

ENERGY AND RESOURCE EFFICIENCY OF SLS/SLM PROCESSES

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Abstract

Manufacturing processes, as used for discrete part manufacturing, are responsible for a substantial part of the environmental impact of products, but are still poorly documented in terms of their environmental footprint. The lack of thorough analysis of manufacturing processes has as consequence that optimization opportunities are often not recognized and that improved machine tool design in terms of ecological footprint has only been targeted for a few common processes.

Additive manufacturing processes such as Selective Laser Sintering (SLS) and Selective Laser Melting (SLM) allow near-net shape manufacturing of complex work pieces. Consequently, they inherently offer opportunities for minimum-waste and sustainable manufacturing. Nevertheless, powder production, energy consumption as well as powder losses are important and not always optimized environmental impact drivers of SLS and SLM. This paper presents the results of a data collection effort, allowing to assess the overall environmental impact of these processes using the methodology of the CO₂PE! (Cooperative Effort on Process Emissions in Manufacturing) initiative.

Based on the collected LCI data, a subsequent impact assessment analysis allows indentifying the most important contributors to the environmental impact of SLS/SLM. Next to the electricity consumption, the consumption of inert gasses proves to be an important cause of environmental impact. Finally, the paper sketches the improvement potential for SLS/SLM on machine tool as well as system level.

Keywords

Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Life Cycle Assessment, Sustainable Manufacturing, Energy and Resource Efficiency, CO₂PE!-Initiative

Introduction

The application of Solid Freeform Fabrication (SFF) techniques such as Selective Laser Sintering (SLS) and Selective Laser Melting (SLM) [1,2,3] has seen a remarkable expansion over the past ten years both in terms of parts produced as well as in the number of machine tools sold [4]. SFF techniques are often prized for being much cleaner than conventional machining processes and being able to fabricate objects with minimum waste. Among others, further ecological advantages can be found in the reduction of transportation and supply chain impacts and the absence of special tooling or hazardous cutting fluids. However, quantitative analyses of the environmental impact caused by SFF processes are very limited and detailed data about environmental metrics such as energy consumption, waste flows and generated process emissions is often lacking [5,6]. Due to lack of thorough environmental analyses, optimization opportunities are often not recognized and improved machine tool design in terms of ecological footprint reduction has often not been targeted. In this paper, results of an environmental analysis of SLS as well as SLM production processes, using the CO₂PE!-methodology [7,8], are presented. First a summarized description of the

used methodology is provided. Based on the results of the LCI data collection effort for SLS and SLM processes, the most important contributors to the environmental impact of SLS/SLM processes are identified by an impact assessment. Finally, the paper sketches the improvement potential for SLS/SLM on machine tool as well as system level.

CO₂PE!-methodology

In order to enable a consistent and accurate inventurisation and documentation of Life Cycle Inventory (LCI) data, a generic data collection methodology [7], shown in Figure 1, is developed within the CO₂PE!-Initiative [8]. While the functional unit and system boundaries are set during the goal and scope definition, the real data collection effort occurs based on industrial measurements and comprises four different studies. First a time study is performed in order to identify the different use modes of the processes. Then power, consumables and emission studies are performed for all different modes on machine tool as well as subunit level.

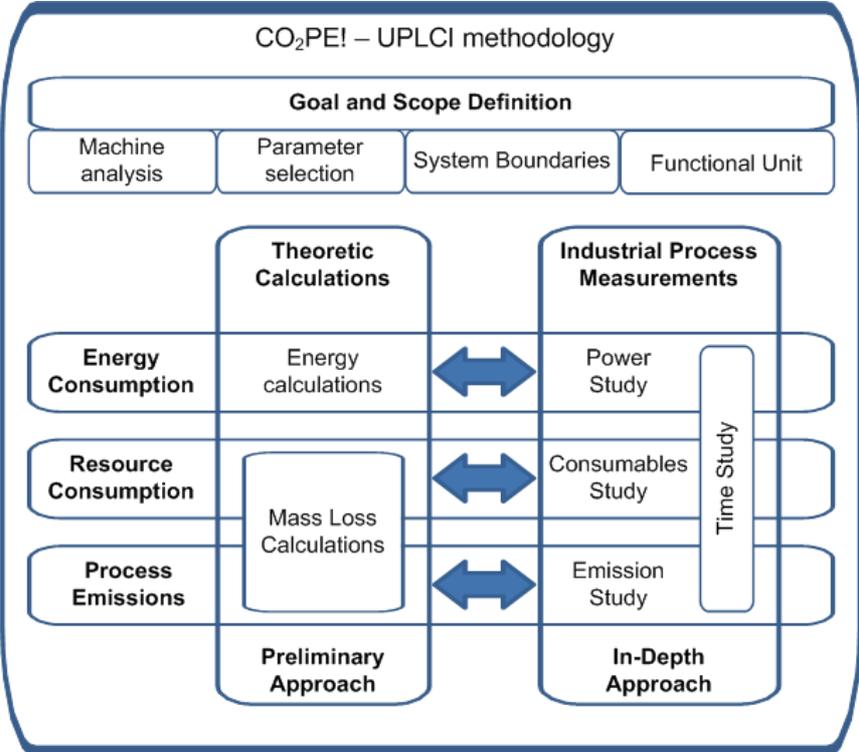


Figure 1: CO₂PE!-methodology, adapted from [7]

