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Review

The Potential of Additive Manufacturing in the Smart Factory Industrial 4.0: A Review

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Abstract: Additive manufacturing (AM) or three-dimensional (3D) printing has introduced a novel production method in design, manufacturing, and distribution to end-users. This technology has provided great freedom in design for creating complex components, highly customizable products, and efficient waste minimization. The last industrial revolution, namely industry 4.0, employs the integration of smart manufacturing systems and developed information technologies. Accordingly, AM plays a principal role in industry 4.0 thanks to numerous benefits, such as time and material saving, rapid prototyping, high efficiency, and decentralized production methods. This review paper is to organize a comprehensive study on AM technology and present the latest achievements and industrial applications. Besides that, this paper investigates the sustainability dimensions of the AM process and the added values in economic, social, and environment sections. Finally, the paper concludes by pointing out the future trend of AM in technology, applications, and materials aspects that have the potential to come up with new ideas for the future of AM explorations.

Keywords: smart manufacturing; industry 4.0; additive manufacturing; 3D printing; industrial sustainability

1. Introduction

Nowadays, the business markets look for up-to-date manufacturing technologies to find a quick response for high demands of variability, efficient supply chain, and optimized energy consumption. As a solution, Industry 4.0 uses the benefits of the integration of modern manufacturing technologies and information systems to promote production capabilities [1]. In this context, smart manufacturing improves long-term competitiveness by optimizing labor, energy, and material to produce a high-quality product, and find a rapid response for variation in market demands and delivery time [2]. As shown in Figure 1, smart factories represent a new generation of the production system in the concepts of industry 4.0 and smart manufacturing and support advanced technologies such as computerization manufacturing, cyber-physical systems (CPS), big data, internet of things (IoT), cloud computing, and automated and robotic systems [3,4].

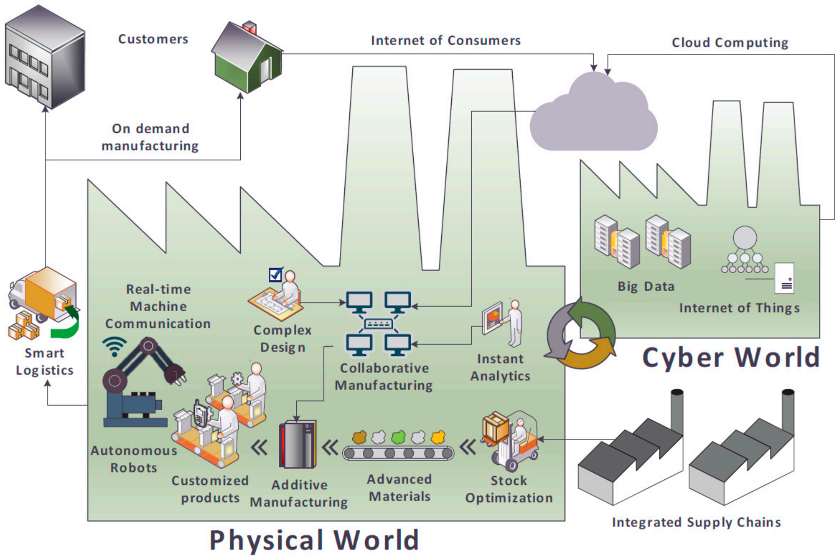

Figure 1. A schematic of smart manufacturing components in Industry 4.0 [4].

In a general view, IoT provides information, including machines, products, or production lines, from all physical objects through a wireless or network connection. Also, the other data sources gather all information about the suppliers, customers, and logistics, then this large quantity of data, which is called big data, is analyzed and investigated by cloud computing [4,5]. In fact, a cyber-physical system (CPS) shares information regarding all machines, utilities, and storage systems and controls them autonomously [1]. CPS technology can help to effectively improve the manufacturing process in the concept of smart manufacturing [6].

The additive manufacturing (AM) technique is applied for the fabrication of various structures and complex components. This technology was first employed by Charles Hull for the stereolithography (SLA) process in 1986 [7]. The other printing methods were discovered over the years and the application of AM technology was extended extraordinarily in only three decades and consequently transformed the manufacturing and logistics processes. There is a significant growth in the investment in AM technology from $4 billion in 2014 to over $21 billion by 2020 [8]. This growth is probably due to many improvements in AM technologies and materials which encourage the market for more investments in various industries, such as biomedical, aerospace, and automotive [4]. However, AM benefits attract many attentions in the field of manufacturing such as mass-customized production, prototyping, sustainable production, and minimized lead time and cost [9]. Recently, new developments in the AM process has made them more attractive, such as bioprinting, four-dimensional (4D) printing, nano-scale, and metamaterials printing [10]. Also, the other advantage of the AM processes is to help effectively smaller companies and end-users to develop their innovative designs and products themselves as a self-designer and manufacturer [11].

Obviously, AM can be a vital component of industry 4.0 or smart manufacturing due to its high capability as a non-traditional manufacturing approach for mass customization in industry 4.0. Among many advantages, the environmental impact of AM is very impressive in the improvement of sustainability in production systems compared to traditional manufacturing methods. The sustainability benefits of AM can be summarized into high resource efficiency, production life, and reconfigured value chain [12–14]. However, the evolution of AM has not been explored sufficiently and is limited to many types of research on individual production technologies, not comprehensively on the components of the manufacturing system. Although AM offers numerous unique capabilities in the manufacturing process, it should be considered in simplifying industrial production such as "design and manufacture" [15]. Table 1 summarizes the recently published works on the applications and advances of AM in smart manufacturing and industry 4.0.

Table 1. Summary of published works on this topic.

No	Author	Year	Topic	Description
1	Diogo José Horst et al. [16]	2018	Additive Manufacturing (AM) at Industry 4.0: A Review	The principles of 3D printing technology and its roles in industry 4.0. The influence of additive manufacturing as a key role in saving time and cost. The benefits of the additive manufacturing process e.g., higher flexibility and individualization of the 3D printing process.
2	Tuan D. Ngo et al. [7]	2018	Additive manufacturing (3D printing): A review of materials, methods, applications, and challenges	The main advantage of additive manufacturing in fast prototyping. The capabilities of additive manufacturing for producing complex structures, mass customization, freedom of design, and waste minimization. The industrial revolution of the additive manufacturing process in various industries e.g., aerospace, biomedical, building and protective structures. A fast transition from conventional machining and traditional methods to the development of manufacturing using 3D processes.
3	Arkadeep Kumar [3]	2018	Methods and Materials for Smart Manufacturing: Additive Manufacturing, Internet of Things, Flexible Sensors and Soft Robotics	Application of additive manufacturing for the factories in the future. Development in industry 4.0 and smart manufacturing systems using a 3D printing process for the existing manufacturing processes and systems. Developing and innovation in manufacturing methods and material using an additive manufacturing process.
4	Jinke Chang et al. [10]	2018	Advanced Material Strategies for Next-Generation Additive Manufacturing	The application of the additive manufacturing process in various fields and industrial productions e.g., microelectronic and biomedical devices. An introduction of the novel additive manufacturing process for the various type of materials including smart materials, biomaterials, and conductive materials.
5	Felix W. Baumann et al. [17]	2017	Additive Manufacturing, Cloud-Based 3D Printing, and Associated Services—Overview	Application of Cloud Manufacturing (CM) in the concept of a service-oriented approach over the internet. Historical development in the field of CM and AM in the smart manufacturing process between 2002 to 2006.
6	Ugur M Dilberoglu et al. [4]	2017	The role of additive manufacturing in the era of Industry 4.0	Recent development if material and process of the additive manufacturing process. The benefits of additive manufacturing in design improvement and industry 4.0. The current technological methods and highlights in the additive manufacturing process.
7	Sameer Mittal et al. [6]	2017	Smart manufacturing: Characteristics, technologies and enabling factors	A review of all published works on various applied technologies and process which are related to the smart manufacturing topic. A comprehensive list of the effective factors that are associated with smart manufacturing and industry 4.0.

Table 1. *Cont.*

No	Author	Year	Topic	Description
8	Mohsen Attaran et al. [18]	2017	The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing	The future of additive manufacturing and identifying the challenges, technologies, and trends. The benefits of additive manufacturing compared with the conventional machining and discuss its influence on the supply chain process. The potential of additive manufacturing and impact on the various industry.
9	Daniel R. Eyers et al. [15]	2017	Industrial Additive Manufacturing: A manufacturing systems perspective	The current applications of the additive manufacturing process in the industry. Investigation in additive manufacturing processes including mechanisms, controls, and activities. The development in industrial applications of the additive manufacturing process and the potentials and opportunities to improve the future of manufacturing.
10	Klaus-Dieter Thoben et al. [1]	2017	Industrie 4.0" and Smart Manufacturing A Review of Research Issues and Application Examples	An overview of smart manufacturing in industry 4.0 and identifying the current and the future states of technology. Analysis of cyber-physical systems (CPS) and investigation on the potential and applications of this system in production, design, and maintenance processes.
11	Sunpreet Singh et al. [19]	2017	Material issues in additive manufacturing: A review	A review of the biomedical applications of the additive manufacturing process. An introduction to Additive Bio-Manufacturing (ABM) technique for having a safer production and review the helpful papers on this topic.
12	Behzad Esmaeilian et al. [20]	2016	The evolution and future of manufacturing: A review	A review on the manufacturing systems and all published works on this topic. The future of manufacturing processes with a focus on design development and sustainability issues such as people, profit, planet.
13	Hyoung Seok Kang et al. [5]	2016	Smart Manufacturing: Past Research, Present Findings, and Future Directions	Analysis of smart manufacturing in the past, current applications, and its future by investigating various research papers. Investigation on a new paradigm of Information and communications technology (ICT) and manufacturing technologies in industrial revolution 4.0 or smart manufacturing, Effective and optimized decision-making processes in advanced manufacturing systems.
14	Mojtaba khorram niaki et al. [21]	2016	Additive manufacturing management: a review and future research agenda	Multidimensional, systematic, and quantitative analysis to discover the structure of the additive manufacturing process in various scopes including management, economic, and business. An investigation on eight principle scopes of the research including: additive manufacturing process, supply chain management, production design and cost model, strategies challenges, manufacturing systems, sustainability, innovation, and business model.

