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Comparative life cycle assessment of two different manufacturing technologies: laser additive manufacturing and traditional technique

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Abstract

Additive manufacturing processes, such as Laser Additive Manufacturing (LAM), has become increasingly established in metal-processing industry offering versatile possibilities for producing individualized components or lightweight structures. LAM machines offer ecological and economical potentials due to comparatively low power and material demand. In general, Additive Manufacturing (AM), has been considered an alternative to the traditional manufacturing techniques, such as Subtractive Machining (SM), because allows the creation of new, light and complex products with an innovative design and manufacturing. Sustainability assessment is essential to identify and select the best technology among the alternative candidates. Sustainability of LAM needs to be evaluated for finding an optimal compromise between technical development and sustainability performance. The Life Cycle Assessment (LCA) methodology is applied to investigate the sustainability of Laser Engineered Net Shaping (LENS) by comparing that of the Computer Numerical Control (CNC) machining. The aim of this research is to analyze and compare the environmental impact between additive and subtractive manufacturing. In particular, CNC (SM) and LENS (AM) technologies have been chosen. A common spur gear has been defined as a case study. Therefore, the analysis allows to define the ecological characteristics of a new production technology compared to a gold standard such as CNC machining. Hence, the advantages and disadvantages of the reviewed additive technology are exposed. The ReCiPe midpoint results, shows advantages in term of environmental impact for the LENS manufacturing process, in particular for the damage to resource indicator.

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1. Introduction

In recent years, the increase in environmental sustainability has become a central requirement in a product for the growth of both legislative constraints and customer environmental awareness. To satisfy this requirement, industry improved various aspects of the product life cycle. The manufacturing phase was one of the most interested in this regard, with the introduction of new approaches and technologies, including Additive Manufacturing (AM) [1]. AM is typically found in opposition to subtractive or deformation-based manufacturing, such as machining processes at machine tools or forming, known as traditional technologies [2]. The most known advantages of AM are the production of highly complex parts and the reduction of waste material and energy consumption.

The growing diffusion of computational simulation and the research on new materials allowed the rapid developments of AM. In particular, one of the processes that are having more relevance is the production of parts through the use of metal [3] [4]. This increasing interest in AM is related to the fact that it is considered to be a technology that could potentially reduce the environmental impact of production, which coincides with 22% of total energy consumption and 38% of global emissions of CO₂ [5] [6]. Furthermore, claim that the interventions on the three dimensions of the sustainable development, i.e. economic, social and environmental, could lead to changes in many industrial fields [7].

In addition to the environmental sustainability, AM can also transform the supply chain of product, favoring the local production of parts to reduce fuel consumption and the related

CO₂ emissions. AM allows the realization of lighter components to reduce the energy consumption during use [7] [8] [9]. Optimized and complex geometries of realized parts can be ensured by AM [7], with the aim to eliminate tools, molds, lubricants and the energy consumption requested for their production, maintenance, transport and use [10].

