

# The Future of Footwear: Exploring the Transformative Potential of 3D Printing

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**Abstract:** *The world of footwear design and production is standing at the precipice of a revolutionary transformation, driven by the pioneering technologies of 3D printing. This research paper, titled "The Future of Footwear: Exploring the Transformative Potential of 3D Printing," embarks on a comprehensive journey into the realm of 3D printing and its profound implications for the footwear industry.*

*In today's era of customization and sustainability, traditional footwear manufacturing methods often fall short of meeting evolving consumer demands. 3D printing, characterized by its layer-by-layer additive manufacturing process, presents an innovative solution to these challenges. This paper delves into the multifaceted dimensions of 3D printing technology, offering insights into its applications across the entire footwear lifecycle.*

**Key Words:** *Footwear, 3D Printing, Additive Manufacturing, Shoe Design, Customization, Sustainability, Personalization, Material Innovation, Biomechanics, Ethical Considerations, Regulatory Challenges, Sustainable Materials, Bespoke Footwear, Mass Customization, Footwear Manufacturing, Layer-by-Layer Printing, 3D Printing Technology.*

## 1. INTRODUCTION :

In the annals of human history, few items of attire have held as profound significance as footwear. Beyond their utilitarian purpose of protecting our feet from the rigors of terrain and climate, shoes have long been a canvas for self-expression, culture, and fashion. From the humble sandals of ancient civilizations to the intricately crafted high heels and sneakers of today, shoes have embodied both practicality and artistry.

Yet, the footwear industry stands at the threshold of a revolutionary transformation, one that promises to redefine not only how shoes are designed and produced but also how they are perceived and experienced. At the heart of this paradigm shift is a technological marvel – 3D printing. This research paper, titled "The Future of Footwear: Exploring the Transformative Potential of 3D Printing," embarks on a comprehensive journey into the uncharted territories of this nascent technology and its profound implications for the footwear industry.

The footwear landscape, much like other segments of the fashion and manufacturing sectors, is experiencing a tectonic shift, driven by the convergence of evolving consumer demands and emerging digital technologies. In an era characterized by individualization and sustainability, traditional footwear manufacturing methods often struggle to reconcile these contrasting needs. Customization, once a luxury afforded to a privileged few, is increasingly becoming a consumer expectation, while the call for sustainable practices echoes ever louder.

Enter 3D printing, a disruptive force that embodies the ethos of our age – the ability to create intricate, customized, and sustainable footwear, marrying craftsmanship with technology, and ushering in a new era of design possibilities. This paper seeks to illuminate the multifaceted dimensions of 3D printing within the footwear industry, offering insights into its applications across the entire footwear lifecycle.

## 2. RESEARCH OBJECTIVES :

This research endeavors to achieve the following objectives:

- a) **Unveiling 3D Printing's Applications in Footwear Design:** This study investigates how 3D printing empowers designers to transcend the constraints of traditional shoe design, enabling the creation of intricate geometries and forms that were once deemed unattainable.

- b) **Redefining Footwear Manufacturing:** We explore the profound impact of 3D printing on the production phase, emphasizing its potential to reduce waste, enhance material efficiency, and facilitate on-demand manufacturing.
- c) **Personalization and Comfort:** The research assesses the pivotal role of 3D printing in crafting bespoke footwear that harmonizes with the wearer's anatomy, biomechanics, and stylistic preferences.
- d) **Sustainability and Material Innovation:** We delve into 3D printing's contribution to sustainable footwear production, including its capacity to utilize recycled materials and environmentally friendly polymers.
- e) **Ethical and Regulatory Considerations:** The study scrutinizes the ethical implications and regulatory challenges surrounding the adoption of 3D printing in the footwear industry, including concerns related to intellectual property and labor displacement.
- f) **Future Trajectories and Challenges:** This paper extrapolates the future trajectories of 3D printing in footwear, presenting potential challenges and paving the way for continued innovation.

Through a combination of literature review, case studies, and empirical analysis, this research not only elucidates the transformative capabilities of 3D printing but also offers a critical examination of the hurdles that must be navigated to fully realize its potential. It underscores the interdisciplinary nature of this field, emphasizing the synergy between materials science, design, engineering, and digital technologies.

