Springer Tracts in Additive Manufacturing

Kamalpreet Sandhu · Sunpreet Singh · Chander Prakash · Karupppasamy Subburaj · Seeram Ramakrishna *Editors*

Sustainability for 3D Printing

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Springer Tracts in Additive Manufacturing

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Preface

The book entitled "*Sustainability for 3D Printing*" aimed to present various experimental outbreaks on the novel methodologies to treat solid waste as different types of feedstock materials, suitable for demanding design and engineering applications, of 3D printing technologies. This book provides a comprehensive knowledge of the innovative models, machine tools, and processing routes adopted for treating solid wastes and recycling/reuse of the same as different types of 3D printing feedstock. In particular, detailed discussions on the life cycle assessment, sustainability, and eco-friendliness of the developed feedstock as well as end user products also be incorporated. The editorial team has understood that number of books already published in the field of the 3D printing with different focuses; however, it is of utmost important to produce an ideal and reader friendly source of literature with "Waste to Wealth" focus as it have huge potential to serve as a reference source to the experts of manufacturing, materials, metallurgy, product design, waste management, and sustainability prospective. Further, it has been believed by the editorial members that every manufacturer, in today's manufacturing era, is bounded to follow the sustainability ethics to minimize the negative impact of manufacturing on environment as well as well-being of the living species. Indeed, this edited book provides wide variety of literature review, case studies, experiential studies, and technical papers to highlight the scope of using waste as wealth through 3D printing.

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Singapore, Singapore — Sunpreet Singh
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About the Editors

Kamalpreet Sandhu is an Assistant Professor in the Product and Industrial Design department at Lovely Professional University, Phagwara, Punjab, INDIA. His primary focus is on design and developed of footwear products and injuries prevention. He was done various projects in Podiatric Medicine at Defence Institute of Physiology and Allied Sciences, DRDO, Delhi, i.e. design and developed new kind of orthosis for social needs and work result in publication "*Effect of Shod Walking on Plantar Pressure with Varying Insole*". His area of research is Design Thinking, Ergonomics for Podiatric Medicine, 3D printing and User Experience Design. He is also the editor of various books: *Emerging Application of 3D Printing during COVID-19, Application of 3D Printing in Biomedical Engineering, Revolutions in Product design for Health care, 3D printing in Podiatric Medicine and Food Printing: 3D printing in Food Sector*. He has also acting as an editorial review board member for *International Journal of Technology and Human Interaction* (IJTHI), *Advances in Science, Technology and Engineering Systems Journal* (ASTESJ) and also a review editor for frontiers in manufacturing section "Additive Processes". He has established a research collaboration with Prof. Karupppasamy Subburaj at Singapore University of Technology and Design, SINGAPORE on Medical device design and biomechanics.

Sunpreet Singh is a researcher in NUS Nanoscience and Nanotechnology Initiative (NUSNNI). He has received Ph.D. in Mechanical Engineering from Guru Nanak Dev Engineering College, Ludhiana, India. His area of research is additive manufacturing and application of 3D printing for development of new biomaterials for clinical applications. He has contributed extensively in additive manufacturing literature with publications appearing in *Journal of Manufacturing Processes*, *Composite Part: B, Rapid Prototyping Journal*, *Journal of Mechanical Science and Technology*, *Measurement*, *International Journal of Advance Manufacturing Technology*, and *Journal of Cleaner Production*. He authored 150 research papers and 27 book chapters. He is working with joint collaboration with Prof. Seeram Ramakrishna, NUS Nanoscience and Nanotechnology Initiative, and Prof. Rupinder Singh, Manufacturing Research Lab, GNDEC, Ludhiana. He is also the editor of three books:

Current Trends in Bio-manufacturing, Springer Series in *Advanced Manufacturing*, Springer International Publishing AG, Gewerbestrasse 11, 6330 Cham, Switzerland, December 2018; *3D Printing in Biomedical Engineering*, book series *Materials Horizons: From Nature to Nanomaterials*, Springer International Publishing AG, Gewerbestrasse 11, 6330 Cham, Switzerland, August 2019, and *Biomaterials in Orthopaedics and Bone Regeneration-Design and Synthesis*, book series *Materials Horizons: From Nature to Nanomaterials*, Springer International Publishing AG, Gewerbestrasse 11, 6330 Cham, Switzerland, March 2019. He is also the guest editor of three journals: Guest Editor of special issue of "Functional Materials and Advanced Manufacturing", Facta Universitatis, Series: Mechanical Engineering (Scopus Index), Materials Science Forum (Scopus Index), and Special Issue on "Metrology in Materials and Advanced Manufacturing", Measurement and Control (SCI indexed).

