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52nd CIRP Conference on Manufacturing Systems

Additive manufacturing from the sustainability perspective: proposal for a self-assessment tool

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Abstract

Emergent technologies and additive manufacturing have a significant role in shaping the future of manufacturing, enabling companies to produce complex products and parts in a more efficient and sustainable way. However, companies are struggling to identify and achieve the full potential of the technology from a sustainability perspective. The purpose of this paper is to develop a checklist to assess the sustainability performance of additive manufacturing adoption and exploitation, based on secondary data from the academic literature, technical reports, and company cases. Results rely on the identification of critical sustainability aspects for additive manufacturing and key performance indicators.

Keywords: Additive manufacturing; sustainable operations; SDGs; checklist; performance indicators.

1. Introduction

Advanced manufacturing technologies play a key role in increasing the prosperity of national economies while contributing to the 12th Sustainable Development Goal (SDG) for responsible production and consumption [1–3]. Implementing sustainability principles in manufacturing is a complex challenge, forcing companies to confront dilemmas and make decisions with conflicting objectives and values. It is necessary to consider the long-term impacts of manufacturing process selection and utilization [4,5].

Differences and opportunities between additive manufacturing (AM) and conventional manufacturing (CM) are, among others: enable complex designs; reduce extraneous material, scrap and waste; use little or no tooling; shorter lead time; on-demand manufacturing, component upgrade, and competitive small batches production [2].

There are different factors linking AM technologies with more sustainable operations, among others: resource efficiency; extended product life; lean supply chain (just-in-time), eliminating work-in-process and stock obsolescence; potential benefits on workers' health and safety (e.g. with less exposure to toxic materials and/or potential hazardous work environments); and customers' engagement [2,6,7].

However, it is important to highlight that some of these aspects are challenging to quantify and highly context-dependent, thus cannot be generalized across cases. Frățilă and Rotaru [8] state that some aspects can be related to manufacturing strategy, machine usage, among others.

Besides potential benefits, previous studies identified issues that also need to be considered, as listed by Rejeski et al.[9]: fusion methods can consume more energy than traditional ones; emissions of particulates and volatile organic compounds can be harmful to workers' health; waste is

generated in non-industrial settings; gaps in the use of biodegradable or bio-based materials; limited data availability for Life Cycle Assessment (LCA); regulatory structures; and, socio-environmental impacts due combination of AM processes/materials with other technologies/processes.

It is necessary to verify when AM can be considered a sustainable manufacturing process [7]. Thus, this paper intends to answer: How can we assess if adoption of AM technologies in production is a more sustainable solution? This paper contributes on presenting best practices related to energy use, waste, and occupational health and safety related to AM adoption, and translate into a set of checkpoints.

The checklist attempts to complement existing literature on aspects to take into consideration when deciding whether to implement AM in production or not. In addition, the links between benefits of AM implementation and the transition towards meeting the UN SDGs [3] become more explicit.

To explore and organize the data, the paper is structured in four sections: review of the use of AM for sustainable production; research design; organization of the extracted data and development of the checklist requirements; and, final thoughts and future research directions.

2. Sustainability implications for Additive Manufacturing

As described by Gimenez et al. [10], economic aspects of sustainability are mainly operationalized as manufacturing costs; environmental aspects are linked to energy and material efficiency, waste and emissions reduction; while social aspects focus on employees, customers and communities.

It is necessary to adopt a system approach to understand how AM can be used in production, beyond its capabilities as an individual technology solution. The effectiveness of all systems and sub-systems, resources and activities, will be responsible for the whole system performance [1,2]. However, there is a gap, as exemplified by Peng et al. [11] and on-going standards' development and improvement, who reported that parameters for quality insurance are being developed but, in most cases not considering sustainability impacts (e.g. increased process time impacts and need of finishing processes increasing energy consumption).

AM creates opportunities for companies to adopt service-based business models (e.g. leasing and maintenance), benefits on transportation and supply chains resulting from simplified assembly design with fewer components, and better overall resource efficiency through more knowledgeable (and thereby effective) deployment of AM-based production systems and value chains [2]. Table 1 lists some of the sustainability advantages from a life cycle perspective.

Table 1. Sustainability advantages of AM over the product life cycle stages.