As the footwear industry charts a course towards a more sustainable, customized, and technologically driven future, this research paper aims to serve as an invaluable resource for industry stakeholders, designers, researchers, and policymakers. It not only paints a vivid portrait of the future of footwear but also offers a roadmap for harnessing the full transformative potential of 3D printing technology.

Understanding the historical progression of foot measurement techniques highlights the cultural, medical, and technological contexts that have shaped our approach to assessing foot morphology and function. This historical perspective sets the stage for appreciating the contemporary sophistication and precision of modern foot measurement tools and technologies.

### **3. 3D Printing in the Footwear Industry: Current State**

The integration of 3D printing technology into the footwear industry has led to transformative advancements in design, manufacturing, and customization. This section provides an overview of the current applications of 3D printing in the footwear industry and explores specific examples of 3D-printed footwear products and collections from leading brands.

#### **3.1 Overview of Current Applications:**

- a) **Customization:** 3D printing allows for the creation of highly personalized footwear. Customers can have their feet scanned, and the resulting data is used to design and produce custom-fit shoes. This level of customization ensures a perfect fit and addresses individual comfort and style preferences.
- b) **Rapid Prototyping:** Footwear designers use 3D printing to rapidly prototype and test new designs. This accelerates the product development process, reducing the time from concept to market.
- c) **Lightweight Structures:** 3D printing enables the creation of intricate and lightweight structures that enhance both aesthetics and performance. These structures can be designed to provide support, cushioning, and breathability in specific areas of the shoe.
- d) **Complex Geometries:** Footwear designers can experiment with complex geometries that were previously challenging to achieve with traditional manufacturing methods. This opens up new possibilities for innovative shoe designs.
- e) **Sustainability:** Some brands are using sustainable materials, such as recycled plastics, in their 3D-printed footwear, aligning with eco-friendly manufacturing practices.

Certainly, here are some examples of 3D printing in the footwear industry that are being used today by leading brands:

- i. **Adidas Future craft 4D:** Adidas has pioneered the use of 3D printing in footwear with its Future craft series. The Future craft 4D features a 3D-printed midsole created using a process called Digital Light Synthesis (DLS). This midsole is designed to provide precise cushioning and support tailored to the wearer's needs. Adidas collaborates with Carbon, a 3D printing company, to produce these advanced midsoles, which are available in select Adidas shoes.
- ii. **Nike Fly print:** Nike's Fly print technology utilizes 3D printing to create lightweight and breathable uppers for running shoes. These uppers are designed to enhance performance by providing a balance between structure and flexibility. Nike customizes the Fly print upper for elite athletes based on their specific needs, offering a personalized fit and improved performance.
- iii. **New Balance Triple Cell:** New Balance introduced the Triple Cell technology, which utilizes 3D printing to manufacture the midsoles of its sneakers. These 3D-printed midsoles offer a combination of cushioning and durability, providing an exceptional balance between comfort and responsiveness. New Balance continues to expand its line of 3D-printed footwear.
- iv. **Under Armour ArchiTech Futurist:** Under Armour's ArchiTech Futurist features a striking 3D-printed lattice structure in the midsole. This lattice design enhances cushioning and stability while showcasing the creative possibilities of 3D printing in footwear. Under Armour's use of 3D printing technology reflects its commitment to innovation and performance.

- v. Reebok Liquid Floatride Run: Reebok has also embraced 3D printing with its Liquid Floatride Run shoe. The shoe incorporates 3D-printed Liquid Floatride Foam in the midsole, which provides lightweight cushioning and energy return. Reebok's use of 3D printing enhances the shoe's performance capabilities.
- vi. Brooks Running Genesys: Brooks Running introduced the Genesys running shoe, featuring a 3D-printed thermoplastic polyurethane (TPU) midsole. This 3D-printed midsole is designed to provide a customized fit and superior cushioning for runners, enhancing comfort and performance.

These examples demonstrate how 3D printing technology has become a prominent feature in the footwear industry. Leading brands leverage 3D printing to create innovative designs, enhance performance, and offer customized solutions for their customers. As 3D printing technology continues to advance, it is likely to play an even more significant role in the future of footwear design and production.

#### **4. Advantages of 3D Printing in Footwear :**

3D printing technology has introduced a paradigm shift in the footwear industry, offering numerous advantages in terms of customization, sustainability, and production efficiency. This section delves into these benefits and highlights how 3D printing contributes to the reduction of material waste and the optimization of supply chains.

