ISSN: 2634 - 8853

Journal of Engineering and Applied Sciences Technology

SCIENTIFIC Research and Community

Research Article

Open Access

Exploring the Potential of 3D Printing Production Model to Promote Sustainable Development

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ABSTRACT

Nowadays, in this volatile post-Covid era, there is an urgent need to develop new and more sustainable production models. The role of industrial production is crucial as it influences the EU economic resilience, it has a significant footprint on the environment while greatly affecting the social well-being of EU citizens. 3D printing is an expanding additive manufacturing technology with many applications in various industrial sectors. It involves the layer-by-layer fabrication of products through a CAD model or a 3D scanner output. The integration of 3D printing into the production process is increasingly attracting the interest of stakeholders. 3D printing technology provides access and participation in the production process to both producers and end-consumers. Despite the multitude of challenges, 3D printing is gaining ground, paving the way for innovative production while promising to promote a new model of sustainable industrialization

The main question raised is whether 3D printing technology is a more sustainable production process in relation to the conventional production model. Can 3D print play a role to the reduction of the industrial environmental footprint? Is 3D printing able to contribute to the development of circular economy and the democratization of production, leading to a new model of sustainable industrialization? What applies so far and how does it respond to the new challenges in relation to the conventional production model? Which are the 3D printing dimensions affecting its sustainability?

This review paper makes an important contribution to the growing area of research on the impact of additive manufacturing, identifying and proposing a new categorization of the factors that affect the sustainability of production through 3D printing. Selected case studies are presented to describe and clarify the literature references. The goal of this review is to investigate whether 3D printing is already or could be a better and more reliable production procedure in the near future, in line with the three pillars of Sustainable Development.

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Received: May 14, 2025; **Accepted:** May 17, 2025; **Published:** May 28, 2025

Keywords: 3D Printing, Additive Manufacturing, Sustainable Production, Sustainability

Introduction

The earliest years of the 21st century have been characterized by significant progress in various fields such as science, medicine and technology. Nevertheless, they have also been marked by numerous serious crises, including the global financial crisis, the recent health crisis of the COVID pandemic and the ecological crisis. Those issues call for the imminent reconsideration of established practices and the application of new, effective and innovative ways that can lead to a sustainable future.

One of the sectors that merits reconsideration is without a doubt the standing industrial production model. In the last decades, 3D printing or "Additive Manufacturing" (AM) has proposed as an alternative to the traditional manufacturing processes, promising a greener, more viable and more inclusive model of production. To what extent however has 3D printing technology achieved to be truly sustainable?

The present article will attempt to answer this crucial research question. In order to do so, it is important firstly to provide some background into the concept of sustainability and secondly to get familiarized with the technology of 3D printing.

Sustainability seems to be a powerful buzzword nowadays. Yet there are too often misconceptions about its meaning. The idea of sustainability gained momentum in the 1970s, as a result of the action of the modern environmental movement and it was presented as a viable alternative to short-term, myopic, and wasteful behaviours [1]. In 1987, the UN World Commission on Environment and Development provided the most highly-regarded explanation of the term, defining sustainable development as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" [2]. Almost two decades later, in 2005, the World Summit on Social Development determined the three pillars mentioned below, that embody the full essence of sustainable development.

- Environmental protection
- Economic development
- Social development

The above areas form the backbone of many national standards and certification schemes, tackling the core challenges that the world is currently facing.

The latest widely accepted international document that promotes sustainable development is the 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015. The document is based on 17 Sustainable Development Goals (SDGs), which constitute an urgent call for action by all countries in a global partnership.

3D printing is a revolutionary technology with countless applications, which has been gaining ground in the last decades, as an alternative prototyping and production technique. The term 3D printing refers to the process of "*fabricating three-dimensional objects by layering two-dimensional cross sections sequentially, one on top of the other*", using a 3D printer and digital 3D Computer Aided Design (CAD) data under computer control [3,4].

It's fascinating history started in the 1980s, in the framework of rapid prototyping research. According to the ISO/ASTM 52900 standard, today there are seven main processes of AM technology: i. Vat Polymerization that includes Stereolithography (SLA), ii. Material Extrusion that includes Fused Deposition Modeling (FDM), iii. Powder Bed Fusion that includes Selective Laser Sintering (SLS), iv. Material Jetting that includes Bioprinting, v. Binder Jetting that includes Color Jet Printing (CJP), vi. Directed Energy Deposition that includes Laser Engineering Net Shape (LENS), vii. Sheet Lamination that includes Laminated Object Manufacturing (LOM).