Life cycle	Advantages
Design	Improved functionality, durability, upgradability, resource efficiency and toxicity, upcycling, etc.
Production	Reduced energy intensity and waste, resource-efficiency, etc.
Use	Lightweight, operational efficiency, functionality, durability, less repair time, etc.
End-of-life	Acceptance of recycled or by-products materials as input, remanufacturing, upgradability, etc.

Source: adapted from [2, p.1584]

Kellens et al. [12] compared AM vs CM processes and some examples are organized in Table 2. The authors stated that, to evaluate the full environmental impact of manufacturing, all resources, direct and indirect emissions must be accounted for, but a more holistic view of the production system also needs to be considered. For example, strategically decentralized AM has the potential to reduce transportation impacts, avoid inventory and distribution problems. However, centralized AM can be a better strategy in uncertain conditions or on the short term [2,12]. The authors summarized that, in its current state, AM can be a good choice for producing customized parts or small batches, and complex part designs enabling more functional advantages in the use phase.

Table 2. Benefits (+) and weaknesses (-).

Type	Benefits (+) and weaknesses (-)
Social	Safety & health risks for workers and the environment (--), industrial employment (+/-), better working conditions (+)
Economic	Cost of part manufacturing (--), longer manufacturing time (-), limited part dimensions (-), shorter process and assembly chains (+), shorter lead times (++), fewer spare parts (++), on-demand manufacturing (++)
Ecological	Higher energy intensity (--), impact of manufacturing stage (--), need for support structures (-), fewer production waste (+/-), higher material efficiency (+), improved remanufacturability (+), weight reduction (++)

Source: adapted from [12, p.5]

Previous studies have also identified that it is necessary to measure different types of impacts to make a more sustainable choice in AM processes. Decisions should be made, for example, based on the demand (to decide to use dedicated printer or job shops services) and the type of the machine (e.g. under certain conditions, some 3D processes can reduce worker exposure to toxins). Other aspects to be considered: material and energy efficiency; industrial waste management; manufacturing costs, avoidance of toxic materials and emissions; improvement of personnel health & safety; appropriated design (e.g. less parts and materials, more functionalities) and reparability, reusability, recyclability, and disposability of the products; and other social life cycle impacts (e.g. raw material extraction) [8,13,14].

Despeisse et al. [14] developed a four-step approach to consider sustainability implications for AM. The first step is about creating a vision based on the Sustainable Development Goals (SDGs). Table 3 illustrates how specific SDGs can help develop a sustainable vision for implementing AM, along with examples of performance indicators.

Table 3. Examples of vision based on the SDGs.

SDG	Goal /Vision	Targets	Indicators
8	Promote inclusive and sustainable economic growth, and decent work.	Improve global resource efficiency; Promote safe and secure working environments	Material footprint Frequency of occup. injuries
12	Ensure sustainable production patterns	Env. manag. of chemicals and wastes throughout life cycle; Reduce waste generation through prevention, reduction, recycling and reuse	Hazardous waste generated and treated Recycling rate, and tons of material recycled

Source: [3]

Then the approach follows the process of technology road-mapping to identify new business opportunities across all stages of the life cycle [15,16]: the second step is about identifying drivers for AM adoption (e.g. product differentiation through customization and personalization, reduced lead-time, innovation capabilities, etc.); the third step is about identifying new business opportunities for each stage of the product of service life cycle (e.g. product features, functionalities, service offers, etc.) to address the drivers of step 2; and finally the fourth step is about identifying the enablers (e.g. software, machines, new materials, quality standards knowledge and skills, etc.) to realize the opportunities identified in step 3. Therefore, trade-offs will be part of the decision process to achieve an optimum benefit.

Considering this background, Figure 1 presents the implications of AM with 8 benefit *dimensions* connected to the SDGs, the triple bottom line (economic, environmental, social), and the relationships between them. As an example, the inner arcs are connecting these categories to the SDGs as each category of sustainability implications has the potential to address multiple SDGs; e.g. the benefit categories 'D – Clean production and pollution prevention' and 'G – Sustainable sourcing' link to SDGs 6 (water), 7 (energy), 9 (industry and innovation), 12 (production and consumption), 13 (climate action), and 15 (biodiversity) through sustainable management of natural resources, efficiency and safety measures in the manufacturing process, and waste and pollutants elimination. The eight dimensions represent recurrent benefits extracted from the literature and below is presented a brief explanation:

A. **Clear strategy & stakeholder collaboration** - the purpose for adopting or integrating AM processes is linked with a clear vision contributing towards sustainability (SDGs), including promotion of global multi-stakeholder partnerships for sustainable development.

