

Reimagining Footwear Production: Advancing Sustainability with Three-Dimensional Printing Technology

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Abstract

We explore the potential of three-dimensional printing technology to revolutionise the footwear industry, solving key challenges in sustainability and customization. The global footwear market produces twenty-three billion shoes per year, of which twenty-two billion end up in landfills, posing significant environmental issues. Furthermore, consumers report that comfort-related issues are a common problem in this industry. The study examines how three-dimensional printing, also known as additive manufacturing, can alleviate these problems through environmentally friendly production methods and versatile capabilities that scale sustainably.

The methodology examines advancements in additive manufacturing processes, particularly fused filament fabrication, and their application in footwear production. The results demonstrate that three-dimensional printed shoes significantly reduce waste, minimise resource consumption, and allow for recyclable materials, contributing to a more sustainable industry. Additionally, this technology enables an unmatched level of customization, addressing comfort and fit issues that plague traditional manufacturing methods.

A survey of 521 college students reveals a strong interest in durable and customizable shoes, with 93.9% prioritizing comfort and fit. The research also highlights recent technological advancements, such as HP's Jet Fusion 5200 Series, which promises increased efficiency and reduced operational costs in three-dimensional-printed shoe production.

In the present work, we study the transformative potential of three-dimensional printing in creating a more sustainable, efficient, and consumer-focused footwear industry, paving the way for innovative solutions to long-standing challenges.

1. Introduction

The footwear industry is a significant contributor to global environmental issues. India is the second-largest global producer of footwear after China, accounting for 13% of global footwear

production of sixteen billion pairs [11]. India alone manufactures over two billion pairs in different categories, constituting an almost equal percentage of leather and non-leather footwear. Another source reveals that of the twenty-three billion shoes produced globally annually, around twenty-two billion end up in landfills [4]. The footwear market in India will generate an individual revenue of Rs fifteen hundred billion by the end of 2024 [4]. The production, consumption, and disposal of shoes have serious environmental impacts with many consequences. The footwear industry is also responsible for contributing to a massive carbon footprint, resource depletion, and waste accumulation, posing serious challenges for scale and sustainability.

Apart from environmental concerns, the footwear industry faces significant challenges related to comfort and fit. Many people face discomfort due to poorly fitting shoes, which can lead to a number of foot problems such as blisters, calluses, corns and more serious problems like bunions and foot pain. This discomfort can affect overall health and hinder daily activities. In addition, most available shoes offer limited customization, leaving consumers with very few options with regard to design, material, and fit. Individuals with specific and special needs or those looking for unique styles need help finding suitable options. In particular, people with foot problems, deformed feet, or orthopaedic needs face significant challenges in finding shoes that alleviate their discomfort and cater to their unique requirements.

In recent years, the importance of *three-dimensional* printing technology has been steadily growing, and many of its innovative applications are emerging in various fields such as medicine, science, engineering, the military, and entertainment. In the apparel industry, *three-dimensional* printing has transformed the way clothing and accessories are designed and manufactured.

Studies show that *three-dimensional* printing has the potential to reduce waste and incorporate recyclable materials, providing a more sustainable approach to production. *Three-dimensional* printing is, thus, employed in footwear manufacturing, where it is also known as additive manufacturing and involves creating three-dimensional objects by layering materials in succession. Additive manufacturing, often called rapid prototyping or solid freeform fabrication, encompasses a range of technologies that use layered manufacturing techniques to produce items.

A literature survey shows insufficient work done to advance sustainability with *three-dimensional* printing technology in apparel production. Hence, the present research paper attempts to focus on the potential of *three-dimensional* scanning and printing technology to revolutionise the footwear industry by addressing these challenges.

2. Methodology

Designing footwear products is a complex and multifaceted process that requires attention to precise detail. One of the critical aspects of this process is ensuring a good fit, which can be achieved by fabricating footwear based on a scanned foot, allowing for the

development of a custom last. This work focuses on implementing a cost-effective structured light scanning system for precise *three-dimensional* foot scanning that forms the basis of our methodology.

We begin by delving into the advancements in the additive manufacturing process that form the core of our work. We then explore the role of *three-dimensional* technology in enhancing the design and production of custom footwear. Finally, we will examine the uses of *three-dimensional* printing via fused filament fabrication for precise footwear component fabrication with material efficiency.

2.1 Three-dimensional Technology

Three-dimensional printing has revolutionised the development, production, and manufacturing of objects, becoming a disruptive force in many industries, including aerospace, medical, engineering, and entertainment, which have benefited from *three-dimensional* printing prototypes and working parts and models of complex machinery that would have otherwise required complex building setups. The ability to produce complex and highly customised objects has created new opportunities, especially in the apparel industry.