LCI Data Collection

This section describes the Life Cycle Inventory (LCI) data collected using the above described methodology. The system boundaries, illustrated in Figure 2, of the analysis are set to include only the operating phase of the involved SLS/SLM equipment: EOSINST P760, EOSINT P360, EOSINT FORMIGA P100 [9] and Concept Laser M3 Linear machine [10]. First results of this data collection effort were already presented in [11].

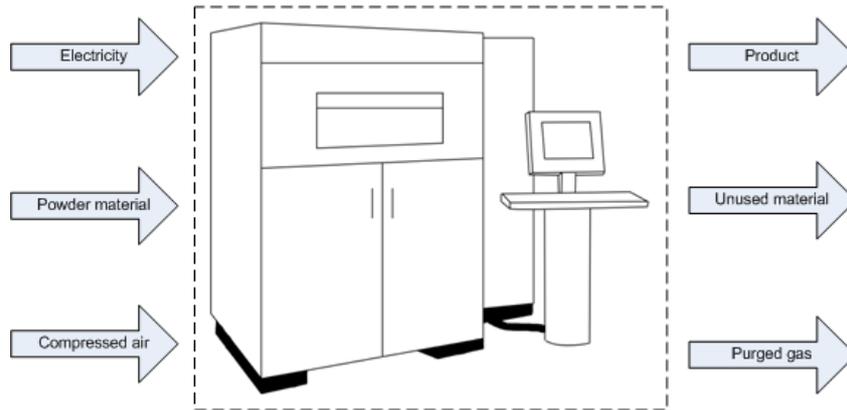


Figure 2: System boundaries (in- and outputs)

Selective Laser Sintering (SLS)

Time study

For SLS, extensive time studies were performed on 3 different EOSINT P760 machine tools [9]. The non-productive modes comprise machine tool cleaning, preheating (2 hours) and cooling down (2 hours). The productive modes are responsible for ca. 87% of the total production time, and can be subdivided further into three main modes: the laser exposure mode, the recoating mode and some other activities like the filling of the feed containers by an automatic powder supply system. Based on 63 batches (5801 products), Figure 3 shows the time distribution for products made of PA2200 with a layer thickness of 0.12mm.

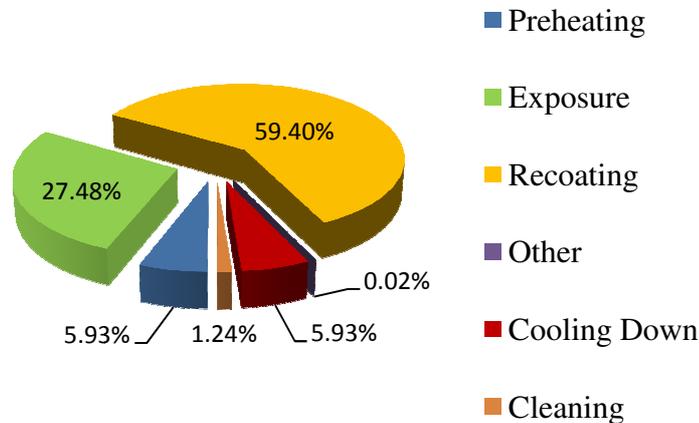


Figure 3: Production modes (PA2200, 0.12mm) [11]

Of course, the contribution of the productive modes depends on the product and batch design (e.g. total product volume and batch height). Based on multiple batches, an average distribution of the productive modes is listed in Table 1 for two different layer thicknesses (0.12mm and 0.15mm) and two materials (Fine Polyamide PA2200 and Glass-filled Fine Polyamide PA3200GF [9]).

EOSINT P760	PA2200	PA2200	PA3200GF
Layer thickness	0.12mm	0.15mm	0.15mm
#batches	63	12	11
Laser Exposure	31.45%	48.71%	21.95%
Recoating	68.53%	51.25%	78.02%
Other Activities	0.02%	0.04%	0.03%
Standard Error	1.13%	5.97%	2.52%
Standard deviation (σ)	8.97%	20.68%	8.35%

Table 1: Distribution of the productive modes [11]

Table 1 and Figure 3 show the significant contribution of the recoating mode to the total productive mode ranging from 50% up to 80% depending on the layer thickness and the material used. Consequently, the part (batch) height has a major influence on the total production time.