Table 1. *Cont.*

No	Author	Year	Topic	Description
15	Yan Lu et al. [2]	2016	Current Standards Landscape for Smart Manufacturing Systems	This report provides a review of the body of pertinent standards – a standards landscape – upon which future smart manufacturing systems will rely. This report will allow manufacturing practitioners to better understand those standards useful to the integration of smart manufacturing technologies. The report concludes that existing manufacturing standards are insufficient to fully enable smart manufacturing, especially in the areas of cybersecurity, cloud-based manufacturing services, supply chain integration, and data analytics.
16	Tim Stock et al. [14]	2016	Opportunities for Sustainable Manufacturing in Industry 4.0	Various opportunities in sustainability issues in smart manufacturing industry 4.0. Development in sustainable manufacturing and provide solutions in the manufacturing processes.
17	Simon Ford et al. [13]	2016	Additive manufacturing and sustainability: an exploratory study of the advantages and challenges	An overview of advanced manufacturing processes and technologies such as additive manufacturing process. Benefits and challenges of the additive manufacturing process on sustainability issues in terms of business model, value chains, and innovation.
18	Wei Gao et al. [11]	2015	The status, challenges, and future of additive manufacturing in engineering	Organization of comprehensive knowledge of the additive manufacturing process, current challenges, achievements and the trend of the future. The potential of the additive manufacturing process to achieve "print-it-all" image as the main goal of the AM process in the near future.

This paper attempts to give attention to the better understanding of the AM in real-world production and focus on the industrial AM systems which can be applied in the production of tools, prototypes, parts, and the entire product in the future of the manufacturing field. The goal of this paper is to classify the fundamental knowledge for investigating the current findings in materials and technologies, applications, and challenges surrounding AM, and provide a comprehensive study on AM's role in smart manufacturing and industry 4.0. The paper begins with an overview of the AM process, then the sustainable dimensions of the AM process, and concludes by outlining the potential of AM in the future of manufacturing.

2. The application of Additive Manufacturing (AM) in industry 4.0

2.1. An Introduction to AM

AM processes are basically the processes that add some materials to the previous surface via different deposition techniques that lead to different part quality, density, and geometrical accuracy [22,23]. The conventional processes are usually subtractive or a combination of several processes in case of complicated parts [24]. The major drawback of conventional processes is the high amount of material waste and lack of control systems to continuously modify the processes based on the current conditions. With the rise of computer-controlled machines, the latter problem is solved to some extent, but the material waste is still a challenge [25]. In the current era, which is also known as the fourth revolution of industry, Industry 4.0, it was decided to utilize the physical facilities with modern information technology [26,27]. The goal of this integration is that the control over different manufacturing processes will reduce while it is possible to make the fabrication in fewer steps with less time and material waste leading to a higher benefit–cost ratio [28].

All the AM processes are computer-controlled and it is possible to control an unlimited number of machines from a computer at once. The general procedure of all AM processes is that a layer of material is deposited, and this cycle continues to the point that the final 3D object is completed [29]. Some of these processes need post-processing and some of them make parts in net shape with the minimal processes needed to be done. Based on the materials used in a specific process, the source of deposition varies. The most common materials used in AM processes are polymers, engineering plastics, ceramics, metals, metallic oxides, and metallic alloys [30]. The feedstock is also available in different forms of solids and liquids, such as liquid polymers/resins, rods, wires, sheets, powders, etc. Depending on the used feedstock and its state of the material, different sources of energy are used, such as resistance heating coils, hot tubes, laser/ion/electron beams, ultrasonic vibration, and Ultraviolet (UV) light [31–36].

As mentioned, Industry 4.0 is a combination of information technology and highly controllable computer-driven machines [4]. AM machines of different types are such devices controlled by computers and the processes can be modified online with a single control unit [37]. As a result, this technology gives the opportunity to integrate many machines in a factory and control them online. The outcome of this combination is that a user-specific product can be produced within each machine [5]. This flexibility in the manufacturing of different products at the same time with the almost unlimited level of complexity provides the opportunity to utilize AM machines as an inevitable part of the modern manufacturing era. There are some terms used in this category of which rapid prototyping, rapid manufacturing, three-dimensional (3D) printing, smart manufacturing, and cloud manufacturing are the most used [38]. Cloud manufacturing refers to the processes that are highly service-oriented and can be modified online [6]. In order to clarify this process, a customer orders the desired geometry to be purchased. After accessing the design tools provided by a factory, they can change the materials, colors, and other aesthetic features of their desired product and at the same time, they can check the availability of the materials, machines, and the transportation systems. By checking all the items, the customers can easily upload their designs and receive their specific and unique product [39]. Figure 2 represents the collaborating segments in a cloud manufacturing scheme.

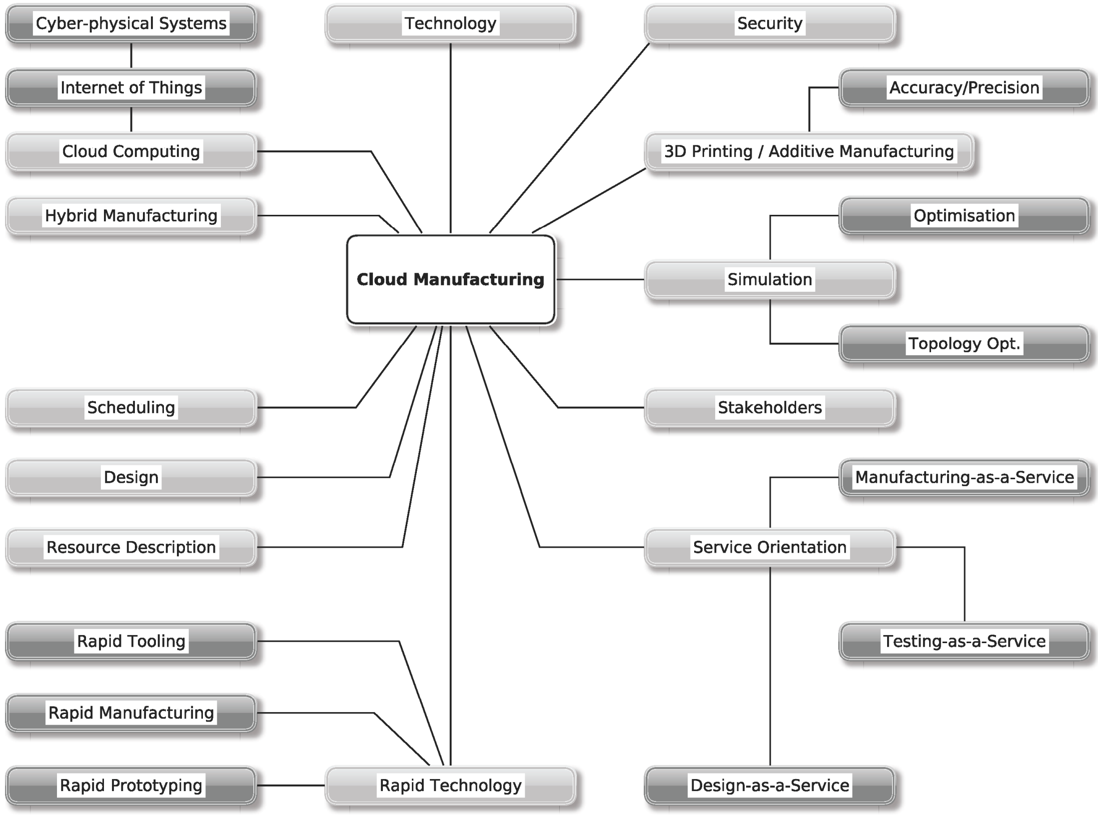

Figure 2. A flowchart of cloud manufacturing and the involved sections [17].

2.2. Different Types of AM

The AM processes, which are commonly utilized in manufacturing parts from engineering materials for different purposes, are extrusion, sheet lamination, vat photo-polymerization, binder/material jetting, powder bed fusion, and direct energy deposition [40,41]. Each of these processes is used to deposit different types of materials based on the energy source. The materials can change from polymers to ceramics and metallic compounds [42]. The extrusion method is mostly used for thermoplastics and requires high operating temperatures. The final parts usually suffer from high porosity but the low processing cost and flexibility in geometry increase its applications in making different mechanical parts. In addition, some researchers have tried to make ceramic-reinforced polymers with this method [43]. Vat photopolymerization is another process employing UV light to cure polymers layer-by-layer and the processing speed is high while it keeps the process' simplicity. In addition to polymers, researchers have tried to mix the polymers with ceramic particles to produce stronger mechanical objects with bio-applications [44]. Sheet lamination is another AM process, which assembles sheets of metal on top of each other in order to form a 3D object. In this process, different glues, welding, and brazing can be used to hold the sheets of material in place for a longer time, but ultrasonic welding is the most efficient and the most common [45]. The sheets are fed into the building area in the needed geometry and an ultrasonic head punches them against the previous layer and lightly welds them together. This process is known to be a cheap and fast process while the second material removal is needed after the parts are done [46]. Material and binder jetting are two distinct processes, but they work on the same principles that are binding materials to the main body of a part. In material jetting, polymers are usually melted and deposited in the shape of droplets to form the needed geometry. The molten polymers then undergo a curing process by heat, light, or chemical reactions to increase the bonding strength [47]. In binder jetting, there is a prepared bed of metallic powder laying under a jetting nozzle that disperses bonding polymers selectively on the surface of the metallic powder. After applying the polymer glue on the surface, a new layer of metallic powder is deposited, and the glue dispersion takes place. This cycle continues until the final shape is achieved. After that, the parts are sintered in furnaces with controlled atmosphere and different temperatures based on the metallic powders and the glue utilized to bond them together [48]. Usually, these two processes are considered fast, but the final product has some porosities. The best application of these processes is making selectively porous mechanical objects.