B. **Workers' health and safety -** the adoption of AM technologies should not compromise the safety of the process, e.g. material toxicity and harmful effect on both human health and the environment [18].

C. **Training and education -** the current knowledge and skill shortage in industrial engineering calls for new education programs to develop a workforce to exploit the benefits offered by AM technologies [17].

D. **Clean production and pollution prevention** - the inherent nature of AM results in a minimal amount of physical waste. However, many of the impacts occurs beyond the manufacturing process itself. While AM can be more energy-intensive per unit produced, a make-to-order model can avoid over-production and storage of unsold parts and products, further reducing material waste and other unnecessary resource use.

E. **Quality control and standards -** AM processes for end-product are relatively immature compared to machining or injection molding, thus they suffer issues of reliability and quality. These have been addressed in the last 5 years with the ASTM and ISO standards regarding test methods for quality control and material characterization.

Fig. 1. Sustainability benefits for AM linked to the SDGs.

F. **Product performance -** the design freedom and resulting new product functionalities enabled by AM can improve product performance during use, such as aesthetic forms, lightweight materials for fuel efficiency, or enhanced structural integrity improving product durability.

G. **Sustainable sourcing (energy/materials) -** as discussed above, AM can be highly energy-intensive and thus, the energy-related air emissions can be a drawback of its implementation. Thus, it highlights the importance of shifting to low-carbon and renewable energy sources. AM can also promote more circular resource flows (e.g. reusable metal powder and recycled polymer filament) as well as enable profitable local and small-scale production systems. However, it is important to raise awareness on the implications of functionally graded or composite materials and integrated multi-material components, as these can hinder the repairability and recyclability of the product.

H. **Simplified supply chain, on-demand production -** by changing the material required for production using AM technologies, new structure and relationships in material supply chains are established, especially in engineer-to-order and make-to-order models for customized and personalized goods, where one must consider both the economies of scale and scope.

The next sections present cases analysis and the checklist.

3. Research Design

This paper seeks to complement previous studies [2,15]. Therefore, additional cases were identified and collected during the review of industry and consultants' reports (e.g. GE, PWC) and websites (e.g. All3DP). The sustainability benefits presented on Figure 1 were used to guide the selection of the cases, totalizing 14 case studies (Table 4).

Table 4. Additive manufacturing use cases.

References

Caterpillar
1. "Caterpillar 2017 Sustainability Report" (https://www.caterpillar.com/en/company/sustainability/sustainability-report.html)
2. "Design and business model considerations for heavy machinery remanufacturing" (https://www.ellenmacarthurfoundation.org/case-studies/design-and-business-model-considerations-for-heavy-machinery-remanufacturing)

GE
3. "Mind Meld: GE's 3D Printing Summit Explores Additive Manufacturing's Exponential Future" (https://www.ge.com/reports/just-press-print-ges-3d-printing-summit-explores-manufacturings-exponential-future/)
4. "Hot Off The Press: 3D Printing Has Pushed This Gas Turbine To New Highs" (https://www.ge.com/reports/hot-off-press-3d-printing-pushed-turbine-new-highs/)
5. "The 3D-Printed Age: Why This Futuristic Ohio Factory Is Proving Mark Twain Wrong" (https://www.ge.com/reports/3d-printed-age-futuristic-ohio-factory-proving-mark-twain-wrong/)
6. "Tour De Force: This Slovak Company Is 3D-Printing Bespoke Electric Mountain Bikes" (https://www.ge.com/reports/tour-de-force-slovak-company-3d-printing-bespoke-e-bikes/)
7. "Printing Heads: 3D Printing Has Launched A New Era In Aircraft Design" (https://www.ge.com/reports/printing-heads-3d-printing-launched-new-era-aircraft-design/)
8. "Transformation In 3D: How A Walnut-Sized Part Changed The Way GE Aviation Builds Jet Engines" (https://www.ge.com/reports/transformation-3d-walnut-sized-part-changed-way-ge-aviation-builds-jet-engines/)

Siemens
9. "EOS Technology opens up new opportunities for industrial gas turbine maintenance cost reduction" (https://www.eos.info/press/customer_case_studies/siemens)

Airbus
10. "The Airbus Roadmap to Additive Manufacturing" (https://www.engineering.com/AdvancedManufacturing/ArticleID/15886/The-Airbus-Roadmap-to-Additive-Manufacturing.aspx)

