Additive Manufacturing for Sustainable Production Systems: A Comprehensive Review

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Abstract
Additive Manufacturing (AM), also known as a three-dimensional (3D) printing, is one of the disruptive technologies in the manufacturing industry that can change current production systems into more sustainable ones. In contrast to the older manufacturing processes, both subtractive and formative, AM produces components by printing layers on top of each other, neither reducing raw material wastage nor deterioration, expands the options of design, and creates products in tiny amounts and on-demand manufacturing. These attributes qualify AM as a central facilitator of the sustainable production systems in accordance with the global goals of resource efficiency, reduction of carbon emissions, and implementation of the circular economy. This in-depth review critically looks at the application of additive manufacturing in sustainable production systems with a synthesis of existing literature on the sustainability aspects at environmental, economic, and social level. The paper covers key AM technologies, assesses benefits of sustainability using life cycle perspectives, lists the key challenges and limitations, and presents industrial uses and research perspectives in the future. The above findings indicate that although AM does provide significant sustainability benefits, it can only be used to full capacity with the development of new technology, standardized assessments systems, and integration of industries on the strategic level.

Keywords:
Additive Manufacturing, Sustainable Production Systems, Life Cycle Assessment, Circular Economy, Industry 4.0

1. Introduction

The current situation of increased environ- -mental degradation, issues of climate change, exploitation of natural resources, as well as strict environmental laws are making sustainable production systems a pillar in the contemporary industrial development.

Traditional manufacturing processes are usually linked to waste of large volumes of materials, heavy use of energy and the unnecessary internationalized supply chains which lead to greenhouse gas emissions to a great extent. Such constraints have compelled industries and researchers to find other manufacturing paradigms that will make the economic growth compatible with the environmental stewardship and social responsibility.

Three-dimensional (3D) printing, or additive manufacturing (AM) has become one of such revolutionary technologies. In contrast to classical manufacturing procedures, be it subtractive or formative, AM builds the object layer by layer on the basis of digital models which reduces the amount of material waste and allows designers to be completely unrestricted in their design. AM was first used in rapid prototyping, but it has since become a full-fledged manufacturing process that produces functional end-use components in

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metals, polymers, ceramics, and composites [1].

The potential of AM in its sustainability is its nature, such as material efficiency, part consolidation, lightweight design capability, and customization, and decentralized production. All of these characteristics lead straight to less use of resources, decreased transportation, and high-performance of the product at the stage of use. Therefore, AM is becoming a crucial facilitator of sustainable production systems and circle economy policies.

Even though this is a promising idea, AM sustainability performance is not always better than the traditional manufacturing. Factors including energy intensive processes of metal AM, a lack of recyclability of some materials, and extensive post-processing are able to counteract possible gains. Hence, it is critical to thoroughly and critically assess AM based on the sustainability perspective.

This review article will be an attempt to generalize the extant literature on additive manufacturing and sustainable production systems. It aims to: (i) overview key AM technologies and sustainability, (ii) discuss environmental, economic, and social sustainability of AM, (iii) review life cycle assessment methods of assessing AM sustainability, (iv) find out some of the challenges and limitations, and (v) recommend the future research direction to improve the environmental, economic, and social sustainability of AM.

2.Overview of Additive Manufacturing Technologies

Additive manufacturing is a wide set of manufacturing processes that are very heterogeneous in terms of material feedstock, energy input, and bonding mechanism, but which all have the similarity of forming layer upon layer components directly based on digital models. Based on these basic features, the international standards classify the additive manufacturing technologies in a few broad categories.

The process of extrusion is most commonly used in Fused Deposition Modeling (FDM), whereby materials in the form of thermoplastics are extruded through a nozzle that is heated and then deposited in a sequential manner to create a three-dimensional object. The reason why these systems are widely adopted is that the cost of equipment and running costs is relatively low, the system is very easy to use and the type of material is not restricted. The increased supply of biodegradable and bio-based polymers, including polylactic acid (PLA), also increases the sustainability potential of the extrusion of materials based on polymers, minimizing the reliance on petroleum plastics and decreasing the environmental impact. Nevertheless, constraints associated with surface finish, dimensional accuracy and mechanical anisotropy are still a challenge to high-performance applications.[3].

Selective Laser Melting (SLM) and Electron Beam Melting (EBM), as well as other Powder Bed Fusion (PBF), processes are based on the use of high-energy laser/electron beams to melt and fuse thin layers of metal or polymer powder selectively. Such technologies can also manufacture high density, high strength components with complex geometries that are hard or impossible to make with traditional manufacturing processes. Due to this, PBF has been widely used in high value industries like aerospace, biomedical implants, and tooling. PBF allows lightweight design and part consolidation, which can lead to a decrease in material consumption and enhancement of functional efficiency at the stage of product use, in a sustainability perspective. However, the energy intensity of these processes is high and, in addition, it is difficult to reuse the powder, oxidize and post-process it, so it may be questioned how such processes impact the environmental footprint.