Powder bed fusion appears in different shapes and selective laser melting (SLM) is one of the most popular ones. In SLM, metallic particles are fed in different layer thicknesses and a laser beam melts the desired regions of the surface. In the next step, a new layer of powder is distributed on the build plate and the laser source melts the powder until the deposition finishes and the final shape is achieved. The sources of melting beams can vary based on conditions and price of the utilized machines [49]. The most common sources are the laser, electron, and ion beams. On the other hand, the atmosphere of the chamber is controlled by purging some inert gases to minimize the oxidation process during melting and solidification of the powder [50]. The most common gases used in SLM are nitrogen and argon. In some rare cases, it has been observed that the chamber is slightly vacuumed. In addition, the interesting feature of SLM is its capability in fabricating functionally graded materials from premixed or separate powders [51]. The other widely used AM process is known as direct energy deposition (DED). In this process, a laser head is utilized as the source of energy and the metallic particles are injected into the building region via a couple of powder nozzles just next to the laser head [7]. DED is significantly faster than SLM, but it suffers from lower geometrical accuracy of the final product. Thanks to its high deposition rate, it is possible to produce parts with a high aspect ratio (height to thickness) [52]. DED processes can be conducted in a controlled atmosphere or in the air. Since the feedstock is jetted via nozzles, DED consumes more powder to fabricate a specific part compared to SLM [53]. Figure 3 represents a schematic layout of an SLM mechanism and apparatus. In this figure, the powder reservoir provides the feedstock to the build chamber that is under the direct effect of the laser beam. The electronic source provides and controls the high energy beam of the laser in order to melt the selected regions of the powder bed. The powder spreading and laser melting are repeated a specific number of times and in a layer-by-layer manner, the final 3D component will be built by depositing metallic materials based on the surface geometry of each slice. In some modern machines, excessive powder can be recycled, which is a noticeable sustainability move in the additive manufacturing industry.

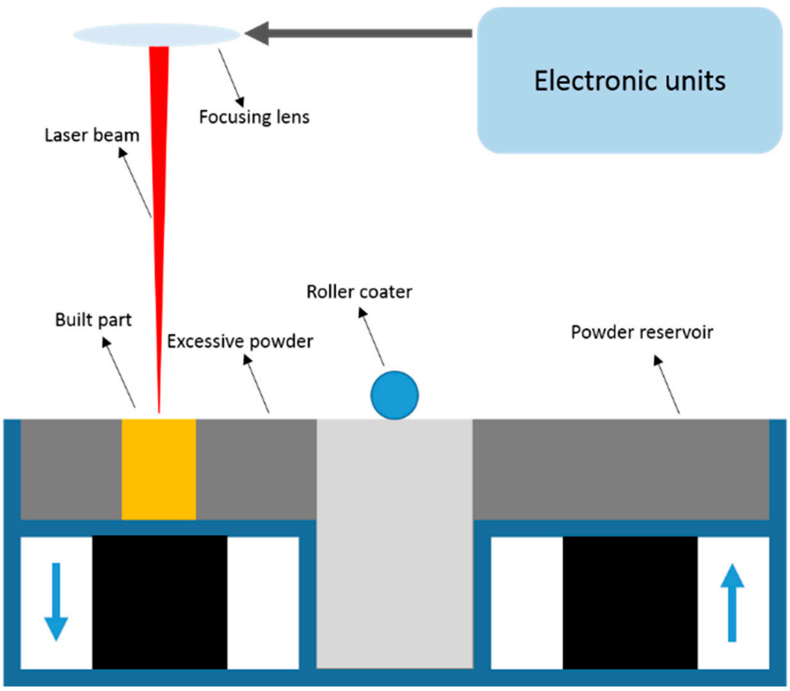

Figure 3. A schematic view of the selective laser melting (SLM) process.

2.3. The Advantages of Additive Manufacturing over Traditional Manufacturing Approaches

Different AM techniques have been developed not to replace all the traditional manufacturing methods, but to widen the selection range of processes for manufacturers and customers. Each process has its own advantages/disadvantages and the choice of which to employ is application-dependent. To review the advantages of AM processes, characterizing their key features is required. There are three important key features, i.e., time, cost, and flexibility, based on which the advantages of AM can be evaluated. One of the main purposes of using AM is to save manufacturing time and increase production speed. This will accelerate prototyping and reduces the time of production of spare parts and replacement parts [54]. Spare parts' supply chain performance can be improved by altering the location of manufacturing facilities and decentralizing manufacturing in different regional sites close to principle markets [55]. The benefits of distributed production related to spare parts include lower downtime, lower overall costs, lower capacity utilization, a reduced need for inventory management, higher robustness, and higher flexibility to supply chain variations [56]. Having manufacturing systems on-site enables rapid production of customized parts by eliminating the transportation time and cost of the parts. Unlike traditional manufacturing, where huge amounts of materials should be removed, AM applies materials proficiently by reusing the leftover materials for building the next part. Case studies have shown that the material waste in AM is reduced by 40% compared to traditional methods and 95% to 98% of the leftover materials can be recycled [57]. The cost-effectiveness of AM products could be related to the reduction of labor cost and avoiding costly warehousing as well. Moreover, AM does not require additional resources such as fixtures, cutting tools, jigs, and coolants. Plus, manufacturing to order reduces inventory risk, with no unsold finished goods.

Flexibility can be referred to as part of the process. Meaning that designers are more flexible to design complex parts and have the freedom to easily alter the process parameters based on their needs. Since there is no-to-little tooling constraints in AM, parts with complex geometries can be manufactured and part functionality would not be restrained by manufacturing constraints. Moreover, it is possible to build a single part with varying properties, having more strength in one part and more ductility in another part [58,59]. Furthermore, since the part quality is dependent on the process rather than operator skills, production can be exactly in line with customer demand. Figure 4 illustrates the interrelation of the three above-mentioned key features with the advantages of AM processes. All the benefits are related to one or two of the key features, such that any of the advantages are either to reduce the time and/or cost of the process or are a result of the flexibility of the AM processes. Despite all these advantages related to the AM technology, the process–properties–geometry correlation in AM components is very complicated and requires more investigations [60].

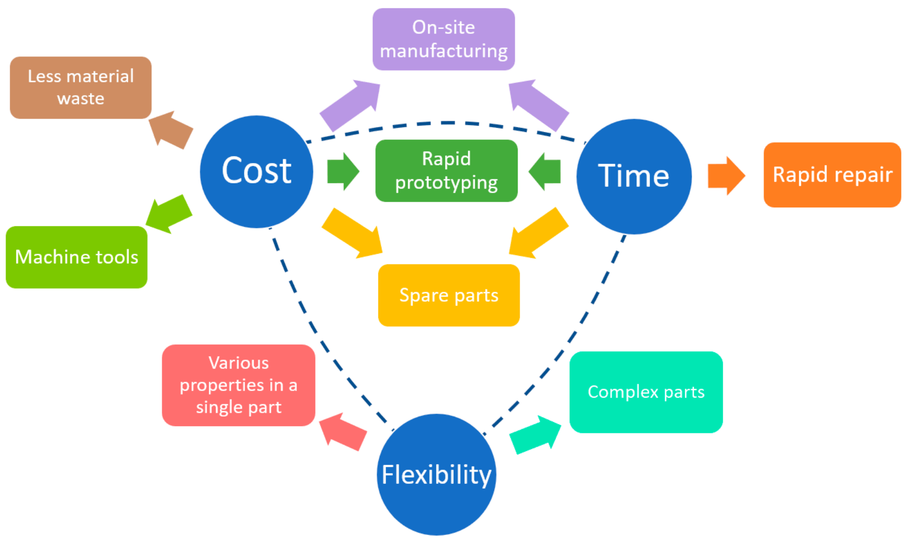

Figure 4. The interrelation between the three key features and additive manufacturing (AM) advantages.

2.4. Challenges, Obstacles, and Limitations

While AM is cutting-edge technology and finding its way in various industries due to its numerous advantages, there are several barriers against its rapid growth. The major challenges are as follows:

- **Imperfections:** Void formation between subsequent layers of materials negatively affect the mechanical performance of AM parts [61]. Parts produced using AM processes often reflect the stair-stepping effect, which is created by adding one layer on top of another and affects the surface quality and roughness. This nature of layer-wise production of components also results in parts with anisotropic mechanical properties microstructures [62]. In most of the AM processes, the surface finish of overhanging surfaces also, due to support removal, need to be post-processed.
- **Cost:** Not only are AM systems and materials expensive, but also a high cost in mass production is a major challenge for AM technology [63]. However, AM cost is reducing significantly compared to in the past. For example, the cost decreased by 51% from 2001 to 2011 for both machines and materials [28].
- **Production time:** AM technologies are more likely to be used in product customization rather than mass production, for which conventional methods are preferred [18].
- **Limitations of materials:** It is possible to use a wide variety of metals and polymers in AM technology [64,65]. However, some interesting materials, such as magnesium and biodegradable polymers, need further research.
- **Size limitations:** AM systems are limited regarding the production of parts bigger than their build chamber. Even regardless of build chamber size restriction, an extended amount of time is required for the manufacturing of large-sized objects [30]. Nevertheless, a technology called Big Area Additive Manufacturing (BAAM), which was developed in recent years, has overcome this limitation by being able to create large-scale parts [66]. Most of the design and application constraints of small-scale AM still apply to BAAM as well [67].

Research is being conducted to overcome the above-mentioned limitations. However, it is unlikely that AM technology will knock out traditional methods. Instead, they may be combined, and an integrated process could be developed to achieve the efficient production of complex products.

