Improving Sustainability of Footwear Production through 3D Printing of Shoes

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1. Introduction

The production of apparel and footwear has a significant impact on the environment. In 2016, emissions for these two product categories accounted for about 8 % of global climate impact or 3.99 billion metric tons CO2eq. (Quantis, 2018). Trends such as "fast fashion" lead to a great demand for new clothes and shoes due to the short wearing times. Since most of the production takes place in Asia, but goods are worn worldwide, long transport routes are necessary. However, not only do transports contribute to a high environmental impact, but many emissions also occur during the material processing and production phases. In addition, the lack of recyclability is another issue. Shoes, especially sneakers, can consist of more than 60 discrete parts and many different materials (HILOS, 2022a). Often, these parts are fused almost inseparably. Therefore, it is not economically viable to separate them by type for recycling. Thus, most shoes can only be shredded and thermally utilised, leading to high demands for primary materials.

To avoid these issues and make shoe production more sustainable, additive manufacturing (3D printing) of shoes might be a promising approach. In this article, we present different approaches to using additive manufacturing technologies to produce footwear. First, we will briefly introduce additive manufacturing, highlight sustainability aspects, and show some examples of how additive manufacturing is used to make clothing and shoes. We then present a new approach to the production of customised footwear using only a Fused Filament Fabrication 3D printer. In Section 4, the environmental impacts of this manufacturing method are calculated and compared with values from other studies. In addition, we show which non-environmental factors still need to be considered in sustainability. The conclusion and the outlook on future work conclude this paper.

2. State of the Art

2.1. Additive Manufacturing

The term additive manufacturing (AM) covers all manufacturing processes whose production principle is based on the assembly or joining of volume elements, usu-

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ally in a layer-by-layer manner. For some time now, "3D printing" has gained acceptance as a collective term for various technologies (Gebhardt, 2016). Table 1 provides an overview of these categories and selected technologies and materials that can be used.

Categories	**Technologies**	**Materials**
VAT photopolymersation	Stereolithography	Photosensitive resins, ceramics
Material jetting	Drop on Demand (DOD)	Photopolymer resins, metals
Material extrusion	Fused Filament Fabrication (FFF) Fuse Deposit Model (FDM)	Thermoplastics (ABS, PLA, PC, nylon)
Binder jetting	Binder jetting	Polymer/ceramic/metal powder
Powder bed fusion	Selective laser sintering	Polymer/ceramic/metal powder
Sheet lamination	Laminated object manufacturing	Plastic/metal/ceramic foil
Direct energy deposition	Laser engineered net shaping	Metal/ceramic powder

Table 1: AM categories, corresponding technologies, and materials (ASTM International, 2012)

Regardless of the specific technology, AM processes have the following characteristics compared to conventional production processes (Gebhardt, 2016):

- 3D CAD data is directly used to generate the layer geometry
- No use of product-specific tools is necessary
- The generation of the mechanical-technological properties occurs during the construction process
- Objects can be produced in any orientation
- All technologies can use the same (STL) data set

These properties enable AM processes for quantities-independent and individualised production. Advances in materials and technologies mean that even materials such as concrete can now be similarly processed (Sanjayan & Nematollahi, 2019).

Thus, the application areas for additive manufacturing technologies span countless fields of application, from construction to fashion, agriculture, automotive, aerospace and healthcare (Jandyal, Chaturvedi, Wazir, Raina, & Ul Haq, 2022; Shahrubudin, Lee, & Ramlan, 2019).

2.2. Sustainability Aspects of AM

There are different approaches to consider sustainability aspects. The most common approach is to divide sustainability into three aspects: social, environmental, and economic, whose interaction and mutual influence can be presented differently. Three of the most common representations are shown in figure 1.