Multiple linear regression analyses indicate that the total production time (t_{prod}) is a function of the total batch volume (V) and batch height (h). Equation 1 presents the formula for the first combination of material and layer thickness (PA2200 / 0.12mm).

$$t_{\text{prod}} [\text{s}] = 8250 + 2135 * h [\text{cm}] + 1.39 * V [\text{cm}^3] \quad (1)$$

with a $R^2 = 0.96$

Since the product volume is determined by the product-design, the total production time can be minimized by optimizing the product orientation or nesting efficiency for batches with multiple products in order to reduce the batch height. These conclusions are consistent with previous work by Mognol et al. [12].

Power Study

The power levels of all different subunits during the productive modes of the EOSINT P760 are presented in Figure 4. The two most important energy consumers are the Laser Cooling Unit (3kW) and the Process Chamber Heaters (ranging from 0.8kW to 3.6kW in order to preheat the new powder material when a new layer is coated.). The peak consumption (up to 8.5kW) during the recoating process is mainly caused by the process chamber heaters warming up the new added powder layer.

Similar power measurements were performed for EOSINST P360 (including an external Laser Cooler Unit of 2kW) and EOSINT FORMIGA P100 machine tools. The average machine tool power levels of these machine tools are listed in Table 2.

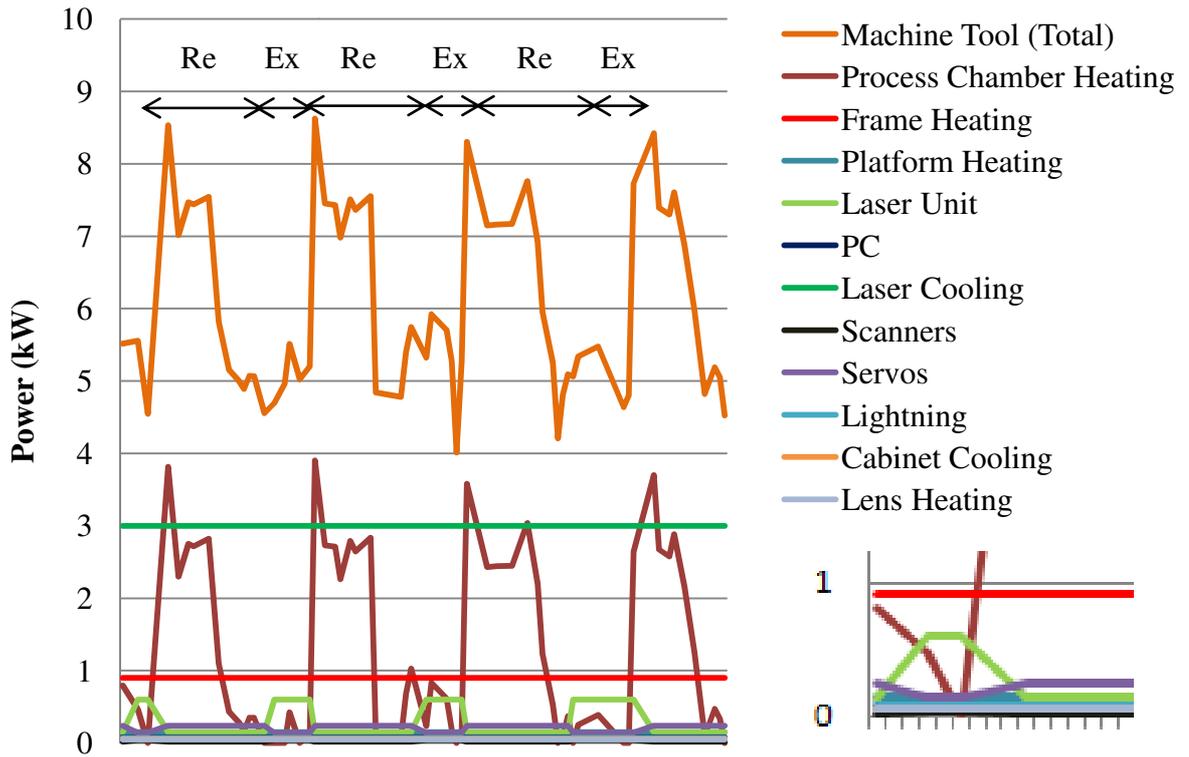


Figure 4: Power levels during productive modes of EOSINT P760 [11]
(Ex = Exposure, Re = Recoating)

	EOSINT P760	EOSINT P360	EOSINT FORMIGA P100
			
Container Dimensions	700 x 380 x 580 mm	340 x 340 x 620 mm	200 x 250 x 330 mm
Laser Source	CO ₂ , 2 x 50W	CO ₂ , 50W	CO ₂ , 30W
Max. Scan Speed	2 x 6 m/s	8 m/s	5 m/s
Average Power Levels	Standby Mode	3.52 kW	2.25 kW
	Heating Mode	8.28 kW	4 kW
	Recoating Mode	6.61 kW	3.74 kW
	Exposure Mode	5.31 kW	

Table 2: Average machine tool Power Levels [11]

Luo et al. [13] and Sreenivasan et al. [14] reported machine tool power levels for SLS machine tools of 3D-Systems [15], as shown in Table 3.