The rapid technological advancements of the period 1990-2010, the improvement of 3D modeling and 3D printing technologies, the invention of new AM processes, the evolving capabilities and the increasing efficiency of 3D printers, the innovations in the material sector along with the rapid decrease of 3D printing cost boosted the popularity of 3D printing. They also rendered it accessible to different kinds of users, ranging from large industrial enterprises to individual hobbyists. By the early 2010s 3D printing was fostered in the collective consciousness as an innovative and affordable prototyping and production technique which could shape the future, meeting current and future needs [5].

Within a few decades 3D printing revolutionized a wide spectrum of sectors including healthcare, pharmaceuticals, construction, architecture, fashion, automotive, aerospace, defense, cooking, art, music and many more. According to a recent report from [6] "*The global 3D printing market size was valued at USD 16.75 billion in 2022 and is projected to grow at a compound annual growth rate (CAGR) of 23.3% from 2023 to 2030*". Having been established as a viable alternative to traditional production, the 3D printing industry promises that it can play a considerable role to the reduction of the industrial environmental footprint, the development of circular economy and the democratization of production, leading to a new model of sustainable industrialization.

The present paper will explore whether 3D printing is able to contribute to a more sustainable production process. Reviewing an extended literature base, it will shed light to the current environmental, footprint, the economic and social implications of 3D printing and will also discuss its response to the new challenges in comparison to the traditional production model. Moreover, the paper will identify and classify in two categories the factors that affect the sustainability of production through 3D printing.

The paper is structured in three main parts. The first part discusses the research methodology, the second part elaborates on the dimensions of 3D printing affecting its environmental, economic and social sustainability. A selected case study per category is presented to provide a better understanding of each clash of dimensions. Finally, the last part discusses the findings of the analysis and proposes a classification of the key factors affecting the sustainability of 3D printing into two main categories. The ultimate goal of this review paper is to examine whether 3D printing is already or could be a more sustainable and more reliable production procedure in the near future, in line with the 3 core pillars of sustainable development.

Research Approach

This study provides important insights into the sustainability of the 3D printing process, identifying the dimensions influencing it and setting an agenda for further research. The authors used a systematic methodological approach consisting of four distinct steps. The first step concerns the definition of the research question. The objective of this study is to examine whether and to what extent the innovative technology of 3D printing is compatible with the 3 main pillars of Sustainable Development. To achieve that, two fields need to be studied: the concept of the revolutionary 3D printing technology and the concept of sustainability. The second step deals with the data collection. The threefold concept of sustainability in 3D printing shaped the strategy of this step. The three main pillars of environmental, economic and social aspects of sustainability formed the methodological background. The research focused therefore on the identification of dimensions of 3D printing that determine its environmental, economic and social sustainability potential. Several papers which have been widely published in English over the last five years (2018-2023) were retrieved from Google Scholar and Scopus databases. Selected papers which have significant contribution and research interest yet they were published earlier than the aforementioned timeframe, were also included in the selection. The keywords used were "3D printing technology", "AM processes", and "Sustainability". The authors first read the abstracts, taking useful notes from each one and then, after making the first selection, studied the full-text articles, before proceeding to their final decision. The inclusion and/or exclusion criteria of the final selection depended on the usability and the contribution of the paper, as well as the degree to which the content was relevant to the research question. The third step of the methodology refers to the analysis and synthesis of the current state of knowledge. In this step, the authors critically managed the material gathered, examined the multivariate patterns of information, and classified it according to the three components of sustainability: environmental, economic and social. Finally, in the fourth step the authors, having gained deeper knowledge, drew conclusions and proposed another classification of the factors affecting the sustainability of 3D printing.

The scope of this research focuses on exploring and understanding the factors that refer to 3D printing and could contribute to the UN SDGs. Thus, the choice of a narrative literature review seemed to be the most appropriate and sufficient methodological approach to develop a conceptual framework, identifying any discrepancies or conflicting views. Although several limitations arose, due to information overlaps and knowledge gaps, the precisely defined search strategy, using appropriate terms, adequate databases and sufficient criteria, provided a map of the dimensions affecting the sustainability of 3D printing, promoting theory development and research.