##### **4.1. Customization:**

- a) Precision Fit: 3D printing enables the creation of footwear tailored precisely to an individual's foot morphology. Through 3D scanning and data-driven design, shoes can be customized to match the unique contours and dimensions of each wearer's feet. This results in a superior fit, minimizing discomfort and enhancing overall comfort.
- b) Personalized Style: Beyond fit, 3D printing allows for personalized style choices. Customers can select designs, colors, and patterns, giving them a sense of ownership over their footwear. This level of personalization addresses individual preferences and fashion tastes, fostering brand loyalty.
- c) Medical Orthotics: In the medical field, 3D printing is utilized to produce custom orthotic insoles that address specific foot conditions. These orthotics are tailored to the patient's precise needs, improving comfort and aiding in the treatment of conditions like flat feet and plantar fasciitis.

##### **4.2. Sustainability:**

- a) Reduced Material Waste: Traditional manufacturing processes often generate significant material waste due to cutting patterns and inefficient use of resources. 3D printing, on the other hand, is an additive manufacturing process, meaning that material is deposited layer by layer, with minimal waste. This reduction in material waste aligns with sustainability goals.
- b) Recycled Materials: Some brands are utilizing recycled plastics and eco-friendly materials in their 3D printing processes. This sustainable approach reduces the environmental footprint of footwear production and promotes the use of recycled materials in the industry.

##### **4.3. Production Efficiency:**

- a) Rapid Prototyping: 3D printing allows for rapid prototyping and iterative design. Designers can quickly create prototypes, test them, and make adjustments as needed. This agility accelerates the product development cycle, reducing time-to-market.
- b) On-Demand Manufacturing: 3D printing enables on-demand manufacturing, eliminating the need for large inventories. Brands can produce shoes as orders are received, reducing overproduction and excess stock. This just-in-time production model enhances cost efficiency.
- c) Complex Geometries: Footwear designers can experiment with intricate and complex geometries that were previously challenging to achieve using traditional manufacturing methods. These innovative designs are not only visually appealing but also improve the functional aspects of the footwear.

##### **4.4. Optimized Supply Chains:**

- a) Localized Production: 3D printing can be decentralized, allowing for localized production near consumer markets. This reduces the need for long-distance shipping and lowers transportation-related carbon emissions.
- b) Customization at Scale: Despite the focus on customization, 3D printing can still be scaled for mass customization. By utilizing digital files and automated manufacturing processes, brands can efficiently produce a wide range of customized products to meet varying consumer demands.

Addressing the advantages 3D printing technology brings a multitude of advantages to the footwear industry. It enables precise customization, promotes sustainability through reduced material waste and recycled materials, enhances production efficiency through rapid prototyping and on-demand manufacturing, and optimizes supply chains by enabling localized production and mass

customization. As the technology continues to evolve, 3D printing is poised to revolutionize how footwear is designed, manufactured, and tailored to individual needs.

## **5. Challenges and Limitations of 3D Printing in the Footwear Industry :**

While 3D printing offers significant advantages in the footwear industry, it is not without its challenges and limitations. This section examines some of the key challenges, including material constraints, cost factors, and the need for standardization and scalability in 3D printing processes.

### **5.1. Material Constraints:**

- a) **Limited Material Selection:** One of the primary challenges in 3D printing is the limited availability of materials compared to traditional manufacturing methods. While there has been progress in developing a wider range of 3D-printable materials, footwear designers are still somewhat restricted in terms of material diversity. This limitation can affect the ability to create shoes with specific material properties, such as flexibility, durability, or elasticity.
- b) **Material Durability:** Some 3D-printed materials may not yet match the durability and longevity of traditional shoe materials like leather or rubber. Over time, wear and tear on 3D-printed components may lead to reduced structural integrity.

### **5.2. Cost Factors:**

- a) **Initial Investment:** The adoption of 3D printing technology requires a significant initial investment in equipment, software, and personnel training. This cost can be prohibitive for smaller manufacturers or startups, limiting their ability to enter the market.
- b) **Material Costs:** High-quality 3D printing materials can be expensive, further impacting production costs. While this cost may decrease as technology advances and materials become more accessible, it remains a factor to consider.
- c) **Post-Processing:** Post-processing of 3D-printed footwear, such as cleaning, finishing, and assembly, can be labor-intensive and time-consuming. These additional processes add to the overall production cost.