3D-Systems	DTM 2000	DTM 2500	Vanguard HiQ
Scanning Speed (m/s)	3	3	10
Road width size(mm)	0.4	0.4	0.4
Layer thickness (mm)	0.15	0.15	0.15
Specific gravity (used powder)	1.08	1.08	1.04
Process overhead coefficient (0.6 – 0.9)	0.6	0.6	0.6
Average Power (kW)	16.8	12.5	19.6
Productivity (kg/h)	0.419	0.419	1.35
Energy (kWh/kg)	40.09	29.83	14.5

Table 3: Energy Consumption Rates [13-14]

Based on the EOSINT P760 batches of the time studies, the process productivity (kg/h) and energy consumption per kilogram (kWh/kg) are analyzed and listed in Table 4. In comparison with the data available in literature (Table 3), the EOSINT P760 has a significant lower productivity. Nevertheless, the energy consumption per kilogram is comparable.

EOSINT P760	PA2200	PA2200	PA3200GF
Layer thickness	0.12mm	0.15mm	0.15mm
Productivity (kg/h)	0.17	0.15	0.24
Energy / hour (kWh/h)	6.20	5.97	6.32
Energy / kg (kWh/kg)	36.5	39.8	26.3

Table 4: Process productivity

Consumables Study

EOSINT machine tools, considered here, are equipped with compressed air driven nitrogen generators to create the inert atmosphere. The compressed air flow rates for the different machine tool types are listed in Table 5.

	Flow Rate
EOSINT P760	20 m ³ /h
EOSINT P360	6 m ³ /h
EOSINT FORMIGA P100	10 m ³ /h

Table 5: Compressed Air Flow Rates [9]

Other SLS machine tools often use externally produced gasses (e.g. nitrogen or argon) to create the required protective atmosphere.

As indicated in the CO₂PE!-methodology [7], the total material flow (determined by the product design and equal for all processes in a comparative study) is not relevant for a Unit Process Life Cycle Inventory (UPLCI), but the generated amount of waste is process dependent and included in our study.

Despite the wide coverage of material production processes in LCI-databases, the production processes (e.g. atomisation processes) of powder materials used in SLS is still poorly documented in terms of their environmental impact.

For SLS processes, Telenko et al. [16] approximated the specific energy consumption for 1 kilogram of nylon 12 powder. The final estimate for energy use during nylon manufacture is 85 MJ/kg using a mix of electricity and energy stored in fossil fuels, however neglecting the precipitation process [16,17,18].

Based on industrial observations, half of the remainder powder of SLS is recycled. Table 6 shows the powder utilization (PU) rates based on weight and volume as well as the waste flow rates for the different combinations of material and layer thicknesses. The waste material rates around 45% fit well within the manufacturer's recommendations about the refresh rates, which is the ratio between virgin and used powder (Table 7), using a very high portion of new powder material [9,15,18].

EOSINT P760		PA2200	PA2200	PA3200GF
Layer thickness		0.12mm	0.15mm	0.15mm
#batches		63	12	11
PU	Weight	5.2%	5.9%	3.7%
	Volume	10.2%	12.2%	7.2%
Waste material (Weight Based)		44.9%	43.9%	46.4%

Table 6: Powder utilization rates [11]

Material		Refresh rate (%)
EOS GmbH [9]	PA2200	30 to 50
	PA3200GF	50 to 70
3D-Systems [15]	DuraForm	30 + (30 overflow)
	GF DuraForm	50 + (overflow)

Table 7: Recommended refresh rates [9,15]

Selective Laser Melting (SLM)

Time study

For SLM processes a time study is performed on a Concept Laser M3 Linear machine [10], using AISI 316L stainless steel (X5CrNi18-10) and a layer thickness of 30 µm. Four use modes have been identified in accordance with the process principle: preheating the process chamber and creating the inert atmosphere (always 30 minutes), exposure (i.e. selective scanning by the laser), recoating a new powder layer, and final cooling down and part/powder extraction (cleaning). Figure 5 shows the time share of the identified modes, based on a sample batch with a total production time of four hours.

