of the complete eyeglasses. The lenses are, however, produced to meet a specific user’s requirements. We considered that, although in a first step it would be difficult to match the production of the lenses to the production demand of the frames if these are exchanged very often on a weekly or monthly basis. However, this is unlikely to be an obstacle for a manufacturer offering new models on a regular basis as the lenses can be easily mounted to the new frames; (2) extending the study to a wider range of filament materials and potential printable products. In this regard, it is necessary to understand in which industrial sectors it is expected that DMS could ramp up and to identify the different products that, from a user perspective, can potentially be substituted by 3D printed products; and (3) AM is still a new technology and its efficiency is expected to be increased drastically in the near future. Further, only one exemplary product was considered in this study. We chose to investigate the case of the production of eyeglass frames because it qualifies with a high degree of personalization

in size and appearance while being small enough to handle in desktop 3D printers. Therefore, it is generally favorable to be produced with 3D printing in a DMS close to the customer. This study is not a representation of the entire manufacturing systems, but only a case study for the production of the specific investigated exemplary product. The results for 3D printing in a DMS are likely to be transferable to other products as the only variations will be the material consumption and therefore the printing time and energy consumption, whereas the CMS results are very much product specific and are limited in their applicability for other cases due to a variety in materials and machinery optimized for certain products.

Conclusion

This paper has compared two different ways of manufacturing one product that offers the same equivalent function. Using eyeglass frames as an example, we investigated the relative environmental implications of moving from manufacturing a product conventionally to producing it in a distributed manufacturing system by means of AM technologies. Although the overall results of the study do not indicate precisely whether one production system has potential environmental advantages against the other one, this paper has identified the main aspects in a DMS that are relevant to understand how this technology might impact the environment as well as the opportunities for this technology to improve. Nevertheless, the emergence of a digitally supported distributed manufacturing system imposes several threats to environmental sustainability. The operation of manufacturing companies under a CMS is highly constrained with regulations and production standards that have contributed to decrease the impact of manufacturing activities. In the case of DMS, regulating production processes in a DMS might result in complexity leading to increments of the environmental impact of products on a per-part basis. As the printing electricity was found to drive the environmental impact in several impact categories, the electricity mix selected for the printing processes influences significantly the environmental performance of the DMS. Moreover, it was found that the material used can strongly influence the environmental footprint in other impact categories, causing therefore important trade-offs. Although the simplification in logistics has been usually identified as an advantage of DMS, we found that, in our case, the effect of transportation is negligible compared to processes like the electricity use for printing and the production of the filament. For a better understanding, the implications of this so-called new manufacturing paradigm, it is necessary to broaden the research to a representative range of products considering consumption rates, variety of materials, and products with complex material mixtures.

