Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 61 (2017) 582 – 587

www.elsevier.com/locate/procedia

The 24th CIRP Conference on Life Cycle Engineering

Environmental Impact of Additive Manufacturing Processes: Does AM contribute to a more sustainable way of part manufacturing?

Karel Kellens [a,b,]*, Raya Mertens [a], Dimos Paraskevas [a], Wim Dewulf [a,c], Joost R. Duflou [a]

[a] *Department of Mechanical Engineering, KU Leuven, Celestijnenlaan 300, 3000 Leuven, Belgium*
[b] *Technology Campus Diepenbeek, KU Leuven, Agoralaan gebouw B bus 8 , 3590 Diepenbeek, Belgium*
[c] *Technology Campus Group T, KU Leuven, Andreas Vesaliusstraat 13, 3000 Leuven, Belgium*

* Corresponding author. Tel.: +32-16-32-24-99 ; fax: +32-16-32-29-86. *E-mail address:* Karel.Kellens@kuleuven.be

Abstract

While additive manufacturing applications are progressing from rapid prototyping to the production of end-use products, the environmental impacts caused by these manufacturing processes and related material flows are still a rather open question. Therefore, this paper will provide an overview of available life cycle inventory data and compare the environmental impact caused by a series of additive manufacturing processes: selective laser melting, selective laser sintering, electron beam melting, fused deposition modelling and stereolithography. Next to the energy and resource consumption of the AM unit processes itself, also the impact caused during the (powder) material production and part post treatment are addressed. From environmental perspective it is clear that the additionally generated impacts during manufacturing should be compensated by functional improvements during the use phase of the AM manufactured part. As example, the case of lightweight components is discussed.

Peer-review under responsibility of the scientific committee of the 24th CIRP Conference on Life Cycle Engineering

Keywords: Additive Manufacturing; Specific Energy Consumption; Environmental Impact; Lightweight Components

1. Introduction

Additive manufacturing (AM) technologies, producing components from 3D-model data by joining materials layer by layer, are progressing from rapid prototyping to the production of end-use products in a wide range of applications [1].

Nomenclature

EBM	Electron Beam Melting
EDM	Electrical Discharge Machining
FDM	Fused Deposition Modelling
SEC	Specific Energy Consumption
SL	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering

Following the growing interest in environmentally benign manufacturing [2], researchers started analyzing AM processes from an environmental perspective and compare their performance with alternative, more conventional manufacturing routes such as machining or injection molding processes [e.g. 3-5]. Of course the correctness of these analyses depends strongly on the availability of the required life cycle inventory (LCI) data and their representativeness, which is still a challenge. In consequence, most of the available studies present (rough) estimations or focus on one very specific use case [3]. Therefore, the aim of this paper is to provide an overview of available LCI data on AM production chains, covering AM feedstock production (Section 2), AM unit processes (Section 3), and AM post treatment processes (Section 4). Finally, the reported data are reflected towards the complete AM product life cycle in Section 5.

Peer-review under responsibility of the scientific committee of the 24th CIRP Conference on Life Cycle Engineering
doi:10.1016/j.procir.2016.11.153

2. AM - Material Production

Compared to conventional manufacturing processes, AM processes need very specific feedstock materials. Often this results in extra material preparation steps resulting in additional environmental impact. In contrast to available LCI data on semi-fabricated material shapes, such as cylinders, pipes or sheet metal plates, AM feedstock materials are less well documented in terms of their environmental performance.

Dawes et al. [6] present an in-depth description of atomization routes for metal AM powders. While a schematic overview of these processes is provided in Figure 1, the related powder materials and achievable particle sizes are listed in Table 1.

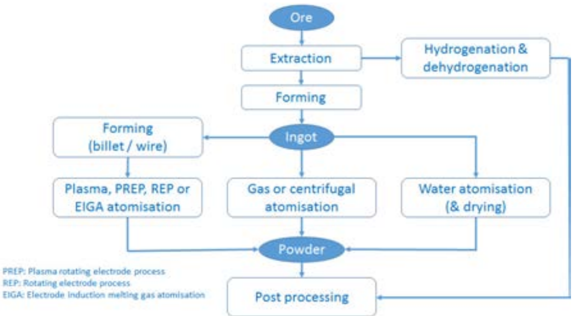

Fig. 1. Metal atomization routes. Adapted from [4].

Table 1. Particles sizes and materials of metal atomization processes.

