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Measure Additive Manufacturing for Sustainable Manufacturing

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Abstract. Additive manufacturing technologies are still brand new in industrial production. Although It has widely been used in prototypes development, either low or very low scale production are also able to incorporate such technologies nowadays. The application of additive manufacturing in large scale has been presented as a paradigm to be overcome. Nevertheless, the application of these technologies worldwide might affect production systems dynamics in addition to organizations structures. At the same way, applying additive manufacturing technologies in medium and large scale might also create either novel businesses models or improve marketing segments that were underestimated. For that reason, the main goal of this paper is to investigate the metrics applied in additive manufacturing to identify the main advantages and disadvantages of these scenarios in a systematic study which correlate the economic, social and environmental key points which provide current manufacturing companies to identify the suitability of each additive manufacturing technology in accordance with its business goals. Therefore, the sustainable metrics for additive manufacturing processes will prove that it is really a sustainable manufacturing. Moreover, these results were results of others preliminary studies which might open a new discussion topic among manufacturing companies.

Keywords. Additive manufacturing, Metrics, Measure, Sustainable manufacturing

Introduction

In general way, additive manufacturing (AM) is defined as a manufacturing process which is used to produce three-dimensional objects by adding layers of material based on a three-dimensional computer model. Among the several definitions of this process, we can highlight 3:

"3-D printing employs an additive manufacturing process whereby products are built on a layer-by- layer basis, through a series of cross-sectional slices" [1].

"Process of joining materials to make objects from 3D model data, usually layer upon layer, opposed to subtractive manufacturing methodologies, such as traditional machining" [2].

"AM systems build parts by depositing, fusing, curing, or laminating consecutive layers of material" [3].

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Depending on process, material and technology, AM can be used in different sectors segments, such as architecture, aviation, aerospace, art, automobiles, consumer products, education, electronics, energy, entertainment, healthcare, nanotechnology, repair, tools and visualization [4]. Moreover, the suitable AM process for a product can be selected according to the application, the material, the mechanical resistance and other considerations [5, 6].

AM has been presented by many people as a clean technology and also a sustainable manufacturing. The main argument might be based on the rational and efficient use of raw materials, low waste production, reuse of raw materials and waste, reducing additional productive resources, a flexible production and demand, among others.

In spite of the potential of the AM, there is not measurement enough that supports the definition ofthose processes as sustainable manufacturing. For this, it is still necessary to have a proper definition of sustainable production in its broadest aspect, and verify whether the AM fits within all requirements. Thus, the main objective of this work is to check whether AM can be considered a sustainable manufacturing by analyzing the economic, environmental and social indicators applied to this technology.

1. Literature Review

1.1. Additive Manufacturing

Usually, AM main processes are: a) fused deposition modeling (FDM), b) stereolithograpy (SLA), c) inkjet printing (IJP), d) laminated object manufacturing (LOM), e) selective laser sintering (SLS), f) three dimensional printing (3DP), as show in Figure 1.

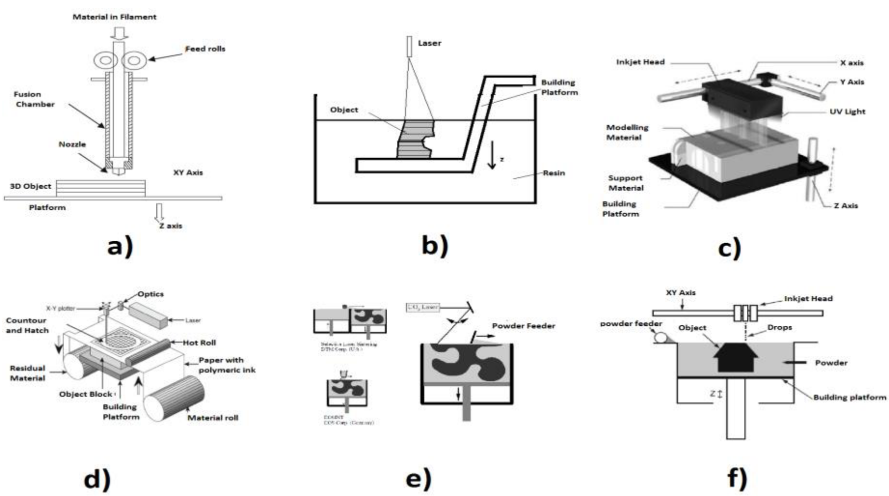

Figure 1. AM technologies processes schematic illustration (adapted from [5, 6]).