References

- ASTM F2792-12a. 2012. Standard terminology for additive manufacturing technologies (Withdrawn 2015). West Conshohocken, PA: ASTM International.
- Baumers, M., C. Tuck, R. Wildman, I. Ashcroft, and R. Hague. 2011. Energy inputs to additive manufacturing: Does capacity utilization matter? In Proceedings of the 23rd Annual International Solid Freeform Fabrication Symposium, 6–8 August, Austin, TX, USA.
- Baumers, M., C. Tuck, R. Wildman, I. Ashcroft, E. Rosamond, and R. Hague. 2013. Transparency built-in: Energy consumption and cost estimation for additive manufacturing energy and cost estimation for additive manufacturing. *Journal of Industrial Ecology* 17(3): 418–431.
- Boschetto, A., L. Bottini, and F. Veniali. 2016. Finishing of fused deposition modeling parts by CNC machining. *Robotics and Computer-Integrated Manufacturing* 41: 92–101.
- Chen, D., S. Heyer, S. Ibbotson, K. Salonitis, J. G. Steingrímsson, and S. Thiede. 2015. Direct digital manufacturing: Definition, evolution, and sustainability implications. *Journal of Cleaner Production* 1–131.
- Coletti, P. and T. Aichner. 2011. Mass customization. In *Mass customization: An exploration of European characteristics*, 23–40. Berlin; Heidelberg, Germany: Springer Berlin Heidelberg.
- Conner, B. P., G. P. Manogharan, A. N. Martof, L. M. Rodomsky, C. M. Rodomsky, D. C. Jordan, and J. W. Limperos. 2014. Making sense of 3-D printing: Creating a map of additive manufacturing products and services. *Additive Manufacturing* 1–4. Elsevier B.V.: 64–76.
- Dahlgren, E., C. Göçmen, K. Lackner, and G. van Ryzin. 2013. Small modular infrastructure. *The Engineering Economist* 58(4): 231–264.
- Dufflou, J. R., J. W. Sutherland, D. Dornfeld, C. Herrmann, J. Jeswiet, S. Kara, M. Hauschild, and K. Kellens. 2012. Towards energy and resource efficient manufacturing: A processes and systems approach. *CIRP Annals—Manufacturing Technology* 61(2): 587–609.
- Durão, L. F. C. S., A. Christ, R. Anderl, K. Schützer, and E. Zancul. 2016. Distributed manufacturing of spare parts based on additive manufacturing: Use cases and technical aspects. *49 Cirp Cms* 57: 704–709.
- ecoinvent Center. 2015. Ecoinvent. Dübendorf, Switzerland: Swiss Center for Life Cycle Inventories.
- Edenhofer, O., R. Pichs-Madruga, Y. Sokona, J. C. Minx, E. Farahani, K. Susanne, K. Seyboth, et al. 2014. *Climate change 2014: Mitigation of climate change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.
- Faludi, J., C. Bayley, S. Bhogal, and M. Iribarne. 2015. Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment. *Rapid Prototyping Journal* 21(1): 14–33.
- Ford, S. and M. Despeisse. 2016. Additive manufacturing and sustainability: An exploratory study of the advantages and challenges. *Journal of Cleaner Production* 137: 1573–1587.
- framelapp printed eyewear. 2017. Framelapp. Wiesbaden, Germany: FrameLApp UG.
- Frank, K. and R. Malthaner. 1994. Plastic frame for eyeglasses. U.S. Patent No. US5331355 A. Washington, DC: U.S. Patent and Trademark Office.
- Gajdoš, I., E. Spišák, L. Kaščák, and V. Krasinskyi. 2015. Surface finish techniques for FDM parts. *Materials Science Forum* 818: 45–48.
- Galantucci, L. M., F. Lavecchia, and G. Percoco. 2009. Experimental study aiming to enhance the surface finish of fused deposition modeled parts. *CIRP Annals—Manufacturing Technology* 58(1): 189–192.