Despite all advantages shown, these technologies still represent a small part of the total production (less than 0.1%) [3]. The literature also presents the evaluation of an emerging technology such as AM in relation to well-established manufacturing processes such as machining [11] [12] [13] [14] [9], forming [10] [14], casting [15] [9] and laser cutting [16]. Yi et al. Compare the environmental impact of AM and traditional technologies in the production of a gimbal, also considering design optimization techniques, which improve the impact of additive technologies [10]. Machining and forming are also compared with AM by the research of Ingarao et al. [14]. This shows how additive technology is only sustainable if parts with complex and light shapes are produced. The difference between AM and machining is also addressed by Lunetto et al. [12] which emphasizes the strong influence on the energy consumption of the laser source for Electron Laser Melting (EBM). Ingarao et al. also evaluate the environmental sustainability of conventional and additive production through the LCA methodology, showing that EBM has greater energy efficiency even without product re-design thanks to the lower production of waste materials [13]. Regarding the comparison between casting and AM, Prakas et al. explain how AM is advantageous as it eliminates the production of sacrificial molds and anodes [15]. At the same time, Bekker et al. compare the environmental impacts arising from the production of 1 Kg of stainless steel through Wire Arc Additive Manufacturing (WAAM) and sand casting [9]. The same result is also achieved through CNC with a fraction of 0.75. On the other hand, Guarino et al. [16] investigating economic, technical and environmental assessments of Selective Laser Melting (SLM) and laser cutting, highlight how the first one increases the mechanical performance at the expense of the cost of the single component and the energy consumption. At the same time, the study of Kellens et al. indicates how the energy value per unit of product is 1 - 2 orders of magnitude greater for AM, compared with conventional manufacturing methods [17]. Therefore, only in the aerospace and railway field, the better performances of the printed products can compensate the higher energy cost of production. In summary, the literature presents varied LCA comparisons between poles apart manufacturing technologies, without taking into consideration two of the most used production processes (CNC and LENS) for a widely renowned mechanical part, such as a spur gear. Therefore, in the first part of this paper, manufacturing processes are presented, and the scope of the analysis is defined. In the next research step, the Life Cycle Inventory is produced, and the inventory data are shown. Then, the Life Cycle Impact Assessment is realized and finally, LCA result are exposed with authors' arguments.

2. Method and Tools

Numerical control machines (CNC) allow to gather a series of processes within a single manufacturing machine. This result is made possible through software combined with machine control system. Modern numerical control systems allow to centralize the functions of turning, punching, milling and cutting. Being a key element of modern industry, their global energy consumption is not negligible [18]. [19] show that only 14.8% of the energy absorbed by the machine is used for the process of subtracting the raw material. A recent breakthrough in CNC machines is the implementation of additive technologies. This approach is called hybrid additive and subtractive processes (WHASPs), which integrates additive Direct Energy Deposition (DED) with tools for subtractive machining [20].

By concentrating the energy through controlled laser source, the LENS, an emerging and niche AM technology, also known as DED, welds raw material in the form of stream in different chosen points [21]. It is common knowledge that AM permits to produce complex structures without waste of material and energy. Indeed, 3D printers realise complexities and customizations with no additional machine cycle time. However, what are the real environmental benefits and complication for a fringe DED process compared to a well-known machining device? In the biomedical field, prostheses with a porous surface produced using DED are emerging, and they have performance qualities comparable to traditional prosthetic devices, with the advantage of being able to modify the design to adapt it to different patients [22].

This technology is also used in the repair of components: in this way it is possible to limit the environmental impact as it increases the useful life of a product [23] [24]. In this study, the environmental sustainability of the LENS technology and a common CNC machine are assessed and compared.

LCA methodology (ISO 14044) was adopted to determine the environmental impacts since among the supporting methodologies is unanimously considered one of the most useful for quantitatively evaluating the sustainability of the current technologies, to critically discuss the choices to implement during eco-design and to evaluate the environmental performances of the new developed technologies [25].

2.1. Goal and scope definition

The environmental impacts of LENS and CNC were compared to produce a same steel gear [26], the properties are reported in Table 1. This component has been selected because the resulting surface properties, dimensional tolerances, and time of production ensured by the two considered technologies are comparable. The functional as defined as the transmission of power through a spur gear of geometric, mechanical and technological characteristics of Table 1. The product can be made with a different production technology, in this case study

the CNC methodology will be compared with the LENS methodology. The study is a "cradle to gate" type, this means it refers only to a specific step of the life cycle of gear. All processes from the extraction of the raw materials to the realization of the product have been considered.

Not taking into consideration the impacts resulting from the production of LENS and CNC machines, and the impact of the use phase and end of life period. Considering the functional unit, this is possible because it compares a product with the same characteristics, the same lifetime and the same end of life. For CNC machining, the materials consumed in the gear manufacturing are AISI 4140 bulk material, while AISI 4140 powders and argon are needed for the gear fabrication in the LENS process.