In Figure 1, the six AM processes are illustrated and the manufacturing method is based on the object layer-by-layer, in all cases. Generaly, the FDM process to create the object through the thermoplastic material deposit on a platform while a liquid resin is photopolymerizable by laser SL processes. In IJP processes, an inkjet head turns drops of liquid resin, and a UV lamp solidifying these drops. For LOM, the main material is paper, plastic or metal laminate form. The object is formed by cutting and adhesive bonding and cutting processes. In a SLS process, the powdered material is melted by laser or siterizad, to form object, 3DP process as glue powder inkjet binding [5-7].

1.2. Sustainable Manufacturing

Sustainable manufacturing involves the contribution of the productive sector companies [8], this means that the entire production system in the broadest aspect, including the supply chain, should not polluters; energy and natural resources conservatives; economically viable; safe and not evil with workers, communities and consumers; socially and creatively rewarding with all workers [9-11].

Some regulations and standards has been proposed for regulating and ensure the sustainable manufacturing are some of them: *Accountability* – AA 1000; *Social Accontability* – AS 8000; *Global Reporting Initiative* – GRI; *Environmental Management Standards* – ISSO 14000; *International Guidelines for Social Responsability* – SR ISO 26000 [11, 12]; *Commission on Sustainable Development* [13]; *Tripple Bottom Line* – TBL or 3BL [14, 15]; *Dow Jones Sustainability Index* – DJSI [16]; ETHOS [17]; *Corporate Sustainable Index* BOVESPA – ISE BOVESPA [18].

It is observed that there are several measuring proposals for sustainable manufacturing, the approaches are different, and it is impossible to consider that only one is correct and it be universal. But they note that the indicators have a greater approach to corporate sustainability. And, this does not prevent them from being applied to measuring sustainability production system of a company.

For a manufacturing measurement application must comply with broad aspects of economic, environmental and social, by means of specific sub-indicators manufacturing. Thus, data will be collected on the production system that will confirm the sustainability of this particular manufacturing.

As in AM several technologies the verification can occur in two ways. The first can check the production indicators in the economic, environmental and social aspects of each technology in AM. The other is the same check and list them in order to find equivalencies that can determine the equality of these indicators in all aspects. Thus, this correspondence would assert a compliance between all indicators for the different AM technologies.

1.3. Indicators of sustainable production

Beyond the concept of sustainable development from UNCED [19] bring up the concept of sustainable production. Before that many industries are realizing advantages in sustainable and measuring it in full sustainability aspects. Sustainable production as LCSP [20]: “the creation of goods and services using processes and systems that are: non-polluting; conserving of energy and natural resources; economically viable; safe and healthful for workers, communities, and consumers; and, socially and creatively rewarding for all working people“.

The companies that had sustainable production goals, have sustainable production pratices, and need to measure sustainable production progress. For the measurement are used indicators, exclusively numerical, that provide information about the economic, environmental and social production.

Most of the indicators are already tracked by the companies, but it still necessary to understand sustainable production with economic, environmental and social emphasises in addition to the aspects which companies production practices, according Veleva et al. [9]. The same authors have stated that it is more operational, since it highlights six main aspects of sustainable production [21]:

- energy and material use (resources);
- natural environment (sinks);
- social justice and community development;
- economic performance;
- workers, and;
- products.