The textile industry has adopted *three-dimensional* printing, as it offers new opportunities for efficiency, sustainability, and customisation by creating prototypes of basic textile structures and accessories such as jewellery, belts, and hats. Fashion designers can work on designs faster and create physical prototypes using *three-dimensional* printing, reducing the time required from ideation to production of a new line of collections. Following the advancements, *three-dimensional* printing technology has been employed in footwear production. With *three-dimensional* printing, we can now create highly customised shoes tailored to each individual's preference and foot shape.

At its core, *three-dimensional* printing creates three-dimensional objects by layering materials onto one another using additive manufacturing technology. Additive manufacturing, also known as solid freeform fabrication, includes a variety of techniques that build objects layer by layer. This method allows for the precise creation of complex and highly customised objects, making it a revolutionary force in a variety of industries.

2.2 Advancement in Additive Manufacturing

Additive manufacturing is a cutting-edge production method in which digital models build footwear components layer by layer. Compared to traditional manufacturing, which typically involves cutting, moulding, and assembling multiple components, this approach reduces material waste and can facilitate the use of a variety of cutting-edge materials. Additive printing makes it possible to produce complex and personalised shoe designs. Overall, this process increases manufacturing efficiency, promotes design customisation options, and improves the sustainability of the footwear industry.

Regardless of the specific technology, additive manufacturing processes have the following features compared to conventional production processes [1]:

- i. The generation of the mechanical-technological properties occurs during manufacturing and can be produced in any orientation.
- ii. The use of product-specific tools is not necessary.
- iii. *Three-dimensional* computer-aided design data generates the layer geometry.

Although additive manufacturing has the potential to revolutionise production processes, the footwear sector is embracing it. Recent research indicates that the technology can drastically cut down on material waste, making it a more ecologically friendly alternative to traditional manufacturing methods. Its use eliminates the common issues of pain and poor fit by enabling the precise creation of complex designs and shoes with a personalised fit. Furthermore, additive manufacturing makes on-demand production and quick prototyping possible, which shortens lead times and increases design iteration flexibility. By using recyclable materials and minimising the need for mass production, this strategy not only improves the overall efficiency of the footwear sector but also helps it transition to more ecologically friendly methods [9].

The American company HILOS [6] manufactures and markets a variety of footwear, such as clogs, mules, and sandals, with *three-dimensional*-printed soles or individual parts. The straps or uppers are constructed from leather and adhesive at the same time. The manufacturer states that every shoe part can be fully disassembled and the individual pieces reused.

Nike has also introduced a product utilising *three-dimensional* printing technology to the market with Flyprint [10]. In this instance, though, a traditionally made sole is adhered to a cloth upper that has been *three-dimensionally* printed.

A Spanish startup, ATHOS [12], with its ground-breaking invention, has made it to the national finals of the esteemed James Dyson Award. This shoe combines innovation, customisation, and a strong emphasis on consumer health to revolutionise the sports footwear market. ATHOS is leading in this shift by using HP Multi Jet Fusion *three-dimensional* printing technology to create customised shoes to meet each climber's specific requirements. To do this, ATHOS has teamed up with Sculpteo, a well-known online *three-dimensional* modelling provider and member of HP's Digital Manufacturing Partner Network, and has locations in California and France.

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 *three-dimensional* printing is an effective technology for meeting specific requirements [3].

2.3 Three-Dimensional via Fused Filament Fabrication

Fused Filament Fabrication, or Fused Deposition Modelling, is a versatile three-dimensional printing process that uses a heated extruder head to deposit thermoplastic filament layer by

layer. Common filament materials include acrylonitrile butadiene styrene, polylactic acid, polyethylene terephthalate glycol, and nylon [5]. Fused Filament Fabrication printers are affordable and accessible, making them popular for hobbyists and small businesses. They offer many applications, from rapid prototyping and education to customisation of items such as phone cases and jewellery. The strong layer adhesion in Fused Filament Fabrication ensures durable prints, while its versatility allows for the production of functional prototypes and artistic creations.

Melting the material by extrusion is the foundation of Fused Filament Fabrication technology. When the temperature is suitable, the material melts enough to create the required form. To form an object, each layer builds upon the one before it. However, low temperatures hinder the correct bonding of the individual layers. On the other hand, high temperatures result in insufficient cooling, leading to a distorted shape.

Thermoplastic polyurethane, which is used in many objects for its characteristics, is used in this *three-dimensional* printing technique. Despite being made of plastic, these items are considered durable and fully recyclable.