Table 1. Spur gear characteristic [26]

	Characteristics	Value
Component	Spur gear	
Material	AISI 4140	
Shape and mass	Length	25.79 mm
	Width	25.78 mm
	Height	4 mm
	Volume	1.26 cm ³
	Mass	9.81 g
Quality	Average surface roughness	1 µm
	Tolerance on tooth thickness	0.05 mm
Production times	CNC	65 seconds
	LENS	280 seconds

2.2. Life Cycle Inventory analysis

Life Cycle Inventory is the basic activity to assess the impact of the life cycle, allowing to quantify the flows into and out of the system boundaries. These flows include the use of resources (raw materials and energy), as well as releases into the air, water and soil associated to the system. During this phase, a list of substances consumed and released into the environment and the used energy was produced. The procedure followed for our inventory analysis, according to ISO 14040 [27], consists of the following phases: the primary data for process were collected in the company production plant. The secondary data were extrapolated from the updated literature and from GaBi professional database 2021.

In this case study, AISI 4140 powders and argon are needed for the gear fabrication in the LENS process while for CNC machining, the materials are AISI 4140 bulk material and coolant. According to the functional unit, the material properties of the gears fabricated by the two technologies are the same. The main material, resources and energy consumption used in CNC machining and LENS are shown in Table 2.

For the LENS technologies, the values of powder, argon, electricity have been measured directly on the machine. The same consideration can be done for the finish grinding and

recovery powered. The raw material data, transport and process, have been obtained from the material suppliers. To produce a one gear through the LENS technology it is necessary to use 77.85g of powder. This material is necessary both for the realization of single piece 9.81g, but also for the processing.

The difference between 77.85 e 9.81 grams is almost totally recovered. In this analysis, the material not recovered is sent to the landfill. The study has been modelled in GaBi software. Figure 1 show the system boundaries of this study.

Table 2. Life Cycle Inventory data

Scenario	Phase	Flow	Quantity
LENS technologies	Transportation by aircraft and truck	Truck transport (Euro 5, 3.5-7.5 tons lorry)	50 km
		Aircraft transport	2500 km
	Gas atomization by high-speed gas	Electricity	0.1296 MJ
		Steel ingot	84.16 g
	LENS process	Powder	77.85 g
		Argon	221 g
		Electricity	2.6532 MJ
	Finishing grinding	Electricity	0.1404 MJ
	Recovery powered process	Powder to recovery	58.23 g
		Electricity	0.097 MJ
		Recovery powder	46.4 g
CNC technologies	Transportation by aircraft and truck	Truck transport (Euro 5, 3.5-7.5 tons lorry)	40 Km
		Aircraft transport	2000 Km
	Casting	Steel ingot	94.01 g
		Electricity	0.2376 MJ
	Roughing by form milling	Lubricant	15.9 g
		Electricity	0.0792 MJ
	Finishing grinding	Electricity	0.1404 MJ

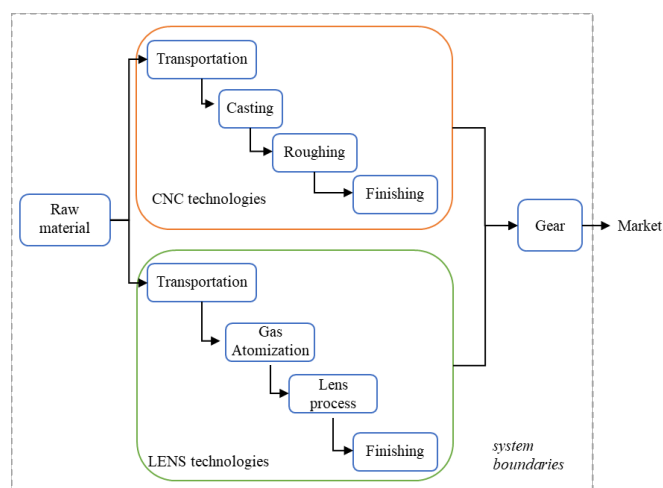


Figure 1. System boundary of the study

2.3. Life Cycle Impact Assessment

The assessment environmental impacts calculation has been realized by using GaBi tool as LCA software tool, equipped with the Gabi database. The selected impact assessment

method is the ReCiPe 1.08 Hierarchist. Midpoint method that allows to quantify the impacts in 18 different categories [18]. Table 3 and Table 4 reports the environmental impacts contributions of the different scenarios considered while Figure 2 provides a graphical comparison