1.4. Indicators for AM

Bell and Morse [22] believe that the indicators can be defined for a particular interest and not according to what it really necessary to be measured. They define the indicators that will be used to focus in aspects that can bring advantages and hide those which can jeopardize company's image and interests, even if knowledge about these aspects are important by others.

The indicators to measure AM in the range of sustainability are few extensive, inconsistent and uncorrelated. The metrics should be more focused on performance and sustainable manufacturing, which actually comply with demonstrating the reality.

The metrics found in the literature are more on economic indicators to try to enable this technology for products, manufacturing and supply chain. There are many articles comparing AM technologies with traditional manufacturing even though a inappropriate indicators use is applied. Nevertheless, economic indicators are clearly the highlighted advantage againstthose technologies disadvantages. Thus, it can be said that AM tecnologies have not been possible to be categorized as sustainable manufacturing yet. That confirms what Bell and Morse [22] tell us about indicators.

Environmental indicators reflect more reality, measuring up the waste, consumption of raw materials, energy consumption, among others. In this case, they are more specific and demonstrate the green benefits and benefits to the corporate image. Already social indicators are not addressed in a manufacturing vision, which certainly involve the health and safety of those involved directly AM technology. Only report benefits as the development of customized medical products for more specific care of some special needs, such as prostheses developed with AM technology.

Another aspect disregarded in a simple point view isthat these indicators are not correlated. And it certainly affects each other.

2. Methodology

The theoretical development and results comes from conceptual discussions of literature from a literature review in order to respond the goals. Searches in AM references databases following topics: additive manufacturing, sustainability and indicators.

The content raised perceive the importance of this new technology in the global industrial landscape, the possibilities in product development, which refer to all existing AM processes. Addition, came the need to check each alignment or differentiation of AM processes indicators existing, noting the peculiarities of each.

Should be noted that there are diverse AM technologies, and the approach of the indicators aim to respond to AM's sustainable manufacturing, i.e., is not been measuring the technology or its advances, but the application of these technologies in production systems directly, even though at this moment it is only a conjecture.

As a result of these initial considerations studies AM indicators for sustainable production in its broadest aspect (economic, environmental and social) were incipient. Therefore, another direction was adopted. Passed to work with sustainable production indicators applied AM technologies to respond the research question.

The work of Veleva and Ellenbecker [21] shows indicators for the sustainable production and a classification for maturity levels on a framework. It is expected that verification of AM technologies indicators is sufficient, to the end, be able to state that AM is a sustainable manufacturing.

3. Development

We can see in Table 1, that literature about AM and sustainable manufacturing were found, and it have not answered the current research question yet. It was really motivating to find in the literature only indication that AM is a sustainable manufacturing. And, at this time, Veleva and Ellenbecker [21] sustainable production indicators revealed the solution to this research.

Sustainable Production indicators are common in any type of production system, giving the adjustments in the metrics. The aspects of sustainable production indicators can be applied without adjustment for energy and materials use; economic performance; justice and social community development; workers; and products.

Even without the need for adjustment is still needed for some indicators more detail. The materials used and energy used indicators have to be in full measure and per unit of product. The costs associated with environmental, health and safety (EHS) compliance reduce the economic performance, i.e., are costs through pollution prevention and cleaner production means real savings and Increased profits, reduce product/service price, increased shareholder value, wages, worker benefits, investment in R&D, fines, liabilities, worker compensation, fees for waste treatment and disposal, tradable permits, remediation costs, cost/depreciation of control equipment, labor costs [21].

The rate of customer complaints and returns indicator is about the number of complaints returns per product sale. And, the rate of employees'suggested improvements in quality, social and EHS performance need to collect employee suggested improvements about job satisfaction and morale, providing rewards to the participants [21].

In natural environment aspects, specifically the waste generated indicator, which can be emissions, solid and liquid waste, should be measured after the recycling process. Global warming potential (GWP) and potential acidification indicators had changed the metrics for emissions of gases applied AM technologies. And, the indicator for persistent, bioaccumulative and toxic (PBT) chemicals used has not been changed.