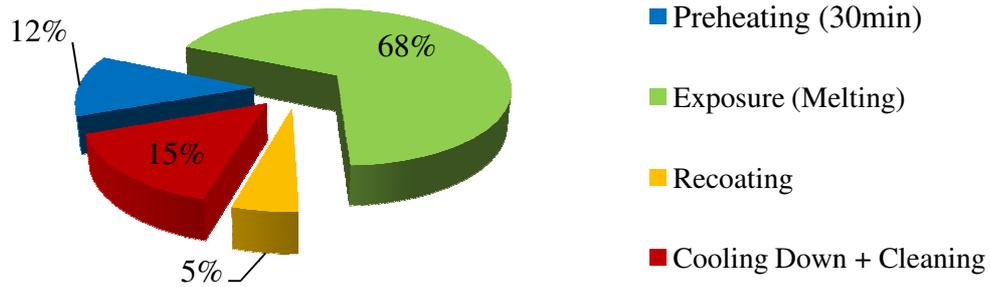


Figure 5: Share of the different modes

Power study

During the machine tool analysis of the Concept Laser M3 Linear machine [10], 8 different subsystems were identified: laser unit (including the laser cooling unit), powder dosage chamber, building platform, coater, XY-Positioning of the scanner, nitrogen circulation unit, cabinet cooling and the computer unit. During the productive modes (exposure and recoating modes), the laser source is firing continuously. Figure 6 shows the power levels for all subsystems during the productive modes. The peaks (around 3.5 kW) coincide with periods during which the recoating system (sweeper) is moving. The laser unit (2.24 kW for an output power of 100 W), is with 68% of the total machine tool power the most power consuming subunit. Table 8 lists the average machine tool power levels during all modes.

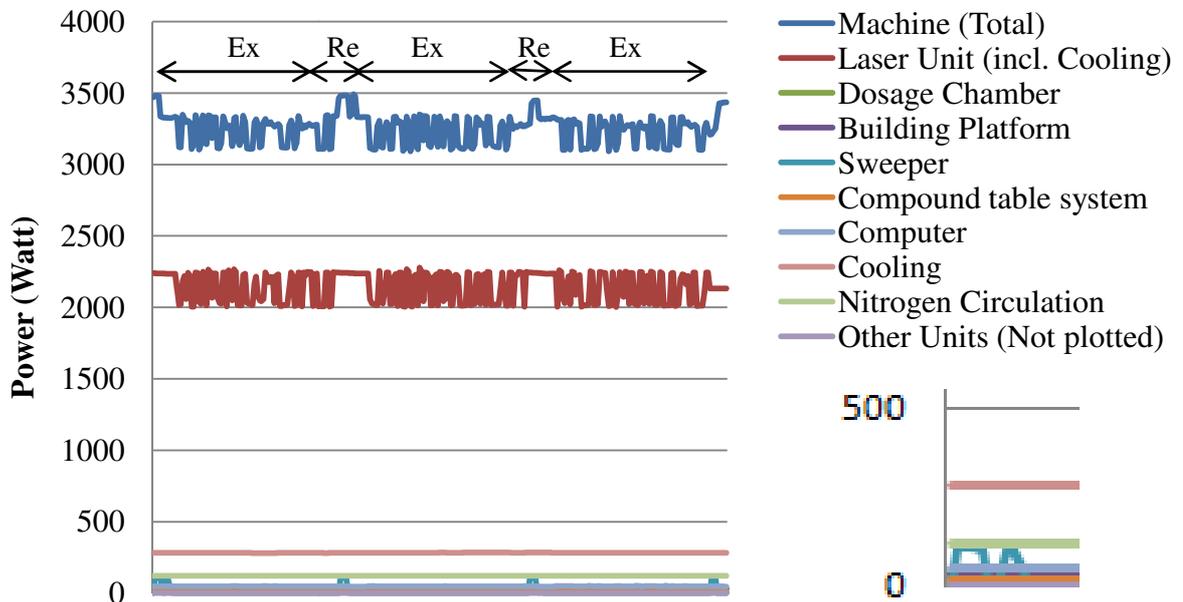


Figure 6: Power levels during productive modes of Concept Laser M3 Linear (Ex = Exposure, Re = Recoating) [11]

The energy consumption of another SLM machine tool: the EOSINT M250 Xtended [9] was analysed by Mognol et al. [12]. The average electrical powers during standby and operation mode were 2 kW and 4 kW respectively.

Concept Laser M3 Linear	Power
Preheating + Creating Inert Atmosphere	2.25 kW
Exposure (Melting)	3.25 kW
Recoating	3.45 kW
Cleaning + Product Removal	0.7 kW

Table 8: Average Power Levels

Consumables study

To avoid oxidation problems, SLM processes operate in a protective (inert) atmosphere. Since nitrogen is used to create this protective atmosphere in the process chamber of the Concept Laser M3 Linear machine for stainless steel, this should be taken into account as consumable. A pre-flushing rate of 6.5 m³/h during the start-up mode (30 min) is followed by a continuous flow rate of 3.5 m³/h of nitrogen during the actual production phase.

Morrow et al. [19] indicate the required specific energy consumption (SEC) and generated airborne emissions for direct and indirect (where powder is produced from finished metal slabs or plates) H13 steel powder production processes, as listed in Table 9.