Table 3. Life Cycle Impact Assessment of the CNC technology

Impact category	Total	Electricity	Steel billet	Steel scrap landfill	Aircraft transport	Truck transport	Lubricant
Climate change [kg CO ₂ eq.]	8.53E-01	2.81E-01	1.14E-01	8.23E-04	6.47E-02	1.94E-04	3.92E-01
Fine Particulate Matter [kg PM _{2.5} eq.]	3.50E-04	9.41E-05	6.84E-05	5.69E-07	4.01E-05	1.79E-07	1.47E-04
Fossil depletion [kg oil eq.]	5.92E-01	1.06E-01	2.17E-02	2.82E-04	2.17E-02	6.47E-05	4.43E-01
Freshwater Consumption [m ³]	2.27E-03	1.61E-03	1.49E-04	1.58E-07	1.06E-05	5.16E-07	4.96E-04
Freshwater ecotoxicity [kg 1.4 DB eq.]	4.73E-04	1.74E-05	8.23E-06	6.45E-08	2.21E-05	6.66E-08	4.25E-04
Freshwater Eutrophication [kg P eq.]	1.14E-06	1.81E-07	8.49E-08	6.29E-10	9.03E-09	1.33E-09	8.64E-07
Human toxicity, cancer [kg 1.4-DB eq.]	6.85E-04	5.92E-05	1.16E-05	1.92E-07	2.97E-05	8.81E-08	5.85E-04
Human toxicity, non-cancer [kg 1.4-DB eq.]	1.65E-01	5.62E-03	4.61E-03	3.32E-05	7.65E-03	2.24E-05	1.47E-01
Ionizing Radiation [kBq Co-60 eq. to air]	7.08E-03	5.76E-03	7.92E-05	3.03E-06	1.78E-05	7.40E-08	1.23E-03
Land use [Annual crop eq.·y]	1.00E-02	5.56E-03	2.72E-03	8.90E-06	4.77E-05	9.28E-06	1.65E-03
Marine ecotoxicity [kg 1.4-DB eq.]	1.05E-03	4.13E-05	3.67E-05	2.75E-07	4.53E-05	1.37E-07	9.25E-04
Marine Eutrophication [kg N eq.]	7.50E-06	2.23E-06	5.54E-07	4.02E-09	5.41E-08	6.55E-09	4.65E-06
Metal depletion [kg Cu eq.]	3.97E-03	1.79E-04	3.43E-03	5.44E-05	1.30E-05	1.21E-07	2.90E-04
Photochemical Ozone Formation [kg NO _x eq.]	1.26E-03	2.47E-04	1.73E-04	1.71E-06	2.97E-04	1.45E-06	5.37E-04
Ozone Depletion [kg CFC-11 eq.]	1.41E-07	4.85E-08	7.78E-09	1.34E-10	3.04E-08	4.96E-11	5.40E-08
Terrestrial Acidification [kg SO ₂ eq.]	1.11E-03	2.95E-04	2.06E-04	1.69E-06	1.31E-04	5.64E-07	4.75E-04
Terrestrial ecotoxicity [kg 1.4-DB eq.]	1.77E-01	3.20E-02	4.18E-02	5.40E-04	1.27E-03	7.53E-06	1.01E-01