Table 1. AM for sustainable manufacturing from literature.

Author/Year	AM Technology	Short paper considerations
Mani, Lyons and Gupta/2014 [23]	General AM Tech	AM advantages.
Nation Institute of Standards and Technology – NIST/2013 [24]	Metal-Based	Metal-Based advantages only on reduce the waste in manufacturing, reducing energy used in production of raw materials and in the processing steps.
Le Bourhis et al./2013 [25]	General AM Tech	Presented a new methodology for environmental impact assessment in the AM machine.
Huang et al./2013 [26]	General AM Tech	Societal impact of AM from a technical perspective.
Bertling et al./2013 [27]	SLS	Presented sustainability environmental aspects for AM and the FabLab as a paradigm shift in consumer-producer-relationship.
Isanaka and Liou/2012 [28]	General AM Tech	Overview for sustainable quality control, time and predictive maintenance of the AM equipment to the roles of AM technologies.
Scott et al./2012 [29]	General AM Tech	Overview of technical challenges to measuring the environmental impacts and sustainability of AM processes.
Nopparat and Kianian/2012 [30]	General AM Tech	Investigated AM technology through the result-oriented Product-Service Systems (PSS) approach. And AM has higher efficiency in raw material usage, has higher energy consumption too.
Brackett et al./2011 [31]	General AM Tech	Overview of topology optimization methods for AM are key drivers toward realizing energy efficiency and reducing environmental footprint.
Baumers et al./ 2011 [32]	Polymeric Laser sintering	Overview of energy consumption and reporting specific energy consumption during the production of dedicated test parts.
Diegel et al./2010 [33]	FDM	Overview of design perspective: design quality and sustainability.
Hao et al./2010 [34]	FDM (Food application)	Overview of sustainable production efficiency improvement by optimizing AM process parameters and reduction of energy consumption.
Sreenivasan et al./2010 [35]	SLS	Overview of reduce energy consumption in SLS of non-polymeric materials.
Hiller and Lipson/2009 [36]	FDM	Overview of flexible fabrication processes in which 3D multi-material objects are fully recyclable and re-usable.
Morrow et al./2007 [37]	SLS, 3DP, LENS, DLF, DMD	Case studies about Direct Metal Deposition (DMD)-based manufacturing can reduced environmental emissions and energy consumption.

Table 2. Indicators of sustainable production and adapted for AM technologies.

Aspect for SP	Indicator	Metric	Indicator adapted for AM	Metric
Energy and material use	Fresh water consumption	Liters	Fresh water consumption	Liters
	Materials used	kg	Materials used	kg
	Energy used	kWh	Energy used	kWh
Natural environment (including human health)	Waste generated before recycling	kg	Waste generated before recycling	kg
	Global warming potential (GWP) (CO_2 or equivalent)	Tons	Global warming potential (GWP)	m^3
	Acidification potential (SO_2 or equivalent)	Tons	Acidification potential	m^3
	PBT chemicals used	kg	PBT chemicals used	kg
Economic performance	Costs associated with EHS compliance	$	Costs associated with EHS compliance	$
	Rate of customer complaints and returns	No.	Rate of customer complaints and returns	No.
	Organization's openness to stakeholder review and participation in decision-making process (scale 1–5).	No. (1-5)	Organization's openness to stakeholder review and participation in decision-making process (scale 1–5).	No. (1-5)
Community development and social justice	Community spending and charitable contributions as percent of revenues	%	Community spending and charitable contributions as percent of revenues	%
	Number of employees per unit of product or dollar sales	No./$	Number of employees per unit of product or dollar sales	No./$
	Number of community-company partnerships	No.	Number of community-company partnerships	No.
Workers	Lost workday injury and illness case rate (LWDII)	Rate	Lost workday injury and illness case rate (LWDII)	Rate
	Rate of employees'suggested improvements in quality, social and EHS performance	No.	Rate of employees'suggested improvements in quality, social and EHS performance	No.
	Turnover rate or average length of service of employees	Rate (years)	Turnover rate or average length of service of employees	Rate (years)
	Average number of hours of employee training per year	Hours	Average number of hours of employee training per year	Hours
	Percent of workers, who report complete job satisfaction	%	Percent of workers, who report complete job satisfaction	%
Products	Percent of products designed for disassembly, reuse or recycling.	%	Percent of products designed for disassembly, reuse or recycling.	%
	Percent of biodegradable packaging.	%	Percent of biodegradable packaging.	%
	Percent of products with take-back policies in place	%	Percent of products with take-back policies in place	%