Exploring the Dimentions Affecting the Sustainability of 3D Printing

Dimensions Affecting the Environmental Footprint of 3d Printing

3D printing technology expands in many industrial areas with various applications. Recently, research interest has focused on the sustainable development and application of 3D printing technology. New optimized materials, improved manufacturing processes, and innovative integrated systems support and drive the growing search for environmentally sustainable options in the 3D printing field. In what follows we will attempt to identify the key dimensions that determine the environmental footprint of 3D printing.

The literature review suggests that (1) the choice of the technology used in production, (2) the materials applied and (3) the printing settings alter significantly the 3D printing environmental impact.

Regarding the technology, stereolithography (SLA) is the first released 3D Printing method, where liquid feedstock turns into a solid object. This kind of resin material tends to harden when exposed to light. The 3D printing process takes place inside a vat, where through a laser, the resin is heated and hardened until the final solid object is formed. Fused Deposition Modeling (FDM) is a material extrusion (MEX) process, which commonly applies thermoplastic materials [26], such as Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS). The material is heated to a specific temperature and fed into a 3D printer nozzle at a certain extrusion speed. Afterwards, when the filament is melted, the building procedure begins.

Selective Laser Sintering (SLS) is a powder bed fusion (PBF) method, which applies powder feedstock. Similarly to SLA, the powder is heated through a laser device to reach a melting point forming the final object. Among the materials used metal, glass and ceramics are also applied. Laminated Object Manufacturing (LOM) is a sheet lamination (SHL) process, in which the different material sheets (usually paper or plastic) are sticked and cut together to formulate the final desired result [7]. According to ISO/ASTM 52900:2021, other AM processes involve Binder Jetting (BJT), Directed Energy Deposition (DED) and Material Jetting (MJT). Each process applies different technology requiring different energy consumption and producing different waste volume.

Specifically, PBF processes consume more energy than FDM methods. However, MEX methods produce less waste than MJT and BJT technologies. Recently, EcoPrinting came up as a new, innovative 3D printing process that works using a solar-charged battery, minimizing energy consumption. Additionally, new technological systems (nEMOS) are being integrated into the 3D printers to monitor environmental issues, report harmful gas emissions and calculate the sustainability level [8]. As a result, the selection of the appropriate technology seems to be a key aspect for the environmental footprint of 3D printing.

Literature review has revealed many material types used in AM. The most common material is the polymer that applies in different forms, like powder, resin, and solid filament. Special features, such as UV resistance, flexibility and toughness make it suitable for use in various industries. Concerning the polymers, Acrylonitrile-butadiene-styrene (ABS) and Polylactic acid (PLA) are mostly usable materials in 3D Printing. They are both eco-friendly, presenting differences in printing behavior and final results in printed objects [9]. Another material type used in 3D Printing is the metal. Automotive industry, as well as military and aerospace use metals to create spare parts. Finally, a promising material is also the ceramics. Mostly used in aerospace, healthcare and automobile industry, ceramics show great resistance in high temperatures unlike polymers and metals.

Innovative materials have already been tested. These materials require lower melting and printing temperatures; they are biodegradable and non-toxic, reducing at the same time both energy requirements and environmental pollution. Algae and corn-based plastic for example are plant-based materials used in 3D printing, which limit greenhouse gas emissions and contribute positively to the development of more sustainable production processes [10]. Recycled materials are also becoming dominant in 3D printing. Today, construction debris maritime industries' plastic litter food left overs can be transformed into filament, resulting in the reuse of valuable materials that were considered waste [11,12]. Based on the above, it is evident that the selection of the material used for 3D printing affects its environmental impact. 3D printer settings must be considered before "creating" an object. The temperature of the nozzle and the print bed determines the actual melting point of the material. The higher the temperature of the print bed, the better the adhesion achieved between the bed and the nozzle [13]. However, higher melting temperatures are likely to have a greater environmental impact due to higher energy consumption. The orientation of the model is another default parameter in the slicing program. There are two main directions: horizontal and vertical. Typically, empirical case studies suggest a 45-degrees orientation for easier support removal and better gaps between layers [14]. The printing direction of the object influences the final result, as it potentially changes its height, which leads to prolonged printing time and therefore to additional energy consumption and waste generation [15].

