A Futuristic Paradigm Shift in Footwear Manufacturing - An Approach to Innovation and Sustainability by Additive Manufacturing Process (3D printing)

Conference: 13th AICLST, Kolkata, 6–8 March 2026

Paper reference: TF-81/O

Printed pages: 292–296

Source: *Leather 2050: Challenges & Opportunities*, ILTA (2026)

A Futuristic Paradigm Shift in Footwear Manufacturing - An

Approach to Innovation and Sustainability by Additive

Manufacturing Process (3D printing)

Karthikeyan Kattaiya*; Ambika Kumaresan

Scientist, Shoe and Product Design Development Centre, CSIR- Central Leather Research Institute (CLRI), Chennai.

Ref. No. TF-81/O

Abstract

The integration of 3D printing (additive manufacturing) into footwear production is transforming traditional design and manufacturing paradigms. This innovation enables unprecedented customization, rapid prototyping, and material efficiency by allowing designers to create complex geometries, lightweight lattice structures, and anatomically precise fits that conventional methods cannot easily achieve. Current advancements—such as multi-material printing, bio-based polymers, and automated digital workflows—are accelerating the shift toward sustainable and on-demand manufacturing. Major footwear brands and start-ups are already deploying 3D-printed midsoles, uppers, insoles, and fully printed shoes, reducing waste and shortening supply chains. Looking to the future, 3D printing is expected to catalyse hyper-personalized footwear ecosystems, where shoes are produced from individual gait scans, respond to biomechanical data in real time, and incorporate smart adaptive materials. Emerging technologies such as recyclable monomaterial shoes, and localized micro-factories will enable circular production models and near-instant delivery. As additive manufacturing continues to evolve, it promises a paradigm shift in the footwear industry merging digital fabrication, sustainability, and human-centric design to redefine how footwear is conceived, manufactured, and experienced.

Correspondence author email : karthik.clri@csir.res.in

Keywords:3D Printing, Footwear, Digital manufacturing, Sustainability

1. Introduction

Conventional footwear manufacturing relies heavily on labour intensive processes, complex tooling, and global supply chains, often resulting in high material waste and carbon emissions. With increasing consumer awareness of environmental issues and demand for personalized products, the industry is seeking advanced manufacturing solutions. Additive manufacturing has emerged as a key enabler of this transformation, offering both technological and ecological advantages. Nowadays, rapid prototyping has a wide range of applications in various fields of human activity: research, engineering, fashion, education, the computer industry and many others [1].

1.1 Additive Manufacturing in Footwear

The footwear industry is undergoing a transformative shift driven by technological innovation and growing sustainability demands. Additive manufacturing, commonly known as 3D printing, presents a disruptive approach to footwear production by enabling design freedom, customization, material efficiency, and reduced environmental impact. This paradigm shift moves manufacturing away from traditional mass-production models toward digital, on-demand, and localized production systems. Fused deposition modelling (FDM), stereolithography (SLA), and selective laser sintering

(SLS) are the most prevalent methods via which the technology operates. Layers of an object can be created using FDM by extruding heated thermoplastic filaments through a nozzle. In contrast, stereolithography (SLA) achieves excellent accuracy and smooth surfaces by hardening a photosensitive resin using an Ultraviolet (UV) laser [2]. This paper explores how 3D printing is redefining footwear manufacturing, highlighting its role in innovation, sustainability, supply chain optimization, and future industry

Figure 1: 3D Printing flow diagram

2. Methodology

2.1. nTopology Design Strategy for 3D Printing

nTopology is used because it's field-driven and rule-based, which works extremely well for lattices, topology optimization, and lightweight structures that traditional CAD struggles with. Topology is a branch of mathematics that studies properties of shapes and spaces that don't change under continuous deformations. The phenomenon of fast fashion has aroused the need to apply methods that will accelerate time-to-market duration amid limited product life cycles [4]. A "continuous deformation" means stretching or bending, but not tearing or gluing. As foot structure evolves, the areas of high peak pressure also shift. To address this, individualized algorithms and 3D printing can be used to create rockers and self-adjusting pressure-reducing insoles [5].