Source: Indicators of sustainable production (adapted from [21])

4. Results

Now, after the sustainable production indicators have been adapted for AM technologies, it was possible to interpret the data from these indicators. It was found, according to Table 3, whether there was relationship between the aspect of sustainable production and indicators with their AM technologies. We found some similarities and other differences that have not leaded to a conclusion if AM can be considered sustainable manufacturing. This analysis only exposed that there are evidences for this state.

Table 3. Identified economic, environmental and social indicators of sustainable production for AM tech.

Aspect for SP	Indicator	FDM	SLA	IPJ	LOM	SLS	3DP
Energy and material use	Fresh water consumption	✓	✓	✓	✓	✓	✓
	Materials used	✓	✓	✓	✓	✓	✓
	Energy used	✓	✓	✓	✓	✓	✓
Natural environment	Waste generated before recycling	✓	✓	✓	✓	✓	✓
	Global warming potential (GWP)	✓	-	-	✓	✓	✓
	Acidification potential	✓	✓	✓	-	✓	✓
	PBT chemicals used	✓	✓	✓	✓	✓	✓
Economic performance	Costs associated with EHS compliance	✓	✓	✓	✓	✓	✓
	Rate of customer complaints and returns	✓	✓	✓	✓	✓	✓
	* Organization’s openness to stakeholder review and participation in decision-making process (scale 1–5).	✓	✓	✓	✓	✓	✓
Community development and social justice	* Community spending and charitable contributions as percent of revenues	✓	✓	✓	✓	✓	✓
	* Number of employees per unit of product or dollar sales	✓	✓	✓	✓	✓	✓
	* Number of community-company partnerships	✓	✓	✓	✓	✓	✓
Workers	* Lost workday injury and illness case rate (LWDII)	✓	✓	✓	✓	✓	✓
	* Rate of employees’suggested improvements in quality, social and EHS performance	✓	✓	✓	✓	✓	✓
	* Turnover rate or average length of service of employees	✓	✓	✓	✓	✓	✓
	* Average number of hours of employee training per year	✓	✓	✓	✓	✓	✓
	* Percent of workers, who report complete job satisfaction	✓	✓	✓	✓	✓	✓

Aspect for SP	Indicator	FDM	SLA	IPJ	LOM	SLS	3DP
Products	* Percent of products designed for disassembly, reuse or recycling.	✓	✓	✓	✓	✓	✓
	* Percent of biodegradable packaging.	✓	✓	✓	✓	✓	✓
	* Percent of products with take-back policies in place	✓	✓	✓	✓	✓	✓

* Depending on organization structure, policies, strategy adapted on sustainable production.

5. Conclusion

Companies need to measure sustainable aspects in order to manage their performance. AM performance still need to include sustainable production indicators in order to be considered sustainable production. In summary those indicators are in the Table 3.

Even though all indicators of sustainable production can be applied on AM technologies, as a common production system, some specific advantages of AM still lack to be counted in this analysis. We might see that,considering the indicators defined for this application are wide and coherent, i.e., it involves sustainable production in economics, environmental and social the measurement do not still show advantages or hide disadvantages. On the other hand, we have also found indications that AM might a sustainable manufacturing through specific indicators for sustainable production.

Thus, it is not possible to assume that AM is a sustainable manufacturing yet. Further studies are still needed to be done and applied The in case studies and different technologies AM.

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