Binder jetting processes involve the careful deposition of a liquid binding agent over a powder bed to create a bonded together mass of particles, or a green part, which needs to be further cured or sintered to form a final part. The fact that binder jetting can be run at relatively low temperatures during the printing stage is also one of the major benefits of the technology; since it dramatically lowers thermal stresses and energy usage in comparison to fusion-based processes. Binder jetting also is fast and scalable so that is why it will be applied in manufacturing large volumes and also in sand mould and core production in the foundry industry. Recyclability of the powder and minimisation of thermal distortion, again adds to its sustainability attributes, but the post-

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processing and an emissions binder issue has to be carefully handled.

Directed Energy Deposition (DED) systems use a concentrated thermal energy typically a laser or an electron beam to eventually melt the material that is being deposited through a nozzle. Contrary to powder bed-based solutions, DED has the ability to add material to existing parts allowing repair, refurbishment, and remanufacturing of high value parts. This is especially the case in terms of sustainability, since it increases the lifespan of the component, minimizes extraction of raw materials and waste is kept to a minimum. DED is also best suited to the manufacture of functionally graded materials, where the composition of materials can spatially be varied to improve performance. Nevertheless, work-related issues to be considered to expand its use in industry are process control, surface finish, and dimensional accuracy problems.

Vat photopolymerization, including Stereolithography (SLA) Resin, is a method of creating highly detailed and dimensionally accurate parts with the involvement of selectively curing liquid photopolymer resins either with ultraviolet light or laser light. They are known to be the best in terms of surface finish and accuracy and can be used in the field of medical equipment, dental models, and micro-scale devices. These strengths notwith--standing, issues of sustainability remain because the recyclability of photopolymer resins is limited, and the uncured materials may be toxic as well as a problem of resin disposal on the environment. Continued development of bio-based and recyclable photopolymers is being conducted to alleviate these problems, and improve the sustainability picture of vat photopolymerization technologies.

Altogether, every type of additive manufacturing has its own benefits and restrictionsasfar as sustainability, performance, and industrial applicability are concerned. It is critical to understand such differences to choose the best AM technologies to meet the goals of the sustainable production systems.

3. Sustainable Production Systems: Concept and Requirements

Sustainable production systems are created in such a way that they bring about balanced incorporation of economic feasibility, environment protection as well as social wellness throughout the whole product life cycle, including the extraction of raw materials, and the disposal of the final products. The focus of such systems includes effective resource use, environmental reduction, safe and healthy working environment, uniformity of products, and sustainability of the economic competitiveness. To achieve these purposes, the manufacturing technologies should be in a position to deal with various dimensions of sustainability as opposed to concentration on one performance measure.

The concept of additive manufacturing is compatible with the idea of sustainable production because it allows the use of design-based sustainability measures, including the following: lightweight structures, part consolidation, and functional integration, which decrease material use and resource intensity. Besides this, AM also facilitates the creation of shorter and more flexible supply chains by creating localized and on-demand production also reducing transportation-induced emissions and inventory needs. The fact that the products can be customized without a large cost penalty also increases economic and social value. However, the sustainability performance of additive manufacturing is very situational and subject to material choice, energy utilization, volume of production, efficiency of the process, and post processing needs. Consequently, attentive analysis and application specific consideration is needed [6].

4. Environmental Sustainability of Additive Manufacturing

4.1 Material Productivity and Reduction of Waste.

Among the most noticeable environmental benefits of additive manufacturing is the fact that it is much more efficient in terms of materials compared to the traditional manufacturing methods of subtractive manufacturing. In the conventional machining processes, a significant percentage of the initial work piece is taken out in the form of chips, resulting into a high material wastage, particularly in the manufacturing of intricate machining parts of materials that are costly or hard to machine. Additive manufacturing, conversely, layers parts by depositing material at the location where it is needed based on the digital model thus creating a large reduction in

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material waste. Other studies have indicated material utilization rates of over 90 percent with some additive manufacturing processes, especially polymer based technologies like Fused Deposition Modeling (FDM) with the unused material frequently being reused or recycled.