2.2. Concept Design

This is the ideation phase and the initial phase. Define the problem, function, and user requirements based on the end user requirement. Sketch ideas (hand sketches or digital) for discussing with the clients for finalising for proceeding to the next stage. These explorations would the form or shape, the ergonomic issues the customer would face and the feasibility of the production process. 3D printing allows for precise customization and personalization of footwear products to meet individual customers' needs and preferences. Through 3D scanning

trends. 3D printing builds components layer by layer

directly from digital models, eliminating the need for moulds and reducing material waste. A growing sense of

interdependence exists between developments in 3D printing technology, materials science, and digital design

tools [3]. Fig.1 show the flowchart the 3D printing process. In footwear, this technology is primarily used for midsoles,

insoles, uppers, and custom-fit components.

and data-driven design, bespoke footwear can be created, enhancing comfort and fit while enabling self-expression through style [6]. The basic set of constraints such as size, cost, strength and aesthetics would be finalised in this phase.

2.3. CAD Modelling

Based the design parameters and inputs obtained from the ideation process three-dimensional (3D) geometry models are done with suitable CAD software. Various dimensions with tolerance and other required features are calculated and applied. The manufacturing geometry are designed required for the product that need for the manufacturing. Figure 2 and Figure 3 displays the concept development by injection moulding and 3D printing by nTopology concept.

Figure 2. Show manufactured by injection moulding

Figure 3. Show manufactured by n-Topology concept

by 3D printing

2.4. Selection of 3D Printing Process

The most crucial consideration part of application of additive manufacturing is selecting the suitable printing technology based on the design needs. The various types of technology currently available in market for development are as follows:

a) Fusion Deposition Modelling (FDM): This is the most common and affordable type of 3D printing. It works by melting a plastic filament and depositing it layer by layer to build an object. Suitable for low cost, fast, good for prototypes for visual study. b) Stereolithography Apparatus (SLA): It's one

of the oldest and most precise types of 3D printing technologies. Instead of melting plastic like FDM printers, SLA uses liquid resin that is cured (hardened) by UV light. This process gives high details and smooth surface. c) Selective Laser Sintering (SLS): 3D printing that uses a high-power laser to fuse powdered material layer by layer into a solid object. Instead of printing with filament or liquid resin, SLS spreads a thin layer of powder (usually nylon or other polymers) across a build platform. A laser then traces the shape of the part, sintering (heating

and fusing) the powder where the object should be. This repeats until the part is complete. This is strong with no support structures and for complex parts.

The major consideration for choosing a 3D printing process are the final products strength requirement, the surface finish, the parts complexity, cost of manufacturing and the total lead time for the development process.

2.5. Material Selection

3D printing selection is the process of choosing the most suitable printing technology, material, and parameters based on the specific requirements of a project. It depends on factors such as mechanical strength, surface finish, dimensional accuracy, cost, production time, and intended application. For example, FDM is commonly selected for low-cost prototyping and simple parts, SLA is chosen for high-detail and smooth surface finishes, and SLS is preferred for strong, functional components with complex geometries. Material selection is equally important, as plastics, resins, and metals each offer different properties like flexibility, heat resistance, and durability. The benefits of using 3D printing, such as decreased material waste, cheaper production costs, and the capacity to respond quickly to market changes, make it an important instrument for competitiveness in the Indonesian footwear business [7]. Proper 3D printing selection ensures optimal performance, efficiency, and quality of the final product.

3. Result & Discussion:

3.1. Visualization

3D printing would present the design clearly and professionally for the rendering of the products, the exploded views with colour and texture with realistic lighting and backgrounds. For making use of the developed products for marketing and presentation to clients. 3D printing visualization is the digital process of transforming an idea into a detailed, three-dimensional model that can

be viewed, rotated, and analysed on a screen before it is physically created. It allows designers and engineers to see the shape, size, structure, and proportions of an object from every angle, helping them detect errors, refine details, and optimize functionality. Through colours, textures, and layer-by-layer previews, visualization shows how the object will be built during printing, including internal supports and material usage. Figure 4 shows the visualization effect and can be developed by 3 D printing process. This step improves accuracy, saves time and resources, and ensures that the final printed product closely matches the original design intent.

Figure 4. Concept visualization with different materials

3.2. Innovation Through Design and Customization

3D printing drives innovation by allowing designers and engineers to move beyond standard, mass-produced solutions and create highly customized, complex, and efficient products. Unlike traditional manufacturing, it enables rapid prototyping, design freedom, and ondemand production, which significantly reduces development time and cost.

Through design innovation, 3D printing makes it possible to create complex geometries that are impossible or expensive with conventional methods. Optimize structures for strength, weight, and material efficiency and iterate designs quickly based on testing and feedback. Through customization, it allows personalized products for prosthetics, footwear, and consumer goods. Small-batch

and one-off production without high tooling costs and tailored solutions for specific user needs or environments. Figure 5 shows a complex shoe designed and then developed by 3D printing process.

