Sustainability in Additive Manufacturing-A Review

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Abstract

This paper presents a review of the developments in sustainability performance indicators (SPI) as well as various applications thereof in Additive manufacturing (AM). AM is a manufacturing process where material is added rather than subtracted to produce a functional part. Common AM technologies such as fused deposition modeling (FDM) allows the user to create parts that conventional machine is not be able to reproduce all in a single process, not including post-process finishing. Mechanical parts with hollow insides and optimized shapes are easily fabricated using AM. Since the process adds material instead of removing material, less material is wasted. Material is only deposited where it is needed. The only case where more material is used than is needed is when support structures are used. Support structures allow a complex shape to be manufactured where there is not sufficient material to support the structure on the machine's build surface. As AM is fully capable of fabricating complex shapes, the user can alter the shape of the part to reduce the amount of material needed to produce it. A general rule of thumb is that the more material required, the more time and energy the process will consume.

Keywords

Additive manufacturing, sustainability, fused deposition modeling, subtractive manufacturing

1. Introduction

Sustainability focuses on the conditions of economic development, ecology, and societal equity. Generally engineering processes occupy, but is not limited to, the economic sector. The main factors of economic sustainability include material, energy, water, and process enablers (Sreenivasan, et al., 2010). The development of additive manufacturing technologies has led to the increase in application in fields of product development, conceptual design, functional parts, and tool making. The uses of AM in these fields have shown economic feasibility. A general lack of standards in the field of AM is a big contributor to the lack of further adoption of the technology (Mani, et al., 2014). The further standardization of AM may lead to sustainability enhancements. The adoption of AM in industry may lead to a future with shorter value chains and impressive sustainability benefits. AM is a lot less wasteful than subtractive manufacturing technologies. Products that are manufactured using AM are more resource efficient, the product life is also longer as remanufacturing is much easier and the process chains are much simpler and shorter.

Most research on sustainability performance in AM have been done in a broad sense or with focus placed on material and energy consumption (Ford & Despeisse, 2016). AM is still far from being mainstream standard practice. Most of AM users are innovators which are mostly small volume manufacturers. A considerable amount of AM innovation can be seen in aerospace, automobile, and medical fields. These sectors have been able to find many novel solutions to modern as well as old problems. Recently there has been an increase in the research conducted on the adoption of large-scale AM technologies in the construction and built environment. There are technologies available that produce large stone-like free-form structures. These technologies have shown some promise in the fields of sustainable building design and manufacturing. AM in construction has the potential to reduce the complexity as well as the process and supply chain in the construction field (Panda, et al., 2017).

Sustainability Performance Indicators

When studying sustainability in the manufacturing sector it is important to know and understand the full material and product life cycle stages. Sustainability in manufacturing requires the concise breakdown of levels of sustainability performance indicators.

Table 1 categorizes sustainability performance indicators for AM. Each category highlights key areas of sustainability in the manufacturing sector. In depth studies on sustainability performance indicators have mostly been focusing on environment and economic performance as they are often easier to quantify. Social sustainability performance indicators may be vary across different manufacturing sectors as well as over the world.

Table 1. AM sustainability performance indicators

Sustainability performance indicators		
Environment	**Economic**	**Social**
Material	Economic viability	Employment
Energy	Market presence	Occupational health and safety
Water	Indirect economic impacts	Training & education
Biodiversity		PSS Labeling
Emission, effluent and waste		Marketing & communication
Product &U service		Compliance to social standards
Conformance		Governance
Transport		

1.1. Environmental PI's

In the case of traditional subtractive manufacturing methodologies, the design engineer is responsible for planning as much of the pre-and-post-manufacturing processes as possible. In many cases the fabrication process may require the building of jigs and specialized tools to get the job finished. This will result in an increase in the consumption of material, time, and labor cost. AM allows for the manufacture of complex geometries with far less process and material requirements. The maintenance process is also simplified as refurbishment and remanufacture of parts require less resources, tools, materials, and time (Ford & Despeisse, 2016).

Environmental sustainability focuses primarily on the consumption and efficient use of material, energy, and, water. Using the production of a varying diameter shaft as an example; it can be seen in Figure 1 that the amount of material required is far less than what is used to create the part (in the case of subtractive manufacturing).