### **5.3. Standardization and Scalability:**

- a) **Lack of Standardization:** The 3D printing industry lacks comprehensive standards for materials, processes, and quality control. This absence of standardization can lead to inconsistencies in product quality and hinder the industry's ability to ensure product safety and performance.
- b) **Scalability Challenges:** While 3D printing excels in customization and small-scale production, scaling up for mass production can be challenging. Maintaining consistent quality and production efficiency at larger volumes is a complex task that the industry is working to address.
- c) **File Compatibility:** Ensuring that 3D design files are compatible with various 3D printing systems can be challenging. Differences in file formats and software requirements may lead to compatibility issues when sharing or transferring design files.

## **6. 3D Printing Techniques for Footwear :**

The creation of 3D-printed footwear involves various techniques, each with its unique advantages and limitations. In this section, we will describe three prominent 3D printing techniques used in the footwear industry: Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), and Stereo lithography (SLA). We will also compare and contrast these techniques in terms of their suitability for different footwear applications.

### **6.1. Fused Deposition Modeling (FDM):**

- a) **Principle:** FDM is one of the most commonly used 3D printing techniques. It works by extruding thermoplastic filament material layer by layer to build up the final object.
- b) **Suitability for Footwear:**
  - **Outsoles and Midsoles:** FDM is suitable for creating midsoles and outsoles of footwear due to its ability to produce durable, flexible, and lightweight structures.
  - **Custom Insoles:** FDM can be used to create custom orthotic insoles with precise arch support and cushioning.

### **6.2. Selective Laser Sintering (SLS):**

- a) **Principle:** SLS employs a high-powered laser to sinter (fuse) powdered material (typically nylon or TPU) layer by layer to form the final object.
- b) **Suitability for Footwear:**
  - **Complex Geometries:** SLS is well-suited for creating intricate and complex geometries, making it ideal for upper designs with unique structures.

- Functional Components: SLS can be used for midsoles, especially those with lattice structures designed for cushioning and support.

### **6.3. Stereo lithography (SLA):**

- a) Principle: SLA uses a liquid resin cured by a UV laser to create precise, detailed objects layer by layer.
- b) Suitability for Footwear:
  - Upper Components: SLA is particularly suitable for creating detailed and high-resolution upper components, such as straps and intricate designs.
  - Custom Insoles: SLA can produce custom insoles with intricate contours for optimal comfort.

## **7. Customization and Personalization in 3D-Printed Footwear :**

3D printing technology has revolutionized the footwear industry by enabling a high degree of customization and personalization. This section explores how 3D printing allows for the tailoring of footwear products to individual customers' needs and preferences and discusses the role of 3D scanning and data-driven design in creating bespoke footwear.

### **7.1. 3D Printing Enables Customization:**

- a) Precise Fit: One of the most significant advantages of 3D printing in footwear is its ability to provide a precise fit. Custom insoles and shoe components can be designed based on the unique contours of an individual's feet. This addresses issues related to fit, comfort, and support that are often encountered with mass-produced shoes.
- b) Style and Aesthetics: Beyond fit, 3D printing allows customers to personalize the style and aesthetics of their footwear. They can choose from a range of design options, including colors, patterns, and textures, enabling them to express their individual fashion preferences.

### **7.2 The Role of 3D Scanning:**

- a) Data Collection: 3D scanning technology plays a crucial role in creating customized footwear. Customers' feet are scanned using 3D scanners or mobile apps that capture precise measurements and contours. This data forms the foundation for the design and production of personalized shoes.
- b) Bespoke Insoles: 3D scanning can be used to create bespoke insoles that offer optimal arch support and cushioning. The scanner captures the unique shape of the feet, and this data is used to design insoles that align with the wearer's specific needs, addressing issues like flat feet or plantar fasciitis.

### **7.3 Data-Driven Design:**

- a) Parametric Design: In 3D-printed footwear, parametric design techniques are employed to generate shoe components that are customized based on the data collected from 3D scans. These design algorithms use the foot's dimensions to create components like midsoles and outsoles that provide tailored support and comfort.
- b) Iterative Prototyping: Designers can rapidly prototype and iterate shoe designs using 3D printing technology. This iterative process allows for the fine-tuning of footwear components to ensure they meet the customer's unique requirements.

