Title:
Sustainability and Environmental Impact of Additive Manufacturing: A Literature Review

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Introduction:
Additive Manufacturing (AM) offers many advantages over traditional subtractive manufacturing (SM) methods. For example, complex geometric parts can be easily fabricated, light weight parts can be formed while maintaining the required strength [2]. Although AM has huge potential in many applications, there are some areas to be improved such as sustainability, reliability, productivity, material diversity and part quality. This paper reviews studies on sustainability and environmental Impact of AM. The progress of the latest research is presented. The review covers studies on the complete life cycle of AM processes and AM product (AMP), i.e. from the raw material production, product design, manufacturing, post-processing, and usage to the product end-of-life. AM sustainability evaluation methods are analyzed including life cycle assessment (LCA), comparative and predictive sustainability assessment frameworks, energy modeling, and improvement strategies for different AM processes. Related literature is collected from different journals and conference proceedings. The review also provides discussions and conclusions to highlight the current research, research gaps and recommendations for the future research, which fills gaps in the existing review papers for the latest research on the sustainability evaluation and improvement strategies for AM.

Main Idea:
Method: Our method of the literature review is shown in Figure 1. Sustainability of AM has 3 dimensions: environmental, economical and social sustainability. Our scope focuses on the environmental impact analysis of AM technologies. Databases of Scopus, Web of Science and Science Direct were searched for relevant papers. Keywords used in search were sustainability, environmental impact, energy consumption, additive manufacturing, and 3D printing. Over 100 papers were selected for the detail review after screening over 300 papers collected. The selection criteria were contents of environmental impacts of AM. Papers were selected after analyzing titles (20 papers excluded), abstracts (70 papers excluded) and paper contents (110 papers excluded). Detailed analysis was performed for the selected articles in the review (Over 100 papers). The analysis and summary of the state of research were conducted. Discussions present the current research focus, methods, gaps and opportunities on sustainability and environmental impacts of AM. The reviewed papers indicate that most of research on sustainability of AM was conducted in the last 10 years as shown in Figure 2.

Sustainability and Environmental Impact of AM: Sustainability is to meet our present needs without affecting needs of future generations [4]. A comprehensive assessment of AM from a global sustainability perspective shows that AM has the potential to reduce CO_2 emissions 130.5–525.5 Mt and the total primary energy consumption 2.54–9.30 EJ by 2025 [3]. This paper aims to explore methods used for energy modeling and environmental impact assessment of AM. Diverse research related to sustainability of AM is reviewed and presented in three categories: environmental sustainability from LCA perspective, energy modeling, and environmental impact improvement strategies.

Environmental Sustainability of AM from LCA perspective: LCA considers AM impacts for the complete life cycle of an AMP [6]. LCA evaluates the material production, product printing, usage and end-of-life of AMP as summarized in Table 1. Commercial software tools such as ReCiPe Endpoint H and EcoIndicator LCI are commonly used to analyze resource flows of energy, material waste and emission. Processes of cradle-to-gate and cradle-to-grave were considered. The cradle-to-gate includes the life cycle up to the AM stage, while the cradle-to-grave considers usage and the end-of-Life stage too. A LCA framework can consider all three dimensions of sustainability [6]. LCA can evaluate the environmental impacts of each phase based on environmental and resource data [5].

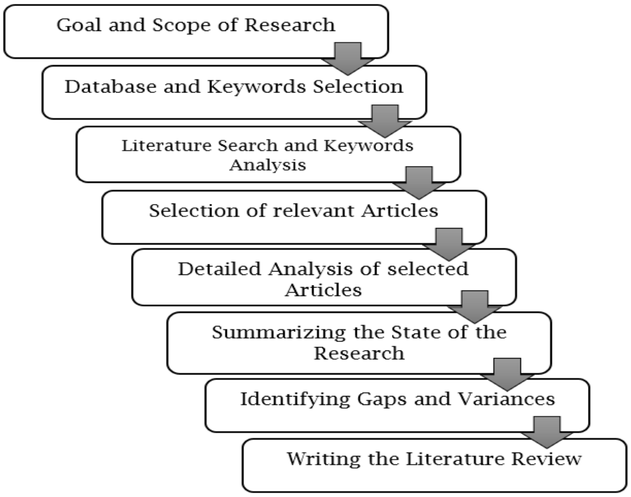

Fig. 1: Literature Review Method.