Additive manufacturing opens more than mere material savings; other benefits include sophisticated design approach to more material efficiency. The ability to create intricate geometries, including lattice structures, cellular structures, and topology-optimized structures enables the engineer to add material only in the part of the structure that supports load and zero unnecessary mass. These light designs do not only lower the use of raw materials in the manufacturing process but also help in better functional performance such as better strength-to-weight ratios. Ecologically, the decreasing amount of materials used directly decreases the effect of the extraction, processing and transportation of raw materials, which leads to minimized total environmental footprint.

4.2 Energetics and Carbon emissions.

The energy usage is one of the most important variables of the environmental sustainability of additive manufacturing technologies. AM is a heterogeneous energy demanding process depending on the type of process and material used and operating conditions. The AM processes based on polymers such as FDM and Stereolithography (SLA) typically have lower energy requirements because of reduced processing temperatures and less complex system designs. Conversely, metal-based technologies including Powder Bed Fusion (PBF) and Directed Energy Deposition (DED) use high-energy laser or electron beams to melt or fuse metal powders or wires leading to a large amount of electricity use during the production step.

Nevertheless, the evaluation of energy consumption at the level of the machine or even the process presents a partial view of sustainabilityperformance.Additivemanufacturing can provide substantial reductions in energy and emissions when considered in a more systemic or life cycle approach. AM allows part consolidation, which results in fewer parts and assembly processes, and reduced energy demand in subsequent manufacturing processes. Also, the removal of tooling and molds lessens the amount of energy and emissions on the fabrication of tools. Close proximity to the point of use also reduces the transportation distances and thus reduces carbon emission further. Life cycle analysis has indicated that additive manufacturing may be more energy-efficient and less greenhouse gas emitting than traditional manufacturing operations when making low volume, high-complexity, and lightweight components.

4.3.Life Cycle Environmental Impact Assessment.

Life Cycle Assessment (LCA) has become a popular approach to the quantitative analysis of the environmental impact of additive manufacturing throughout the entire life cycle of a product such as the extraction of raw materials,feedstockmanufacturing, fabrication, use, and disposal. Research based on LCA always suggests that the environmental advantage of additive manufacturing is highly situational and prone to very many factors that include part geometry, volume of production, material type, and the sector of application. Although additive manufacturing is more likely to have significant environmental impacts at the manufacturing phase (primarily because of the high energy consumption inherent to most of the processes, as well as post-processing), these impacts can be compensated at the use phase. This has been notable especially in the aerospace and automotive industries where lightweight AM elements have been instrumental in fuel consumption and reduced emissions during the lifetime of the product in use.

The use of LCA to additive manufacturing is, however, challenged by a number of issues despite being important. Lack of standard LCA procedures and the scarcity of valid and transparent inventory information of AM processes do not permit similar assessments that are consistent. The differences in machine efficiency, process parameters, material quality, and energy sources may result in major differences between studies. These issues support the necessity of unified LCA frameworks, universal data reporting, and process-specific databases that would allow strongly assess the environmental sustainability of additive manufacturing technologies.

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5. Economic Sustainability of Additive Manufacturing

5.1 Cost Structure and Production Economics

Additive manufacturing has a radically different cost base than traditional manufacturing procedures in the economic sustainability approach. Eradication of tooling, molds, as well as dies, one of the greatest economic benefits of AM, is traditionally linked with the high initial capital cost and lengthy lead time involved in conventional manufacturing. This feature is especially appealing in low-volume production, custom products, and rapid prototyping, where the design can be quickly changed, and it does not require new equipment to be purchased. Moreover, AM is digital, which allows quick design-cycle and minimizes product development time, therefore, lowering time-to-market and the number of development costs [11].

Even with these merits, there are still a number of economic obstacles that make the adoption of AM to large scale production restricted. Industrial-grade AM machines, particularly those made of metal, are costly to buy, which can be a heavy investment. Moreover, the feedstock cost like metal powders, and special polymers are usually very expensive compared to the conventional raw materials. The other activities such as heat treatment, surface finishing and the quality inspection that follows the processing is also an additional cost to general production. Consequently, AM economic feasibility greatly relies on the volume of production, intricacy of parts, material consumption and necessary performance qualities.

5.2 Supply Chain Transformation.

The additive manufacturing can bring a considerable change to the traditional supply chain through the chance of decentralizing and on-demand manufacturing. AM gives the opportunity to make products and spare parts closer to the point of use instead of using centralized manufacturing plants and long logistics chains. Such a localized production system lowers transportation expenses, lead times and inventory levels and therefore, the total operation costs. Digital inventories, in which design files are substituted by physical stock, also help achieve savings in costs through reduced risk of warehousing and obsolescence.