During the digital file edit, users can also set the support mode and infill patterns. Using the support option, where necessary, users ensure the successful printing of the model. In terms of the infill option, the user defines the pattern density, i.e. the extent to which the printed model will be filled. Based on the literature, there are several infill patterns, each of which provides a different effect on the final object, as durability and strength are affected [16]. A recent study shows that infill patterns that use at least 80% density create stronger and eco-friendlier models, as less material is used while printing time is reduced [17].

Finally, the environmental impact of 3D printing also depends on the layer thickness, which refers to the distance between two successive layers [17]. Several authors have examined the effects of layer thickness on final objects, arguing that as the thickness of a model decreases, the printing time increases [18]. Thus, for more sustainable 3D printing results, users tend to increase the thickness between layers in order to reduce the overall printing time while saving material.

Summarizing, 3D printing appears to be eco-friendlier and more sustainable, compared to conventional production processes. The key factors affecting the environmental footprint of 3D printing include the technology used, the material applied, and the printing configuration, including the 3D printer model, the filament color, the machinery temperature, the process speed, the model design and the slicing settings.

The Environmental Footprint of 3D Concrete Printing

Aiming for a better comprehension of the dimensions affecting the environmental footprint of 3D printing it is worth examining its application in the construction industry through the case of 3D

Concrete Printing (3DCP). The term describes the process of additive manufacturing with cementitious materials or real concrete, using large-scale 3D printers, which usually come as gantry or robotic arm systems [19]. Nowadays, 3DCP technology is used for the construction of residential units and complexes, schools, offices, places of worship, emergency shelters and installations including bridges as well as building parts (walls, foundations etc.) (Figures 1-4) [20].

Figure 1: A Complex of 3D Printed Residences by Mighty Buildings. (Source: [21])

Figure 2: 3D Printed Pop-Up Store in Dubai was made with a Mix of Clay, Sand, and Natural Fibers Using Construction Printers from WASP (Source: WASP)

Figure 3: 3D Printed Concrete Bridge in Nijmegen. (Source: Municipality of Nijmegen/Michiel van der Kley)

Figure 4: 3D Printed Pad Foundation by Hyperion Iberdrola and Peikko Group (Source: https://www.archdaily.com/979145/3d-printing-with-low-carbon-concrete-reducing-co2-emissions-and-material-waste)

The advantages of the technology in question, as compared to conventional construction, include higher construction speed and productivity, greater degree of design freedom, formwork elimination, lower need of labour and capability of construction in high-risk and remote locations. Besides those advantages, 3DCP is also celebrated as a catalyst that can potentially enable the transition to a more sustainable model of construction [20,22]. Which factors determine its ecological footprint?

According to a wealth of publications, the minimization of construction materials and waste as well as the selection of material used for 3DPC render it ecologically sound [21,23,24]. 3DPC, paradoxically does not usually use traditional concrete, as it presents poor extrudability and buildability [19]. Most of the time, 3D printable concrete is a cement-based mixture of several materials, that resemble mortar. The most sustainable materials used in 3DPC are the ones which can be sourced locally, such as local earth and clay, the ones made of recycled materials, such as waste concrete from demolished buildings, as well as some innovative materials developed for this particular use, like low-carbon concrete and polymer composite [20,23]. Such materials are environment-friendly, they reduce the construction's carbon footprint as well as the concrete consumption, that generates about 2.5 billion tons of CO_2 emission (about 8%) every year [21].

In specific, according to, 3DPC contributes to a 50% reduction in the environmental impact when compared with cast concrete construction [19]. Furthermore, 3DPC can reduce the material usage by 40%, and the material waste by 30%. It eliminates the noise pollution produced during the construction process while reducing the consumption of fuel and associated emissions related with the transportation and the operation of heavy construction equipment. More environmental benefits include the performance of 3D printed constructions made of sustainable materials after erection [23].