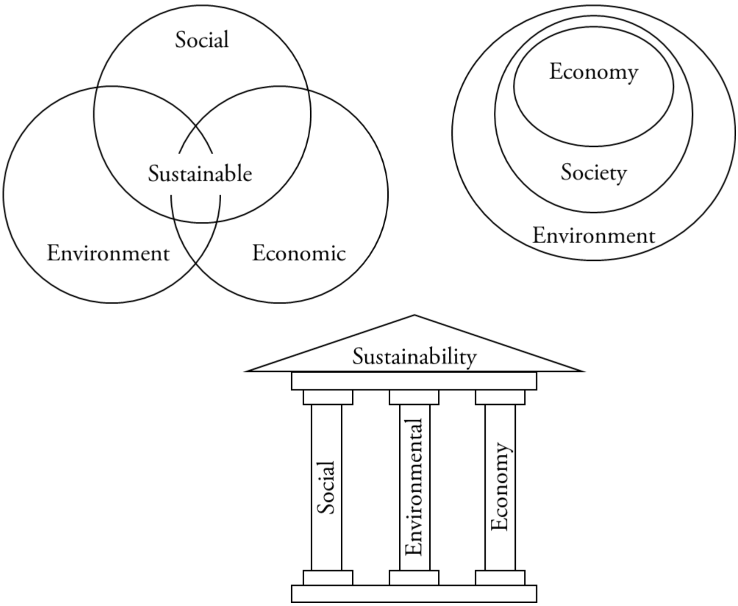

Figure 1: Different representations of the concept of sustainability (Purvis, Mao, & Robinson, 2019)

The individual aspects can be connected and weighted differently depending on the approach. One approach describes sustainability as the intersection of the three aspects. In contrast, another approach describes the individual perspectives as pillars that support the unifying roof of sustainability. A third option sees the environment as the comprehensive perspective in which society and, in turn, the economy are located. However, regardless of the specific approach, it is essential to note that sustainability is more than just considering possible environmental impacts.

The most significant impact on the environmental sustainability of AM production processes lies in the ability to execute make-to-order strategies. By producing only on demand, significant material savings can be achieved, reducing emissions (Despeisse & Ford, 2015).

Another advantage lies in the production method itself. Adding material instead of removing it means that less material needs to be pre-produced overall, thus reducing production waste. This is further enhanced since hardly any moulds, or other auxiliary materials are needed (Chen et al., 2015; Fastermann, 2014). Primary material requirements can also be reduced by using high or fully recycled materials (Büth, Juraschek, Thiede, & Herrmann, 2020). Further material savings can be achieved by optimising the geometries and design of lightweight components (Chen et al., 2015).

Most AM production processes do not require large factories or challenging logistical connections. This means that smaller, decentralised production structures can be set up, which overall lead to a reduction of transports within the supply chain and thus also to emissions savings (Chen et al., 2015; Mani, Lyons, & Gupta, 2014).

While environmental impacts of AM are well researched, knowledge about social impacts is much more limited. One aspect is that many toxic substances can be eliminated from the production process. In addition to a reduction in environmental impact, this means, above all, an immediate improvement for people since working conditions improve as the working environment becomes less harmful (Matos et al., 2019).

In addition, positive social impacts can be seen through the possibility of participation by customers. Certain AM technologies, especially FFF 3D printers and corresponding software, are already available at low prices and can change people's purchasing behaviour. People can develop from passive consumers to active prosumers through active participation in the production process by making products by themselves. By joining together to form global communities, further social cohesion and exchange are created (Chen et al., 2015). However, participation can also arise because, for example, exhibits in museums can be replicated so people with visual problems can also have an experience (Matos et al., 2019).

From an economic perspective, AM can help reduce production costs and enable more people to purchase products or spare parts and thus become part of the production process themselves, which are closely linked to social impacts (Khorram Niaki, Nonino, Palombi, & Torabi, 2019). This participation is the real benefit here and not the possibility that simply more products can be sold.