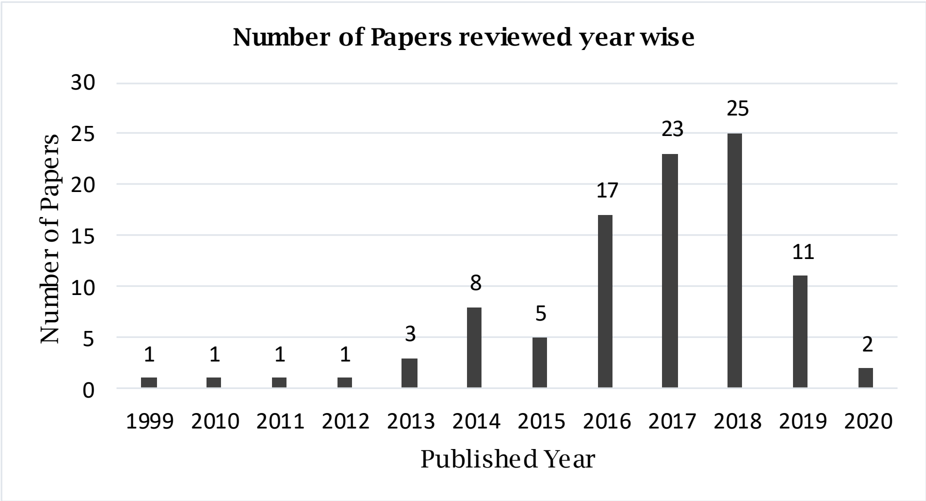

Fig. 2: Reviewed papers.

Many studies integrated product design and cradle-to-gate methods to estimate the energy consumption of AM. The topology optimization was used for product design and design of support structures, allowances and features for post-AM operations. LCA was also used to examine environmental and resource implications of AM for short- and long-term perspectives based on the technological development and adoption of AM technologies. Results show that one of the sustainable potentials of AM is the weight reduction of AMP. LCA was also widely used to compare environmental impacts of different AM and SM technologies. Energy analysis was integrated using LCA to identify factors that influence environmental performances of AM. Results show that only 10% of energy were used in the AM process and remaining 90% were lost as heat and bulk wastes. Energy-based sustainability index and predictive assessment tools were developed to evaluate environmental impacts of AM processes considering energy consumption, material use, unused material and recycling. LCA was also used to study effects of different AM build parameters, such as the total build height, orientation, infill percentage, raster angle and batch size on the complete lifecycle of AMP. Process energy consumption was found as a major contributor in the environmental impact of AM.

LCA Dimensions	Aspects Analyzed	LCA Methods	LCA Databases	Indicators (Impact Categories)	LCA Software	AM Technologies studied
Cradle to Gate Cradle to Grave Conception to Grave	Energy Material Fluid Wastes Emissions	IMPACT 2002+ ReCiPe 2008 ReCiPe H/A weighting ReCiPe Europe Midpoint H ReCiPe Europe Endpoint H/A ReCiPe Endpoint H Global Warming Potential CExD CML 2 Baseline 2000 CML2001 IPCC 2013	Ecoinvent EcoIndicator 99 ERMD data Eco-indicator (PR Consultants of Netherlands)	Midpoint level Damage Endpoint level Upstream and Downstream ILCD	SimaPro Gabi	SLS, SLA, FDM, DMLS, EBM, LBM, PBF, LENS

Tab. 1: Summary of LCA articles for environmental impacts of AM.

Energy Modeling of AM: Energy modeling investigates energy consumptions of different AM methods in material production, printing process, post-processing, usage and end-of-Life [1,7]. Specific energy consumption (SEC) of different AM processes found in literature is shown in Figure 3. There are large variations in energy consumptions of different AM technologies. Studies found that the printing stage has the highest energy consumption. Quantitative methods were also developed for the energy analysis. Generalized multi-objective decision-making methods were proposed for considering the total energy consumption and environmental impacts. Data analysis techniques including linear regression, decision tree, neural networks, and genetic algorithms were proposed for understanding and prediction of the energy consumption in AM. Tools for the process selection were also developed to compare AM vs SM sustainability potential and to model energy for the life cycle of AMP.

Environmental Impact improvement strategies: Strategies were presented to reduce environmental impacts of AM. Design for AM methods such as the topology optimization, mass customization and part consolidation were proposed to reduce environmental impacts of AM [7]. These methods can reduce both energy and material consumptions of AMP. Design of experiments approach was used to optimize energy use and reduce waste of AM. The optimization of AM building parameters such as layer height, building orientation, raster angle, shells, support and percentage infill can also improve environmental impacts of AM. Process planning was performed to optimize the process energy and material waste. Some studies highlighted the role of product redesign for AM. The impact of redesign for light parts was investigated for both manufacturing and usage stages. Results show that the reduced weight of printed parts can make a big impact to reduce the process energy, material consumption and emissions in the life cycle of AMP. Bio-inspired geometries like honeycomb, diamond and bone structures were used to achieve light parts. Modelling and simulation methods were used to investigate lightweight component structures. Finite element modeling was applied to predict the microstructure of components for lightweight design and essential properties. A sustainable value road mapping tool was developed to analyze the sustainability potential of AM.