Chander Prakash is Professor in the School of Mechanical Engineering, Lovely Professional University, Jalandhar, India. He has received Ph.D. in mechanical engineering from Panjab University, Chandigarh, India. His areas of research are biomaterials, rapid prototyping and 3D printing, advanced manufacturing, modelling, simulation, and optimization. He has more than 11 years of teaching experience and six years of research experience. He has contributed extensively to the world in the titanium and magnesium-based implant literature with publications appearing in *Surface and Coating Technology*, *Materials and Manufacturing Processes*, *Journal of Materials Engineering and Performance*, *Journal of Mechanical Science and Technology*, *Nanoscience and Nanotechnology Letters*, *Proceedings of the Institution of Mechanical Engineers*, *Part B: Journal of Engineering Manufacture*. He has authored 60 research papers and 10 book chapters. He is also the editor of three books: *Current Trends in Bio-manufacturing*; *3D Printing in Biomedical Engineering*; and *Biomaterials in Orthopaedics and Bone Regeneration—Design and Synthesis*. He is also the guest editor of three journals: special issue of "Functional Materials and Advanced Manufacturing", Facta Universitatis, Series: Mechanical Engineering (Scopus Indexed), Materials Science Forum (Scopus Indexed), and special issue on "Metrology in Materials and Advanced Manufacturing", Measurement and Control (SCI indexed).

Karupppasamy Subburaj is an Assistant Professor in the Pillar of Engineering Product Development (EPD) at Singapore University of Technology and Design (SUTD). He leads an interdisciplinary research team to design and develop medical devices, assistive technologies, image-based quantitative biomarkers, and computing tools (machine learning, artificial intelligence) for diagnosing, monitoring, treating, and potentially preventing musculoskeletal disorders (osteoarthritis/ osteoporosis) and disabilities by understanding bio-mechanical implications of those diseases and disabilities. He collaborates with physicians and clinical researchers from Tan Tock Seng Hospital (TTSH), Technical University of Munich (TUM), Singapore General Hospital (SGH), and Changi General Hospital (CGH) to combine research and technical expertise to address real-life clinical problems affecting Asia-Pacific and the World. Before joining SUTD, he did his postdoctoral work in the Musculoskeletal Quantitative Imaging Research (MQIR) laboratory at the University of California San Francisco (UCSF). At UCSF, he worked with a spectrum of clinicians (from radiology, orthopaedic surgeons, sports medicine, and physiotherapy/rehabilitation science) on characterizing magnetic resonance image (MRI) based bio-markers to understand the physiological and biochemical response of knee joint cartilage to physical exercise and acute loading. He has also developed and validated 3D modelling and quantification methods to study joint (hip/knee) loading patterns and contact kinematics in young healthy adults and patients with osteoarthritis. He received his PhD from the Indian Institute of Technology Bombay (IIT Bombay), India, in 2009. During his PhD, he collaborated with Tata Memorial Hospital (TMH), Mumbai, on developing a Surgery Planning System for Tumour Knee Reconstruction. He also worked with orthodontists from local hospitals in Mumbai, India, on designing and developing prostheses and surgical instruments/guides for reconstructing maxillofacial defects. After his PhD, he worked as a research specialist (surgery planning) in the Biomedical Engineering Technology incubation Centre (BETiC) at IIT Bombay, before moving to UCSF for his post-doctoral studies.