Figure: Fully three-dimensional printed sneaker (Source: Zellerfeld)

3 Result

The result of this work is believed to have a two-fold advantage for the footwear industry. Firstly, it benefits the processes in the industry by making them more efficient, eco-friendly, and sustainable with scale. On the other hand, there is an infinite scope for optimizing the end consumer needs. We talk more about it in the subparts.

3.1 Eco-Friendly and Recyclable Innovations

The three-dimensional printed footwear will be more sustainable, eco-friendly and a product of a more efficient process pipeline. They can greatly reduce waste and resource consumption when compared to the orthodox vanilla methods employed in the present-day footwear factories. Thanks to additive manufacturing, the printed shoes are built in layers, piled up over each other, directly from the digital design. This is close to completely eradicating the need for additional material and also the need for cutting and assembling processes that are known to

generate much of the waste. Three-dimensional printing also allows for on-demand production, thereby eliminating overproduction and problems and environmental costs associated with unsold goods.

Several studies aim to certify that three-dimensional printed footwear produces less carbon emission than that produced by traditional shoes. The reduction can be attributed to the fact that the process of three-dimensional printing is extra simplified, thereby eliminating multi-step manual manufacturing. The three-dimensional printed shoes can also be locally produced, which can reduce transportation emissions.

The three-dimensional printed shoes can also be made from recyclable materials, which is a major highlight in the sustainability story. Advances in three-dimensional printing technology have now enabled the usage of environmentally friendly materials, like the biodegradable plastics and recycled polymers, that can be repurposed and reused to make shiny new shoes. Employing three-dimensional printing techniques creates a closed-loop system that contributes to the overall reduction of carbon footprint in the footwear production by reducing usage of virgin materials and also reducing waste to landfills.

The recyclability of *three-dimensional*-printed shoes made from thermoplastic polyurethane also contributes to a significant reduction in carbon footprint compared to conventional shoes. Studies show that recycled thermoplastic polyurethane reduces greenhouse gas emissions compared to thermoplastic polyurethane production from virgin materials. This is due to the energy savings associated with recycling and the reduced need to extract and process raw materials.

Additionally, it is important to note that some shoe soles, particularly those made from synthetic materials such as polyurethane, can remain in landfills for up to 1,000 years [4]. This long decomposition time highlights the environmental impact of conventional shoes and emphasises the need for sustainable alternatives such as *three-dimensional*-printed shoes.

Therefore, in the present work, an attempt will be made to investigate *three-dimensional*-printed shoes that offer a sustainable alternative to conventional shoes by minimising waste, reducing resource consumption, and promoting the use of recyclable materials. As the technology advances, we can expect to see greater improvements in the sustainability of *three-dimensional*-printed shoes, making it a promising solution for the future of the fashion industry.

3.2 Versatile Customisation Capabilities

Unmatched customisation options are offered by *three-dimensional*-printed shoes, enabling on-demand manufacturing to meet each individual's unique needs. Unlike conventional production techniques that rely on standardised designs and sizes, *three-dimensional* printing allows us to create shoes tailored to each individual's unique foot measurements. Advanced *three-dimensional* scanning technology, which accurately measures and moulds the foot to ensure a perfect fit, makes this degree of customisation possible.

Shoes can now be made on demand using *three-dimensional printing*, eliminating the need for bulk production and cutting down on wasted inventory. There are now customisation options available to customers, ranging from material choice to shoe size, shape, and design. This improves user performance and comfort while also meeting each individual's needs and preferences.

Three-dimensional printing is an attractive option for customers seeking comfort and individuality due to its exceptional precision in creating custom-fit shoes and reducing frequent problems such as discomfort and poor fit. Due to its amenability to customisation, *three-dimensional* printing has been established as a transformative technology in the footwear sector, providing customised solutions that meet each consumer's specific needs.

4 Discussion

To better understand people's preferences and perceptions about footwear, we undertook a small survey that was particularly focused on three-dimensional printed shoes. The survey was completed by as many as 521 college students. By closely studying and analyzing the responses, we gained deeper insights about the consumer insights, potential market gaps, and, most importantly, the appeal and need for technology like three-dimensional printing in footwear.

An interesting finding in the survey conducted was the high level of importance given by our cohort to the comfort that ultimately comes from the fit. This was agreed by a whopping 93.9% of the sample, for whom fit and comfort are the most important parameters while buying footwear. Out of those who value comfort, 42.7% reported difficulty in finding the right size/fit for them. Since the problem is gravely highlighted, we acknowledge that poor fitting or unavailability of the right fit is one of the constant issues faced by consumers. This further calls for the need for more customisability in footwear than currently exists in the market, which calls for stepping up processes to certainly provide a much diverse fitting options by lowering the barrier to moulding production as needed.

