3D Printing Technology and Sustainable Design

Taiwen Zhang[1] and Jiayuan Lyu[2](✉)

[1] Brunel University London, Uxbridge, UK
[2] Royal College of Art, London, UK
Jiayuan.Lyu@outlook.com

Abstract. 3D printing technology, or additive manufacturing, offers significant advantages over traditional manufacturing techniques in terms of weight reduction, energy consumption, material utilization, and customization as well as sustainability. Notably, sustainable 3D printing methods have become crucial due to sustainable development strategies and environmental-friendly sustainable development practices all around the world. In this study, we analyze the advantages and sustainability of 3D printing technology in the production process, concluding that it is a significant driver of sustainable development. This study proposes three applications of 3D printing technology to promote a sustainable future for manufacturing and society, thereby reducing environmental impacts. By achieving goals such as reducing energy consumption, resource requirements, and carbon emissions over the product life cycle, inducing changes in the structure of the workforce. It will also shift the supply chain to a more digital and localized structure.

Keywords: 3D printing technology · sustainable development strategies · sustainable materials · mould manufacturing

1 Introduction

Manufacturing is the backbone of the world's real economy and the most innovative sector. Nowadays, nations around the globe are increasing their investment in manufacturing and employing cutting-edge technologies such as 3D printing to encourage the upgrading of manufacturing, which is a subject of company growth, comprehensive national strength, and international standing. Due to the introduction of new cutting-edge technologies such as 3D printing, the traditional manufacturing industry has been exposed to numerous drawbacks, including high labour costs, high energy consumption but low productivity, resource waste, and environmental damage. In response to these limitations, future development must place sustainability at the forefront. Sustainable Development is the concept of serving the present generation's requirements without sacrificing future generations' ability to do the same. Therefore, sustainable development is a long-term objective for society's multidimensional development. Environmental protection is equally as vital as technical innovation for reducing the human influence on micro and macro ecosystems. The technology of 3D printing provides an opportunity for sustainable development and the upgrading of manufacturing.

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From a social and environmental perspective, 3D printing's distributed production enables better working conditions for more people in more regions. In addition, 3D printing can eliminate waste in the manufacturing process through mass customization and logistical optimization. Consequently, many view 3D printing as a beneficial factor that can assist firms in operating sustainably. However, this is insufficient; 3D printing technology can be utilized in novel ways to lessen the social and environmental impact of manufacturing. Simultaneously, many businesses are adopting measures to cut energy usage, expand the use of recycled materials, and proactively design future-proof workspaces. Future manufacturing sustainability will focus on how to make 3D printing a more sustainable manufacturing technology. It will not focus on whether 3D printing is a more sustainable manufacturing technology.

Based on an analysis of the production principles of 3D printing technology and related industry applications, this study explores the impact and advantages of 3D printing technology in manufacturing and sustainable design by examining and applying the concept of sustainability and proposes recommendations to promote the sustainability of 3D printing technology and specific ways to integrate 3D printing with a sustainable design based on its advantages and the research conducted to date. The findings may have implications for sustainable design and production viability.

2 3D Printing Technology Overview

2.1 Origins of 3D Printing Technology

Officially referred to as additive manufacturing technology, the term "3D printing" has appeared since 1996. Due to the emergence of 3D scanning and additive manufacturing technology, 3D printing has been encouraged and developed since the late 1980s. Francois Willème, a French sculptor, patented a multi-camera solid sculpture in 1859 [7]. He simultaneously captured 24 cameras in a 360-degree circle and then outlined the model using a scale plotter connected to a cutting machine. This was the first time he invented a method for creating a multi-angle three-dimensional image of an object. Joseph Blanther, a Frenchman, created a method for creating topographic maps by layering contours on wax plates in 1892. The appropriate wax sheet was embossed with topographic outlines before slicing, layering, and smoothed. This became the fundamental tenet of additive manufacturing.

In 1986, American scientist Charles W. Hull invented the first 3D printer, which operates by first putting photosensitive resin into a container. A laser connected to a computer above the liquid surface controls the digital model data. The laser emits ultraviolet light in response to computer orders, and when a specific region on the liquid surface is irradiated by the ultraviolet light, the photosensitive resin liquid quickly undergoes a photopolymerization reaction and solidifies. Until the print is complete, a lifting platform below the liquid level is lowered by 0.05mm to 0.15mm increments. As the photosensitive resin on the platform cures layer by layer, the digital mold in the computer is eventually converted into a physical entity.