- Gao, W., Y. Zhang, D. Ramanujan, K. Ramani, Y. Chen, C. B. Williams, C. C. L. Wang, Y. C. Shin, S. Zhang, and P. D. Zavatieri. 2015. The status, challenges, and future of additive manufacturing in engineering. *Computer-Aided Design*. Elsevier Ltd. <https://doi.org/10.1016/j.cad.2015.04.001>.
- Gebler, M., Anton J.M. Schoot Uiterkamp, and Cindy Visser. 2014. A global sustainability perspective on 3D printing technologies. *Energy Policy* 74:158–167.
- Gibson, I., D. Rosen and B. Stucker. 2015. *Additive manufacturing technologies*. Additive manufacturing technologies. New York, NY: Springer New York.
- Granta Design Limited. 2013. CES Selector Software. Cambridge, UK: Granta Design Limited.
- Guinée, J. B. 2002. *Handbook on life cycle assessment: Operational guide to the ISO Standards / Jeroen B. Guinée (final editor)*. *Eco-Efficiency in Industry and Science: V. 7*. <https://doi.org/10.1007/BF02978897>.
- Guo, Q. and J. C. Crittenden. 2011. An energy analysis of polylactic acid (PLA) produced from corn grain and corn stover integrated system. Proceedings of the 2011 IEEE International Symposium on Sustainable Systems and Technology, ISSST 2011, 16–18 May, Chicago, IL, USA.
- Gutowski, T. G., J. M. Allwood, C. Herrmann, and S. Sahni. 2013. A global assessment of manufacturing: Economic development, energy use, carbon emissions, and the potential for energy efficiency and materials recycling. *Annual Review of Environment and Resources* 38(1): 81–106.
- Huang, R., M. Riddle, D. Graziano, J. Warren, S. Das, S. Nimbalkar, J. Cresko, and E. Masanet. 2015. Energy and emissions saving potential of additive manufacturing: The case of lightweight aircraft components. *Journal of Cleaner Production*. <https://doi.org/10.1016/j.jclepro.2015.04.109>.
- ifu Hamburg GmbH. 2015. Software for life cycle assessment, material and energy flow analysis (MEFA) and carbon footprint calculations. Hamburg, Germany: ifu Hamburg GmbH.
- Juraschek, M., V. Bhakar, G. Posselt, A. Kaluza, S. Böhme, C. Herrmann, and K. S. Sangwan. 2016. Recycling of plastic waste using fused deposition modeling as a production process. Proceedings of the Indo-German Conference on Sustainability, 28–33.
- Kellens, K., R. Renaldi, W. Dewulf, J.-P. Kruth, and J. R. Duflou. 2014. Environmental impact modeling of selective laser sintering processes. *Rapid Prototyping Journal* 20(6): 459–470.
- Khajavi, S. H., J. Partanen, and J. Holmström. 2014. Additive manufacturing in the spare parts supply chain. *Computers in Industry* 65(1): 50–63.
- Kietzmann, J., L. Pitt, and P. Berthon. 2014. Disruptions, decisions, and destinations: Enter the age of 3-D printing and additive manufacturing. *Business Horizons* 58(2). Kelley School of Business, Indiana University: 209–215.
- Kohtala, C. 2015. Addressing sustainability in research on distributed production: An integrated literature review. *Journal of Cleaner Production* 106: 654–668.
- Kreiger, M. and J. M. Pearce. 2013. Environmental life cycle analysis of distributed three-dimensional printing and conventional manufacturing of polymer products. *ACS Sustainable Chemistry & Engineering* 1(12): 1511–1519.
- Kreiger, M. A., M. L. Mulder, A. G. Glover, and J. M. Pearce. 2014. Life cycle analysis of distributed recycling of post-consumer high density polyethylene for 3-D printing filament. *Journal of Cleaner Production* 70: 90–96.
- Kuo, C. M. and R. T. Bogan. 1997. U.S. Patent No. US5608050 A. Washington, DC: U.S. Patent and Trademark Office.
- Le Bourhis, F., O. Kerbrat, L. Dembinski, J.-Y. Hascoet, and P. Mogno. 2014. Predictive model for environmental assessment in additive manufacturing process. *Procedia CIRP* 15. Elsevier B.V.: 26–31.
- Luo, Y., Z. Ji, M. C. Leu, and R. Caudill. 1999. Environmental performance analysis of solid freeform fabrication processes. Proceedings of the 1999 IEEE International Symposium on Electronics and the Environment, 1–6, 11–13 May, Danvers, MA, USA.
- Mani, M., K. W. Lyons, and S. K. Gupta. 2014. Sustainability characterization for additive manufacturing. *Journal of Research of the National Institute of Standards and Technology* 119(October): 419.
- Matt, D. T., E. Rauch, and P. Dallasega. 2015. Trends towards distributed manufacturing systems and modern forms for their design. *Procedia CIRP* 33: 185–190.
- Meteyer, S., X. Xu, N. Perry, and Y. F. Zhao. 2014. Energy and material flow analysis of binder-jetting additive manufacturing processes. *Procedia CIRP* 15. Elsevier B.V.: 19–25.
- Mourtzis, D. and M. Doukas. 2012. Decentralized manufacturing systems review: Challenges and outlook. *Logistics Research* 5(3–4): 113–121.
- OpenStreetMap. 2015. OpenStreetMap Foundation. www.openstreetmap.org. Accessed 8 September 2016.
- Optoid eyewear. 2016. Optoid Eyewear. Optometrist East Willamsburg Brooklyn, NY: Optoid Print3d Eyewear & Primary Eyecare. www.myoptoid.com/. Accessed 22 May 2017.
- Pqeyewear. 2017. Pq by Ron Arad customize frames by Ron Arad 2017. Via Crevada, Susegana Italy. www.pqbyronarad.com/. Accessed 22 May 2017.
- Prasad, M. M., N. Jaya Krishna, and O. Y. Venkatasubbareddy. 2014. Improving the surface roughness of FDM parts by using hybrid methods. *International Journal of Engineering Research & Technology* 3(12): 650–654.
- Protos eyewear. 2016. Protos. 3D Printed Eyewear Tailored to Fit You. www.protoseyewear.com/. Accessed December 1, 2016.
- Rauch, E., P. Dallasega, and D. T. Matt. 2016. Sustainable production in emerging markets through distributed manufacturing systems (DMS). *Journal of Cleaner Production* 135: 127–138.
- Sea-distances.org. 2015. Sea distances/port distances - online tool for calculation distances between sea ports. sea-distances.org. Accessed 19 December 2016.
- Serres, N., D. Tidu, S. Sankare, and F. Hlawka. 2011. Environmental comparison of MESO-CLAD© process and conventional machining implementing life cycle assessment. *Journal of Cleaner Production* 19(9–10): 1117–1124.
- SGL Group. 2016. Sustainable production in Moses Lake. <http://www.sglac.com/en/production/moses-lake-usa/sustainable-mol.html>. Accessed 1 December 2016.
- Shen, B. and Q. Li. 2015. Impacts of returning unsold products in retail outsourcing fashion supply chain: A sustainability analysis. *Sustainability* 7(2): 1172–1185.
- Spiering, T., S. Kohlitz, H. Sundmaeker, and C. Herrmann. 2015. Energy efficiency benchmarking for injection moulding processes. *Robotics and Computer-Integrated Manufacturing* 36: 45–59.
- Stephens, B., P. Azimi, Z. El Orch, and T. Ramos. 2013. Ultrafine particle emissions from desktop 3D printers. *Atmospheric Environment* 79: 334–339.
- Stieben, Roman. 2015. *Internal data acquisition: Process data on filament extrusion*. Braunschweig, Germany: Das Filament, not published.
- Telenko, C. and C. C. Seepersad. 1997. A comparative evaluation of energy consumption of selective laser sintering and injection