2.5. The Applicable Materials in the AM Process

In the current advanced technology, many applications need a combination of different materials to work with each other in order to satisfy a need [68]. The application of materials in smart manufacturing is critical, especially in the fields of sensing, Internet of Things, and human-robot interaction. On the other hand, it is needed to reduce the size of these components while improving their functionality, which results in complicated parts that require specific materials [3]. The need of advanced materials is divided into two different categories that are the high-tech materials for data transfer within the smart manufacturing components (i.e., machines, data transfer units, processors, semiconductors, etc.) and common materials for everyday applications (i.e., plastics/polymers, glasses, ceramics, metals, and their combination) [69]. In the former category, sensors consist of the largest portion of the applications that require a combination of insulators, conductors, and actuators, which change phase depending on the incoming signals [70]. In the latter group, a wide range of materials and their combinations are used in order to achieve the final object with the desired functions that might be simple or very complicated. These applications can be fabricating bioactive, hydrogels, biopolymers, piezoelectric, and phase-shifting parts of simple mechanical parts such as gears [10].

Based on Dilberoglu et al. [4], the used materials can be divided into four groups, including metals (stainless steel, aluminum, nickel and its alloys, cobalt, and titanium and its alloys), smart materials (shape memory alloys, shape memory polymers, and piezoelectric), hydraulics/electronics (conductive, solid-liquid, and multi-materials), and special materials (concrete, textile, etc.). The majority of the metallic materials is made by lasers or by binder jetting, which are consequently sintered in furnaces. These applied thermal conditions change the microstructure of the final parts and make it a crucial task to heat-treat the parts prior to use [71]. For the smart materials, it is important to keep the correct ratio of the components of the parts in order to keep their designed functions in the final part. In many cases, a slight change in the weight percent of the composition results in a drastic change in behavior or a reverse function [72]. For the hydraulic/electronic parts, the procedure is to fabricate solid bodies filled with specific liquids that are merely possible via conventional manufacturing processes, while it is impossible to fabricate such parts in one round. The problem for this group is that the process needs high levels of accuracy and precise material feeding, resulting in the need for precision machinery that is controlled in high accuracy to meet the resolution of these parts [73]. Table 2 represents a summary of the described methods, materials, and their applications along with information on their accuracy, advantages, and disadvantages.

Table 2. Summary of different techniques of AM, materials used, and other properties of these methods.

Technique	Materials	Application	Advantages	Challenges	Accuracy	Post-Processing	Reference
Direct Energy Deposition (DED)	Metals, ceramics	Industrial purposes, part repairing, implants, joining	High fabrication speed, high aspect ratios of parts, functionally graded materials can be obtained by several material nozzles	In some cases, the materials are burnt due to high laser power, the final part accuracy is relatively lower than SLM	100–250 µm	Heat treatment, in some cases a slight deburring	[73,74]
Selective Laser Melting (SLM)	Metals, ceramics	Industrial purposes, bio-applications, implants, actuators	Unlimited level of geometrical complexity, a wide range of metallic and ceramic powders, clean parts, high density	Fine powder is needed, fabrication chamber needs inert gas, slight metal evaporation in high laser powers	50–150 µm	Heat treatment, in some cases a slight deburring	[29,75]
Binder jetting	Polymers, ceramics, metals	Industrial purposes, research, bio-applications	High quality of the final part, high geometrical accuracy, flexibility in feedstock material	Residual thermal stresses, unwanted porosity due to using bonding materials	50–200 µm	Sintering, heat treatment	[76,77]
Metal jetting	Polymers, plastics	Desktop applications, research purposes, bio-applications	High speed of fabrication, high flexibility in process, low cost	Limitations in feedstock material selection, low geometrical accuracy in complex parts and it is not consistent	5–200 µm	Usually some slight deburring and residue removal with hand	[7,31]
Sheet lamination	Polymers, metals, and ceramics	Electronics, tissue fabrication	High speed of fabrication, low residual stresses	Low accuracy of the final product, chance of delamination under harsh thermal/mechanical conditions	Depends on the thickness of the sheets	Internal material residue removal, clamping in some cases that glue is used	[78]
Photo-polymerization	Acrylonitrile butadiene styrene (ABS), epoxy, polystyrene, acrylate	Biomedical, electronics, alpha prototyping	High geometrical accuracy, high surface quality	Limitation in feedstock material selection, low fabrication speed	<10 µm	Slight deburring	[79,80]
Extrusion	Thermoplastics such as ABS, Polylactic acid (PLA), polyethylene, polyether ketone, polycarbonate	Visual aids, educational models, alpha prototypes, tooling models	Simplicity, low cost, high speed	Low geometrical accuracy, low surface finish, only for polymers and thermoplastic materials	~100 µm	–	[81,82]

2.6. Hybrid Additive Manufacturing in Micro/Nano-Scale

The process of micro/nano-scale additive manufacturing is considered as the next generation of the AM processes and is highly under investigation for new opportunities and solutions to the new problems. Having parts in the micro/nano-scale requires precision machines that are accurately controlled by computers [10]. However, based on the literature, as yet, the best results are achieved out of hybrid manufacturing processes that are a combination of additive and subtractive processes [83]. These processes can take place either concurrently or in sequence to complete the required task from the machines and there is no limitation on the number of processes utilized in order to produce the 3D object. The goal of hybrid manufacturing is to get the input materials and change them to the final product in one machine or workstation [84]. On the same page, the goal of the hybrid manufacturing processes is to utilize AM processes as the primary step of the manufacturing and use the benefits of the other assistive processes to get the highest accuracy [85]. The idea of hybridization of AM machines with the other processes is that in most of the AM-fabricated parts, there is still a need for mechanical polishing. On the other hand, all these processes are computer-controlled and they can be easily integrated as a unit which satisfies the goal of Industry 4.0 [10]. As an example, an AM machine makes the core of a sphere and after that, a machining process reduces the burrs and increases the geometrical accuracy of the sphere. Figure 5 represents a schematic flowchart of a hybrid AM-machining process, which can be used in micro/nano-scale applications. In this process, the input material is fed into the system and a fully computer-controlled system and based on the feedback, it will go to the finished parts or it will go back to different stages of the manufacturing process. After the point that the part has met all the required criteria, it will pass the manufacturing stage and gets prepared for other steps prior to being delivered to the customers [85–88]. Figure 6 represents a future example of how hybrid manufacturing can be conducted in micro/nano-scale in order to have a final product in one machine or one workstation regardless of the steps which take place in order to complete the parts [82]. As it is shown, different computer-controlled processes are integrated into one station. In the first position, the support structures are deposited, and some machining processes will make the desired mold shape for polymer injection. At the second station, laser machining makes the ideal shape for part placement while a circuit maker provides the electronic connections embedded into the internal features of the component [89]. In the last station, the finalization processes take place to make the product that is, in fact, a complete product ready to work.

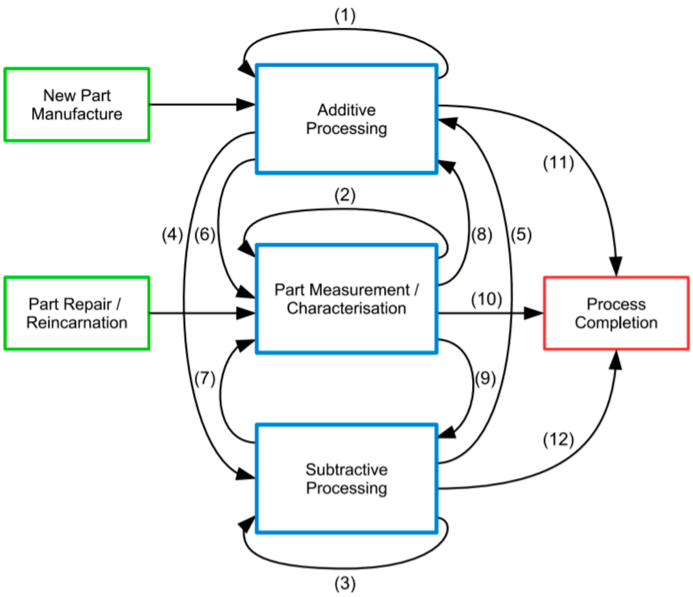

Figure 5. A closed loop of hybrid manufacturing for micro/nano-scale additive manufacturing [85].

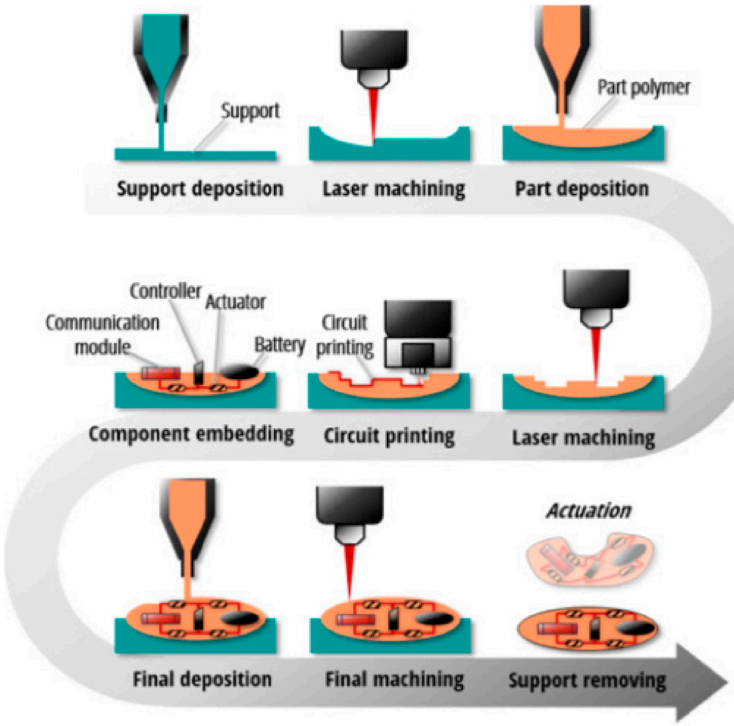

Figure 6. Schematic illustration of a future hybrid manufacturing process in micro/nano-scale [82].