Renishaw
11. "Making time for Holthinrichs Watches" (https://www.renishaw.com/en/making-time-for-holthinrichs-watches--42651)
12. "KOMET® GROUP innovates cutting tools using metal 3D printing technology" (https://www.renishaw.com/en/komet-group-innovates-cutting-tools-using-metal-3d-printing-technology--42311)
13. "Renishaw produces a prototype nose tip for the BLOODHOUND Supersonic car" (https://www.renishaw.com/en/renishaw-produces-a-prototype-nose-tip-for-the-bloodhound-supersonic-car--31907)
14. "Hydraulic block manifold redesign for additive manufacturing" (https://www.renishaw.com/en/hydraulic-block-manifold-redesign-for-additive-manufacturing--38949)

Considering the exploratory purpose of this paper, the cases are considered as supporting examples of successful implementation of AM rather than a representation of a population. The analysis was carried out to identify critical sustainability aspects for additive manufacturing during different life cycle stages defined by Ford and Despeisse [2], and performance indicators (KPIs). Data was organized in Excel sheets and the full table is not presented; a summary of the analysis is presented in the next two sections.

4. Results

This section starts by presenting results from the use cases analyses, Table 5 and 6 present a summary of analysis by case study. However, before discussing the cases, it is important to highlight that it was not possible to identify direct benefits connecting AM processes with workers health and safety, however, indirect effects can be linked to reduction of production steps (e.g. less welding or less exposition to other hazardous processes and materials).

The main goal with the analysis was to identify emergent sustainable best practices across the cases, and results are reported by category of benefits reported, from most to least common. Results indicate that 'Product Performance' as a strong dimension to be considered, both to reach sustainability gains in production (e.g. case 9) as well as in the use-phase (e.g. cases 4 and 5). Caterpillar and Siemens highlighted the development of remanufacturing capabilities, focusing on the closing loop stage. GE, Airbus and Renishaw highlighted benefits during the production and use phases, e.g. design of lower weight parts with higher quality, improving equipment efficiency and energy consumption and reduction of logistics impacts. Examples of sustainability benefits linked to this dimension identified in the cases: enabling remanufacturing and reuse processes, extending products life-cycle (including improving quality/durability, promoting waste reduction, and creating employment (cases 1, 2, 8, 9, 10 and 14); reducing raw material usage and waste (case 2, 10, 11 and 13); reducing logistics impacts (case 3); reducing production process steps (case 9 and 12); reducing emissions and energy consumption in the use-phase (cases 3 and 4); partnerships (cases 5 and 14).

Thus, considering the arcs connecting the SDGs, the 'Product Performance' dimension can enable positive impacts on different SDGs 8 (employment), 9 (industry and innovation), 11 (air and waste), 12 (production and consumption), 13 (climate action), 15 (biodiversity), 17 (partnerships).

Table 5. Sustainability impacts on SDGs from the use cases.

Case	A	B	C	D	E	F	G	H
1	✓					✓	✓	
2	✓				✓	✓	✓	✓
3						✓		✓
4				✓	✓	✓		✓
5	✓		✓	✓		✓		✓
6			✓			✓		✓
7			✓			✓		✓
8			✓			✓		✓
9				✓		✓		✓
10						✓		✓
11			✓	✓		✓		✓
12						✓		✓
13			✓		✓	✓	✓	
14	✓				✓	✓		✓

Table 6. Sustainability impacts across the life cycle stage.

Case	Design	Production	Use	Closing the loop
1		✓		✓
2		✓		✓
3	✓	✓	✓	
4	✓	✓	✓	
5	✓	✓	✓	
6	✓	✓	✓	
7	✓	✓	✓	
8	✓	✓	✓	
9	✓	✓	✓	✓
10	✓	✓	✓	
11	✓	✓		
12	✓	✓		
13	✓	✓		
14	✓	✓		

Results also pointed 'Simplified supply chain, on-demand production', as a relevant dimension; e.g. enabling reverse logistics channels (case 2), reducing logistics impacts (cases 3 and 9), customer engagement (cases 11 and 14), on-demand production (case 3), industry collaboration (cases 5 and 14). Considering the arcs connecting the SDGs, this dimension can enable positive impacts on SDGs 9 (industry and innovation), 11 (air and waste), 12 (production and consumption), 14 (oceans) and 17 (partnerships).