2.2 Concepts and Types of 3D Printing Technology

There are three types of manufacturing processes: subtractive, formative, and additive. 3D printing, typically known as additive manufacturing, is a form of additive manufacturing. It employs data such as computer models to manufacture objects by printing bondable materials such as metal powder or plastic powder, layer by layer, by machine. 3D printing technology is revolutionary for the manufacturing business because it accepts direct (CAD) instructions for the digital design of products and produces parts, moulds, and models without the need for molds and tools [4]. Listed below are some of the most prevalent and commonly utilized additive manufacturing technologies currently accessible.

Stereolithography (SLA)
Stereolithography is an additive manufacturing technique that utilizes photosensitive resin as the raw material and scans the photosensitive resin by sending a laser beam of light along the path of the digital model slicing information, causing the photosensitive resin to undergo a light-curing reaction and forming. The technology has the advantages of rapid speed and precision, but the drawbacks of high cost and environmental contamination (Fig. 1).

Fused Deposition Modeling (FDM)
FDM technology consists of servo motors, wire feeding mechanisms, nozzles, support materials, raw materials, and other components. It functions by melting the material inside the nozzle by heating the nozzle, then extruding it along a predetermined path with a particular amount of pressure, and ultimately creating it by stacking layers. This method offers the advantages of low cost, simple cleaning, and straightforward post-processing, but it also has the disadvantage of somewhat inferior precision and quality of the formed product.

Selective Laser Sintering (SLS)
SLS sintering technology employs a laser as an energy source to scan and irradiate the already laid powder along a predetermined path, bringing it to the melting point, sintering and glueing it to the formed part below. After the table has been created, it is lowered to a

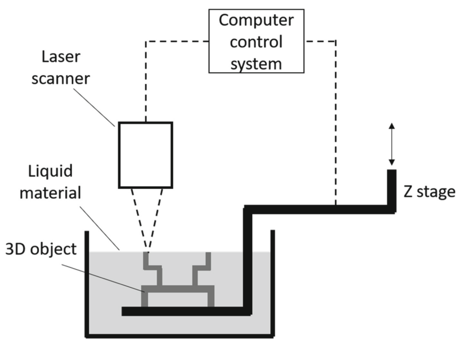

Fig. 1. Stereolithography 3D printing technology (Source from the web)

specified height and re-sintered. The surplus powder is collected and post-processed after the sintering is complete. This method has the advantages of a large variety of materials and a straightforward procedure, but the disadvantages of low forming precision and expensive prices.

2.3 Applications of 3D Printing Technology

2.3.1 3D Printing Technology in the Field of Art and Design

In art and design, 3D printing technology is extensively employed in industrial design, architectural design, handcraft manufacturing, and heritage restoration. With the advancement of 3D printing technology, the 3D printing market in the sphere of art and design has increased significantly. Although there are still various restrictions on the usage of 3D printing technology, resulting in a relatively low adoption rate, 3D printing technology has considerably facilitated the invention and growth of art and design. Why Not Provide a "Shelter" for Hermit Crabs? As a metaphor for the phenomena of worldwide social mobility, Japanese artist AKI INOMATA constructs unique "homes" for hermit crabs, merging the features of different places with the shells of hermit crabs [1]. As a metaphor for the global phenomena of social mobility, he combines the characteristics of other towns with hermit crab shells. The author 3D scans actual hermit crab shells, develops a digital model, and then merges the shells with architectural models of the city by applying software [8].

2.3.2 3D Printing Technology in Other Areas

Numerous industries employ 3D printing technology, including jewellery, footwear, construction, automobile, education, medicine, and even aerospace. In medicine, 3D printing technology has significantly contributed to the production of rehabilitation devices such as orthoses, bionic hands, and hearing aids. For instance, 3D printing technology has drastically transformed the conventional method of creating hearing aids. First, the staff uses a 3D scanner to collect the patient's ear canal data and transmits it to CAD software. Next, the program modifies the digital model of the hearing aid before transferring the data to the 3D printer.

In aircraft applications, the extraordinary benefits of 3D printing technology are represented in three primary areas. First, metal additive manufacturing streamlines the production of high-performance metal parts and structural components, lowering the time required to design new aircraft equipment [8]. Second, strategic aerospace materials, such as titanium and nickel-based high-temperature alloys, are often pricey. In conventional manufacturing techniques, the percentage of material utilization rarely exceeds 10 per cent. In contrast, items produced by metal additive manufacturing can be utilized with minimal processing, and the material utilization rate can reach 60 to 90 per cent. Thirdly, 3D printing technology can lower the weight of a component while preserving its performance by reducing its complex construction. In addition, optimizing the component's structure and stress distribution can effectively limit the incidence of fatigue fractures on the component, hence extending service life [3].