In another aspect, the survey, which was designed to factor in sustainability, revealed the growing concern of cohorts about the sensitive topics of environmental impact and pollution caused by the production processes in the footwear industry. 51.1% of the sample feels that there should be consideration of these factors in buying decisions. In general, we have seen such concerns worldwide in other industries as well, which have certainly influenced trends across entire industries. We predict the same with the footwear industry as well, and 3-dimensional printed shoes provide a much more viable and friendly solution. With 3-dimensional printing of our shoes, we can be sure that recyclable material is used in it and the production waste is minimized.

We further asked the people about their understanding of the 3-dimensional printing technique as a concept and the impact it can make. While 42% say that they are unaware of it, only thirty-five point nine percent know about it on the surface. This leaves a minority of people who are

confident in their knowledge about it, thereby warranting an urgent need to educate people about this new technology and its impact on different industries, including footwear. Despite the unawareness, when we talked about the impact potential, the majority of the people were accepting of the idea and showed genuine interest in having custom-made 3-dimensional printed shoes. While fifty-three point one percent wanted to adopt the product immediately, as they reach the market, we note that around forty percent price as a given barrier, but they are willing to adopt as they get more affordable.

In terms of exploring the desired customization that people are looking for, our survey found that most people wanted colour options, as agreed by twenty-seven point five. The second most requested was the sole type option (67.4%). This could be one of the driving forces for the adoption of 3-dimensional printed shoes, providing a much more viable and friendly solution. With 3-dimensional printing, our printing for footwear, wherein there could be hundreds of customized and wanted varieties of a product in the market, is compared to only a handful today.

To sum up, our survey does confirm a clear and adequate demand for footwear that blends comfort with customization with a clear story about sustainability. While it also shows that work needs to be done in increasing awareness and understanding in 3D printing, we cannot simply undermine the potential market out there.

5 Future Work

Several aspects were further developed to improve the production process and its sustainability assessment. Increasing the three-dimensional printing process's efficiency is essential because power use contributes significantly to emissions. Also, we can reduce the printing time and increase product quality by putting automated quality control systems into place. In addition, the use of materials with a high percentage of recycled content can increase environmental sustainability. More in-depth calculations to evaluate sustainability should be part of future work, including indirect emissions and other elements, such as material toxicity and water use. Comparisons will be easier to understand and more practical if these results are presented as relative values.

There have been many recent advancements in the field of three-dimensional printing. The modern generation of three-dimensional printers, examples being the likes of the Jet Fusion 5200 Series [7] by HP, are definitely one of the most important steps to date in transitioning the footwear industry's processes to high-volume and sustainable ones. The new generation of printers comes with increased throughput and is at least 40% more efficient while being 30% more cost-effective than the previous models in line. Moreover, the innovation in material science, like the ULTRASINT thermoplastic polyurethane by HP, makes three-dimensional printing a more suitable and environmentally secure process to be used for mass-producing customisable footwear. These developments, in themselves, are enormous and well-positioned to make an impact on the entire footwear industry, making it both more evolved and eco-friendly.

6 Conclusion

The work put together here showcases the immense potential that lies in harnessing the three-dimensional printing technology to change the footwear industry by addressing the two most prevailing problems of sustainability and customisation. By means of three-dimensional printing, enabling demand-driven production is very much achievable, thereby reducing wastage. Also, the technique makes use of recyclable materials, which will help combat environmental pollution, among other challenges. As we found out through our work, customisation requirements by customers pose one of the biggest challenges; the technique described in the paper inherently solves that by giving the ability to the producers to devise a pipeline that can weigh in customers' exact needs to remediate problems of discomfort and poor fit.

Looking at the recent advances in the field, the development of complex and versatile three-dimensional printers, like HP's Jet Fusion 5200 series, certainly demonstrates that such technologies can be blended successfully with mainstream manufacturing methods of the footwear industry. The innovations henceforth will only get better, improving the overall process efficiency while keeping down the price point. Altogether, it will pave a solid foundation for better adoption.

As technology advances, three-dimensional printing will play a pivotal role in the future of footwear production, helping the industry become more sustainable, efficient, and consumer-focused. Apart from the above, an insight into the academic approach to probing various untouched research areas is essential to inviting other researchers in this field. The work put together here showcases the immense potential that lies in harnessing the three-dimensional printing technology to change the footwear industry by addressing the two most prevailing problems of sustainability and customisation. By means of three-dimensional printing, enabling demand-driven production is very much achievable, thereby reducing wastage. Also, the technique makes use of recyclable materials, which will help combat environmental pollution, among other challenges. As we found out through our work, customization requirements by customers pose one of the biggest challenges; the technique described in the paper inherently solves that by giving the ability to the producers to devise a pipeline that can weigh in customers' exact needs to remediate problems of discomfort and poor fit.

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