The 'Training' dimension is relevant for developing capabilities to exploit sustainably the benefits offered by AM technologies, upgrade the technological capabilities of industrial sectors/ access to information and communications technology and promote employment (cases 2, 5 and 8) impacting on the SDGs 4 (education), 8 (employment), 9 (industry and innovation).

The 'Clean production and pollution prevention' benefits are connected with waste reduction and resource efficiency (cases 5 and 11), production scalability (case 4), reduction and simplification of the production steps and maintenance (case 9). These benefits can impact the SDG 12 (production and consumption). The cases also pointed out that AM processes are maturing and providing better "Quality" in products, parts and equipment, obtained by remanufacturing (case 2), redesign (case 5), precise/accuracy manufacturing (case 13 and 14). Possible impacts are expected on the SDGs 9 (industry and innovation) and 12 (production and consumption).

'Clear strategy & stakeholder collaboration', cases 1, 2, 5 and 14 presented a clearer strategy connected with the SDG's 8 (employment), 12 (production and consumption), and 17 (partnerships), through strategies focused on remanufacturing and reverse logistics, waste reduction in production, energy efficiency during use, and customer engagement.

Results from Table 5 and 6 also indicate that AM can be considered a sustainable manufacturing process, helping to answer the question raised by Kai et al. [7]. Economic benefits are also presented in the cases but not explored in this paper, among others: cost reduction, reduced lead-times, and increased profit-margins.

5. Synthesis of findings as a checklist

The checklist seeks to support the evaluation of when the adoption of AM technologies in the production will represent a more sustainable solution. The first insight from the literature and the cases is that sustainability impacts need to be considered in all life cycle stages, but the design phase connected with 'Product Performance' dimension is the most critical to ensure positive impacts in other dimensions and across all life cycle stages. Second, ensure workers health and safe is also critical. The fact that it has not been explored in the cases raises a question if health and safety issues are still a challenge or whether they have been addressed with standard and complementary technical measures.

The checklist is the first step in developing a self-assessment tool. Thus, binary answers (yes/no) can be used to evaluate if the AM adoption will enable:

1. A vision that guides a clear strategy towards the SDGs?
2. The development of new types of partnerships that can result in positive impacts for sustainable development?
3. The development of products that uses sustainable material sources and equipment not harmful to workers' health and safety in the production?
4. Increased competence and knowledge about benefits of the AM processes within partners, workers and customers?
5. Increased competence to exploit the sustainability benefits of AM processes (from design to closed loop phases)?
6. The development of products with remanufacturing or recycling properties extending the product life cycle, reducing waste after use, and reducing use of raw materials?
7. The design of products for more efficient use of raw materials, less waste, and cleaner production processes?
8. Products that uses biodegradable or bio-based materials?
9. The development of products that promote resource efficiency and less pollution during the use phase (e.g. energy consumption and air emissions)?
10. The design and processes that improve the quality of products and equipment, in the production and use phases?
11. A product design that create opportunities for scalability?
12. Reduction of logistic impacts (e.g. transport-related pollution, reduced inventories)?
13. Creation of reverse logistics channels?

A set of performance indicators also can be used to evaluate the sustainability of the AM process [3,18]: number of employees per product or sales; number of accidents and incidents; training hours per employee; job satisfaction rate; percentage of employees cross-trained to perform all tasks; rate of employees involved in improvement activities; waste before recycling; global warming potential (CO_2); acidification potential (SO_2); persistent bio-accumulative toxic chemicals used; water use (total and recycled); energy used; energy from renewables; hazard waste; resource efficiency; customers complaints and returns; quality ratio; take-back policies; share of reused or recycled materials; material per unit of production; productivity; overall equipment effectiveness; availability.

6. Conclusion

The set of questions and performance measures presented as a checklist seeks to guide companies to evaluate if adopting AM will result in environmental and social benefits aligned with the SDGs. The case analysis indicates that AM processes can result in more sustainable operations, which however need to be supported by a strategy that considers the sustainability impacts in all life cycle phases.

Issues connected with AM processes are not been explored or clearly discussed by the companies, contributing to the gap of knowledge. More complete and transparent case reports will be useful to increase the knowledge and promote best practices.

Future steps in this research aim to operationalize the checklist in a self-assessment tool that will support the evaluation of sustainability implications, and thereby a more informed decision-making, for the adoption AM technologies.

Acknowledgements

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