- molding of nylon parts. In Proceedings of the 22nd Annual International Solid Freeform Fabrication Symposium, 41–54, 8–10 August, Austin, TX, USA.
- Ullmer, H. 2014. Injection mold life expectancy. Wyandotte, MI: BASF Corporation. www8.basf.us/PLASTICSWEB/displayanyfile?id=0901a5e180004878. Accessed 22 May 2017.
- Vink, E. T. H., K. R. Rábago, D. A. Glassner, and P. R. Gruber. 2003. Applications of life cycle assessment to natureworks™ polylactide (PLA) production. *Polymer Degradation and Stability* 80(3): 403–419.
- Wittbrodt, B. T., A. G. Glover, J. Laureto, G. C. Anzalone, D. Oppliger, J. L. Irwin, and J. M. Pearce. 2013. Life-cycle economic analysis of distributed manufacturing with open-source 3-D printers. *Mechatronics* 23(6): 713–726.
- Wohlers, T. and T. Caffrey. 2015. *Wohlers report 2015: 3D printing and additive state of industry*. Fort Collins, CO, USA: Wohlers Associates.
- World Bank. 2016. World databank: Manufacturing, value added (% of GDP). <http://data.worldbank.org/indicator/NV.IND.MANF.ZS>. Accessed 2 September 2016.
- Wu, D., D. W. Rosen, L. Wang, and D. Schaefer. 2014. Cloud-Based design and manufacturing: A new paradigm in digital manufacturing and design innovation. *Computer-Aided Design* 59: 1–14.
- Yoon, H.-S., J.-Y. Lee, H.-S. Kim, M.-S. Kim, E.-S. Kim, Y.-J. Shin, W.-S. Chu, and S.-H. Ahn. 2014. A comparison of energy consumption in bulk forming, subtractive, and additive processes: Review and case study. *International Journal of Precision Engineering and Manufacturing—Green Technology* 1(3): 261–279.

Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information contains tables and figures showing product tree diagrams, system boundaries, and life cycle inventory summaries for both the centralized manufacturing system (CMS) case and the distributed manufacturing system (DMS) case.

Supporting Information S2: This supporting information contains two tables showing the minimum and maximum environmental impacts for eight impact categories and six geographical regions. The first table shows absolute results for the centralized manufacturing system (CMS) case. The second table shows absolute results for the distributed manufacturing system (DMS) case.