Despite the discussed merits however, the 3D concrete printing industry must overcome a number of challenges before it can effectively contribute to a noteworthy reduction of the environmental footprint of the construction sector overall. It is still a relatively expensive technology; it presents limitations in the construction scale that can accommodate and it is still restricted in a rather limited selection of materials. Furthermore, it requires high technical expertise for the printers' operation and maintenance while its results cannot always conform to the standing building regulations [20]. Moreover, there is still room for improvement of the environmental footprint of 3D Concrete Printing itself, too. 3DCP cement consumption, which produces high rates of CO_2 for its production, is still very high [23]. Furthermore, it is still too early to evaluate the performance of 3D printed structures during their full life-cycle and the related ecological impact.

Dimensions Affecting the Economic Sustainability of 3D Printing

In the new era of smart technology, the use of additive manufacturing leads to new forms of industrial economic competitiveness. The next industrial revolution is a fact due to 3D printing technology. In Industry 4.0, the use of additive manufacturing with its flexibility provides decentralized production processes, rapid prototyping, reduced complexity, as well as time and cost savings. Additive manufacturing is an option for more and more industries. 3D printing technology can affect supply chains, company strategies, competition, industrial geography, sustainability and production [25,26].

The process of converting the raw materials into goods creates the production chain. Many different steps are required to convert available resources (inputs) into products (outputs), such as designing, planning, manufacturing and selling. A new production chain is now a fact, with 3D printing technology having transformed the steps of production. While factors that affect traditional production are: waiting time, delivery cost, inventory cost and risk of unwanted stocked products, the additive industry can minimize the benefit of traditional economies of scale, rendering local production more economically sustainable [27,28]. 3D printing technology has the potential to simplify the supply chain and enable simultaneous manufacturing in multiple locations, close to the point of interest, with multiple benefits for the customer, the local economy and the environment [29].

With the use of 3D printing technology, there is no need of centralized manufacturing and less tooling are required, so supply chains are expected to become shorter [30]. Moreover, supply chains now include digital sketches mostly than physical goods [31]. Cost and minimization of processes in production are perhaps the most important features that characterize 3D printing production chain. The marginal production cost of 3D printing remains either the same or, in some cases, higher than the corresponding cost of manufacturing objects in the traditional way, mainly due to the high cost of the required materials and energy consumption. Printed objects are either finished products or semi-finished, while the storage processes of finished products and materials are absent, since the printing process starts after the sale of the digital file of the object. Products are produced as they are ordered and paid for by consumers and there is no unsold manufactured inventory, reducing the risk of inventory (fewer raw materials) or storage [26,32]. As no product assembly is required (items are printed in layers), that will affect supply chains and also reduce labor and distribution cost. Printing products in layers seems to reduce the labor costs.

Additionally, print after an specific order placement is another advantage of 3D printing as it doesn't stock inventory, unlike traditional manufacturing processes. This reduces costs and space as there is no need to print in large volumes unless is required from a customer's order. The 3D printing industries are only store digital sketches and begin printing when needed. A small or big change to the initial design can be made at very low costs by editing individual files without wastage of inventory (apart from "cloud" storage) and investing in tools. The cost of producing a differentiated product is zero (changes are made to the original digital file). With 3D printing technology, a design file can be transformed directly to a product, skipping many traditional manufacturing step [33].

Finally, what has really changed, in these new types of supply chain, is the role of the consumer. The advent of personal 3D printers has made it possible to manufacture directly at home, thus by passing the (physical) distribution stage.

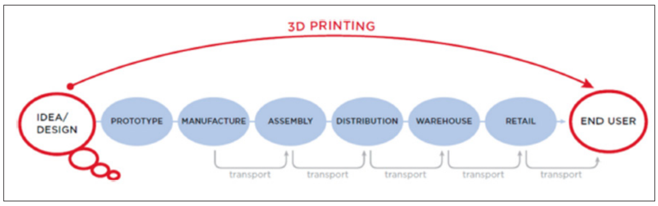

Figure 5: Shortening the Supply chain in 3D printing (Source: [34])

A simplified supply chain system for 3D printing materials is presented, where material reuse is emphasized Figure 5) [34]. 3D printed parts can be also recycled and used for further 3D printed parts using other manufacturing processes.