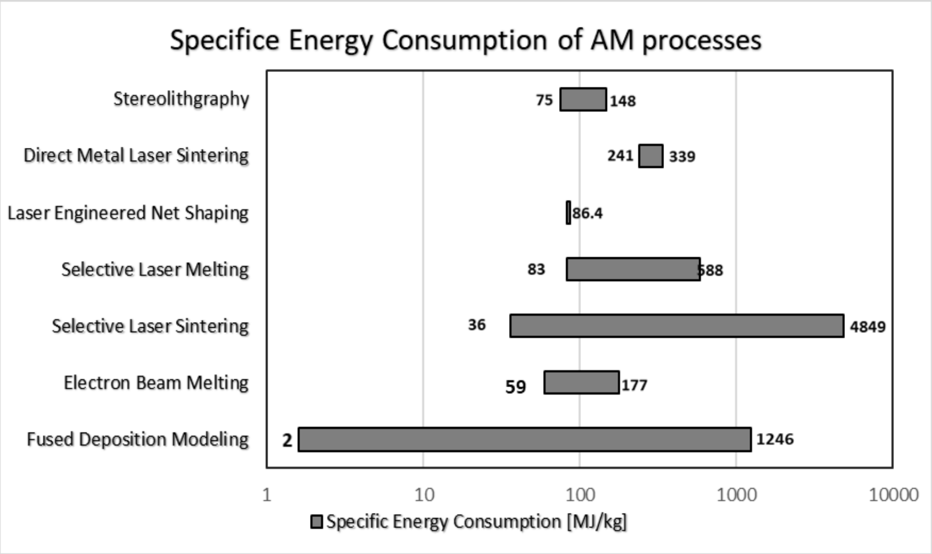

Fig. 3: Specific Energy Consumption of different AM technologies found in literature.

Discussion and Recommendations: Research shows that AM is more environment friendly than conventional SM methods. AM provides great potential in the sustainable production, but there are still many areas that require improvements to optimize energy and material usage of AM. Following important solutions are concluded.

- Cradle-to-Grave is a complete LCA method to investigate environmental impacts of AM. Improvements are required to consider impacts of AMP design, feedstock production, usage, and end-of-life process for a detailed evaluation of life cycle impacts of the AM process.
- Sustainable AM analysis should include product design in the sustainability evaluation. The design solution has a big impact on environmental performances of AM with most opportunities of the sustainability improvement.
- Lightweight design is significant to reduce environmental impacts both in manufacturing and usage phases. Design for AM plays an important role in this area. Methods like the part consolidation, topology optimization, lattice structure, and bio-inspired geometries are promising for improving the lightweight design of AM products.
- Formation and analysis of the sustainability index for AM processes can provide effective tools in evaluating sustainability impacts of AM.
- Big variations were found in the energy consumption rate for different AM processes in both energy models and experiments. More experimental work is required to improve variations. More detailed energy models are required to include all those factors that have impacts on the energy consumptions of AM. Identification of those factors will not only help create precise energy models but also provide opportunities to reduce the energy consumption.

- Product quality is a very important factor. Integrating product quality and sustainability for the final product design is essential. Product quality and sustainability have the inverse relation, but AM has the potential to achieve sustainability in the desired part quality. Multi-criterion decision-making methods should be developed to consider the product quality in a close loop control system for the sustainability assessment.
- The lack of standards for AM processes is a major disadvantage for understanding the sustainability potential of AM, which hinders the adoption of AM by industries. Development of sustainability methods in conjunction with standards organizations will help identify the sustainability potential of AM.
- For achieving sustainable AM in all three dimensions, research work from the triple bottom line perspective is required. AM has the potential to make sustainable products in all three dimensions of sustainability. But most of the researchers considered only one of these three dimensions of sustainability. Multi-criterion decision-making methods should be developed in a close loop control system to predict the sustainability evaluation in all three dimensions of sustainability, i.e. economy, environment and society.
- Achieving environmental sustainability also benefits the reduction in cost. Research is required to develop models to integrate sustainability and cost of AMP to investigate the relation and highlight the economic and sustainable potentials of AM.

Conclusions:

In general, we conclude that AM has the great potential to achieve sustainable products than SM. Energy consumption is a major contributor to the environmental impact of AM, while the product design for AM is promising to achieve sustainability of AM. This review could facilitate the research to cope up challenges and provide opportunities for AM sustainability to benefit the AM adoption by industries.

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