Seeram Ramakrishna is a co-director, NUS Nanoscience and Nanotechnology Initiative (NUSNNI). He has received his Ph.D. from the University of Cambridge and is a global leader in electrospinning and nanostructured materials. His research has resulted in approximately 1000 peer-reviewed articles with over 115, 888 citations and an h-index of 160. He has published several books and book chapters. He has been recognized as a Highly Cited Researcher in Materials Science.

Chapter 1
Sustainablity for 3D Printing

Henrique Almeida, Eujin Pei, and Liliana Vitorino

Abstract Since the industrial revolution in the eighteenth century, mankind has focused on industrial and economic dominance in the production of products. Due to evolving technologies, processes and materials, economic dominance has become a key factor for product development. But in the last decade, environmental issues have gained importance and it is a critical issue for current and future industries. In this context, additive manufacturing and digital technologies have allowed us to also create new environmental awareness amongst the industrial and scientific community. From the commercial perspective, economic, marketing and social impact are key issues to be addressed. From the industrial perspective, the design, material and processing parameters are critical aspects. All of these issues will influence the uptake and adoption of Additive Manufacturing while increasing environmental awareness. This chapter will provide a global overview on how Additive Manufacturing (AM) has a huge influence on the environment, while increasing both industrial and commercial benefits to society.

Keywords Sustainability · Life cycle assessment of additive manufacturing · 3D printing · Rapid prototyping

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1.1 Introduction

The exponential growth of human economic expansion has had a devastating effect on the world's natural resources and consequently on the environment [1]. Kates et al. claims the importance of understanding the fundamental character of interactions between nature and society as a new paradigm of sustainability science [2]. Everyone has a responsibility to contribute to a better world. If sustainability becomes a reality, consumer behaviour and perspectives will have to change [3]. Organisations should change to "green" management and develop initiatives in accordance to the circular economy principles and keep in mind that the organisation goals are now dual: social and financial [4]. On the other hand, consumers should pay more attention to their attitudes and concerns with environmental issues. Some activities of green consumption behaviours are already in practice and some examples of their behaviour are [5].

- Consumers to avoid those products which have impact on environment;
- Aerosols containing products avoided;
- Prefer recycled based products, e.g. papers;
- Focus on organic foods;
- Foods: Prefer local one;
- Local stores prefer for purchase.

From a marketing point of view, we understand that industries need to recognise this new trend in consumer behaviour to align their marketing strategies with their consumer personal values [6] and eventually change its product program (formula, package, labels). However, some studies showed that consumers that report positive attitudes towards services and eco-friendly products follow through with their wallets revealing a gap between intention and action [7, 8]. *Thus, the role of designer and/or product developer is to keep three pillars (environmental, social and economically) of sustainability in mind while design and development of any product* [9].

Sustainability may be achieved through many different ways, including governments, new technologies, industries and markets [10]. Additive manufacturing (AM) or 3D printing as it is commonly called, has been recognised as a sustainable and efficient technology. These technologies allow manufacturers to use only the necessary amount of materials, an advantage that can add economic value by reducing both material and production costs [11]. 3D printing also improves operating efficiency by reducing design, production, inventory, store management costs, distribution and transportation, leading to sustainable industrial practices [12, 13]. Additive manufacturing also allows to eliminate supply chain operations associated with productions and requires extra new tools, enabling the repair and remanufacturing of obsolete or damaged tools and dies, eliminate scrap, eliminate the need for tooling and eliminate the use of environmentally hazardous processes

[14–18]. Fruggiero et al. [19] presented a paper on the comparison between subtractive and additive manufacturing of metal parts and they demonstrate within several domains that AM is much more sustainable in comparison to subtractive manufacturing.

Additive manufacturing systems are typically small in size, therefore they can be easily located nearby any existing market, thus reducing transport logistics of products around the world [20]. On the other hand, the raw materials for 3D printing systems are common, thus leading to a net reduction in transportation costs [21]. Several previous studies [15, 16, 22] have defined the carbon footprint reduction for 3D printing technologies.