	Particle size (μm)	Materials
Water atomization	0-500	Non-reactive
Gas atomization	0-500	Ni, Co, Fe, Ti, Al
Plasma atomization	0-200	Ti
Plasma rotating electrode	0-100	Ti, exotics
Centrifugal atomization	0-600	Solder plates, Zinc and alkaline batteries
Hydride-dehydride process	45-500	Ti

In the absence of LCI data on AM powder production, multiple authors estimated the additional energy required to atomize 1 kg of metal powder starting from regular material shapes. Table 2 provides an overview of these efforts.

Table 2. LCI data of metal powder atomization processes.

Material	SEC (MJ/kg)	Others	Reference
Ti_6Al_4V	7.02	Argon: 0,18m³/kg	[5]
$AlSi_{10}Mg$	8.1	n/a	[16]
Ti_6Al_4V	31.7	n/a	[17]
Ti_6AlV	23.8	Argon: 5,5m³/kg Process Efficiency: 97%	[18]

No LCI data could be identified for the required precipitation step within polymer powder production nor for the production of photopolymers used in stereolithography processes.

3. AM - Unit Processes

This section provides an overview of available life cycle inventory data for five of the most commonly applied AM technologies: selective laser melting (SLM), selective laser sintering (SLS), fused deposition modelling (FDM), stereolithography (SL) and electron beam melting (EBM) processes.

While, among others, Kruth et al. [8] and Gibson et al. [9] provide extensive descriptions of AM technologies and related consolidation phenomena, a short description of the working principle of the covered AM unit processes is given below.

SLM, SLS and EBM are powder bed fusion processes that utilize a container filled with powder that is processed selectively using an energy source. While SLM (full melting) and SLS (partial melting or liquid phase sintering) use a laser source as energy input, EBM operates with an electron beam.

FDM is a material extrusion process depositing a material by extruding it through a nozzle while scanning a pattern that produces a part cross-section.

Stereolithography is a vat photopolymerization process using a liquid photopolymer contained in a vat and processed by selectively delivering energy to cure specific sections of a part cross-section.

3.1. Selective Laser Sintering

Table 3 provides an overview of available life cycle inventory efforts for SLS processes [10-15]. While the average operational and standby power demands highly differ between machine tools, the obtained specific energy consumption (SEC) values range from 107 up to 145 MJ/kg.

For SLS a comprehensive environmental assessment has been conducted by Kellens et al. [13]. As shown in Figure 2, the created waste powder fraction (up to 50%) causes approximately half of the environmental impact.

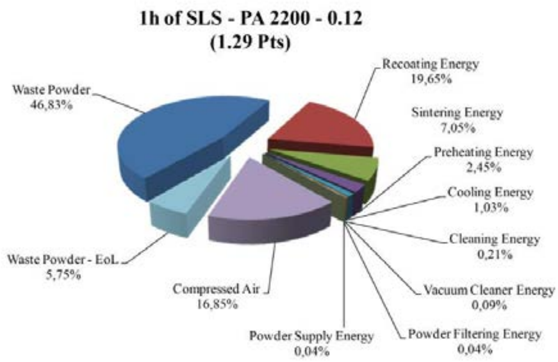

Fig. 2. Environmental impact (ReCiPe Europe H/A method) distribution of 1 hour of SLS of PA2200 with a layer thickness of 120 µm [13].

Table 3. LCI data of selective laser sintering (SLS) processes

Machine Tool	Material	Average Power (kW)		SEC (MJ/kg)	Resource consumption	Reference
		Operational	Standby			
DTM Sinterstation 2000	Polymer	16.800	n/a	144.3	n/a	[10]
DTM Sinterstation 2500	Polymer	12.500	n/a	107.4	n/a	[10]
EOSINT M250 Xtended	Polymer	4.000	2.000	n/a	n/a	[11]
EOSINT P760	PA2200 PA3200GF	6.610	3.520	129.6-145.1	Compressed air: 20m³/h up to 50% waste powder	[12-13]
EOSINT P360	PA2200	3.740	2.250	n/a	Compressed air: 6m³/h	[12]
EOSINT FORMIGA P100	PA2200	1.300	0.340	n/a	Compressed air: 10 m³/h	[12]
EOSINT P390	PA12	2.920	n/a	107.0	n/a	[14]
3D-Systems HiQ + HiS	PA12	5.500	n/a	130.0	n/a	[15]