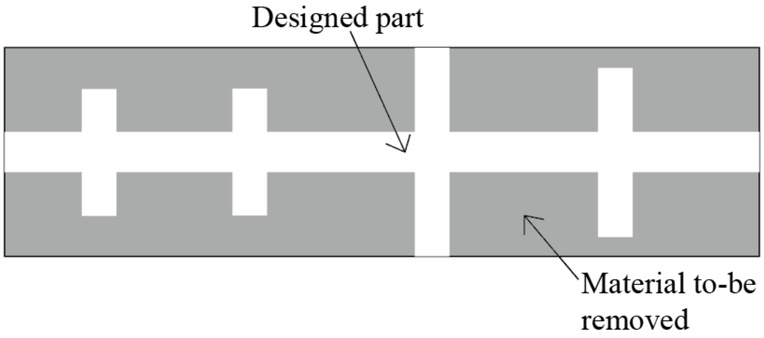


Figure 1. Varying diameter shaft

In subtractive manufacturing the part is often cooled using cutting fluid or oil-water mixtures. This ensures the longevity of the cutting tool as well as sustaining acceptable machining conditions for the material. The increase demand for high productivity production has led to an increase in the speeds and feeds for manufacturing machines. This leads to exceedingly high heat generation in the fabrication process which in turn led to an increase in cutting fluid consumption. High level of technical knowledge and experience is required in choosing an appropriate cutting fluid (Debnath, et al., 2013)

Consumption

Consumption refers to the material used in the entire manufacturing process but may also include material and resources used in the transport of products and services. Less material and resource consumption may also lead to a decrease in production time. Material savings result in transport cost savings also.

Efficiency

Described as all savings that are attributed to the additive manufacturing process. Possible processes and initiatives that can recycle material that was used for support structures will benefit the overall efficiency.

Availability

The appropriate application of material selection in the design phase. Scarcity and level of difficulty in machinability are factors that influence the decision tree. Calculated and defined as the fraction of available resources consumed.

Value recovery

Value recovery is based on the level of value that can be recovered at the end of life of a fabricated part. Options such as reuse, upgrade and refurbishment add to this aspect of sustainable design and manufacture. Durable products are considered add great value.

1.2. Economic PI's

Economic performance in manufacturing is measured through economic viability, market presence, and indirect economic impacts. The minimization of cost and the drive to improve value of products has a direct impact on the economic performance. AM unlike traditional SM will require more financial resources as the complexity of parts increase.

Value

A direct measurement of economic performance is that of product value. Value that is generated and distributed through revenues, operational cost, remuneration, and other investments.

Cost

The cost of machines and all relevant materials and resources such as labor, manufacturing, repair, maintenance, and recycling. All cost related factors affect the overall lead time which will influence the responsiveness from market.

Research and Development

In the essence of sustainability lies relevant research and development. Herein lies some financial implications and opportunities that may contribute greatly to a company's road to sustainability.

Financial benefit and assistance

Some government policies may lead to an incentive scheme or reward system for the implementation and development of more economically sustainable ventures.

Suppliers

Policies that unite both business and suppliers in the name of sustainability. Practices, policy, and proportion of spending on locally based suppliers at significant locations of operation.

Local community

Ensuring the employment of competent local community at locations of significant operations.

Investment

A mutually beneficial development of local infrastructure aimed primarily at public benefit. Focusing on both investments and services as pro bono engagement.

Impact knowhow
The research and understanding of economic impacts on both local and global scale. Developing an understanding of the extent of the impacts which typically focus on job creation and increase in low to high level productivity.

1.3. Social PI's

General health and safety practices, development of social performance focused management impact the overall social performance of products and services. Employees, customers, and the community are the focus areas for this level of sustainability.

Type
The average workforce employment type and employment level within the business, broken down by gender and other transformative measures.

Job creation
The frequency and level of new hiring positions withing the company. Overall accessibility to the labor market.

Retention rate
Measured through remuneration and benefits offered to all employees.

Job security
This is related to the stability of the market in which the business operates. Is measured by the average number of years committed to the business.

Health and Safety
Risk of being exposed to harmful substances, compliance to local health and safety regulations.

Satisfaction
Measured by the frequency of complaint reports submitted by employees, suppliers, and customers.

Demographic structure
The distribution and levels of different groups of people according to age, gender and, education.

Performance
This indicator is not just measured by the existing performance but also the investment into continuous improvement of performance.

2. Improving Environmental SPI's in AM

Component and product design

Specialized applications of AM such as porous medium manufacturing allow for novel parts and solutions. The incorporation of open cellular foams and mesh arrays further add to the attributes of AM parts. There are possible improvements in increased strength, stiffness, energy efficiency and corrosion resistance (Guo & Leu, 2013).