Table 4. Life Cycle Impact Assessment of the LENS technology

Impact category	Total	Electricity	Argon	Steel powered	Steel scrap landfill	Aircraft transport	Truck transport
Climate change [kg CO ₂ eq.]	8.25E-01	5.90E-01	1.73E-01	1.37E-02	5.72E-04	4.70E-02	1.46E-04
Fine Particulate Matter [kg PM _{2.5} eq.]	3.03E-04	2.15E-04	5.03E-05	8.11E-06	3.95E-07	2.91E-05	1.35E-07
Fossil depletion [kg oil eq.]	2.90E-01	2.20E-01	5.01E-02	3.82E-03	1.96E-04	1.57E-02	4.88E-05
Freshwater Consumption [m ³]	2.28E-03	1.54E-03	6.83E-04	5.24E-05	1.10E-07	7.69E-06	3.89E-07
Freshwater ecotoxicity [kg 1.4 DB eq.]	5.83E-05	3.04E-05	1.08E-05	9.05E-07	4.48E-08	1.61E-05	5.02E-08
Freshwater Eutrophication [kg P eq.]	9.35E-07	1.74E-07	7.11E-07	4.25E-08	4.37E-10	6.55E-09	1.01E-09
Human toxicity, cancer [kg 1.4-DB eq.]	2.05E-04	1.26E-04	5.38E-05	3.65E-06	1.33E-07	2.16E-05	6.65E-08
Human toxicity, non-cancer [kg 1.4-DB eq.]	1.89E-02	8.73E-03	4.04E-03	5.71E-04	2.31E-05	5.56E-03	1.69E-05
Ionizing Radiation [kBq Co-60 eq. to air]	1.10E-02	8.02E-03	2.79E-03	1.65E-04	2.11E-06	1.30E-05	5.58E-08
Land use [Annual crop eq.·y]	1.90E-02	4.64E-03	1.34E-02	9.08E-04	6.19E-06	3.46E-05	7.00E-06
Marine ecotoxicity [kg 1.4-DB eq.]	1.56E-04	7.79E-05	3.65E-05	7.97E-06	1.91E-07	3.29E-05	1.03E-07
Marine Eutrophication [kg N eq.]	8.17E-06	2.45E-06	5.35E-06	3.17E-07	2.80E-09	3.93E-08	4.95E-09
Metal depletion [kg Cu eq.]	7.49E-04	3.08E-04	3.21E-04	7.32E-05	3.78E-05	9.40E-06	9.11E-08
Photochemical Ozone Formation [kg NO _x eq.]	8.46E-04	4.26E-04	1.81E-04	2.11E-05	1.19E-06	2.15E-04	1.09E-06
Ozone Depletion [kg CFC-11 eq.]	1.92E-07	7.97E-08	8.50E-08	5.18E-09	9.30E-11	2.20E-08	3.74E-11
Terrestrial Acidification [kg SO ₂ eq.]	9.65E-04	6.84E-04	1.61E-04	2.37E-05	1.17E-06	9.45E-05	4.25E-07
Terrestrial ecotoxicity [kg 1.4-DB eq.]	1.39E-01	6.73E-02	5.64E-02	1.43E-02	3.75E-04	9.25E-04	5.68E-06