Table 4. LCI data of selective laser melting (SLM) processes

Machine Tool	Material	Average Power (kW)		SEC (MJ/kg)	Resource consumption	Reference
		Operational	Standby			
Concept Laser M3 Liner	316L	3.350	0.700	97.0	Nitrogen: 3.5m³/h 20.4% waste powder	[12]
MTT SLM250	316L	1.090	n/a	83.0-108.0	n/a	[14]
Concept Laser M3 Linear	316L	3.330	n/a	423.0-588.0	n/a	[14]
Concept Laser Mlab	Aluminium	0.790	0.480	309.1-533.0	Argon: 0.7l/min	-
Renishaw AM250	$AlSi_{10}Mg$	1.166	0.430	566.2	n/a	[16]

Table 5. LCI data of electron beam melting (EBM) processes

Machine Tool	Material	Average Power (kW)		SEC (MJ/kg)	Resource consumption	Reference
		Operational	Standby			
Arcam AB – A1	Ti_6Al_4V	2.220	n/a	61.0-177.0	n/a	[14]
Arcam A1	Ti_6Al_4V	2.220	n/a	60.0	Helium gas: 1 l/h	[17]
Arcam	Ti_6AlV	2.133	n/a	375.0	Argon gas: 5.5m³/h	[18]

Table 6. LCI data of fused deposition modeling (FDM) processes

Machine Tool	Material	Average Power (kW)		SEC (MJ/kg)	Resource consumption	Reference
		Operational	Standby			
Stratasys FDM 1650	ABS	1.320	n/a	1247.0	n/a	[10]
Stratasys FDM 2000	ABS	2.200	n/a	414.7	n/a	[10]
Stratasys FDM 8000	ABS	2.200	n/a	83.1	n/a	[10]
Stratasys FDM Quantum	ABS	11.000	n/a	589.3	n/a	[10]
Stratasys FDM 3000	n/a	0.570	0.530	n/a	n/a	[11]
Stratasys FDM 400 mc	PC	2.450	n/a	519.0-536.0	n/a	[14]
Stratasys Dimension SST	n/a	1.100	0.400	n/a	n/a	[19]
Stratasys Dimension 768 STT	n/a	1.100	0.250	688.7 MJ/kg	n/a	[20]

Table 7. LCI data of stereolithography (SL) processes

Machine Tool	Material	Average Power (kW)		SEC (MJ/kg)	Resource consumption	Reference
		Operational	Standby			
3D-Systems SLA 250	SL 5170	1.200	n/a	116.9	n/a	[10]
3D-Systems SLA 3000	SL 5170	3.000	n/a	149.0	n/a	[10]
3D-Systems SLA 5000	SL 5170	3.000	n/a	74.5	n/a	[10]
PAN 1 (Fast MIP-SL)	SI 500	n/a	n/a	49.9	Waste material quantified	[21]

3.2. Selective Laser Melting

While Kellens et al. [12] indicate the high environmental impact share (up to 45%) of the nitrogen consumption for a Concept Laser M3 Linear machine tool, Faludi et al. [16] quantified the environmental impact generated by a Renishaw AM250 and concluded that the process energy was in almost all scenarios the dominant factor (66 to 75%) in the generated environmental impact (ReCiPe H/A method). Powder impacts never accounted for more than 10-12%. Waste material, argon gas consumption, machine transportation and disposal resulted in negligible impacts. As listed in Table 4, the SEC for SLM varies between 83 and 588 MJ/kg.

The LCI data for the Concept Laser Mlab machine tool were gathered in the framework of this paper for two aluminum sample batches with a total part mass of respectively 0.896 and 0.721 kg. The related volumes of the support structures were 19642 and 27743 mm³. Figure 3 shows the power profile during the recoating and sintering modes.

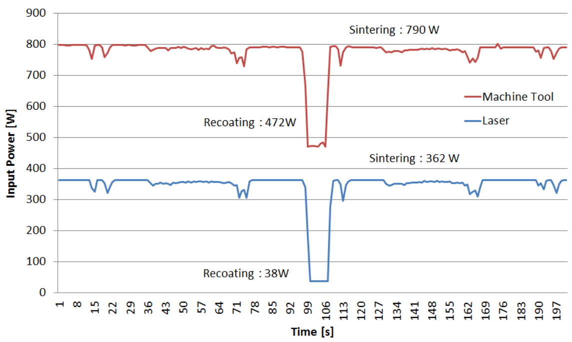

Fig. 3. Power profile during operational mode of a concept laser Mlab machine tool.