2.7. Advanced Additive Manufacturing Processes

Additive manufacturing processes are proven to be reliable methods of fabrication for complex geometries, tough materials, and user-specific designs [90]. Although AM processes are being used in industries, their full capacity is not well exploited yet. Since AM machines are computer-numerical-controlled (CNC), they provide significant features to integrate the machines via computers and transfer data between the processing units. The benefit of this integration is that the processes can be controlled online, and the products can be highly customized [91]. In addition to that, digitization helps in continuous monitoring of feedstock monitoring, supply evaluation, and availability of machines for a fabrication process. Many different research groups have studied the proper modeling of digitized AM processes to increase the advantages of AM processes in industry 4.0. One of the proposed approaches is the hierarchical object-oriented model (HOOM), which considers different steps of fabrication from design to post-processing and includes evaluation of object features [91]. Industrial companies which fabricate mechanical objects via AM processes are continuously seeking to digitize their production processes by looking into different aspects of part design, tooling considerations, supply chains, and quality tests on the fabricated specimen throughout the life cycle of the parts they produce. The data generated in the whole stages of idea generation for a new product to waste management or reuse of the products can be digitally sorted and investigated to further optimize the parameters that are involved through the fabrication process. These data management and evaluation processes are known as a digital thread (DT) [92]. Considering the volume of fabricated parts via AM processes all over the world on different materials with different process parameters, a valuable source of data can be integrated to optimize the AM processes in use and take further advantage of them. Many US patents are published on different aspects of utilizing these huge data sets which emphasizes the importance of DT [93].

The other ability of AM processes is known to be cloud manufacturing including the internet of things, the utilization of cloud computing, virtualization, and advanced service-oriented manufacturing processes, for developing the most efficient models of manufacturing regarding material and equipment usage [94]. Based on a proposal by Jin et al. [95], to make the personalization of the products easy, smart product manufacturing and its service features are conceptualized to form a Smart Service Product (SSP) which attributes to the change in consumer attitudes and the development of advanced information communication technology (ICT). This concept can be utilized in managing and understanding the personalized demands of the market and the customers. The implication of SSP results in easy demonstration of customizable smart product design. Since the digitization of the manufacturing processes is closely related to the implication of computer-controlled machines, AM processes are the best targets of cloud manufacturing [96]. Lehmhus et al. [97], showed that data-related manufacturing processes, and especially AM processes, are based on automated machines which are precisely controlled by computers and as a result, there is always the flexibility of controlling and customizing processes based on customer needs and supply availability. In this case, product optimization can be conducted more efficiently, and the processes and software used for them are more user-friendly. Other studies showed that the AM processes can be investigated on process deployment, resource management, material flow, and task management in industry 4.0 which are not easily accessible in other manufacturing processes [98]. This shows the potential of AM processes as the future tools for making customer-specific products with the lowest price. Wang et al. [99] have proposed a new IoT-based cloud manufacturing process utilizing AM machines to share the hardware and software contributing to a single product and process. In this proposal, the feedstock material, 3D printer machine, and other physical equipment are shared while the knowledge of how to test the data to have a complete control over the printing process from beginning to the end was not investigated. This unique property is provided by IoT that was not available in conventional AM machines. In addition to all the discussed schemes of implementing AM processes in cloud manufacturing, Wang et al. [100] proposed that computer vision algorithms can be used to apply production planning in AM processes. In this process, the tasks are first sorted based on their importance, their order, the difficulty of fabrication, geometry of the product, etc., and the sorted tasks go through levels of fabrication and the computerized control over the process continues to the point that the product is finalized. The proposed algorithm is shown to be useful after verification with experimental investigations.

The physical phenomena that happen during the AM process have a significant influence on product quality. These physical phenomena are caused by the manufacturing paths employed to produce parts. Therefore, it is necessary to considerate them from the design step in the process [101]. Lately, CAD (computer-aided design)/CAM (computer-aided manufacturing), and Design for Additive Manufacturing (DFAM) have been developed to improve product performance by process, design, and materials [102,103]. Xiong et al. [104] proposed a method, which uses a data-driven approach in design and optimizes the successive steps of a design procedure. Another framework that benefits various businesses and technologies is big data and it is forming an interdependent relationship with AM. The use of big data-based analytics in the context of industry 4.0 helps to improve the process performance and energy efficiency and increases the quality of manufactured products. AM's reliance on big data grows with increasing AM applications in the industry since by its growth it needs more data to perform its capabilities [104]. Big data plays a role in CAD and quality control aspects of AM processes. In the case of the complex AM parts and structures, an alignment error or a fraction of a millimeter geometrical inaccuracy can be dangerous depending on the part application. This is where big data can analyze each AM process and inspect every element to find when these imperfections occur. These advantages encourage tool sharing to decrease the time and cost in product realization. Chan et al. [105] developed a novel cost assessment framework according to big data analytics tools being able to estimate the production cost based on a new job, similar to ones in the past. This framework can be implemented in AM processes, where the similarities of processes and parts are established by recognizing related features.

2.8. Applications and Industries

The three key features of AM processes discussed in Section 2.4, i.e., time, cost, and flexibility, result in benefits which interest many industries in using AM, especially industries which are in need of rapid prototyping and/or component manufacturing, which require low quantities of parts to be produced with certain specifications because industries dealing with rapid prototyping and component manufacturing are challenged by complex and customized parts production and on-demand manufacturing of components and prototypes. According to King's report [106], AM parts manufactured in automotive and aerospace industries have taken over 20% of the whole AM market. Following is a summary of the industries, which are interested the most in AM processes:

- Aerospace: AM techniques are ideal for producing aerospace components as they need small batches of components, which have complex geometries, which is necessary for airflow and heat dissipation functions [107]. Furthermore, on-demand and on-site manufacturing are needed to be established for astronauts to produce parts for repair or maintenance of space stations. Moreover, AM is capable of producing parts with a low weight-to-strength ratio, which is necessary for airplanes and space shuttles. Since the materials used in the aerospace industry are expensive and AM processes are known for having less waste material, AM has become popular among manufacturers in the aerospace industry.
- Medical: One of the first signs of AM appearing in the medical industry was producing medical implants [9]. In addition to high complexity in design, medical implants have the patient-specific necessity. As it is mentioned in Section 2.3, AM, compared to traditional techniques, is more cost-effective for manufacturing small batches of parts, which is typical in the medical industry. Manufacturing patient-specific implants reduce the cost and time of surgeries as well [108]. Hip stems with functional gradation in porosity characteristics have been made from Ti6Al4V by laser engineered net shaping (LENS) [109].
- Automotive: Complexity and low weight-to-strength ratio is a necessity for a part in the automotive industry as well. AM is not only used for prototyping for automobile parts, but its advantages have also made it able to be used for AM of actual components and vehicles [110]. For Example, Optomec used LENS to reduce the material, time, and cost of manufacturing of Red Bull Racing car components including drive shaft spiders and suspension mounting brackets [111].
- Architectural: From AM of historical buildings [112] to the construction of a village on the moon [113] the architectural industry has benefited from AM in two ways: models and construction. AM of models is an ideal tool for architects as it allows them to improve their designs on a smaller scale and refine their architecture plans. AM also benefits the construction industry by altering the three key features, that is decreasing production time and cost, and increasing flexibility.

There are other applications of AM which do not fall into the above-mentioned categories. Due to the flexibility and multifunctionality, e.g., load-bearing, while being lightweight, of AM lattice structures [113], they have been thoroughly analyzed for energy absorption applications [86]. AM has also been introduced to other industries such as food [114] and clothing [18], because of its flexibility and capability of manufacturing custom products on demand. Figure 7 illustrates how AM advantages are employed for different industries.

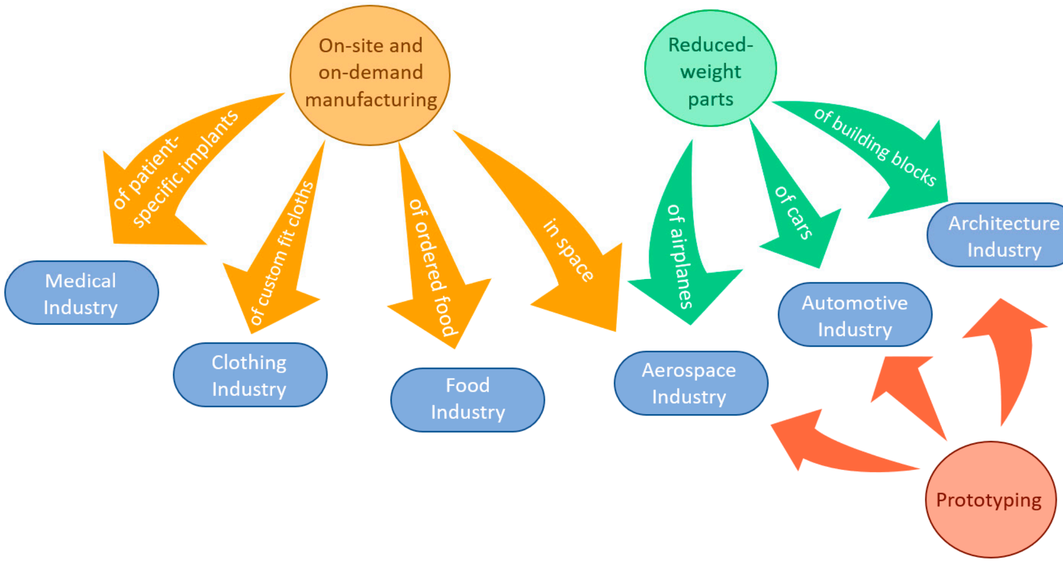

Figure 7. Application of AM features in different industries.

3. Sustainability of Additive Manufacturing

The Brundtland Report [115] defined sustainable development as "development that meets the needs of the present without compromising the ability of the future generations to meet their needs." As a matter of fact, sustainable development can be defined based on three principal dimensions, namely, economic, environmental, and social [116] that they are addressed by 6 R concepts: reduce, recover, recycle, reuse, redesign, and remanufacture [117]. Therefore, the aims of sustainable manufacturing are, according to the reduction of environmental impact, improving the social and economic impacts of the entire life cycle of the product [20].

Additive manufacturing (AM) has been known as an effective and sustainable production in advanced manufacturing processes, which has the potential to provide a number of sustainability advantages [13]. AM provides various opportunities to substitute the conventional manufacturing method as a higher sustainable production approach and minimize the carbon footprint in novel product and production development, and life cycle processes. As a matter of fact, the capability to repair, update, and remanufacture tooling shows an opportunity for considerable decreases in energy consumption, costs, and emissions [118].