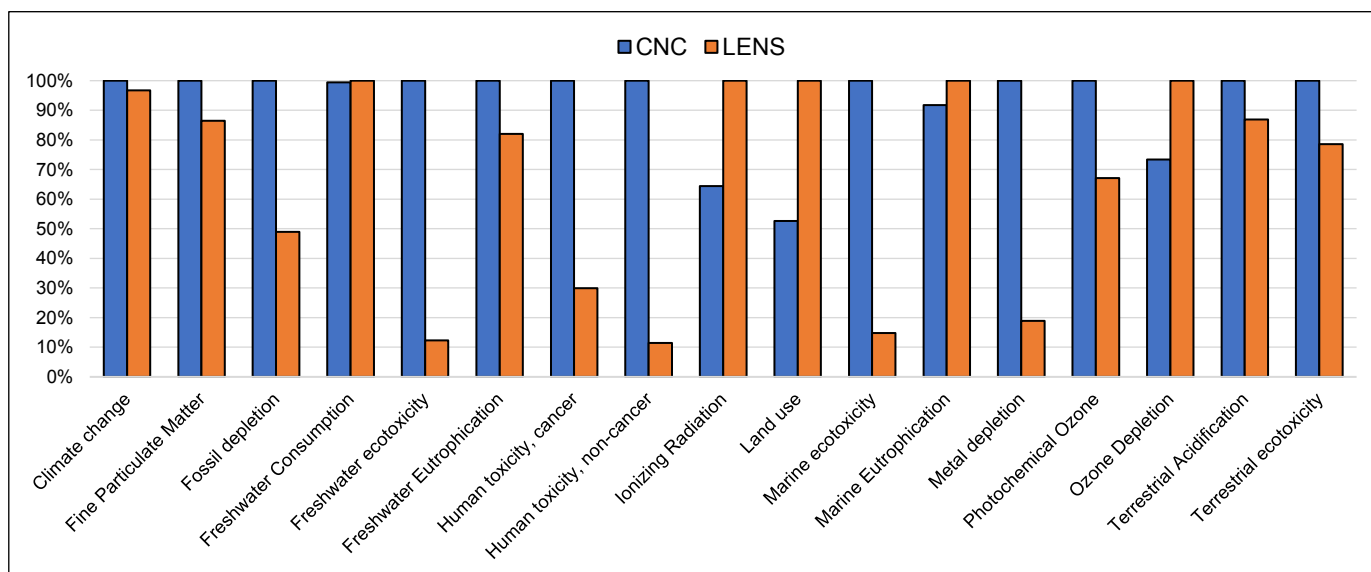


Figure 2. Comparison of the two scenarios, blue CNC technologies and orange LENS technologies

3. Results and discussion

From the analysis of the results showed in Figure 2 the better technology cannot be identified in absolute. In CNC technology the indicators with the highest impact are marine ecotoxicity, human toxicity, metal depletion and fossil depletion. Except for metal depletion, which is directly linked to the consumption of raw material the other indicators strongly depend by the use of lubricant during machining operations. In fact, in the CNC scenario there are 20% more of materials than in LENS and the waste recovery process is more onerous in environmental terms. This result was confirmed by several studies present in from the literature, e.g. Landi et al. [27], that highlighted the high environmental impact of the fossil-based lubricants.

While in LENS technology, ozone depletion, land use and ionizing radiations are greater. The values of these indicators mainly depend on the high electricity consumption and the use of argon to protect the melt pool. Some indicators such as the climate change and freshwater consumption they have similar values, but the impacts are due to different factors. Considering the climate change, in the CNC scenario, the about 80 percent is due to the use of lubricant and electricity consumption, but in the Lens scenario, the 70% of climate change is due to the production of the raw material. The same consideration can be made for the freshwater consumption.

For a better and a faster understanding of the more sustainability solution, Figure 3 shows the end points trends. For all end point categories, ecosystem, human health and resources the CNC technologies produce a major damage. As mentioned before, the greater consumption of material and the use of fossil-based lubricants produce a high impact on resource consumption. Going into the details, for example considering the climate change, the trend is similar. However,

the main causes of impact are different: in CNC technology, the use of lubricants and energy consumption are responsible for approximately 80% of the Climate change; in the LENS technology, the greatest contribution is due to the production of metal powders. Similar considerations can also be drawn for the other indicators. However, there results suffer from some limitations. The sustainability assessment of the LENS process and CNC machining is conducted on the assumption that the quality of the gears manufactured by these two technologies and the shape is the same. The advantage of using additive techniques is the possibility of creating free geometric shapes without constraints due to the production phase. In LENS technology one of the main causes of impact is the production of powders, a topological optimization could be considered to reduce the row material used. Finally, CNC is well known and optimized technology, while lens is an experimental technology. From this preliminary study it is possible to identify similar overall impacts, but due to different causes. Therefore, further assessments are needed to understand how an additive process can reduce the impact on the environment.