3.3. Electron Beam Melting

The environmental performance of EBM processes has been analyzed by Baumers et al. [14,17] and Paris et al. [18]. The first authors indicate the weak connection between extra product shape complexity and increasing per layer manufacturing energy requirements and indicate that the cross-sectional melting area must be viewed as the most determinant factor of energy consumption per layer. The reported SEC values range from 60 to 375 MJ/kg.

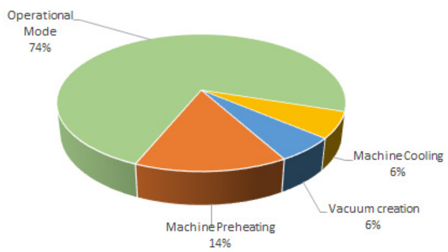

Fig. 4. Distribution of energy consumption for the EBM production of an aeronautical turbine with a volume of 53.56cm³ [18].

Figure 4 shows the distribution of the energy consumption for the production of a 53.56cm³ aeronautical turbine (Ti_6AlV) on an Arcam machine tool [18].

3.4. Fused Deposition Modelling

Luo et al. [10], Mognol et al. [11], Baumers et al. [14], Balogun et al. [19] as well as Yoon et al. [20] investigated the energy demand of FDM processes. The reported SEC values (see Table 6) significantly vary between 83.1 and 1247 MJ/kg. No information on the resource consumption of FDM processes could be identified.

Yoon et al. [20] estimated that approximately 60% of the energy consumption occurs during the warming up phase of the FDM system. Therefore, a significantly decreasing SEC value can be noticed when multiple parts are consecutively produced.

3.5. Stereolithography

Malshe et al. [21] analyzed the environmental performance of a novel stereolithography process: mask image projection stereolithography (MIP-SL). The authors quantified the SEC for the Fast MIP SL process to be lower than the values obtained by Luo et al. [10] for standard SL machine tools: 3D Systems SLA 250, SLA 3000 and SLA 5000. The reported SEC values range between 49.9 and 149.0 MJ/kg (see Table 7).

4. AM - Post Treatment Processes

After the completion of an AM manufactured part, typically a post treatment is required to disconnect the parts from the build plate, to remove support structures (e.g. scaffolds) or to obtain the required dimensional and/or surface qualities. Commonly applied AM post treatment processes are electrical discharge machining (EDM), ultrasonic cleaning and part finishing by conventional machining processes.

In order to separate parts from the build platform in laser-based powder bed fusion systems, Baumers et al. [14] applied a wire erosion process (wire EDM) and estimated an energy consumption of 142.5 MJ per build. Faludi et al. [16] quantified that the EDM energy share can be up to 25% of the total energy consumption during AM part manufacturing. Further environmental analysis of wire EDM processes are provided by Kellens et al. [22] and Dhanik et al. [23].

The energy consumption related to the ultrasonic removal (combining ultrasonic waves, heat and a detergent) of FDM support structures has been quantified by Mognol et al. [11] as well as Balogun et al. [19]. While the former indicates a constant power demand of 500W, resulting in an energy demand of 14.4 MJ for an immersing period of 8 hours, the latter reports an average power level of 250 Watt and 1 hour of post processing time.

Despite these post treatment processes are a vital part of the AM process chain, the related impacts caused by these processes are often neglected or underestimated in environmental comparisons of alternative process manufacturing routes.

Table 8. Fuel consumption reduction coefficients for different vehicle types and related life time impact savings per kg of weight reduction.

Transport system	Energy source	FRC [26]	Service life	Eco-Impact (ReCiPe H/A)	Life time savings (ReCiPe H/A)	Equivalent electrical energy
Gasoline car	Gasoline	0.5 l / (100kg*100km)	200000km	0.121 Pts/l	1.21 Pts/kg	85 MJ
Diesel car	Diesel	0.24 l / (100kg*100km)	200000km	0.141 Pts/l	0.68 Pts/kg	48 MJ
Short distance train	Electricity	300 kJ / (1000kg*km)	$3.5*10^6$ km	0.051 Pts/kWh	14.88 Pts/kg	1050 MJ
Long distance train	Electricity	100 kJ / (1000kg*km)	$10*10^6$ km	0.051 Pts/kWh	14.17 Pts/kg	1000 MJ
Short distance aircraft	Kerosene	12.5 ton / (100kg*year)	25 year	0.134 Pts/l	335 Pts/kg	23647 MJ
Long distance aircraft	Kerosene	103 ton / (100kg*year)	25 year	0.134 Pts/l	2760 Pts/kg	194852 MJ

5. Discussion

The rather large variation in reported energy and resource consumption demand between various analyses can be explained, among others, by the differences in machine tool design, applied process parameters (e.g. layer thickness), machine tool utilization (single part versus full build), selected case study material and part design.