The strength of AM-enabled supply chains has been especially noticeable in the times of global disruption, like the COVID-19 pandemic when the traditional supply-chain was severely affected. The quality of producing vital components quickly and responding to fluctuating demand is the feature that illustrates the economic strength of AM in improving the flexibility of the supply chain and going away with the reliance on the highly multifaceted global networks. As a result, AM is becoming an even more significant factor in favor of economically sustainable and resilient production systems.

5.3 Value of Product and Innovation.

Additive manufacturing aids in economic sustainability since it facilitates high-value innovative products that may be challenging or even impossible to make in the traditional manufacturing process. This ability of creating elaborate geometries, internal components and a tailor-made design enables the producers to provide products with greater functionality as well as performance. Such freedom of design makes it easier to generate value through innovation and help companies to distinguish their products and respond to a certain need of the customers in a better way.

In addition, AM allows performing mass customization without the high cost penalties that are often related to traditional manufacturing where customization may demand unique tooling or modification of the process. Instead of scale economies, AM enables manufacturers to bring about economies of scope since customized components are produced based on digital designs. Such a change reinforces emerging business patterns, including customization of products and decentralized production, that lead to long-term economic sustainability. In general, the capacity of additive manufacturing to lower the development expense, increase the efficiency of the supply chain, and create value based on innovations highlights its increasing significance in sustainable production systems.[12].

6. Additive Manufacturing Social Sustainability.

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Additive manufacturing also assists in achie--ving social sustainability in transformation of nature of work and making the occupation safer and making production systems more inclusive and resilient. High automation and computerized controls that accompany AM reduces the face-to face contact between the dangerousmachiningactivities,hightemperatures, and cutting fluids that are typically found in the customary manufacturing environment, thus improving ergonomics and safety in the workplaces. In the meantime, in the case of AM usage, the requirement of high-technical capabilities in the gun of the computer-aided design, organization of digital processes, materialsscience,anddata-drivenmanufacturing is what enhances the upskilling and professional development of the working force.

In addition, additive manufacturing promotes the localized and distributed production paradigm, which can give a boost to the economic growth of regions and introduce jobs nearer to final consumers. This localization makes them less dependent on central manufacturinglocations and allows responding more quickly to the needs of local markets. The production of patient-specific medical devices, implants, and prosthetics in the healthcare industry has shown a high level of social benefits in terms of enhancing the treatment effects and life quality. Also, since AM is capable of rapid manufacturing, this feature has been very useful in emergency cases when the manufacturing of components that are vital is urgent like it is in the case of public health crises and during natural disasters. However, the issue of possible demotion of the workforce and skill imbalances should be solved by means of specialized education, reskilling, and curriculum design to provide an inclusive, socially sustainable shift towards additive manufacturing-based production systems.[13].

7. Challenges and Limitations

Although the potential of additive manufacturing is rather high, its sustainable implementation is limited by a number of technical, economical and organizational issues. Higher energy usage in AM processes of metals is one of the most severe limitations impacting the environmental performance that cannot be offset by downstream benefits. Moreover, supply of sustainable, recyclable, and bio-based materials that can be utilized in industrial AM is also low which limits the advancement to circular production.

Lack of standardized process parameters, material specification, and certification guidelines are other major challenges and make it difficult to ensure quality and restrict its implementation in safety-critical industries. The inconsistency of process stability and part quality, and the post-processing requirement further impact sustainability and cost-effectiveness. Furthermore, there are no universallyrecognizedsustainability assessment systems and trusted life cycle inventory data that will facilitate a uniform evaluation and comparison of AM processes. The solution to these issues will involve concerted efforts between researchers, manufacturers of equipment, suppliers of materials and policymakers.

8. Conclusion

Additive manufacturing has a significant potential to provide a sustainable production system through enhanced material efficiency, the ability to design products and make them light, and the ability to enhance the use of the circular economy, including repair, remaking, and personalization. Its capacity to minimize waste, reduce supply chains, and develop high-value products makes AM one of the important technologies in the next generation of manufacturing sustainable development. Yet, the sustainability of additive manufacturing is strongly situational and should be assessed with great attention considering the holistic perspectives of life cycle that take into consideration process and use-specific aspects.

In order to achieve the full sustainability advantages of additive manufacturing, further research and development are required, specifically with regard to energy-saving procedures,sustainablematerials,standardization, and reliable assessment procedures. Concurrently, there is a need to have supportivepolicies,industry-academiapartnership, and workforce development strategies so that AM can be taken up in a responsible and large-scale way. By implementing these actions, additive manufacturing will be able to have a critical role in developing economically viable,

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sustainable, and socially inclusive manufacturing systems.

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