3 3D Printing Technology and Sustainable Design

3.1 Sustainable Design

The foundation of sustainable design is sustainable development. The term sustainable development first debuted in the 1987 publication Our Common Future, the first worldwide declaration. Sustainable Development is defined in the statement as "development that serves the requirements of the present without sacrificing the demands of future generations [6]." The declaration examines the environment and development holistically, stating that the sustainable development of human society can only be based on the sustainable and stable support of the ecological environment and natural resources, and that environmental problems can only be resolved within the context of sustainable development.

Today, sustainability is a prominent trend, and the evolution of sustainable design can be broken down into four stages, the first of which was the introduction of green design and the use of materials and energy sources with reduced environmental impact. This phase introduced environmental concerns as a design factor for the first time and significantly increased the social value of design. As the sustainable design was in its infancy, it did not develop sustainable methods capable of addressing critical concerns. Lifecycle design constitutes the second phase [2]. This stage, unlike the first, focuses primarily on using design to mitigate the environmental consequences generated by by-products at all stages and in all elements of their life cycle. The design of the product service system is the third step. This intervention occurs at the product and service design level, changing product design into service system design. Product and system design can integrate the numerous design aspects that exist in the social and corporate environment in order to generate new sustainable concepts and business models that represent the future of sustainable economic development. The fourth step is designing for social equality and harmony. This stage is an expansion and refining of sustainable design that focuses on social equality and harmony, as well as people's perspectives on consumption and values. This phase of sustainable design thinking focuses on the localization of design, the respect for cultural and species variety, and the care of disadvantaged people.

3.2 The Impact of 3D Printing Technology on Sustainable Development

By reducing the production process, 3D printing technology minimizes product lifecycle energy requirements and carbon emissions. Additionally, 3D printing technology decreases the demand for product manufacturing tooling and handling demands and reduces material-related indirect energy requirements by increasing material utilization. Additionally, 3D printing technology provides more cost-effective production or optimization of complex-shaped objects, resulting in lightweight designs [10]. A case study of an aircraft structural component demonstrates that 3D printing technology can reduce manufacturing-related energy requirements and carbon emissions by up to 75% and that the component's lightweight design saves an additional 63% of energy and carbon emissions over its entire lifecycle.

Additionally, 3D printing technology significantly decreases the investment in manufacturing resources because it only consumes the material required for the end product and the support material is frequently reused (except for FDM). In aerospace manufacturing, the ratio of raw material needed for the production of general parts to the amount of material in the finished product is typically 20:1. Nevertheless, 3D printing technology can obtain an almost 1:1 ratio [11]. Case studies have demonstrated that 3D printing technology may prevent up to 40 per cent of material waste while reusing 95 to 98 per cent of unfused raw materials. In addition, no environmentally hazardous compounds are created because the 3D printing technique does not require additives such as coolants and lubricants.

With high degrees of automation and the growth and transformation of localized production methods, 3D printing technology has prompted changes in the social structure and workforce. The high level of automation may have positive benefits for wealthy countries with a high rate of ageing, but it may bring unemployment and societal instability in densely populated emerging countries. The workforce must be restructured to accommodate the evolving structure of the supply chain. Depending on the viability of 3D printing technology for sustainable development, the application of 3D printing technology in an open-source manner may help socio-economic growth in lower economic regions.

3.3 3D printing technology combined with sustainable design

3.3.1 Applying Sustainable Materials in 3D Printing

Materials for 3D printing have long posed a significant barrier to the advancement of 3D printing, but they are also a vital driver of 3D printing innovation. The development of new materials can effectively increase the application areas of 3D printing technology; consequently, the development of sustainable materials is vital to the advancement of 3D printing. Currently, the most common materials for 3D printing are polymers, metals, ceramics, and composites.

Polylactic acid (PLA) is a thermoplastic polymer often produced from starch derived from renewable plant resources (such as corn, cassava, etc.) and is a new type of renewable, biodegradable material. PLA offers superior qualities, whereas most other regularly used polymers are derived from nonrenewable energy sources, such as the distillation and polymerization of petroleum. First, PLA is thermally stable, with a processing temperature between 170 and 230 degrees Celsius, and produces a product with strong heat resistance when printed. The performance of PLA goods created through these technologies can be equivalent to that of conventional polymers. PLA is also very biocompatible. L-lactic acid, the monomeric raw material of PLA, is a human-active substance, therefore 3D-printed PLA items are not only non-toxic and safe for the human body, but they can also be absorbed by the human body [9]. The most essential characteristic of PLA as a sustainable material is its superior biodegradability. Under particular conditions, microorganisms can entirely destroy PLA in the soil, producing carbon dioxide and water. The carbon dioxide created will be absorbed by soil organic matter or plants and will not be released into the atmosphere.