Comparing the SEC values of the covered AM unit processes with these of conventional machining (e.g. [24]) or injection molding processes (e.g. [25]), the reported values for AM are 1 to 2 orders of magnitude higher. Of course it should be noted that while for AM the SEC values are quantified per kg of deposited material, these of subtractive processes are expressed per kg of removed material. In consequence, the volume of material removal ratio plays an important role when comparing different manufacturing routes [18].

Furthermore, the additional energy and resource demands of additional material preparation (Section 2) and required post treatment (Section 4) processes need to be taken into account when comparing alternative manufacturing process chains.

From environmental perspective, the higher environmental impact created during the AM manufacturing stage should be compensated by functional improvements during the part use stage. While multiple potential functional improvements are the central topic of current research [3], the available reports are still often based on (rough) estimations or focus on a very specific use case. More generic and in-depth LCA studies, covering all life cycle stages, are needed to clarify whether a shift to AM makes sense from environmental perspective.

An often cited functional improvement can be found in lightweight components for transport systems. As example, Table 8 provides an overview of fuel consumption reduction coefficients and related environmental impact savings (ReCiPe Europe H/A method) per kg of weight reduction. The last column of this table provides the equivalent electrical energy (UCPTE) savings in MJ calculated based on the achieved life time savings. Based on the resulting values, it can be questioned whether weight reductions of typically a few 100 grams obtained by AM manufactured automotive components make sense at all considering the order of magnitude of the additional manufacturing impacts (powder production, AM processing and post treatment). For railway and aerospace applications, the potential environmental benefits seem more realistic and relevant.

6. Conclusion

This paper provides an overview of available LCI data collection efforts and related environmental analysis of AM feedstock production, unit processes (SLS, SLM, EBM, FDM and SL), and post treatment processes.

Following conclusions can be made:

- Most available studies focus mainly on energy consumption. LCI data on resource consumption and direct or indirect process emissions are mostly not available.
- AM feedstock production processes are not well documented in terms of their environmental performance providing a highly relevant topic for future research.
- In general, the reported specific energy values for AM unit processes are 1 to 2 orders of magnitude higher compared to conventional machining and injection molding processes.
- From environmental perspective, the higher environmental impact caused during the AM manufacturing phase should be compensated by functional improvements during the use stage of AM manufactured parts.
- Comparing the estimated AM manufacturing energy demands and potential fuel consumption reduction coefficients, application of lightweight components in automotive only offers environmental benefits if significant weight reductions can be obtained. For railway and aerospace applications, the required weight reductions are much more realistic.

A comprehensive review of the current environmental dimensions of additive manufacturing, covering the complete life cycle of AM manufactured products, is provided by Kellens et al. [3].

Acknowledgements

The authors would like to thank the KU Leuven for the financial support via the GOA SUMMA (Sustainable Materials processing in Manufacturing – 3E140361) project.

References

[1] Wholers report. 3D Printing and Additive Manufacturing State of Industry – Annual Worldwide Progress Report. 2016. ISBN: 978-0-9913332-2-6.

[2] Duflou JR, Sutherland, JW, Dornfeld D, Herrmann C, Jeswiet J, Kara S, Hauschild M, Kellens K. Towards energy and resourece efficient manufacturing: a processes and systems approach. CIRP Annals – Manufacturing Technology 2012; 61/2:587-609.

[3] Kellens K, Baumers M, Gutowski TG, Flanagal W, Lifset R, Duflou JR. Enrironmental Dimensions of Additive Manufacturing. Mapping application domains and their environmental implications. Journal of Industrial Ecology 2017; Accepted for publication.

[4] Chen D, Heyer S, Ibbotson S, Salonitis K, Steingrimsson JG, Thiede S. Direct digital manufacturing: definition, evoluation, and sustainability implications. Journal of Cleaner Production 2015; 107:615-625.

[5] Bradley R, Jawahir IS, Badurdeen F, Rouch K. A Framework for Material Selection in Multi-Generational Components: Sustainable Value Creation for a Circulare Economy. CIRP Procdia 2016; 48:376-381.

[6] Dawes J, Bowerman R, Trepleton R. Introduction to the Additive Manufacturing Powder Metallury Supply Chain. Johson Matthey Technology Review 2015; 59/3:243-256.