Together, design and customization via 3D printing transform how products are developed and delivered. Industries such as healthcare, automotive, aerospace, fashion, and architecture use this technology to create innovative, user-centred, and sustainable solutions.

Figure 5. Complex shoe development by 3D printing

3.3. Sustainability and Environmental Impact

Sustainability and environmental impact in 3D printing are often seen as more positive compared to traditional manufacturing, but they also come with challenges. 3D printing has strong potential to support sustainability by reducing waste, enabling local production, and improving material efficiency. this resulted in a reduction of the advantages typically associated with using less material— such as increased sustainability and lower costs—and shortened production time [8]. for each specific user, the appropriate optimized design can be determined and satisfy their demands [9]. The optimized results lead to the high quality, strength and performance product [10]. However,

its environmental benefits depend on how it is used, what materials are chosen, and how energy-efficient the process is.

3.4. Reduced Material Waste

Traditional manufacturing usually removes material (cutting, drilling, machining), which creates a lot of waste. 3D printing adds material layer by layer, using only what is needed. This can reduce material waste by up to 30–90% in some industries. For small, complex parts, 3D printing often uses less energy than conventional manufacturing. However, for mass production, traditional methods (like injection moulding) can be more energyefficient. So, 3D printing is more sustainable for prototyping and low-volume production, but not always for large-scale manufacturing.

4. Conclusion

In conclusion, 3D printing has transformed the way products are designed, developed, and manufactured. It enables faster prototyping, reduces material waste, lowers production costs for small batches, and allows for highly customized designs that were previously difficult or impossible to achieve. As technology continues to advance, 3D printing is expected to play an even greater role in industries such as healthcare, engineering, construction, and education. Its ability to turn digital ideas into physical objects with speed and precision makes it a powerful tool for innovation and a key driver of future technological progress. Additive manufacturing represents a futuristic paradigm shift in footwear manufacturing by merging innovation with sustainability. By enabling customized design, reducing environmental impact, and reshaping supply chains, 3D printing offers a viable pathway toward a more efficient and responsible future for the footwear industry.

References:

1) Vinod G. Gokhare, Dr. D. N. Raut, Dr. D. K. Shinde,

A Review paper on 3D-Printing Aspects and Various Processes Used in the 3D-Printing, International Journal of Engineering Research & Technology (IJERT), Vol. 6 Issue 06, June – 2017

2) Hajare DM, Gajbhiye TS. Additive manufacturing

(3D printing): Recent progress in the advancement of materials and challenges. Mater Today Proc. 2022;58:736–743. doi:10.1016/j.matpr.2022.02.391

3) Nugroho WT, Dong Y, Pramanik A. 3D printing

composite materials: A comprehensive review. Compos Mater. 2021: 65–115.

4) Ukobitz D, Faullant R. Leveraging 3D Printing

Technologies: The Case of Mexico’s Footwear Industry. Research-Technology Management. 2021; 64(2):20-30.

5) Malki A, Baltasar Badaya M, Dekker R, Verkerke,

Hijmans JM, Effects of individually optimized rocker midsoles and self-adjusting insoles on plantar pressure in persons with diabetes mellitus and loss of protective sensation, Diabetes Research and Clinical Practice. 2024; 207:111077.

6) Mr. Prashant Kumar Saxena, The Future of

Footwear: Exploring the Transformative Potential of 3D Printing, International journal of research culture society, ISSN(O): 2456-6683.

7) Ellysa Kusuma Laksanawati, Tjokorda Gde Tirta

Nindhia, Made Sudarma, Wahyu Susihono, The Application of 3D Printing in the Shoe Manufacturing Industry in Indonesia, Journal of Information Systems Engineering and Management, e-ISSN:2468-4376

8) FIRTIKIADIS, Panagiotis KYRATSIS, Konstantinos KAKOULIS and Nikolaos EFKOLIDIS, Computational product design and prototyping of customized sandals lazaros, ACADEMIC JOURNAL OF MANUFAC-TURING ENGINEERING, VOL. 23, ISSUE 1/2025

9) Kuipers, T, Wu J, Wang CC, (2019) CrossFill: foam

structures with graded density for continuous material extrusion. Comput Aided Des 114:37-50. doi.org/10.1016/j.cad.2019.05.003

10) Shreeprakash B, (2023) Review on design and

additive manufacturing of cellural lattice strucrtures by extrusion technologies. Academic J Manuf Eng. 21(3). doi:10.1201/b11341-40