Production Operations Management (POM) Implications of 3D Printing During the COVID Pandemic

A number of papers at literature estimate the probability of using 3D printing technology for mass production. What does the use of additive manufacturing in production of large volumes really mean? Does it imply the replacement of machines by 3D printers, when all other procedures remain totally the same? Does it signify a new production model, with less processes and different structure of facilities? Until recently, 2020, when the covid pandemic, the literature claimed that we can't use 3D printing technology for mass production.

COVID-19 refuted this claim, highlighting that production in big volumes is be possible via the use of 3D printers. 3D printing industry was an alternative channel of supply medical equipment for local or national healthcare systems of the majority of affected countries. Hobbyists, enterprises, universities, and FabLabs 3D printed face shields, surgical mask straps, respirator valves, and adapters to turn snorkelling masks into non-invasive ventilators in order to protect both healthcare workers and individuals. The pandemic boosted the adoption of 3D printing technology of manufacturing industries.

Except from shorten supply chains, less steps in production chains, and less inventory, 3D printing could also transform manufacturing industries in terms of both operations and structure. At the two next paragraphs, we present the two different production models and we suggest that production by 3D printing seems to be more sustainable

In terms of operations, a traditional manufacturing flow chart comprises the following: facilities (building and maintenance), design (product development and design, detailed product specifications), manufacturing (tooling, fabrication, and assembly), quality assurance control, and industrial engineering (effective use of personnel, space, and machines). A factory's production line is shown in Figure 6. Every process of the product manufacturing chain is carried either internally or externally. The production management team based on the demands of the market chooses the type and the volume of production. Processes are done either internally or outside, depend on the facilities and machinery that a factory has available.

As shown at figure 6 product design, quality control, packaging, inventory management, and delivery processes essentially stay the same. Nonetheless, the work centers are not confined to the same area. This factory employs a large number of diverse labor centers that are dispersed over the same or another region or area. There may be one or more 3D printers operating in each work center. Using its own 3D printers, each work center creates objects based on the same digital file. Objects/Products are transported to a factory for quality control after printing. Following packaging, products are sent to designated destination centers and kept in inventory centers. The factory's management group coordinates this production according to batch size, problems that might arise, and questions about printers' settings

The following two Figures 6 and 7 present the structure of a traditional factory and a factory that produces by using 3D printers instead of machines

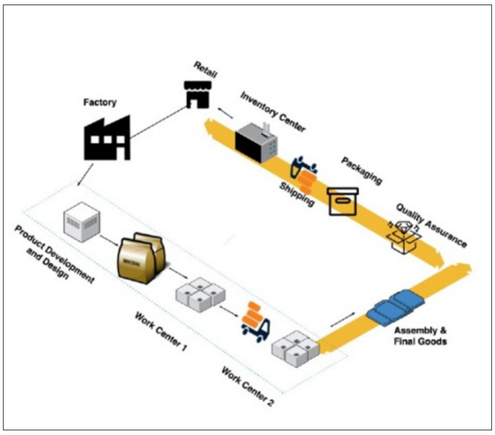

Figure 6: A traditional Production Chain (Source: [35])

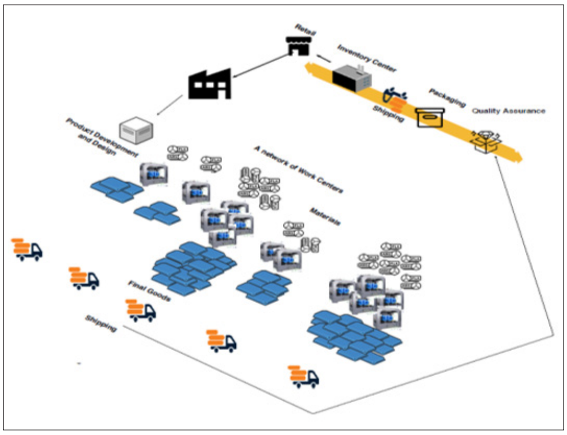

Figure 7: A 3D Printing Production Chain (Source: [35])

Based on observations on the structure and operations of global projects to print medical equipment, we draw the conclusion that large-scale production using 3D printing could be viable with this new production model. The main component of this production model is the external network of 3D printing units that take the place of internal labor centers. We conclude that using 3D printing technology, industry managed to provide a financially viable and sustainable alternative, solving important issues created by the coronavirus pandemic, to making a difference while saving lives [36,37].