The studies describes, the main environmental and sustainable benefits from adopting 3D printing technologies are presented:

- In supply chain required efficient and less amount of materials, however, which are available through natural resources.
- Try to avoid energy-consuming and wasteful type manufacturing processes, e.g. Investment casting and cutting fluids machining, e.g. computer numerical control.
- Ability to design higher efficient products with enhanced operational performance that are more effective than conventionally manufactured components by incorporating conformal channels for cooling and heating and gas flow paths and also allowing to produce more complex components that reduce the number of conventional components and their assembly, etc.
- Ability to eliminate fixed asset tooling, allowing for the manufacture to occur at any geographic location close to their customers, reducing transportation costs within the supply chain.
- Parts of lighter weight when used in the transportation industry (automotive, aeronautics, etc.) more focus on fuel efficiency and eliminates the carbon emissions, e.g. (CO_2, CH_4).

Majeed et al. [23] developed a framework which is based on big data analytics that may be used as a guideline to select related product manufacturing cycle stages that influences the sustainable production of a specified AM system. The results from their work indicate that controlled energy consumption and product's quality are helpful for smart sustainable manufacturing, lower emissions and cleaner productions.

The above benefits allow AM to have the following environmental impacts: lower resource consumption of both energy and material, less waste management and improved pollution control [24]. For a global understanding of the sustainability of additive manufacturing, the next figure will provide its impacts not only on the environment but also on both the economy and society (Fig. 1.1).

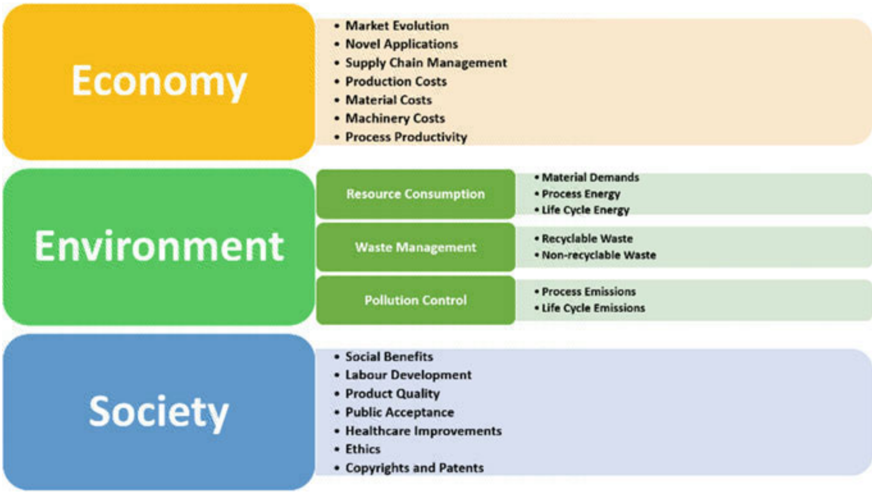

Fig. 1.1 Sustainability of additive manufacturing (adapted from [24])

1.2 Sustainability

1.2.1 Design in 3D Printing (Df3DP)/Design for DfAM

The concept of Design for 3D printing (Df3DP) proposes a structured, design-centric approach that combines the use of AM technologies to minimise the manufacturing steps during new product development and its associated processes, yet achieving maximum functionality with a lower unit cost [25]. Df3DP capitalises on the benefits of AM such as realising freedom of geometry, offering customisation, enabling integrated assemblies and aligning towards automated production. Wiberg et al. [26] provided a state-of-art review of the Df3DP research domain in terms of design guidelines, methodologies and available software. They state that Design for 3D printing could be broadly categorised from the perspective of system, process and part design, where system design covers what should be manufactured using AM technologies and the component's boundaries. Process design involves the steps of how the preparations and steps of the component should be performed with clear objectives. Lastly, part design investigates how a single part should be designed and it is recognised as being the most important category.

Vaneker et al. [27] summarise the tools and methods that could be used within Df3DP for designing lightweight parts including the use of Generative Design, Topology Optimization, Lattice Structure Filling, Functional Material Complexity, Internal Geometries, Printed Permeability and Assembly and Part Integration. By considering these aspects for DfAM and subsequent methods, end-users would be able to achieve better efficiency with sustainability in mind. This is in line with Niaki et al. [28] who cited that the use of AM offers several benefits from a sustainability perspective by using less resources [29] and with less operational requirements [30]. Another example is cited by Yang et al. [31] about the use of part consolidation produced via AM with other strategies including high void-to-solid ratio, weight reduction and selecting the most environmentally friendly processes.