2.3. Additive Manufacturing in the Apparel and Footwear Industry

AM processes are already used in the fashion and footwear industry. For example, Spahiu, Canaj, and Shehi (2020) produced a dress using an FMD 3D printer and conducted an online survey to determine the acceptance of potential customers.

They concluded that most of the 100 respondents were aware of the 3D printing process and its benefits and would wear a 3D printed dress.

In addition to making garments from different plastics, new materials are also being developed. For example, by applying 2D braiding methods, Wu et al. (2022) have produced a 3D printing wire that can provide a wearing feeling similar to cotton by incorporating cotton powder.

3D printing of soles is often considered in the context of footwear. For example, Amorim, Nachtigall, and Alonso (2019) investigate how mechanical meta-material structure (MMS) can be used to create customisable footwear. They showed that this process has great potential but that there is still a need for development so that designers can use the materials in a more targeted way.

Zolfagharian, Lakhi, Ranjbar, and Bodaghi (2021) have developed different structures for midsoles and investigated them from the point of view of functionality regarding pressure absorption and dissipation during various sporting activities. They concluded that 3D printing is an effective technology for meeting specific requirements.

The US manufacturer HILOS produces and sells different types of shoes, e.g. sandals, clogs or mules, where the soles or individual parts are 3D printed. At the same time, the uppers or straps are made of leather and glued. The company claims that each component of the shoes is designed so that the shoes can be completely disassembled and the individual parts can be reused (HILOS, 2022b).

Well-known manufacturers have also used additive manufacturing processes to produce individual products. In cooperation between Adidas and the 3D printing specialist Carbon®, the Adidas Futurecraft 4D midsole was developed as a product for running shoes that can be manufactured using the 3D printing process. Different structures within the sole could create multiple functional zones to optimally absorb the respective loads that occur during running (Carbon, 2022). However, the processing of this sole into a shoe then follows the classic procedure by glueing the upper material to the sole.

With Flyprint, Nike has also launched a product on the market using 3D printing technology. However, in this case, the textile upper is 3D printed and then glued to a conventionally produced sole (Nike, 2018).

3. A New Approach for 3D Printing of Shoes

The previous section showed that many shoes are described as 3D printed. However, only individual components are made by using this technology.

In the following, we present an approach to producing customised shoes that are 3D printed as one single part. Therefore, at its core, the production process consists of only the following three steps:

- Individualisation of standard shoe models
- 3D printing using an FFF 3D printer
- Automated quality inspection

3.1. Individualisation of Standard Shoe Models

The approach provides of the possibility for customers and designers to meet on an online platform. Designers have the opportunity to offer their models for sale or printing. At the same time, care is taken to ensure that the shoe models are also printable. Customers can select the desired models and choose whether the shoe should have a fixed standard size or whether it should be customised to their own feet. If the latter is the case, customers can use a smartphone app to make a 3D scan of their own feet. These scans are then used to determine the measurement lines needed for the customisation. The standard shoe models are adjusted in length, width, and shape. Despite the customisation, decisive design patterns, such as logos, remain in their intended form.

3.2. 3D printing via Fused Filament Fabrication (FFF)

After selection and possible individualisation, the shoe models are prepared for printing. A slicer derives the required print commands from the CAD model and saves them in the print file, which is then transmitted to the FFF 3D printers. The 3D printers were designed and built by our project partner, the New York-based shoe manufacturer Zellerfeld Shoe Company Inc. to achieve the best possible results.

The operating principle of FFF technology is based on the extrusion of molten material. Setting the right temperature, the material melts enough to build the desired shapes. Each new layer joins the previous one to form an object. However, low temperatures prevent the individual layers from bonding properly. In contrast, high temperatures mean that the material does not cool fast enough, causing deviated contours.

In this 3D printing process, thermoplastic polyurethane (TPU) is used, which can be found in many products due to its properties. Although it is plastic, there are many products to be obtained whose recyclability and corresponding sustainability are certified by different institutions.