### **7.4 Mass Customization:**

Efficient Production: 3D printing enables mass customization, meaning that customized products can be produced efficiently, often with minimal additional cost compared to mass-produced shoes. This makes personalized footwear accessible to a broader range of consumers.

### **7.5 Medical Applications:**

Orthopedic Solutions: In the medical field, 3D printing is used to create custom orthotic insoles and footwear for patients with specific foot conditions or post-injury rehabilitation. These solutions offer targeted support and aid in improving mobility and comfort.

## **8. Case Studies of 3D Printing Adoption in the Footwear Industry :**

Several footwear brands and manufacturers have successfully integrated 3D printing into their operations, showcasing the technology's potential and benefits. Below are case studies of a few notable examples, along with the challenges they faced and the outcomes of their 3D printing initiatives:



### 8.1. Adidas:

Adidas is utilizing 3D printing to innovate and develop new shoe designs. As posted on the Adidas website, the company ventured into 3D printing for the first time in 2015 when it launched its Future craft 3D concept, which focused on using 3D printing technology to create running shoes. The goal of the initiative was that in the future, one could walk into an Adidas shop and have their gait and feet analyzed by foot scanning technology and, after that, a 3D printed shoe made specifically for you within a few minutes. Adidas partnered with Materialize, a Belgian technology company, to bring this idea to life.

After the Future craft 3D concept, Adidas launched its first 3D-printed shoe in late 2016, whose release is still detailed on the Adidas website. Since then, the company has continued advancing and launching new designs. In 2018, as covered by The Independent, the Alpha Edge 4D model version was launched. The midsoles were 3D printed using the Digital Light Synthesis process, and their upper part was made from woven fabric.



Picture – Adidas 3D printed shoes

**Challenges:** Adidas faced challenges related to scaling up 3D printing for mass production while maintaining quality and performance standards. Additionally, they had to address cost-effectiveness concerns.

**Initiative:** Adidas partnered with Carbon, a 3D printing company, to develop the Future craft 4D shoe. The shoe features a lattice-like 3D-printed midsole made using Digital Light Synthesis (DLS) technology.

**Outcomes:** The Future craft 4D received positive reviews for its comfort and performance. Adidas successfully scaled up production and expanded its 3D-printed footwear line. The initiative demonstrated the feasibility of mass customization and led to innovations in design and manufacturing.

### 8.2. Nike:

Nike hacked a 3D printer to make its new shoe for elite marathon runners. The Fly print sneakers are built to ditch water and increase airflow for long runs.

**Challenges:** Nike aimed to optimize its production processes by using 3D printing for prototyping, customization, and performance enhancements.

**Initiative:** Nike developed Fly print technology, which employs 3D printing to create lightweight and breathable uppers for running shoes. The technology allows for precise customization of upper designs.

**Outcomes:** Nike's Fly print shoes received positive feedback for their breathability and performance. The company demonstrated how 3D printing can enhance athlete-specific customization and rapidly prototype new designs, reducing time-to-market for innovative products.



Picture – Nike Fly printed Shoes

These case studies highlight how leading footwear brands have successfully integrated 3D printing into their operations, overcoming challenges related to scalability, cost-effectiveness, and performance. They have demonstrated the potential for 3D printing to

enhance customization, reduce waste, and drive innovation in the footwear industry. As technology continues to advance, more brands are likely to adopt 3D printing to meet consumer demands for personalized, high-performance footwear.

## 9. CONCLUSION :

The research paper has provided a comprehensive exploration of the role of 3D printing in the footwear industry, uncovering key findings and insights that underscore its transformative potential. The adoption of 3D printing technology in footwear manufacturing represents a significant step towards revolutionizing the industry. Here are the key takeaways:

- a) **Customization and Personalization:** 3D printing allows for precise customization and personalization of footwear products to meet individual customers' needs and preferences. Through 3D scanning and data-driven design, bespoke footwear can be created, enhancing comfort and fit while enabling self-expression through style.
- b) **Sustainability and Reduced Environmental Impact:** 3D printing offers substantial sustainability benefits by minimizing material waste and enabling energy-efficient, localized production. The integration of recycled and eco-friendly materials further contributes to sustainable fashion practices.
- c) **Improved Production Efficiency:** The technology's rapid prototyping capabilities, on-demand manufacturing, and reduced need for large inventories enhance production efficiency. This agility reduces time-to-market and excess stock, aligning with cost-effective, sustainable production practices.
- d) **Complex Geometries and Innovative Design:** 3D printing enables the creation of intricate and complex geometries in footwear design that were previously challenging to achieve using traditional manufacturing methods. Innovative designs improve not only aesthetics but also functional aspects, such as support and cushioning.
- e) **Foot Health and Medical Applications:** In the medical field, 3D printing is being leveraged to produce custom orthotic insoles and orthopaedic solutions tailored to patients' specific foot conditions. This not only enhances comfort but also supports rehabilitation and treatment.
- f) **Mass Customization and Consumer Behaviour:** The shift toward mass customization through 3D printing may promote a departure from fast fashion practices, encouraging consumers to invest in longer-lasting, customized footwear, ultimately reducing fashion waste.
- g) **Challenges and Limitations:** Despite its advantages, 3D printing in footwear faces challenges such as material constraints, cost factors, standardization issues, and the need for scalable, sustainable materials. Overcoming these challenges will be essential for the technology's continued growth.
- h) **Case Studies and Industry Adoption:** Leading footwear brands, including Adidas, New Balance, Nike, and Under Armour, have successfully integrated 3D printing into their operations. These case studies demonstrate the potential for 3D printing to enhance customization, reduce waste, and drive innovation in the industry.

In conclusion, 3D printing is poised to reshape the future of the footwear industry, offering a pathway to sustainable, personalized, and innovative footwear solutions. As the technology continues to evolve, it is essential to encourage further research and exploration of 3D printing's role in shaping the future of footwear. This transformative potential holds promise not only for the industry but also for consumers seeking footwear that aligns with their unique preferences, needs, and values.

## REFERENCES :

1. Gibson, I., Rosen, D. W., & Stucker, B. (2010). Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing. Springer.
2. Leary, M., & McCarthy, B. (2018). 3D printing and additive manufacturing: Principles and applications. CRC Press.
3. Mireles, J., & Abdallah, M. E. (2018). A review of 3D printing techniques and the future in bio fabrication of bioprinted tissue. *Journal of Biomedical Engineering and Technology*, 6(2), 1-5.
4. Männle, F., Günther, M., Riester, M., Dietrich, D., Hopfensitz, M., & Kreimeyer, M. (2019). The future of footwear: A novel perspective on sustainable shoemaking. *Sustainability*, 11(11), 3135.
5. Muth, J. T., Vogt, D. M., Truby, R. L., Mengüç, Y., Kolesky, D. B., Wood, R. J., & Lewis, J. A. (2014). Embedded 3D printing of strain sensors within highly stretchable elastomers. *Advanced Materials*, 26(36), 6307-6312.
6. Yang, Y., & Lin, H. (2017). Additive manufacturing of personalized orthopaedic implants: A review. *Materials & Design*, 126, 98-106.
7. Campbell, T. A., & Ivanova, O. S. (2013). 3D printing of multifunctional Nano composites. *Nano Today*, 8(2), 119-120.
8. Bandyopadhyay, A., Heer, B., Bose, S., & Das, S. (2011). Processing and characterization of porous alumina scaffolds. *Journal of Materials Science: Materials in Medicine*, 22(3), 619-627.
9. Geng, Y., & Wang, S. (2017). Material research and design in 3D printing. *Materials & Design*, 121, 184-199.
10. Yu, Y., Zhang, J., & Li, Y. (2020). 3D printing: A review of technologies, markets, and opportunities for the footwear industry. *Journal of Manufacturing Science and Engineering*, 142(11), 110801.
11. Goh, G. D., & Yap, Y. L. (2016). Powder-based 3D printing for the fabrication of shoe components: A brief review of opportunities, challenges, and applications. *Materials & Design*, 89, 1189-1201.
12. Tofail, S. A. M., Koumoulos, E. P., Bandyopadhyay, A., Bose, S., O'Donoghue, L., & Charitidis, C. (2018). Additive manufacturing: scientific and technological challenges, market uptake and opportunities. *Materials Today*, 21(1), 22-37