(MJ/kg)	Atomization Process	
	Direct	Indirect
Electricity Consumption	15.90	26.86
Other Energy Consumption (e.g. fuel oil, natural gas)	1.72	5.95

Table 9: Specific Energy Consumption (SEC) [19]

It is observed that, relative to the production of steel plate (20.4 MJ/kg), the direct atomization route to producing steel powder requires approximately 20% less energy per kilogram of produced powder while the indirect atomization route to produce steel powder requires approximately 25% more energy [19].

Based on five consecutive batches (with rather small parts) of the same material (X5CrNi18-10), including one complete emptying and cleaning operation of the building platform as well as the feed container, a ratio of 20.4% was found between the weight of the waste material and the weight of the product. This means that for a product of 1 kg, 204 g waste material is created (e.g. filter residues, aerosol emissions, post processing including the EDM cut to remove the parts from the base plate).

Life Cycle Analysis (LCA)

In this section, for both SLS and SLM, a Life Cycle Analysis (LCA) of a sample batch is described in order to identify the most important contributors to the environmental impact of the processes. The impacts are calculated based on the Europe ReCiPe H/A-method [20] using the ecoinvent database [21] and expressed in millipoints (Pts). Incineration is selected as end of life (EOL) treatment for the waste powder materials. Process emissions (gaseous and aerosols) are not yet included.

Selective Laser Sintering (SLS)

The SLS case study took place on an EOSINST P760 machine tool for a sample batch of PA2200 material with a total product volume of 3.32 kg and total production time of around 15 hours. The used layer thickness is 120µm. Table 10 and Figure 7 show the environmental impact and share of the different contributors respectively.

			Impact (Pts)
Energy Consumption		120 kWh	6.34
Compressed Air Consumption		340 m ³	3.53
Waste material (PA2200)	Powder Production	10.27 kg	7.80
	End of Life Treatment		1.16

Table 10: LCA of SLS sample batch

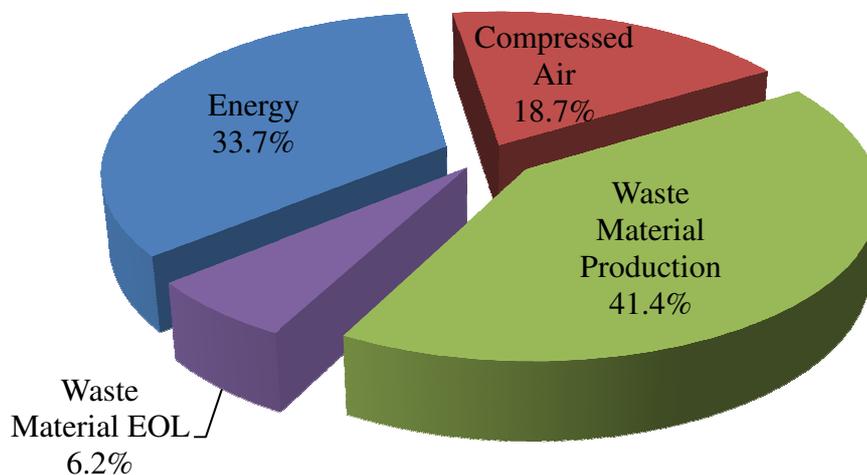


Figure 7: LCA of SLS sample batch

Selective Laser Melting (SLM)

Table 11 and Figure 8 show an overview of the environmental impact created during the production of a sample batch with a total product weight of 409 gram and a total production time of 4 hours on the Concept Laser M3 Linear machine tool.

			Impact (Pts)
Energy Consumption		11 kWh	0.581
Nitrogen Consumption		15.5 m ³	0.743
Waste material (X5CrNi18-10)	Powder Production	0.084 kg	0.042
	End of Life Treatment		0.002

Table 11: LCA of SLM sample batch

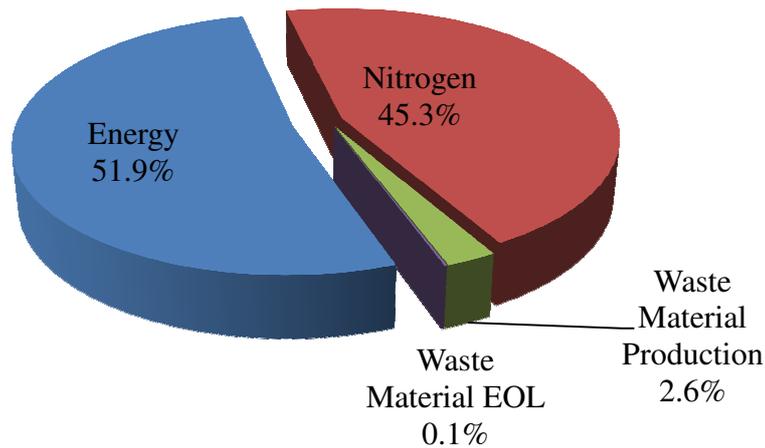


Figure 8: LCA of SLM sample batch

Of course, the relative proportions will change depending on the product (batch) size and design.