To have the 3D printing as efficient as possible, the shoe is 3D printed standing on the heel. This way, only a small amount of material is needed to create the required support structure. Figure 2 shows a snapshot of the 3D printing process.

Figure 2: 3D printing process (© Zellerfeld)

The shoe 3D printed with black material is held in place by the white support structure. In addition, it can be seen that the shoe consists of different structures inside. The choice of suitable configurations in different shoe areas ensures that the sole gets its cushioning effect. At the same time, the upper is elastic and firm enough to achieve the necessary stability and mobility.

Once the 3D printing is complete, only the support material needs to be removed, and the shoe is ready for sale. Although this process is still in development, a successful beta test has shown that both the customisation and the chosen manufacturing process are suitable. Figure 4 shows the "HERON01", the first fully 3D printed sneaker designed by Heron Preston and produced by Zellerfeld.

Figure 3: Fully 3D printed sneaker "HERON01" (© Zellerfeld)

3.3. Quality Inspection

While our project partner, Zellerfeld, designs the shoe models and performs the 3D printing, we were developing an automated quality control system intended to fulfil two tasks: quality control and knowledge building about occurring defects.

Within the scope of quality control, the 3D printed products need to be inspected concerning possible defects. Thus, the fulfilment of the quality standards has to be confirmed. In addition, possible defects are to be analysed. This includes not only the detection of defects but also their positioning. These findings will be used to adapt the printing process for critical areas, e.g. where deviations have occurred more frequently, thus reducing the probability of defects.

In mass production, many identical products generate a lot of information about possible defects. Therefore, methods of artificial intelligence (AI) such as Convolutional Neural Networks (CNN) which require many data for their training, can be easily used for automated quality control (Kuric, Kandera, Klarák, Ivanov, & Więcek, 2020). Since the process of 3D printing of individualised shoes is still under development, the number of pieces produced and thus the corresponding defects are still small. Hence, we are pursuing a different approach so that automated quality control can occur early in the development process. We use the defect-free CAD model of the shoe to be 3D printed as a reference. The printed shoes are digitised using a 3D scanner to determine the actual state. They can then be compared with the original CAD models, determining possible deviations. These deviations are grouped into corresponding clusters, evaluated according to their severity, and their position is noted. This way, it should be possible to recognise possible causes of defects and take appropriate measures for future prints despite the slightly different characteristics of the personalised shoes. These measures can be, for example, an adjustment of the printing speed for specific sections. However, this is not only about a possible printing speed reduction to improve quality but possibly also an increase for non-critical areas. In doing so, both better quality and reduced printing time can be achieved. Thus, less production waste and shorter printing times lead to a more sustainable manufacturing process.

4. Sustainability of 3D Printed Shoes

4.1. Calculation Emissions for 3D Printed Shoes

While traditionally produced sneakers can consist of up to 65 individual parts made of different materials (Cheah et al., 2013), by full 3D printing, only one element is produced, and one plastic is needed for production in the 3D printer. The calculation of the environmental impact is correspondingly straightforward. In addition to the emission during plastic production, only the energy required during 3D printing must be considered. The environmental impacts can be calculated by multiplying a specific emission factor by the amount of material or used energy, respectively. For the 3D printed shoe shown in section 3, this means:

Emission source	**Quantity**	**Specific emission factor**	**Resulting emission**
Thermoplastic Polyurethane (TPU)	0.5 kg	4.1 kg CO2eq./kg[1]	2.1 kg CO2eq.
Energy consumption	25 kWh	0.366 kg CO2eq./kWh[2]	9.15 kg CO2eq.
			11.25 kg CO2eq.

Table 2: Calculation of emissions for a 3D printed shoe

[1] Biron (2018)
[2] Umweltbundesamt (2021)

With the quantities for TPU and energy consumption measured by Zellerfeld while printing prototypes, the total value for a pair of 3D printed shoes is around 22.5 kg CO2eq.