1.2.2 Designing for 3D Printing

As discussed in the previous section, part design investigates how a single part should be designed within the Df3DP process. Part design should consider design rules for AM as well as process-specific design guidelines for AM. According to Mani et al. [32], design rules consider aspects of design potentials, design restrictions and process capabilities that provide insight into manufacturability. This is extended from the work of Adam and Zimmer [33] who proposed Direct Manufacturing Design Rules (DMDR) where key aspects of such design rules encompass design for function (functional integration, design potentials, etc.), design for tolerance (e.g. physical restrictions) and capabilities (speed, accuracy, repeatability, material, etc.). Mani et al. [32] also proposed Design Principles that are logical aspects derived from guidelines and fundamentals; whereas fundamentals are purely logical primitives that capture process and control parameters. They state that guidelines aim to provide an understanding of AM categories, processes, operating procedures and best practices.

Other more specific guides include those for part orientation [34]; part consolidation [35]; general metal AM [36]; design rules for Selective Laser Melting [37] and design rules for Wire Arc AM [38]. Design guides have also been published by independent machine manufacturers such as EOS GmbH [39], Stratasys Direct Inc. [40] and other service bureaus [41]. Standardisation efforts are also being pursued between ASTM International sub-committee F42.04 and the International Organisation for Standardisation ISO/TC261 to develop joint projects. Currently, standards have been published for ISO/ASTM 52910:2018, ISO/ASTM 52911-1:2019, ISO/ASTM 52911-2:2019 and ISO/ASTM WD 52911-3.

1.2.3 Summary

Design for DfAM provides a structured, design-centric approach towards effective use of AM. In addition, Part Level DfAM Methods and other Principle-to-Rule DfAM Methodologies, as well as academic research, publications by independent machine manufacturers, service bureaus and standardisation organisations exist. By being well versed in these guides that offer industry best practices, users can capitalise on the use of AM to their fullest advantage and with sustainability in mind (Table 1.1).

Table 1.1 Categories and methods for DfAM

Categories of DfAM [26]	Part level DfAM methods [27]	Principle-to-rule DfAM methodology [32]
System level	Topology optimization	Design guidelines (States AM categories, processes, operation and best practices)
Process level	Generative design	Design rules (States potentials and constraints based on principles)
Part level	Lattice structure filling	Design principles (States logical principles based on fundamentals)
	Internal geometries	Design fundamentals (States process and control parameters)
	Printed permeability	
	Functional material complexity	
	Assembly and part integration	

1.3 Sustainability and 3D Printing Processes

Over the past few years, many researchers have gained awareness of sustainability in 3D printing processes. Some 3D printing processes have had higher focus of research than others due to their specific characteristics. But, in spite of their differences, there is a global similarity between all 3D printing systems. Determining the optimal orientation of the part for production is both a time consuming and difficult task since one has to trade-off numerous contradicting objectives such as production time and the part's surface finish [20, 42–45]. An inappropriate choice results in physical model with a significant "staircase effect" resulting in parts with poor surface quality [46] or excess production time consuming unnecessary material and/or energy.

By consuming only the necessary amount of raw material for building the desired part, AM improves the material management for part production reducing both the energy consumption (not always) and the amount of waste material and when compared to other conventional technologies, also eliminates scrap, the need for tooling and the use of environmentally hazardous process enablers [14, 15, 18]. In some cases, the energy consumption might be higher due to the moderately low productivity and the use of elevated power and temperature processing. Mognol et al. [47] presented a study using the design of experiments methodology for energy consumption reduction considering the following parameters: Layer thickness, part orientation and part position in the build chamber. No specific energy model or optimization rules for time reduction were developed despite the study undergoing on three AM systems. Energy consumption in 3D printing processes are therefore directly related with its classification. According to ASTM International, the existing AM technologies are classified as follows [20, 48]:

1. Material extrusion—process that creates layers by mechanically extruding molten thermoplastic material onto a platform.
2. Powder bed fusion—these techniques use an energy beam, either a laser or electron beam, to selectively melt a layer of powder material.
3. Vat photopolymerization—an ultraviolet laser is used to selectively polymerize a UV curable photosensitive resin creating a layer of solidified material which are subsequently cured until the part is complete.
4. Material jetting—these techniques directly deposit wax or photopolymer droplets onto a substrate via drop-on-demand ink jetting.
5. Binder jetting—this process deposits a stream of particles of a binder material over the surface of a powder bed, joining particles together creating the object.
6. Sheet lamination—layers of adhesive-coated paper or plastic are successively glued together and then cut to shape with a knife or laser cutter.
7. Directed energy deposition—metallic powder or wire is fed directly into the focal point of an energy beam creating a molten pool of material to build the part.

Considering the above classification, one may divide the 7 categories into 3 categories according to their energy consumption, namely:

- Low energy: Material extrusion, Binder jetting, Material jetting, Sheet lamination
- Medium energy: Vat photopolymerization, Material jetting (photopolymer requiring UV light), Sheet lamination (laser cutter)
- High energy: Powder bed fusion, Directed energy deposition

Another aspect to be considered during production is the fabrication of support structures. An inappropriate orientation results in excessive building of support structures around the physical part or creation of supports within specific areas of the desired part, which are difficult or almost impossible to remove, increasing significantly the energy and effort of removal of the support structures [20, 49].

Almeida and Correia presented a work on support structures for material extrusion systems where they studied: (1) the relationship between the volumes of support material used in material extrusion systems and the time necessary to dissolve the support material (2) the environmental impact of different support material schemes for embracing the parts during production [50]. In the first case, the relationship is directly proportional, but in the second case, significant differences were encountered. A normal material extrusion system has a software that allows to define the type of support structure scheme in order to embrace the desired part during production. Most commonly, the software system has the following support structure schemes: Smart, Sparse, basic and Surround. They demonstrated that each one of the support structure schemes influences more than just increased production time which is one of the main criteria. Other issues are the amount of support material used during production, the energy consumption during production, the energy consumption during the support structure removal and the usage of the amount of dissolution liquid for the support structure removal. The comparison was not only performed in hours [h] and kilowatt-hours [kwh], but also in energy consumption impacts [mPT] for ecodesign purposes. The authors also state that these variables are highly influenced by the design of the parts been produced, meaning that in some cases, the differences may have slight significance but in others, the differences are significant.

A systematic review of supports structures for AM was performed by Jiang et al. [51] where they discuss several methods of support structure design for minimising the use of support structures without compromising the part's fabrication. The authors also present suggestions of design modifications of the desired part that will reduce the need for support structures. By reducing the amount of material, time and energy involved, the process becomes more sustainable while producing the desired part or component.

Materials for AM has also been subject to sustainable research [52]. Vidakis et al. [53] studied the mechanical performance of recycling acrylonitrile–butadiene–styrene (ABS) polymer on extrusion-based systems. Standard tensile, compression, flexion, impact and micro-hardness tests were performed on each ABS filament on each recycle repetition for six recycling cycles, evaluating the effect of the thermomechanical treatment on the ABS material during each recycling process. The authors demonstrated that the mechanical performance of the recycled ABS material improved for each recycle repetition for a certain number of repetitions. An optimal mechanical behaviour was determined between the 3rd and 5th recycling repetition, indicating a positive impact of the ABS material recycling for extrusion-based systems, contributing towards improved sustainability.

Daraban et al. [54] presented a review regarding the use of metals for additive manufacturing. Results from their literature review indicate that metal powder recycling and use/reuse technologies could be developed to economise metal powder and the use of metallic AM in existing component redesign and repairs also increase sustainability. The authors also state that the sustainable performance of metallic AM technologies depends on the quality of the metal powder and its lifecycle. Therefore, metal powder recovery and recycling optimisation is both a major research topic and an industrial necessity.