Material input processing

During the pre-manufacturing phase and ideally at the design stage, the user will have to decide on the best material to be used to manufacture the part. In the case of FDM, the user can choose from a range of materials. In many cases of rapid prototyping, the material specification doesn't demand much in the sense of mechanical behavior. In cases where the material spec is not specific, it may be advantageous to choose the material that is easier to use.
AM technologies such as laser sintering may even affect the way large ores are converted into usable form this has the potential to reduce the amount of resources required to convert ore into useful product.

Make-to-order

AM does allow industrial users to reduce costs on inventory expenses of manufactured goods. The advanced manufacturing process only requires a digital file that contains all design parameters and builds parameters to produce a part. No specialized machines, jigs or processes are required to manufacture a part. This is really a major impact on the economics of product manufacturing.

2.1. Sustainability and direct digital manufacturing

Figure 1 illustrates the process steps in FDM, a type of AM technology mostly used in rapid prototyping applications as well as low volume part production. The simplicity of this process is what makes it a perfect direct digital manufacturing (DDM) technology. Mass customization was a product of an increasing demand in high quality, highly specialized products.

Modern day FDM machines, mainly 3D printers, may have led to an overall increase in energy demand and material consumption due to the widespread interest and the level of accessibility of the technology. These machines often use a wide variety of polymers to produce parts. Due to the increase in the use of these machines by average consumers, the amount of material waste is starting to add up to something slightly more significant. The most common material used is polylactic acid or PLA for short, which is an environmentally friendly material. Other materials include ABS, nylon and PETG. An increase in the use of these materials in a manufacturing process such as additive manufacturing may lead to higher levels of plastic pollution on the planet.

Additive Manufacturing (AM) offers more opportunities in sustainable manufacturing compared to conventional manufacturing processes (Faludi, et al., 2014). Traditional machining practice involves one sub-machining processes to obtain the final product. Each of these processes consumes at least one of the following: time, material (via material removal, jig building), electrical demand/consumption, cutting fluids (water and paraffin-based oils) etc. AM reduces all the above, and does not require any cutting fluids that are harmful to the environment and human health (Avram, et al., 2011). The contribution of manufacturing to the world's greenhouse gas emissions and environmental impacts is almost 19% (Diaz, et al., 2010).

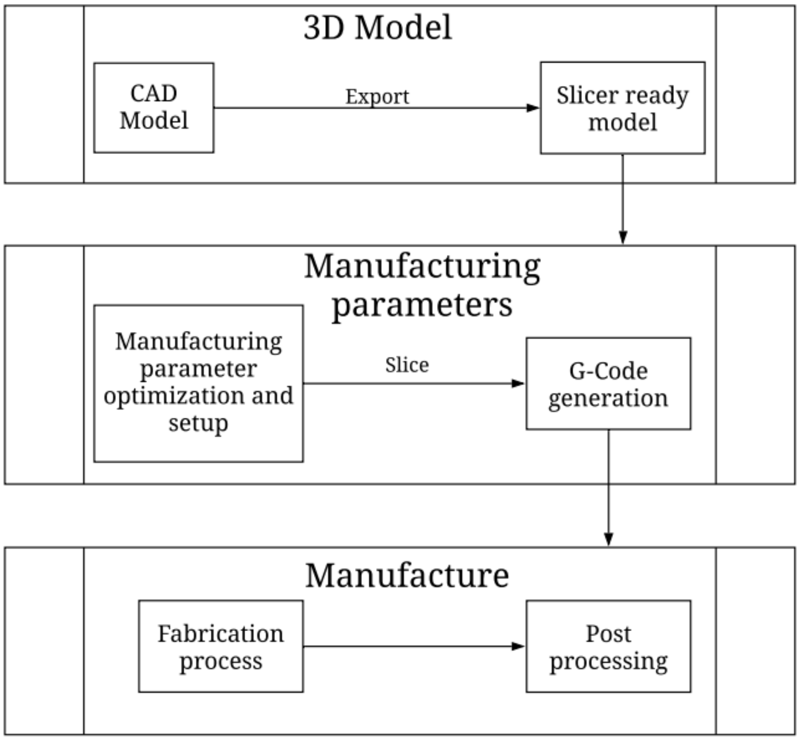


Figure 1. Process flow chart in FDM

Traditional machining technologies also increase the electricity demand and consumption of a workspace. All manually operated processes require adequate lighting for the workers to be able to do their work. Both the workers and the lighting also contribute to the HVAC electrical demand of the workspace (Faludi, et al., 2014).
Tadesse, et al. (Taddese, et al., 2020) suggest three major sustainability performance indicators in AM: environment, economic and social. Not all indicators are easily quantifiable and will require in depth studies to measure be able to measure the effects. The sustainability performance indicators can be broken down further as shown in Table 1.