3.1. Sustainable Benefits of AM

AM introduces numerous significant changes in product design, materials processing, manufacturing processes, and supply chain management. Compared to traditional production (such as machining, forging, finishing, casting, etc.), AM provides a great opportunity in sustainable production [119]. The advantages of sustainable manufacturing provided by AM processes are as following [120–122]:

(1) The less raw material which is required in the supply chain process;
(2) Higher resource efficiency in manufacturing processes;
(3) Reduced consumption, waste material, and pollution in the manufacturing process;
(4) Higher efficiency and flexibility in product design;
(5) The lower number of transportation processes and reduced carbon footprint;
(6) Decentralized and close-to-consumer manufacturing;
(7) Shorter supply chains, more localized production using innovative distribution methods, and collaborations;

(8) Extended product life by novel technical methods such as remanufacturing, reusing, repairing, refurbishing, and sustainable socio-economic production.

Value chains of AM are shorter, smaller, more localized, and they offer considerable sustainability advantages. Therefore, there needs to be a better understanding of value chain reconfigurations in the sort of interactions between stakeholders and relationships while the product life cycles are considered. As shown in Figure 8, four main fields exist in the life cycle of materials, in which the adoption of AM is conducted to improved resource efficiency. These main stages are (1) design of product and process, (2) the material processing, (3) product order and manufacturing processes, and (4) close loop with end-of-life production [13,123].

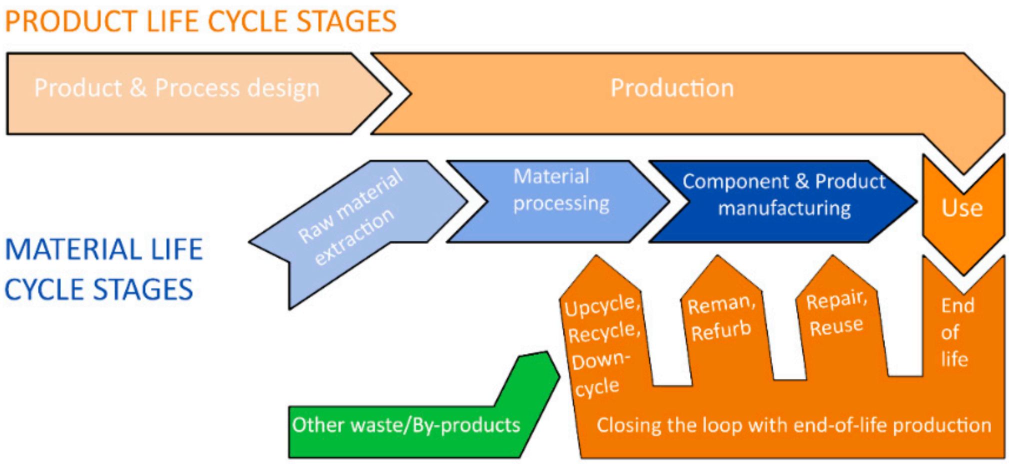

Figure 8. Product and material life cycle stages [123].

3.2. Sustainable Design through AM

The principal application of AM compared to conventional design is in the process of design. The prototyping process is traditionally too expensive due to the essential tools, molds, and specialized workers, whereas the application of AM has a significant influence on the manufacturing of prototypes in terms of time and cost. AM is also able to produce products that are geometrically more complex. The optimal design of AM leads to a reduction in the consumption of around 40% [21].

The definition of eco-design in AM is the consideration of the environment in every design process and fabrication process so that every step has the minimum environmental effect through the product's life [124]. Accordingly, eco-design can be applied as a tool for environmental assessment and environmental design. In this case, life cycle analysis (LCA) is the most appropriate tool to evaluate the environmental effect of a product, which is described in Section 3.3.2 with more details. The LCA analyzing method is employed by numerous users with focuses on the technicalities of the design, for example, the optimization of design and process. Moreover, the other assessment tools such as the Eco-Indicator 99 allow an earlier assessment, nonetheless, at the cost of an accurate evaluation [125]. In general, the applied tools for environmental design principally involve manuals, guidelines, or checklists (such as [126]), or using the green products for inspiration, e.g., the *Eco-Design Handbook* [127]. It leads to evaluate the environment in the design and product development process [125].

Sustainable product design is categorized as an extension of eco-design. Sustainable design is defined as "design which strives to fabricate products that diminish their impact on the environment" while it achieves acceptable economic profits and a positive effect on society at the same time [118,128]. Much research in sustainable product design focuses on features such as reducing the environmental effects of the resource, energy, and material usage while it regularly disregards understanding the quality of the design as a technique which maximizes product advantages [129,130]. Diegel et al. [128] showed that AM has a great capability to address both cost efficiency and design quality while it remains as an operative tool to empower sustainable product design. Hao et al. [119] presented that sustainable product design can be performed through the optimizing of internal lightweight structures. Table 3 demonstrates a summary of the benefits and challenges of sustainable AM process.

Table 3. Summary of benefits and challenges of sustainable AM process [13].

Advantages	Challenges
Product redesign	
Design freedom	Integrating sustainability using the design for
Optimized geometries and performance	environment or eco-design
Reduced cost and time	Training of designers and engineers concerning
Improved product functionality and durability	the potential utilization and benefits of AM
Simplified assemblies and products	Certifying new components
Upgradable and democratized design	
Material input processing	
Improved resource efficiency of raw material processing	Resource efficiency improvements and recycling potential restricted to specific materials
Decreased toxicity of material processing By-products from the waste flow	Increasing the percentage of recycled content in material inputs
Upcycling and recycling of waste materials Localized material recycling	Lack of knowledge of the environmental performance of material processing techniques
Component and product manufacturing	Restricted speed and reliability of AM
Decreased energy consumption	Restricted quality of products
Decreased waste production	High machine costs
Improved access to digital designs and manufacturing systems	Improving cost-effectiveness and energy efficiency at higher production volumes
Decreased material inputs	Lack of knowledge of the environmental
Simplified assemblies and supply chains	Performance of AM technologies and supply chains
Improved productivity, cost and resource efficiency	Requirements for standards and regulations
Product use	
Lightweight products Improved operational efficiency Improved functionality and durability Repair, remanufacturing and recycling Decreased waste produced during the repair process Decreased process time for repair Improved product utilization through repair and remanufacturing Improved material efficiency through recycling Increased acceptance of recycled material content	Uncertain performance of products and components due to low maturity of AM technologies Certifying repair and remanufacturing processes Performing maintenance systems Restricted recyclability of plastics due to quality losses Non-recyclability of AM-produced multi-material goods

3.3. Sustainability Assessment

In recent years, environmental issues of manufacturing processes have been at the center of attention due to the importance of resource-saving and environment protection. Therefore, sustainability studies are essential for AM before being commercially utilized [131]. Reducing fuel consumption in goods transportation and material wastes in manufacturing are the two large challenges in AM sustainability. Comprehensively overcoming these challenges and assessment of their real impacts result in a reduction in overall product cost and sustainability improvement [132]. Sustainability dimensions are progressively identified as an applicable tool for public communication and policy in order to carry information about country and corporation performance [121]. Reduction in energy/material consumption and transportation/packaging systems through different life cycle analysis (LCA) methods have been performed on AM processes in order to make them more sustainable regarding their economic, environmental, and social impacts. Figure 9 summarizes all aspects of the sustainability of AM processes based on three main dimensions.

Sustainability Additive Manufacturing		
Economy	**Environment**	**Society**
Market Evolution	**Resource Consumption**	Social Benefits
Novel Applications	Materials Demands	Labor Development
Supply Chain Management	Process/Life Cycle Energy	Product Quality
Production Costs	**Waste Management**	Public Acceptance
Machinery Costs	Recyclable/Non-recyclable Waste	Healthcare Improvements
Process Productivity	**Pollution Control**	Ethics
.....	Process/Life Cycle Emissions	.....

Figure 9. Sustainability dimensions of additive manufacturing [117].

3.3.1. Economic Impacts of AM

The economic features are in different forms and numerous sustainability-related evaluations can be integrated and utilized in order to reduce production cost [11]. The economic benefits mostly reflect efficiency improvement of design and manufacturing rather than avoiding the tooling costs. In addition, reduction in idle time between design and manufacturing stages and the time between different manufacturing steps will result in a cost reduction. Based on the literature, energy consumption in transportation can lead to a significant saving of $56–$219 billion by 2025, while lightweight components are fabricated [13]. AM technology makes minimum waste because only the needed materials are consumed [18]. Considering all these modifications, AM processes themselves, enjoy lower input materials, less waste, and a shorter supply chain that all together, would provide a saving of $113–$370 billion by 2025 [123]. Caffrey et al. [133] reported that the AM market grew to $3.07 billion in 2013 and it is predicted that it will grow to around $10.8 billion in 2021. In another report by Kellens [134], it is estimated that cost reductions will range from $170 to $593 billion by 2025, for the markets with a great potential of AM processes, such as medical, aerospace, and tool making. Gelbler et al. [135] investigated the markets related to AM as follows:

(1) By 2025, the potential of the mid-term global market of AM is predicted to be $230–$550 billion;

(2) The main markets for AM are consumer products ($100–$300 billion), the products related to medical components ($100–$200 billion), and finally tool and mold industries ($30–$50 billion).

AM has become the subject of numerous research due to the promising industrial potential which is started from product prototyping to industrial end-user applications [134,136,137]. The market evolution, supply chain management, production, and machinery costs are some aspects of economic dimensions, as shown in Figure 9. There are three main aspects of the economics of AM, which are as follows [138]:

1. Measuring the value of the products: The definition of added value involves all aspects related to materials, machining process, and other purchased items for production. In fact, added value can raise the value of the production output with considering all taxes, employees' salary, and gross operating as well. Wohlers et al. [139] estimated that spare parts sales for AM products were $1.307 billion in 2014 around the world while the USA has the largest portion of this amount with $498 million. As a result, the global value-added to the AM process totaled $667 million in 2014, which is 0.01% of the global manufacturing value-added [138].