Regarding the AM processes more specifically, several authors have performed different studies to analyse its sustainable impact. For instance, for SLS systems, Sreenivasan and Bourell [15, 55] performed a quantitative energy calculation regarding several systems, namely the laser system, heater, roller drives, piston control and other miscellaneous systems within the SLS system. They determined that the heating system was the principal energy consumer, followed by the drives and controls and finally the laser system [15]. During their study, the SLS system worked with average power and no relationship with process parameters was discovered.

Fredriksson [56] investigated the material and manufacturing life-cycle stages of INCONEL 718. Energy measurements from an ARCAM A2X Electron Beam Melting system was determined and compared to the embodied energy and indirect CO_2 emissions of the feedstock as well as conventional subtractive manufacturing. Fredriksson [56] demonstrated that the production of the metal powder and the AM process itself contributes considerably to the total energy usage and emissions.

The author used the Ashby's 5-step method for the assessment of sustainable development to briefly discuss the social and economic impacts of additive technologies.

Fargione and Giudice [57] proposed a sustainable oriented DfAM approach, to analyse the dependence of the energy impact on the geometric characteristics and the material (Ti_6Al_4V) of an Electron Beam Melting system. The quantification of the environmental impact of the built parts focused on the determination of energy consumption of the additive process and correlating it to the main process parameters and also to some features that characterise the shape of the part. The authors developed a model for quantifying energy consumption for both the system and material allowing for a direct control regarding energy sustainability, focused on design variable choices and process parameter settings.

Majeed et al. [23] developed a framework based on big data analytics that can be used as a guideline to select the related product manufacturing cycle stages that influence the sustainable production of a specified AM system. The results from their work indicate that the quality of the part and energy consumption are adequately controlled which is helpful for smart sustainable manufacturing, lower emissions and cleaner productions.

Concerning binder jetting processes, Meteyer et al. [58] presented a material and energy consumption model as a function of process parameters and part geometry and later continued their work focusing on the building stage, where both the layer thickness and part orientation was studied [59].

Freitas et al. [60] studied the production of several parts as a function of part internal filling and building orientation, regarding energy consumption, production time and end-of-life scenarios for extrusion-based systems. The authors used eco-indicators and enabled them to compare the environmental impact of the product's material and the energy consumption of extrusion-based systems. They also state that in order to reduce the environmental impact of energy consumption, it is vital to shorten the time the machine is on without production, as well as reducing the amount of productions by combining more parts during production, diluting the pre-heating and cooling of the machine between productions. No specific model was obtained, but by combining life-cycle assessment with production parameters, a better awareness was provided towards the users of extrusion-based systems. Moreover, authors used 3D printed tool to cut soft material and try to minimise the high cost tool for machining [61, 62].

Regarding stereolithography-based systems, Yang et al. [63] presented a mathematical model for the energy consumption. In order to validate their model, experiments to measure the real energy consumption of the SLA system was conducted. A design of experiments method was implemented to study the impacts of the different processing parameters and their potential interactions on the energy consumption. A response optimization method was used to recognise the optimum combination of parameters in order to minimise the total energy consumption. The results demonstrate that the global energy consumption of the SLA system can be significantly reduced with optimum parameter settings without visible quality decay of the produced parts.

1.4 Conclusions

Since the industrial revolution in the eighteenth century, mankind has focused on industrial and economic dominance in the production of products. Due to evolving technologies, processes and materials, economic dominance has become a key factor for product development. But in the last decade, environmental issues have gained importance and is a critical issue for current and future industries.

Sustainability allows to create and maintain the conditions for humans and nature to coexist in a productive harmony, fulfilling the social, economic and other requirements of present and future generations. Environmental and social worries about the human's impact on the environment have pushed the development of sustainable issues. Sustainable industrial practices contribute to the development of more sustainable materials, products and processes. It is critical to apply eco-design principles and develop greener production processes and products, reducing the ecological impacts associated with both production and product consumption.

In this context, AM and digital technologies have allowed us to also create new environmental awareness amongst the industrial and scientific community. From a business perspective, economic, marketing and social impact are key issues to be addressed. From a production perspective, the design, material and processing parameters are critical aspects. All of these issues will influence the uptake and adoption of AM while increasing positive environmental impacts and industrial and commercial benefits to society.

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