Improvement Potential

Tables 10 and 11 indicate that the environmental impacts are caused by several factors. Reduction measures for all these impact creating factors are investigated and the improvement potential for both SLS and SLM is described below.

First, the total energy consumption can be minimized by selectively switching on and off the subsystems over the different modes. For example, the EOSINT P360 and P760 machine tools have a laser cooling unit, which consume 2kW and 3kW respectively, which is active during all identified production modes, including the preheating and off-modes. Since the process heaters (e.g. process chamber heaters, frame heaters, platform heaters...) are responsible for an important part of the total energy consumption, significant energy savings can be obtained by better thermal insulation.

Another reduction measure can be found in the introduction of external cooling down cycles. By use of a second process container, the total machine time can be reduced by 2 hours (at standby power level consumption) and the residual heat of the previous build can be recovered partially.

Furthermore, the total energy consumption depends mainly on the total production time, which is a function of the build volume and height as indicated by Equation 1. Consequently, the energy consumption can be reduced by minimizing the building height of the batch, for example by optimizing the part orientation or nesting efficiency of the batch.

To create the required protective atmosphere in the process chamber, internally or externally generated nitrogen (or another inert gas) is often used. In both cases a significant environmental impact is created by the consumption of compressed air or nitrogen from the external reservoir. Besides a reduction of the total production time (e.g. nesting efficiency, build height), another reduction measure for this consumption can be found in a better sealed process chamber, so there is no longer need for continuous refilling of the process chamber.

Furthermore, and in particular for SLS, a large environmental impact is generated by the high amount of waste powder. Besides measures to increase the nesting efficiency (e.g. reduction of the building height), more optimal recycling procedures can reduce the amount of waste and related environmental impact significantly. Dotchev et al. [19] provide a practical method to collect and separate un-sintered powder. In order to control the input

material quality and use the fresh powder more efficiently, they suggest using different grades according to the melt flow rate of the recycled powder.

Finally, the impact created by almost all factors mentioned above can be reduced by a well-considered choice of the SLM/SLS equipment (e.g. optimal size of the process chamber and build container). Flexible adaptable process chambers (height, width as well as depth) and building containers can allow producing a wide variety of products (batches) on the same machine tool, limiting the created environmental impact.

Resource Efficiency of SLS on System Level

Among different available approaches, the exergy metric for discrete manufacturing processes applications has been under development throughout the last decade [22,23]. Exergy is defined by Szargut et al. [24] as “the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with the abovementioned components of nature”. Unlike energy, exergy is not conserved; thus, exergy can be destructed in a system.

As the exergy analysis in power generation and process industry systems, the exergy analysis in a discrete manufacturing system aims to detect and evaluate thermodynamic imperfection and indicate possibilities for improvement. The exergy efficiency is an important parameter in achieving these objectives. In the present study, the exergy analysis is performed for the SLS process.

First the input-output streams data need to be gathered. The exergy value for different streams is taken from Szargut et al. [24], unless stated otherwise. The specific chemical exergy value of PA2200 is based on Nylon 6 calculated by Dewulf et al. [25]. The compressed air input is fed into nitrogen generator inside the machine to produce nitrogen gas. The nitrogen is utilized to create an inert atmosphere inside the process chamber. The products, unused material and purged gases are the output of the SLS process. The summary of exergy analysis of the same build as in Table 10 is given in Table 12.

	Material	Mass (kg)	Specific Chemical Exergy (kJ/kg)	Exergy (kJ)	Total Exergy (kJ)
Input	Powder (PA 2200)	23.87	33000	787710	1280910
	Compressed air	408	150	61200	
	Electricity			432000	
Output	Product	3.33	33000	109890	829455
	Unused material	20.54	33000	677820	
	Purged gas (N ₂)	90	25.7	2313	
	Purged gas (O ₂)	318	124	39432	

Table 12: Exergy analysis of the SLS process

From the data in Table 12, the exergy efficiency of the SLS process can be calculated accordingly. Here, the degree of perfection η_p will be used as the efficiency metric [23,24,26]. It is the ratio of the useful output exergy, in this case the product exergy, to the total input exergy. Based on this definition, the calculated value of η_p is approximately 8.6%. It should be mentioned that this value disregard the possibility of material recycling, which will be treated below.