The proposed production model is economic sustainable for two different reasons: (a) less carbon emission, (b) less expensive products due to less cost of transportation.

Dimensions Affecting the Social Sustainability of 3D Printing

According to economic theory, the means of production describes land, labour and capital, which can be used to produce products (goods or services). The concept of 'means of production' is used in literature in fields like sociology, politics and economics in order to discuss publicly the relationship between ownership and production.

In Marx's work and subsequently in Marxist theory socioeconomic evolution depends on the ownership of the means of production. Those who own machinery, tools, land, mines, buildings, vehicles and factories, are those who determine the rules, the social relations, the structure of the society and its economy. Marx's theory of class defines classes in their relation to their ownership and control of the means of production. The working class, comprises the majority of the population that lacks access to the means of production and are therefore induced to sell their labour power for a wage or salary to gain access to necessities, goods and services. Marx argues that individuals express their life and what they are, with their production; what they produce and how they produce it. The last infers to what Marx and Engels meant with the concept "relations of production". Individuals enter to some relations in order to produce and reproduce their means of life. The participation at these social relationships is not voluntary or freely chosen, these relationships are involuntary and constitute a stable and permanent structure of the society.

A new concept at social relations emerges with the wide use of 3D Printing or Additive Manufacturing. The means of production no longer belong to few but to many. Owning a 3D printer turns everyone to a small factory owner. All this, is called a flexible factory in the box". To go a step further, claim that 3D printing is the technology that will democratize the production chain [5]. The democratization has to do with the number of individuals who could use their own 3D printer and fabricate products at their home. To be more specific the ownership of 3D printer signifies two different aspects: (a) at production level: many and different points of production and obviously a different structure of a factory, as the work centres could be located at different geographical areas. Using 3D printing technology, anyone can participate in the production chain process and any computer can become a small factory and (b) at customization production level: customers will participate in the design of their objects either by using software to create a design, or by downloading a digital design from open access libraries such as thingiverse (www.thingiverse.com), and by customizing the initial file based on personal needs. In other words, 3D printing has the power to change the traditional manufacturing pattern, away from production in big volumes in centralized factories limited by tools and low labor costs, to a world of mass customization and distributed manufacturing, where the choice of manufacturing location is driven by demographics elements of demand rather than supply economics.

All above implies that individuals have access to free online libraries with various digital designs, with or without cost. This process turns consumers into "makers" and changes the role of individuals [38]. From simple buyers, they are turned into innovative producers. Ratto & Ree introduced the concept of "prosumer" a fusion of the words "consumer" and "producer" [39]. Customers can directly print goods using the digital designs and a (personal or not) 3D printer and steps between raw material and consumer become redundant. The supply chain is shortened, with the specialization of its functions and the digitization of the production chain [40]. Small or large quantities of custom products can be produced at relatively low cost, as changes to the digital file before printing are possible to meet individual consumer needs. The market structure is now more dynamic and the basic boundaries that existed tend to disappear gradually [5]. 3D printing gives ordinary people new powerful design and production tools and also changes the concept of product consumption.

Furthermore, the reduction of cost of "home" 3D printers, offers the ability of personal 3D printer usage and this could reshape business processes from the design of an object to its usage. Customers take part in 3D printing designing and co-create their products in an active way. Consumers propose ideas for new products based on their expectations and needs, or propose improvements on existing products in the market. A co-creation concept between customers and 3D printing industries enables producers to change their business model from manufacturing-centric mass production to consumer-centric mass innovation or customization [33]. 3D printing technology offers the ability to design an object without limitations and then print it. A new solid object is created through imagination. 3D printing is the technology that offers the means of production to everyone; the improvement of technology changes the social relations, changes the way we communicate and produce

Social Implications of 3D Printing During the COVID Pandemic

During the COVID-19 pandemic, many medical supply-chain shortages and logistical challenges were well taken up by 3D printing technology. What we have really learnt from the pandemic wave, is that 3D printing could change not only the production chain, but also individuals' behavior. 3D printing in combination with social media provided in the COVID-19 pandemic, a different social structure. Individuals not only communicated online but they also developed big fabrication projects. They were eager to embrace this innovative technology with great enthusiasm. 3D consumer printing showed a great potential to evolve into social rather than personal construction.