[7] Serres N, Tidu D, Sankare S, Hkawka F. Environmental comparison of MESO-CLAD process and conventional machining implementing life cycle assessment. Journal of Cleaner Production 2011; 19:1117-1124.

[8] Kruth JP, Levy G, Klocke F, Childs THC. Consolidation phenomena in lased and powder bed based layered manufacturing. CIRP Annals – Manufacturing Technology 2007; 56/2:730-759.

[9] Gibson I, Rosen DW, Stucker, B. Additive Manufacturing Technologies. Rapid Prototyping to Direct Digital Maniufacturing. Springer 2010. ISBN:978-1-4419-1120-9.

[10] Luo Y, Ji Z, Leu MC. Environmental performance analysis of solid freeform fabrication processes. Proceedings of the IEEE International Symposium on electronics and the environment 1999; 1-6.

[11] Mognol P, Lepicart D, Perry N. Rapid prototying: energy and environment in the spotlight. Rapid Prototyping Journal 2006; 12/1:36-34.

[12] Kellens K, Yasa E, Renaldi, Dewulf W, Kruth JP, Duflou JR. Energy and resource efficiency of SLS/SLM processes. Proceedings of the 23rd Solid Freeform Fabrication Symposium 2011; 1-16.

[13] Kellens K, Renaldi, Dewulf W, Kruth JP, Duflou, JR. Environmental Impact Modeling of Selective Laser Sintering Processes. Rapid Prototyping Journal 2014; 20/6:459-470.

[14] Baumers M, Tuck, C, Wildman R, Ashcroft, I, Hague R. Energy inputs to additive manufacturing: does capacity utilization matter? Proceedings of the 23rd Solide Freeform Fabrication Symposium 2011; 30-40.

[15] Telenko C, Seepersad CC. A comparison of the energy efficiency if selective laser sintering and injection moulding of nylon parts. Rapid Prototyping Journal 2012; 18/6:472-481.

[16] Faludi J, Baumers M, Hague R, Maskery I. Environmental Impacts of Selective Laser Melting: Do Printer, Powder, Or Power Dominate? Journal of Industrial Ecology 2016. Accepted for publication.

[17] Baumers M, Tuck C, Wildman R, Ashcroft I, Hague R. Shape Complexity and Process Energy Consumption in Electron Beam Melting: A Case of Something for Nothing in Additive Manufactring? Journal of Industrial Ecology 2016. doi:10.1111/jiec.12397.

[18] Paris H, Mokhtarian H, Coatanéa E, Museau M, Ituarte IF. Comparative environmental impacts of additive and subtractive manufacturing technologies. CIRP Annals Manufacturing Technology 2016; 65/1:29-32.

[19] Balogun VA, Kirkwood N, Mativenga PT. Energy consumption oand carbon footprint analysis of Fused Deposition Modeling: A case study of RP Stratasys Dimension SST FDM. International Journal of Scientific & Engineering Research 2015; 6/8: 442-447.

[20] Yoon HS, Lee JY, Kim HS, Kim MS, Kim ES, Shin YJ, Chu WS, Ahn SH. A Comparison of Energy Consumption in Bulk Forming, Subtractive, and Additive Processes: Review and Case Study. International Journal of Precision Engineering and Manufacturing Green Technology 2014; 1/3:261-279.

[21] Malshe H, Nagarajan H, Pan Y, Haapala K. Profile of sustainability in additive manufacturing and environmental assessment of a novel stereolithography process. Proceedings of the ASME 2015 International Manufacturing Science and Engineering Conference MSEC2015. MSEC2015-9371.

[22] Kellens K, Renaldi, Dewulf W, Duflou, JR. Preliminary environmental assessment of electrical discharge machining. Proceedings of the 18th CIRP Conference on Life Cycle Engineering 2011; 377-382.^

[23] Dhanik S, Xirouchakis, P, Perez R. A Systel for resource efficient process planning for Wire EDM. Proceedings of the 18th CIRP Conference on Life Cycle Engineering 2011; 219-224.

[24] Kara S, Li W. Unit Process Energy Consumption for Material Removal Processes. CIRP Annals – Manufacturing Technology 2011; 60/1:37-40.

[25] Thiriez A. An Environmental Analysis of Injection Molding. Master Thesis Massachusetts Institute of Technology 2006.

[26] Deng Y. Life Cycle Assessment of Biobased Fibre-Reinforced Polymer Composites. PhD Thesis KU Leuven 2014. ISBN 978-94-6018-845-9.