2. Estimating the adoption and distribution of AM technology: A firm needs various resources (such as labor, natural resources, and other items required for production process), established processes, and adequate capabilities (such as controllability, flexibility, and integration) in order to make products and services [140]. AM technology has great influences on a firm's capabilities. Accordingly, controllability and flexibility are the principal challenges of any firm that AM can positively improve. AM technology has high controllability, which makes it greatly attractive for more firms as well. Regarding the literature [138], it is estimated that AM business will surpass $4.4 billion in 2020, $16.0 billion in 2025, and $196.8 billion in 2035, therefore, it is required to deviate from its present trends of adoption.

3. Measuring the benefits and costs of applying the technology: The key point of decision making of any production is usually based on costs, and obviously, having a cost model for choosing the best manufacturing process is vital. It is essential to understand the performance of the AM processes cost-effectiveness for an efficient extension of AM. Both knowledge of process capabilities and operative cost modeling can show a helpful vision into the potential cost increase or "real cost" of a special AM process [141]. There are two main ways for evaluating AM costs. The first one is a comparison between AM and conventional processes in order to determine AM cost efficiency. The other category is identifying the applied resources for the AM processes to obtain the optimum consumption as well as a reduction in resource use.

3.3.2. Environmental Impacts of AM

Various research on the environmental influence of these processes was performed 10 years after the first generation of AM machines. Although AM has many benefits, such as freedom of design, flexibility, and sustainable advantages, it also has a minor environmental impact on industrial development [142]. Therefore, the environmental investigation is an essential issue in the AM industry based on regulations leading manufacturing productions and end-of-life disposal of products and growing demand for environmental certification requirements (ISO 14000) worldwide. Numerous studies indicate that AM has a great potential to considerably decrease environmental impact and energy per unit of Gross Domestic Product (GDP) [143–145]. In fact, AM carries the potential to diminish the carbon footprint by optimizing designs and the decrease in the waste flow [30]. By 2025, carbon dioxide (CO_2) emissions are estimated to be 130.5–525.5 million tons (Mt). In this respect, lightweight components, which is produced by AM, play an important role to reduce the energy consumption of the AM process [135]. As reported by Hague et al. [146], an optimal design would save the material usage up to 40%. This fact is more important when we know that a 100 Kg reduction in the weight of a long-range airplane leads to 2.5 million dollars in saving in fuel consumption and 1.3 Mt CO_2 savings during the aircraft's lifetime [30]. The environmental impact of AM can be investigated mainly in three features [117] (see Figure 9) as follows:

- **Resource consumption:** In AM, material and energy consumption represents the principle resource consumption. Conventional manufacturing compared to AM consumes more materials but the energy consumption would be relatively higher due to the lower production size of products [147–149], especially for AM processes that include its processing at high-temperature [117].
- **Waste management:** subtractive manufacturing processes produce a large quantity of waste in order to produce a product, which may be reduced by 90% while using AM [150]. This means that AM generates less waste.
- **Pollution control:** compared to subtractive manufacturing processes, AM eliminates the use of harmful chemicals, e.g., casting release compounds, cutting fluids, and forging lubricants.

Luo et al. [151] studied different environmental impacts in AM, e.g., energy consumption, material preparation, recycling, material toxicity, and landfilling. Numerous studies also show that a comprehensive study on AM helps not only in identifying and preventing negative environmental effects but also in enhancing the satisfactoriness of AM technology. Nevertheless, studying an interdisciplinary technological area, understanding the environmental impact and energy of AM according to the life cycle outlook is really challenging.

A variety of approaches were considered to evaluate environmental impacts, such as environmental impact scoring systems (EISS), life cycle analysis (LCA), and design for environment (DFE) [30]. LCA, established in the 1990s and developed by the Society of Environmental Toxicology and Chemistry (SETAC), is an internationally recognized technique to systematically evaluate the environmental impacts of different industrial products, processes, and activities [152,153]. The LCA method, compared to other approaches of environmental impact assessment such as Design for Environment or Carbon Assessment [154], has a capability to quantify precisely and with diverse criteria, the environmental effect of a global system. This method has been normalized by SETAC and UNEP (United Nations Environment Program) under the standard ISO 14,044 [155].

According to ISO 14,040 [156], LCA consists of four steps. These steps will be performed in a framework, as shown in Figure 10. In the primary step, the goal and scope of the study and the restrictions have to be specified. Accordingly, the definition of a product or process, and the system boundary should be determined as well. Then, the next step is input or output inventory analysis (Life Cycle Inventory: LCI). All input (material, energy) and the resulting outputs (waste, emissions) should be identified and accordingly quantified. After that, the other step (third) consists of the Life Cycle Impact Assessment (LCIA methods such as Impacts 2002+, Eco-Indicator 99, or CML) for achieving the outcome of the quantified inputs and outputs on the ecosystem and human health. In the last step, the consequences could be controlled by the interpretation of the system [157].

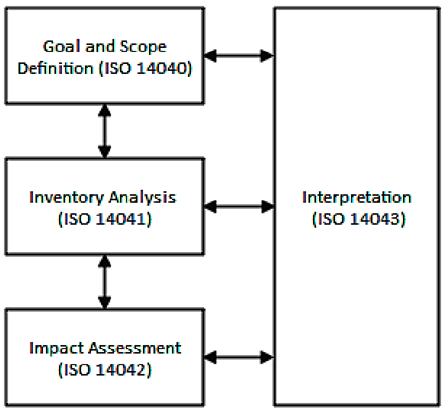

Figure 10. Conceptual framework of life cycle analysis (LCA) [153].

LCA is the most commonly used approach for measuring the environmental impact for the entire life cycle of the product [158], from the purchase of raw materials to fabrication, use, and disposal [157,159] (see Figure 11).

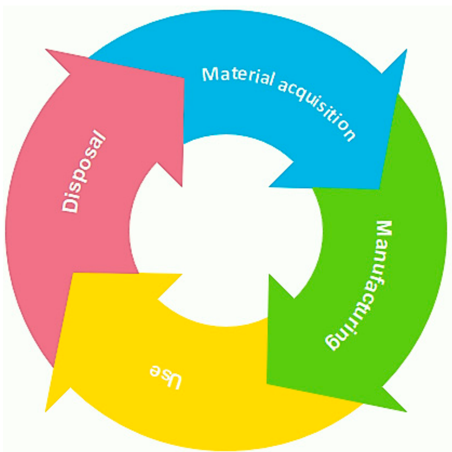

Figure 11. Life cycle phases [157].

In order to have a more accurate understanding of the material, process and energy consumption and production wastes and disposal can be taken into account to estimate the environmental performance of the production process [160]. In recent years, numerous studies have been conducted about the LCA method and its applications. Based on LCA investigations, some AM processes, e.g., Laser Engineered Net Shaping (LENS), Construction Laser Additive Direct (CLAD), and Direct Metal Deposition (DMD), are very environmentally friendly compared to traditional manufacturing processes [11]. Huang et al. [161] quantified the life-cycle energy and greenhouse gas (GHG) emissions savings potential of AM production for metal-based aircraft parts in the US. Based on the results, energy savings for AM processes is estimated to reach 70–173 million GJ/year in 2050 with a reduction in cumulative GHG emission which is predicted to be around 92.1–215.0 million metric tons.

Many studies have investigated the energy consumption and they only depend on the electrical consumption of AM machines during the production process. Contrary to these studies, Yosofi et al. quantified AM processes with its accuracy of inventory data through the production phase of the life cycle of products. They proposed a generic approach for purchases and characterization of inventory of AM processes. Their methodology relied not just on electrical energy, it is also depending on material consumption. They also investigated the environmental impact of AM according to life cycle inventory data, which are related to energy, material, and fluid. Ultimately, they proposed a predictive model and provided a novel methodology for the combination of technical, environmental, and economic assessments [162].

Kerbrat et al. presented an innovative methodology to measure the environmental impact of its CAD model for having more accuracy. Their methodology focused not just on electrical consumption but on material and fluid consumption as well, and it consequently contributes to the environmental impact. Furthermore, this methodology applies a set part process, which leads to considering various production strategies and the resulting influence on the universal environmental impact. The methodology was according to both analytical and experimental models [163]. Le Bourhis et al. also proposed another methodology that all consumptions including fluids, electricity, and material, were considered in the evaluation of the environmental impact. This method evaluates the consumption amount in the machine using a sustainable approach. The method was defined based on a predictive model of the consumption from the CAD model of the part and the manufacturing path [155].

3.3.3. Social Impacts of AM

The social development of the AM process is promising due to numerous potentials and benefits in the optimization of products, growth in product functionality, and a significant reduction in energy consumption, particularly natural resources [110,160]. Social sustainability is involved with the safety and the health of labors and the working conditions. This aspect is not easy to measure because the product benefit of society is relative and can be interpreted differently [11]. AM processes may have health benefits (or less health risk) compared to traditional manufacturing processes since they allow labors to prevent working in hazardous environments. Employment and the distribution of labor, quality of life, creativity, ethics, and self-expression are a part of topics not highlighted in the studies. Obviously, more investigations are needed in order to complement the social sustainability of AM as well [13]. Huang et al. [164] presented the social impacts of AM from a technical point of view in customized healthcare goods to provide a better quality of life and population health. Further research is needed to investigate the potential of hazard assessment for AM processes.

4. The Future of AM in Industry 4.0

Production of complicated shapes at high volume and speed with lower cost is a dream of every industrial unit. In the new world, it is not the big fish which eats the small fish, it's the fast fish which eats the slower (Klaus Schwab, Founder, and Executive Chairman, World Economic Forum). AM has become a key enabling technology that effectively reduces product design and development timelines [165].

In the close future, the 3D printing process will be cheaper and faster. Mass production will be the most discussed by researchers and practitioners. However, many manufacturers still believe that in order to shift their products to the AM processes, the most disruptive effects will be restructuring the future of additive manufacturing to look bright. 3D printing will grow through increasing the applications in existing markets, finding new opportunities in non-industrial markets such as food, fashion products, eyewear, and textiles. Wohlers' report [139] predicted that the AM industrial revenue will rise from $6.1 billion in 2016 to $21 billion by the year 2020.