Table 12 clearly shows one of the advantages of exergy analysis compared to the more conventional energy analysis, namely the inclusion of workpiece material and consumables in the analysis. This way, the improvement potentials, which will be concluded from the analysis, will cover more domains than just energy efficiency. These other domains include process gasses and waste materials. An example of the improvement potential is the effects of material recycle in SLS process. Recycling of powder material is a standard practice for SLS processes [18]. For the specific case in this study, it is reported that approximately 50% of the remaining powder material can be recycled. An exergy diagram (Grassmann diagram) illustrating the SLS process along with material recycling is shown in Figure 9. By including the recycled material, the degree of perfection η_p increases up to 12%. Care should be taken in determining the system boundary while calculating the system efficiency. In this case, in order to show the positive effect of material recycling, only the fresh powder material is included as material input.

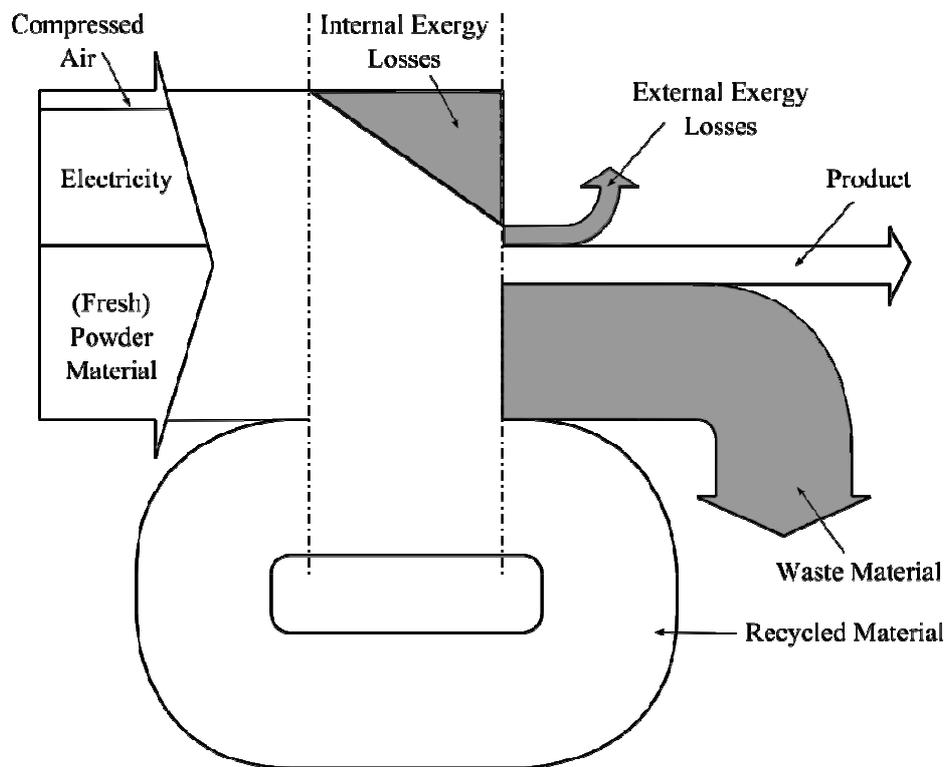


Figure 9: Exergy diagram of the SLS process

In Figure 9, the external exergy losses include the purged process gas and stray heat transfer to the surrounding, e.g. during cooling phase. The waste material is also considered as external exergy loss. Another type of exergy losses is the internal exergy losses, which are process inherent losses and can be attributed to heat and friction losses. These internal and external losses provide two different kinds of improvement potentials.

The effort to reduce internal losses can be labeled process-improvement since these measures will affect the internal process variables. For example, the application of more efficient laser sources will reduce the power consumption of the laser unit. This specific measure does not affect other variables outside the process itself. On the other hand, improvement measures over external exergy losses can be originated from the modification of variables outside the process; hence the name systems-improvement. A better nesting efficiency is one example of this type of improvement. The nesting efficiency itself is a process planning variable, not a process variable. Another example is the re-utilization of the

waste material. As proposed by Dotchev et al. [19], the degraded powder material can be reused for a trial work, for example. This measure might not increase the resource efficiency of the process but it improves the overall efficiency in the broader spatial and longer temporal scale.

Therefore, the exergy analysis provides a useful view on the resource efficiency of the SLS and SLM processes at system level. While typical energy analysis manages to illustrate different power flows inside the system, leading to a better focus on proposing energy efficiency improvement measures, the exergy analysis delineates prospective improvement potential not only from energy point of view, but also from material and consumables utilization. It also pinpoints improvement potentials which are related to systems variables, such as nesting efficiency and material recycling. Furthermore, the exergy efficiency serves as a convenient resource efficiency metric which combines the energy and material utilization.

Summary

Using the CO₂PE!-Methodology [4-5], Life Cycle Inventory (LCI) data is collected and the environmental performance regarding energy and process gas consumption as well as generated waste material of both SLM and SLS processes is investigated in this paper. Impact reducing measures are presented for the most important contributors to the environmental impact of both processes. Finally the resource efficiency of SLS processes is presented using the exergy metric. Future work will include the completion of the LCI data regarding process emissions and powder production processes.

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