However, it must be taken into account that the specific emission factor for TPU, in particular, is only reliable to a limited extent. Although plastic is used in many products due to its favourable properties, there is hardly any reliable information on its environmental impact (Proske, Sánchez, Clemm, & Baur, 2020). The specific emission factor for electricity corresponds to the German electricity mix (Umweltbundesamt, 2021).

It can be seen that the emission of shoe printing is significantly influenced by the emissions associated with the electricity consumed by the 3D printer. Since the manufacturing process presented here is novel, there is potential for process optimisation. Significant savings can be expected through reduced printing times and improved energy efficiency. Target values for electricity consumption of less than 15 kWh can be considered as realistic, resulting in an emission of 5.5 kg CO2eq. for one shoe. Furthermore, the use of electricity from renewable sources can also help to reduce the resulting emissions. Concerning the TPU used, it should be noted that the emission factor estimated here neither applies to bio-based material nor includes possible credits from recycling.

4.2. Classification by comparison with other data

Although some data on emissions related to footwear production can be found, a comparison is not straightforward. One limitation is that different types of shoes were considered, which can differ in complexity and weight. Since not only individual shoes are balanced, but also balances are partly averaged over the entire production, comparing the results in relative values, for example, in relation to 1 kg of shoe, is impossible. Figure 4 shows the emission values of the shoe "HERON01" compared to other results, which refer to 3D printed shoe parts and manufacturers' data on conventionally produced shoes.

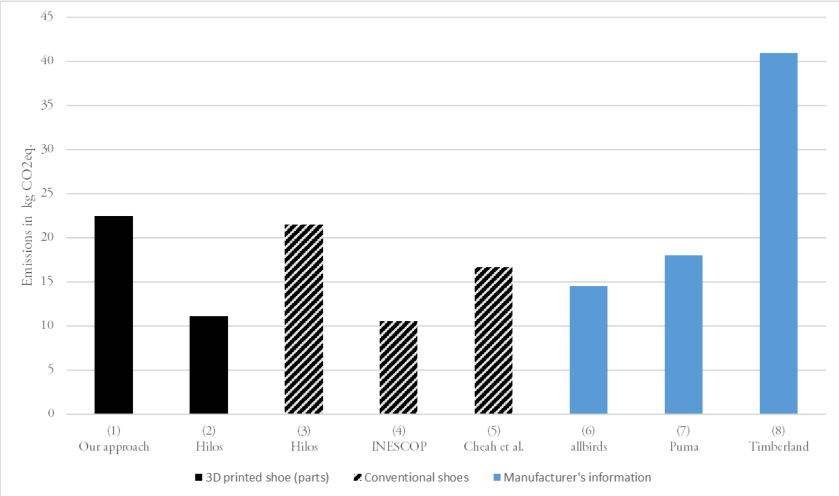

Figure 4: Comparison of different emission specifications for shoes

While our approach presents a fully 3D printed sneaker, a study by Yale's Centre for Business and the Environment investigated the environmental impact of the HILOS "slip on mule" model. This shoe consists of a 3D printed sole and a leather upper. The key findings were that CO2e emissions were reduced by around 48 % compared to traditional production. Thus, they achieved 11.1 kg CO2eq. emissions per pair as shown in Fig. 5 (pillar 2), instead of the 21.5 kg CO2eq. in the conventional manufacturing process (pillar 3) (HILOS 2022a). In addition, the researchers found that water consumption could be reduced by about 99 %. These savings resulted from the on-demand production and the new design, which allows a reduction of work steps and the number of additives such as adhesives. By taking the shoes apart by type, most materials can be reused.

A variety of data can be found for shoes without 3D printed components. For example, researchers in the *CO2Shoe* project came up with an average value of 10.6 kg CO2eq. per pair (INESCOP, 2017), while Cheah et al. (2013) state the emissions for a pair of running shoes are up to 16.7 kg CO2eq. (see Fig. 5, pillars 4 and 5).