2. Advantages and Challenges

Table 2 presents some of the significant benefits of AM technology and also some challenges linked to it (Ford & Despeisse, 2016):

Table 2 - AM Advantages and challenges

Advantages	**Challenges**
Small batches are more feasible	It is tricky to maintain the production cost low and speed high
Direct production from CAD models	
Digital designs are easily shared	Altering perceptions of AM applications
The additive nature adds to material savings	Development and standardization
Novel, complex structures achievable	Selection of the available raw material based on their mechanical and thermal properties
Low porosity	AM production of parts with multi-materials
Lees inventory risk	Automation of AM processes
Digitalization ensures direct interaction between consumer and producer	Post-processing requirements
	Support structure material cannot be recycled
	Intellectual property issues
	Material waste in support and infill structures
	Part design challenges (defects and alterations) before manufacturing

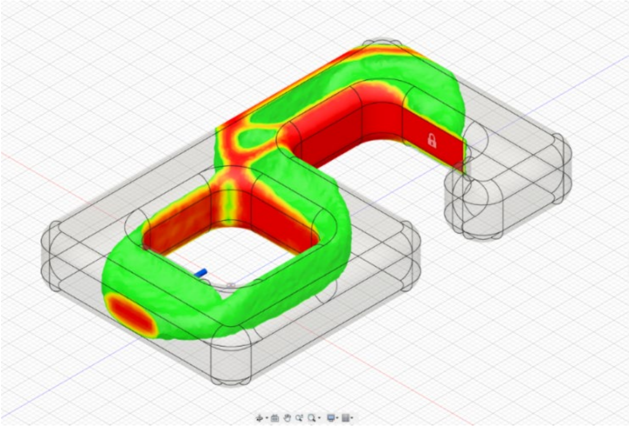
3. Obtaining Sustainability in Additive Manufacturing

The layer-by-layer technique used by most AM processes results in energy and resource efficient manufacturing process. This is especially true in the case of 3D printers. A 3D CAD model can be produced as soon as the engineer is finished with the design and slicer setup of the model. The slicer parameters have a major effect on the production time, material, and energy cost. On the other hand, AM processes such as SLS is not be able to take advantage of optimized infills as the powder material cannot be removed from hollow insides without the use of a 'drainage hole' somewhere on the part (Diegel, et al., 2010). This may be a major setback in some practical settings.
Fused filament fabrication (FFF) is a fabrication process that utilizes 3D modeling software and multi axis machining to produce a physical model. Parts produced using FFF can be used for a variety of applications. There are many materials to choose from flexible thermoplastics to ferromagnetic polymer mixtures. The process applies a specified amount of thermal energy to a continuously fed thermoplastic. The thermoplastic bonds itself with previously extruded layers of itself to form a part. FFF machines are also referred to as 3D printers.
A 3D model is created using any compatible computer software. The 3D model is then exported to machine supported slicer. The slicer is software that converts the 3D model into lines of G-code. The G-code may differ between types of machines as some machines may have extra operations/dimensions. Most FFF machines will specify x-, y-, -and z coordinates of the extruder tip, along with the filament feed rate.
FFF machines start from the printing surface and proceed upward. The parts are produced layer-by-layer. It is common practice to install a heated bed as heated surfaces prove more successful in achieving high quality parts.

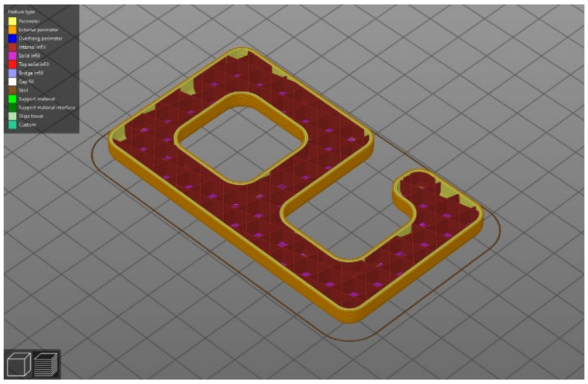
As a fabrication method FFF already offers some advantages in the line of sustainability, some include:

- Less waste material
- Prototypes can be tested before they are mass produced
- Support structures and unused parts can be recycled
- Complex geometries are fabricated in a single process
- Does not require specialized skill

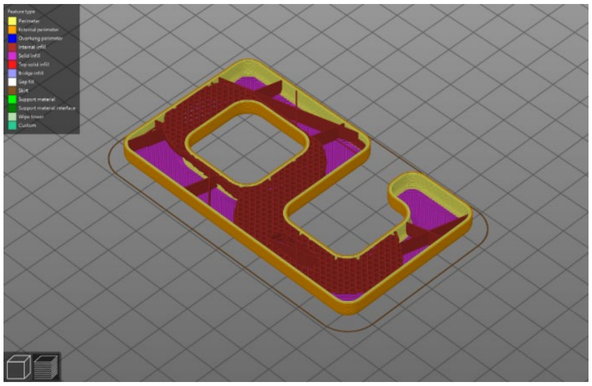
Structural optimization is an umbrella term for mainly three areas of structural design optimization. These are sizing, shape, and topology optimization (Fig. 2).



(a) Topology optimized hook



(b) Standard G-Code generation



(c) Optimized shape mesh modification

Figure 2 Example of topology optimization to achieve sustainability in AM.

With the omnipresent increase of computing power and capacity, structural optimization is becoming a major tool for engineers in the automotive, aerospace, and other relevant industries. FFF along with all its other advantages is a well-suited technology to take even further advantage of structural optimization.

Mechanical performance of FDM parts is directly affected by the manufacturing process. Some AM technologies produce orthotropic parts as they are manufactured layer-by-layer. These parts may show significantly lower mechanical performance in the fabrication direction (tangential to the plane of the layer).

The following techniques offer the user the ability to improve the mechanical performance of the FDM part:

- Alternating layer raster angles
- Raster angles in-line with the expected loads
- Higher extrusion multiplier reduces the airgaps
- Higher infill densities
- Higher number of part perimeters
- Orientation of layers relative to loading case
- Use of curved layer fused deposition modeling slicers

4. Summary

This review paper has reported current and to-date ways of identifying sustainability performance indicators in additive manufacturing. Additive manufacturing is a relatively modern advanced manufacturing technology that is still growing rapidly both in process optimization as well as industrial application. Sustainability performance indicators are defined and categorized as environmental, economical and, social performance indicators.

This paper reviewed the current understanding of sustainability performance in a manufacturing environment. Various measurable performance indicators are defined and possible ventures into the improvement of these measures are discussed.

Additive manufacturing as a rapid prototyping technology offer substantial environmental sustainability improvements over traditional subtractive manufacturing techniques.

The future attempts are required to explore the practical application of shape optimization algorithms to improve the sustainability performance of fused deposition modeling technique. The process parameters mainly infill density and shape are required to be optimized using modern day, and readily available, shape optimization techniques. The goal should be to engineer such a process that consumes less time, material, and energy without compromising on the mechanical behavior of the printed parts.

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Biographies

Andre Espach is an MEng student at the University of Johannesburg. He did his undergraduate at the University of Pretoria. His master's research involves sustainability enhancement of additive manufacturing technologies using structural optimization. He has over three years of engineering design and consulting experience in the fields of static structure design, submersible pump design and sustainable energy design. Key areas of performance include developing numerical and scientific models for complex engineering systems.

Kapil Gupta is working as Associate Professor in the Dept. of Mechanical and Industrial Engineering Technology at the University of Johannesburg. He obtained Ph.D. in mechanical engineering with specialization in Advanced Manufacturing from Indian Institute of Technology Indore, India in 2014. Advanced machining processes, sustainable manufacturing, green machining, precision engineering and gear technology are the areas of his interest. He has authored several SCI/ISI Journal and International Conference articles. He also authored and edited 10 international books on hybrid machining, advanced gear manufacturing, micro and precision manufacturing, and sustainable manufacturing with the renowned international publishers. He has also successfully guest edited special issues of a Scopus indexed journals and he is currently editing a series of handbooks on Advanced Manufacturing as a series editor. He is a recognized reviewer of many international journals and in the advisor/technical committees of international conferences. He has also delivered invited speeches in international conferences and symposiums, and seminar talks at international universities. Kapil Gupta is a NRF [National Research Foundation] rated Researcher in South Africa. Currently, he is supervising 8 Masters and 4 Doctorate students who are busy conducting research in advanced manufacturing and industrial engineering fields.