Future work will concentrate on the development of multifunctional structures, ceramics, Functionally Graded Materials (FGM) e.g., a combination of metals and ceramics which can produce materials with lower brittleness, reducing inventory by on-demand production, reducing time-to-market, automated repair processes, and designing new complicated parts [166,167].

Although 3D printing is growing and benefiting the use of AM technology in many industrial sectors, it still has some limitations [168]:

- The high cost (such as operation, purchase, depreciation, and maintenance) of AM materials and machines;
- The requirement for high-speed 3D-printing technology (such as novel AM technology with higher speed, accuracy and resolution, and bigger build volumes);
- The lack of reliability in quality assurance practices across the sector;
- Design tools (such as software) need to be more investigated to present the full potential of the AM process;
- An overall shortage of appropriately trained workers in AM, and limited opportunities for collaboration and exploit of ideas.

Therefore, these issues will increase the challenging studies throughout the AM processes. In order to overcome the existing obstacles in the AM processes and generate more profitable and effective industry materials, printing technology, design software, and methods require improvement [168].

The future of AM in some important aspects of the industry, e.g., applications, technology, and materials, are considered briefly in the next section.

4.1. Future of AM in Applications

In order to use additive manufacturing and operation of industry 4.0 for equipping the existing manufacturing processes and in the future production, artificial intelligence and innovations in approaches and materials will be inevitable [169]. The most applications of AM processes occur in aerospace and automotive, art industry, medical and even architectural industry.

The aerospace industry has shown interest in these technologies because it enables them to directly manufacture metallic parts such as from titanium (for aircraft) and the ability to easily manufacture complex and high-performance products with significantly less tooling considerations [170]. Selective Laser Sintering (SLS) and Electron Beam Melting (EBM) are now used in the aircraft and aerospace industry. The principle goal of the automotive and aerospace industries is to manufacture lightweight vehicles or aircrafts. These AM-based technologies are capable of manufacturing lightweight components [171]. The AM has many applications in medical fields. It plays a key role in the production and design of bio-models, surgical support tools, and implants. AM processes are able to fabricate the various scaffolds for the restoration of tissues and they are useful in printing organs, cell-laden biomaterials, biomaterials, and producing cells individually. AM technology has excessive potential for the production of complex geometries of the implant. It should not be forgotten that AM technology helps in reducing costs and producing a medical model in a shorter time [167]. The most complex and complicated designs in the jewelry and art industries could be fabricated using AM technology [172]. AM technology can provide effective tools for the work of jewelers and artists, enabling them to create unique shapes in hours instead of days or weeks.

In general, there are many advantages for AM processes over traditional manufacturing processes in rapid prototyping, spare parts, complex workpieces, machine tools, rapid manufacturing, and so on. The most important advantages are dropping time and cost in different categories of production [18]. The methods of production will not change by additive manufacturing. However, improving most areas of the industry is inevitable. As mentioned earlier, the cost and speed of productions are predicted. Figure 12 indicates the production savings based on AM technology for metal products for the next five years.

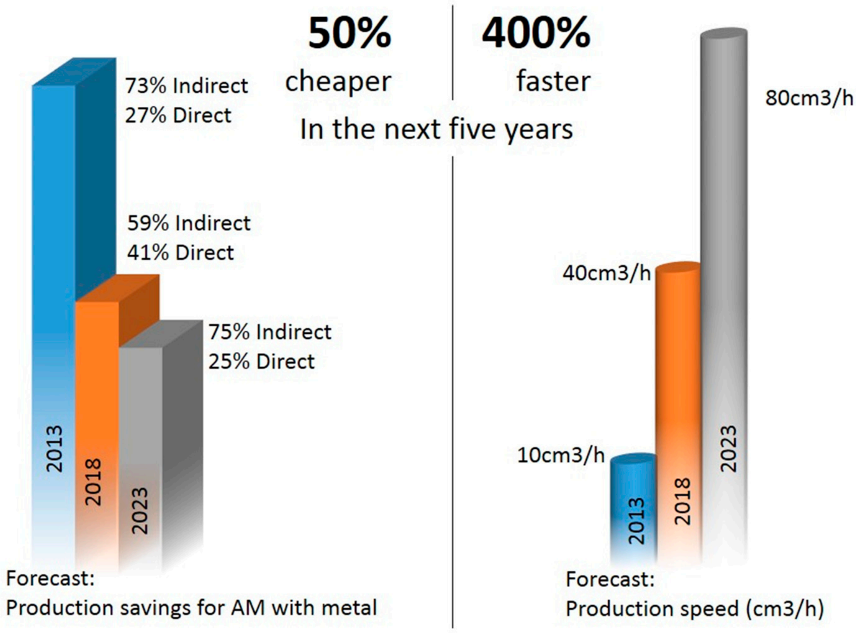

Figure 12. The saving of production in cost and speed, reproduced from Reference [18].

4.2. Future of AM in Technology Developments

Rapid prototypes, the capability to print bulky structures, reduction of printing errors, and improvement of mechanical properties are a part of the major factors in the development of AM technologies [7]. 3D printing has had a significant growth along with great steps in the novel and advanced technologies to make it more competent and cost-effective. AM technology is still in the early stages and will need further development of technology, including decreasing the cost of printers and feedstock, as well as expanding the capabilities of the printers so that they are faster, more precise, and autonomous. AM technology offers new opportunities in production paradigms and production capabilities. Ranging from industry to retail, AM technology has numerous opportunities to have a major impact on how products are manufactured and how the companies implement business.

The marked and industrial companies have a tendency to enter the decentralized industrial revolution. Nevertheless, experts believe that AM would not be able to replace traditional manufacturing processes easily [18]. There is no doubt that 3D printing technology is leading the subsequent main industrial revolution. Because of its versatility, AM plays a major role in Industry 4.0, saving cost and time, determining process efficiency, allowing rapid prototyping, reducing complexity, and very distributed production processes [16].

It can be predicted that the AM systems will be cheaper and could be easily available to the public. Therefore, there will be more opportunities for users. Otherwise, speed will be a major issue which will be improved significantly in the future with the progress of design and materials processes. AM machines and systems will be available in shopping malls and any other locations where the consumers can order and receive the final product in a short time. AM machines can be combined with other technologies, e.g., hybrid AM technology. Moreover, AM systems can be used for multiple materials and as a result, fabrication of different products will be easier [170].

4.3. Future of AM in Materials

The additive metal production facilitates the opportunity to fabricate complex components from costly materials such as titanium alloys, which is significant to the biomedical and aerospace industries [173,174]. AM of metals develops rapidly, and new methods, alloys, and applications are achieved with significant quality improvements and reduced production times. In particular, research and investments by governments, universities, and private sectors are designed to increase the speed and accuracy of AM and raise the number of applicable alloys when monitoring prices [7].

There are many examples of materials development in the AM industry. Future developments in the field of bioprinting will focus on various features, such as biocompatibility, mechanical properties, printing properties, biomimetics, and degradation [175]. The development of new composite biomaterials with various compositions to achieve reprogrammed mechanical properties and functions can be a reliable method for making various organs and tissues with diverse mechanical requirements. One of the major challenges in the field of cellular or organ printing is the development of new biological inks that not only are able to print to maintain a certain tissue structure but also to promote the proliferation and growth of embedded cells.

Developing intelligent materials should be concurrent with some advances in 4D printing technology. By this technique, smart materials can be manufactured into complex and multifunctional structures with precise and particular responsiveness. In addition, intelligent materials might require chemical or physical modifications of particular additives for high-resolution 4D printing such as photo-initiator agents, rheology and viscosity modifiers, sacrificial agents, or cross-linking agents. In this respect, the main path is the developing of composite materials for 4D printing processes using a combination of intelligent materials with printing materials [10].

5. Conclusions

In recent decades, various industrial revolutions have changed the domains of manufacturing in many aspects. Nevertheless, the last industrial revolution, namely industrial 4.0, has exposed a novel integrated manufacturing system using complex information technologies. In fact, this intelligent manufacturing provides a highly flexible production, which is able to rapidly alter individualized mass production and fabricate high-quality customized products. There is no doubt that AM capabilities are a vital part of the fourth industrial revolution since AM has provided a new opportunity to fabricate customized and personal products on the location. In this way, the roles of customers, factories, and designers will be significantly redefined in the future of manufacturing.

As a matter of fact, AM has brought many innovations and opportunities in various industries, mainly medical, aerospace, and automotive. AM helps effectively with cost and time-saving, reducing complexity, rapid prototyping, and highly decentralized production. However, besides the several advantages of AM technology, there are also some barriers against its quick growth, such as size limitation, production time, limitations of materials, and machine and production costs.

AM is also in the group of sustainable and efficient production processes in the field of manufacturing which helps with resource-saving and environmental protection. The sustainability studies show a considerable reduction in material waste and fuel consumption as two principle benefits in AM. In fact, eco-design in AM provides this opportunity that the environmental issues fundamentally be considered in each design and fabrication stage, accordingly, various eco-design tools, e.g., life cycle analysis (LCA), can be applied for evaluating the environmental impact of products.

The future perspective of AM will be a cheaper and faster technology which can be applied for mass production too. The application of the 3D printing process will grow significantly for production of various products in the market and therefore it will provide many opportunities in even non-industrial market such as food, fashion products, eyewear, and textiles. Also, the future of

AM technology will depend on material development for the 3D printing process. For example, the current development in bio-printing or 4D printing using intelligent materials give a hint in future development for printing more complex and multifunctional components.

Overall, 3D printing technology is still not mature and needs more development to reduce the material and machine costs, generate faster and more accurate printing methods, and work autonomously. The smart factories need to be interconnected through IoT with greater individualization and flexibility in manufacturing processes. The future of manufacturing considerably depends on innovation in manufacturing technologies and methods, advances in materials, and even equipping the existing manufacturing systems.

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