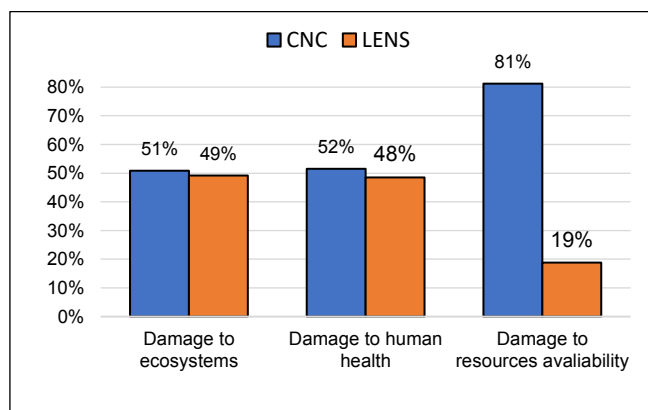


Figure 3. End-point comparison, blue CNC and orange LENS technologies

4. Conclusions

This paper aims to analyze and assess the environmental impact of the emerging AM technology of LENS, in comparison to climate and health effects of the well-defined CNC machining. The research, based on the ReCiPe Midpoint method, permits to show the LC.

A of both manufacturing methods and emphasize their lacks and strengths in environmental impact. In particular, compared to literature, this research permits to define the LCA of opposite production technologies in their methodology maturity.

After the assessment of 18 main impact categories, using GaBi database, this study showed two main conclusions:

- Neither technology is absolutely better than the other considering the ReCiPe method. Considering the uncertainties associated with the impact indicator results and the fact that both alternatives are roughly equivalent for most impact categories, it is still a technology without the right optimization that could reduce environmental impacts.
- The End-point comparison between the two technologies allowed instead to identify that CNC has a higher damage to the resources than LENS.

Due to the deductions mentioned before, future studies should focus on other AM hardware technologies, theoretical approaches, such as Topology Optimization and Generative Design, and how these methodologies can improve the environmental impact in industrial and medical fields.