In detail, during the first wave of covid pandemic, new types of volunteers including hobbyists, 3D printing industries, research institutes and universities had joined their knowledge and tools against COVID-19. A number of initiatives that brought together all types of volunteers with providers of health care equipment had been developed in Europe, America, and Asia. These spontaneous initiatives were not identical in terms of operations or structure. They had many things in common and share the same mission, but they are not identical. All of these initiatives were networks of humans, 3D printers, health care institutions (hospitals or clinics), and in some cases public authorities. The goal of these initiatives was the production of 3D printed equipment which either helps healthcare workers to protect themselves, or helps patients who had been affected by COVID-19 and were being treated in hospitals to recover. Initiatives were popping all around the globe, most often on a local level.

Discussion and Conclusions

The present paper, reviewing an extended literature base, examined the potential of 3D printing to become a more sustainable production model in comparison to the conventional industrial production. The paper, after providing background information of the concept of sustainability and 3D printing technology, identified the dimensions that affect the environmental, economic and social sustainability of production through 3D printing, presenting various examples to further clarify the subject in question. Drawing from the analysis, we propose a categorization of the factors affecting the sustainability of 3D printing into two main categories:

The first category includes the technical characteristics of 3D printing. The analysis showed that factors such as the technology used, the material applied and the printing configuration, including the 3D printer model, the filament color, the machinery temperature, the process speed, the model design and the slicing settings greatly influence over consumption of raw materials, waste production and energy consumption. Therefore, the technical characteristics of 3D printing greatly influence its environmental footprint.

The second category includes the supply chain characteristics of 3D printing. It was illustrated that said technology performs simplified processes with fewer intermediate steps, fewer stakeholders and therefore reduced costs. Production is local and on-demand, so there are energy savings as neither stocking nor shipping is required due to the digital storage of the production models. 3D printing is also more space-efficient as a production method, due to the limited equipment size, which requires less land usage. Being open and accessible to everyone, 3D printing has paved the way for the democratization of manufacturing, while also allowing co-creation of innovative products and/or goods, through smart manufacturing. The supply chain characteristics influence the economic and social footprint of 3D printing.

Is 3D printing after all a more sustainable production model in comparison to conventional production processes? The discussion suggests that the answer lies in the careful choice of technical characteristics, the optimization of various aspects of the supply chain characteristics and the new operational structure of the production chain.

With respect to the technical characteristics, the right choice of technology seems to be critical for waste production. For 3D printing, always in relation to the intended application, it is necessary to give preference to technologies that are superior to others in producing reduced waste and less carbon emissions. The choice of feedstock needs to be targeted to the use of recycled and biodegradable materials, reducing shrinkage, melting points, post-process improvements, and consequently harmful gas emissions and air pollution. In addition, suppliers that offer recycled filaments, refillable cartridges, and/or waste returns should be preferred due to both environmental protection and economic savings. Finally, refining the 3D printer setup is an essential initial step for reducing the environmental impact of 3D printing and optimizing the printing process, the resulting quality, and the overall outcome.

Regarding the supply chain characteristics, a reduction in the costs of 3D printers and the filaments as well as a better familiarization of the public with 3D printing technology can render it more economically and socially sustainable Additionally two factors make the suggested reformed production model sustainably viable: Reduced carbon emissions and lower product costs as a result of lower transportation costs. Although mass and customized production is feasible via 3D printing technology, some other issues have emerged concerning the speed of production, the difficulty of following specific quality requirements and the intellectual properties of printed objects.

On the subject of social sustainability, democratization of means of production implies a very strong argument for healthy and voluntary or freely chosen relations. These relations could be the basis for sustainable communities and cities. Inclusion, accessibility, justice and peace are factors that improve a sustainable society [41-50].

The present paper showed that 3D printing has indeed a high potential to become an environmentally, economically and socially sustainable alternative to the conventional production process. Research interest is well advanced and sustainable applications have already been extended giving the first positive feedback. However, certain challenges remain to be researched to develop improved solutions regarding the sustainability of this technology. In conclusion, it is supported that 3D printing can be sustainable yet there are some steps that should be taken for achieving better results.

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