It can be seen that manufacturers and retailers use sustainability as a marketing tool. As one example, the manufacturer *allbirds* gives a value of 14.5 kg CO2eq. for its "Wool Runner-up Mizzle" (Allbirds, 2022). In addition to presenting the emissions related to the specific shoes, CO2 neutrality is advertised through the financial support of climate protection projects. Results of other studies by manufacturers range between 18 kg CO2eq. (PUMA, 2008) and even 41 kg CO2eq. (Timberland, 2009).

Although the 3D printed shoe presented here currently still has a higher CO2 emission value, the entire production chain (including aspects like production losses or transports) must be considered to compare different production processes. Comparing emissions per pair of shoes shows that customer-independent mass production causes lower emissions due to its efficiency. However, if this overproduction leads to the mass destruction of unworn shoes, the ratios change. The Hilos study shows that significant improvements in environmental impact can be achieved by directly comparing two identical products. Concerning ecological sustainability, aspects such as water consumption are also decisive factors in addition to CO2 emissions.

4.3. Social and Economic Aspects

Even if the pure emission values do not clearly show better sustainability for shoes that are entirely or partially manufactured using 3D printing, the aspects beyond the ecological perspective must also be considered for a holistic view.

As described before, 3D printing reduces both the number of components and thus the required work steps and the types of materials. On the one hand, fewer potentially toxic substances are needed to produce the materials. On the other hand, eliminating many work steps can reduce the workload during production. Both aspects can improve social sustainability.

Using 3D printers to produce shoes can offer even more social and economic sustainability advantages. While large factories are needed for conventional shoe production, 3D printing and especially the FFF process only requires a printer, the printing data, the material and electricity. This leads directly to reduced investment costs. It is relatively easy to set up decentralised production sites allowing new groups of people to participate in the production process. The 3D printers can be easily integrated into environments that are not suitable for conventional production processes, such as retail shops in inner cities or in rural and economically not so strong regions. In this way, production in new places can help to create direct economic added value. In addition to the financial aspects, the required qualifications also open up the circle of people who can benefit from this production process. Without many work steps and no handling of hazardous substances, workers can be qualified quickly and easily. By networking the 3D printers via the internet and connecting them to central systems, aspects such as process monitoring or troubleshooting can be carried out remotely, thus taking off further pressure from the people to qualify. The reduced need for materials and decentralised production can also help to reduce the number of necessary transports. In addition to the ecological aspects, this also means that a contribution can be made to social sustainability by reducing pollution from traffic noise or the risk of accidents.

5. Summary and Conclusion

5.1. Summary

In this article, we presented different approaches to using additive manufacturing (AM) to produce clothing and shoes and highlighted their advantages from a sustainability perspective. With the "HERON01", we presented the first sneaker entirely made using 3D printing and the unique features of the production and quality inspection process. Currently, producing a pair of these sneakers generates around 22 kg CO2eq. emissions, but this value can probably be almost halved through appropriate adjustments in the production process. Other studies show that AM processes' suitability for a make-to-order strategy can significantly save emissions while increasing attractiveness through individualization. In addition to these environmental benefits, AM can also lead to improvements in social and economic areas. By eliminating toxic auxiliary materials, the working environment becomes less harmful. A reduced number of work steps can help to reduce the workload.

5.2. Future Work

Different aspects need to be advanced to improve the production process and its evaluation from a sustainability perspective. It has been shown that electricity consumption is a decisive factor in generating emissions. Thus, increasing the efficiency of the 3D printing process is of great importance. The successful implementation of automated quality control can help to both improve quality and reduce printing time. Further optimisation towards improved environmental sustainability can be achieved by using materials with higher recycled content.

More detailed calculations should be made regarding the evaluation from a sustainability perspective. Besides considering direct emissions, other aspects such as water consumption or toxicity are also of great interest. To make the results even more comparable, a presentation of relative values should be aimed.

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