5. References

- [1] M. K. Niaki, S. A. Torabi, & F. Nonino, 2019. Why manufacturers adopt additive manufacturing technologies: The role of sustainability. *Journal of cleaner production*, 222, 381-392.
- [2] K. Kellens, M. Baumanns, T. G. Gutowski, W. Flanagan, R. Lifset, J. R. Dufloy, 2017. Environmental Dimensions of Additive Manufacturing: Mapping Application Domains and Their Environmental Implications, *Journal of Industrial Ecology* 21, 49-68.
- [3] J. I. Arrizubieta, O. Ukar, M. Ostolaza, A. Mugica, 2020. Study of the Environmental Implications of Using Metal Powder in Additive Manufacturing and Its Handling, *Metals* 10, 261.
- [4] Metal Additive Manufacturing market valued at EUR 2.02 billion in 2019, <https://additive-manufacturing-report.com/additive-manufacturing-market/>.
- [5] S. Peng, T. Li, X. Wang, M. Dong, Z. Liu, J. Shi, H. Zhang, 2017. Toward a Sustainable Impeller Production: Environmental Impact Comparison of Different Impeller Manufacturing Methods, *Journal of Industrial Ecology* 21, 216-229.
- [6] T. Peng, K. Kellens, R. Tang, C. Chen, G. Chen, 2018. Sustainability of additive manufacturing: An overview on its energy demand and environmental impact, *Additive Manufacturing* 21, 694-704.
- [7] C. Fredriksson, 2019. Sustainability of metal powder additive manufacturing, *Procedia Manufacturing* 33, 139-144.
- [8] L. Yi, S. Ehmsen, M. Glatt, J. C. Aurich, 2021. A case study on the part optimization using eco-design for additive manufacturing based on energy performance assessment, *Procedia CIRP* 96, 91-96.
- [9] A. Bekker, J. Verlinden, 2018. Life cycle assessment of wire + arc additive manufacturing compared to green sand casting and CNC milling in stainless steel, *Journal of Cleaner Production* 177, 438-447.
- [10] L. Yi, M. Glatt, P. Sridhar, K. de Payrebrune, B. S. Linke, B. Ravani, J. C. Aurich, 2020. An eco-design for additive manufacturing framework based on energy performance assessment, *Additive Manufacturing* 33, 91-96.
- [11] B. Deboer, N. Nguyen, F. Diba, A. Hosseini, 2021. Additive, subtractive, and formative manufacturing of metal components: a life cycle assessment comparison, *The International Journal of Advanced Manufacturing Technology*, 413-432.
- [12] V. Lunetto, P. Priarone, S. Kara, L. Settineri, 2021. A comparative LCA method for environmentally friendly manufacturing: Additive manufacturing versus Machining case, in: *Procedia CIRP* 98, 406-411.
- [13] G. Ingarao, P. Priarone, 2020. A comparative assessment of energy demand and life cycle costs for additive- and subtractive-based manufacturing approaches, *Journal of Manufacturing Processes* 56, 1219-1229.
- [14] G. Ingarao, P. C. Priarone, Y. Deng, D. Paraskevas, 2018. Environmental modelling of aluminium based components manufacturing routes: Additive manufacturing versus machining versus forming, *Journal of Cleaner Production* 176, 261-275.
- [15] C. Prakash, S. Singh, H. Kopperi, S. Ramakrishna, S. Mohan, 2021. Comparative job production based life cycle assessment of conventional and additive manufacturing assisted investment casting of aluminium: A case study, *Journal of Cleaner Production*, 289.
- [16] S. Guarino, G. Ponticelli, S. Venettacci, 2020. Environmental assessment of Selective Laser Melting compared with Laser Cutting of 316L stainless steel: A case study for flat washers' production, *CIRP Journal of Manufacturing Science and Technology* 31, 525-538.
- [17] K. Kellens, R. Mertens, D. Paraskevas, W. Dewulf, J. R. Dufloy, 2017. Environmental Impact of Additive Manufacturing Processes: Does AM Contribute to a More Sustainable Way of Part Manufacturing?, *Procedia CIRP* 61, 582-587.
- [18] L. Li, C. Li, Y. Tang, Q. Yi, 2017. Influence factors and operational strategies for energy efficiency improvement of CNC machining, *Journal of Cleaner Production* 161, 220-238.
- [19] T. Gutowski, T. Gutowski, J. Dahmus, A. Thiriez, 2006. Electrical Energy Requirements for Manufacturing Processes, In: 13th CIRP International Conference On Life Cycle Engineering.
- [20] J. M. Flynn, A. Shokrani, S. T. Newman, V. Dhokia, 2016. Hybrid additive and subtractive machine tools – Research and industrial developments, *International Journal of Machine Tools and Manufacture* 101, 79-101.
- [21] A. Dass, A. Moridi, 2019. State of the Art in Directed Energy Deposition: From Additive Manufacturing to Materials Design, *Coatings* 2019, Vol. 9, 418.
- [22] W. S. Harun, M. S. Kamariah, N. Muhamad, S. A. Ghani, F. Ahmad, Z. Mohamed, 2018. A review of powder additive manufacturing processes for metallic biomaterials, *Powder Technology* 327, 128-151.
- [23] Shin Y.C., N. Bailey, C. Katinas, W. Tan, 2018. Predictive modeling capabilities from incident powder and laser to mechanical properties for laser directed energy deposition, *Computational Mechanics* 61, 617-636.
- [24] K. Ramani, D. Ramanujan, W. Z. Bernstein, F. Zhao, J. Sutherland, C. Handwerker, J.-K. Choi, H. Kim, D. Thurston, 2010. Integrated Sustainable Life Cycle Design: A Review, *Journal of Mechanical Design* 132, 0910041-09100415.
- [25] M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen, 2018. Life cycle assessment. Springer.
- [26] Q. Jiang, Z. Liu, T. Li, W. Cong, H.-C. Zhang, 2019. Emergy-based life-cycle assessment (Em-LCA) for sustainability assessment: a case study of laser additive manufacturing versus CNC machining, *The International Journal of Advanced Manufacturing Technology* 102, 4109-4120.
- [27] D. Landi, M. Germani, M. Mandolini, M. Marconi, C. Favi, 2019. Environmental and Economic Evaluation of the Sheet Metal Stamping Process Using Alternative Lubricants. *Proceedings of the ASME 2019 IDETC and CIEC. Vol 4: 24th Design for Manufacturing and the Life Cycle Conference; 13th International Conference on Micro and Nanosystems. Anaheim, California, USA. August 18–2, V004T05A027*