3.3.2 3D Printing Technology Involved in Product Manufacturing

Based on layer-by-layer manufacturing, 3D printing provides many advantages, including significantly reducing material waste. After 3D printing is complete, the material used to support the final object can be recycled as raw material, enhancing material utilization. Moreover, the majority of CNC-machined parts are made from more material than is anticipated to be consumed, and the ratio of lost material to actual material utilized in the final product can reach 19:1. Although these CNC-machined scraps are recyclable, they also result in the second consumption of energy and materials as well as environmental pollution. Existing low-cost 3D printers' manufacturing techniques can minimize energy consumption by 41–64%.

Multiple shipments are frequently necessary for conventional product manufacturing procedures, which causes large carbon emissions. However, in the life cycle of 3D printing, the distributed production approach considerably reduces the carbon footprint created by transportation. Before the product is delivered to manufacturing, the designer needs to edit the digital model or parameters to adjust the product's design. Even a product's design and production phases can be completed concurrently in various nations, reducing the need to ship the item many times. In addition, by simplifying or removing complex supply chains, 3D printing technology can drastically reduce transportation carbon emissions, further lowering environmental effects.

In addition, additive manufacturing does not necessitate the use of specialized equipment or fixtures and may be performed on demand, thereby minimizing or eliminating the environmental impact of stockpiling. Moreover, most 3D-printed objects are made up of a single raw material, which simplifies the end-of-life recycling process and reduces the energy waste and environmental effects caused by end-of-life disposal.

3.3.3 3D Printing Technology Replaces Traditional Mould Making

Due to concerns with production scale and cost, there are still a significant number of products and parts that cannot be fully manufactured by 3D printing technology. Therefore the mass production of such products and parts still requires conventional manufacturing techniques. Traditional tooling is a subtractive process that requires more material than 3D printing, often known as additive manufacturing. Second, in the conventional mould-making procedure, the product is assessed, a timetable for mould manufacture is formed before the digital model is modified, and the manufacturing part diagrams are decided. This demonstrates that the typical mould-making process is labour-intensive, material-intensive, and time-consuming.

Using 3D printing technology to produce moulds has numerous advantages over conventional approaches. First, 3D-printed moulds can shorten the duration of the development process. Traditional mould development requires a lot of time; however, 3D printing technology can directly create many mold samples for comparison, reducing production preparation time. 3D printing technology can enhance a company's product renewal rate by syncing moulds with product designs. Second, 3D-printed moulds can decrease production costs. 3D-printed moulds are far less expensive than traditional moulds, regardless of whether they are made of metal or plastic, especially for certain specialized forms. In a matter of hours, 3D printing can manufacture accurate moulds, and designers can swiftly complete mould iterations when revising moulds, hence minimizing the initial expenses involved with mould modification [2]. Thirdly, 3D-printed moulds can increase product functionality options. In conventional manufacturing techniques, many moulds are required to make the parts, which are then assembled. According to the benefits of 3D printing technology for one-piece moulding, both the number of parts and the number of moulds can be effectively decreased, hence streamlining the process of assembling the product for sustainable purposes. Fourthly, 3D-printed moulds for customized products are durable. In conventional mould production, designers must constantly modify the design of products and moulds based on customer requirements, which may be highly costly in terms of time, money, and personnel. 3D-printed moulds are particularly suited for customized products and may be generated straight from the finished product. This method of production is highly accurate and reduces tooling costs by a substantial amount.

4 Conclusion

Based on the characteristics and case studies of 3D printing technology and sustainable design development, this paper evaluates the benefits and significance of 3D printing technology in sustainable design. Sustainable Development is currently a practised development approach in every area of the global economy, including manufacturing. Due to the numerous benefits of additive manufacturing, 3D printing technology offers a more sustainable production method than conventional manufacturing techniques. Many sustainable materials are already available in 3D printing technologies in the materials industry. 3D printing may drastically cut a product's cycle time, reducing carbon emissions and material use from the design phase through production and reducing manufacturing costs. 3D printing also enables a more precise and straightforward presentation of customized products to fulfil the needs of a wide variety of users.

This study provides three 3D printing techniques for achieving sustainable design. One is to use more sustainable materials, such as PLA, in the 3D printing production. The second strategy is to reuse 3D printing scrap materials and employ distributed production methods to manufacture products. The third is using 3D printing technology to create components or product moulds.

Regarding the future of 3D printing technology, its regulation must be adapted to the new technological environment, including the adoption of clear legal laws and regulations about 3D scanning and the online publication of digital models. Moreover, if 3D printing technology can be put to mass production, it will significantly impact society's sustainability as manufacturing technology with enormous sustainability potential.

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