Environmental analysis of SLM and SLS manufacturing 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 environmental footprint. In this paper, first a short description is offered about the CO2PE! – Initiative [1] and the methodology used to analyse manufacturing unit processes. In a second part, the energy and resource flows inventorisation and impact assessment of some sample products made by Selective Laser Melting (SLM) and Selective Laser Sintering (SLS) processes are performed.

Keywords

Selective Laser Sintering, Selective Laser Melting, Life Cycle Analysis, Life Cycle Inventory, Ecodesign

1 INTRODUCTION

Until recently, functional performance and the initial purchase price of machine tools were the main selection criteria for the purchase of new machine tools. Currently, a movement towards environmentally benign manufacturing can be observed based on 3 pillars. Besides more stringent regulatory mandates, also competitive economic advantages and proactive green behaviour are motivating factors to switch to environmentally benign manufacturing [2].

Despite the fact that manufacturing processes, as used for discrete part manufacturing, are responsible for a substantial part of the environmental impact of products, they are still poorly documented in terms of environmental footprint. On the one hand, the coverage of the wide range of manufacturing processes by LCI databases is limited. On the other hand, most of the available data on manufacturing processes in LCI databases are incomplete: their focus is often limited to theoretical energy consumptions and data on the machine tool infrastructure or on potential emissions are rarely found [3]. 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 reduction has only been targeted for a few common processes. At the same time a trend can be determined towards more energy intensive, non-conventional processing techniques [4].

2 CO2PE! – INITIATIVE

To deal with the lack of thorough environmental analysis of manufacturing processes, the CO2PE! (Cooperative Effort on Process Emissions in Manufacturing) – initiative [1] has been launched. This initiative has the objective to coordinate international efforts aiming to document and analyze the overall environmental impact for a wide range of available and emerging manufacturing processes with respect to their direct and indirect emissions, and to provide guidelines to improve these.

Recently, the initiative is officially recognized by the International Academy for Production Engineering CIRP as part of the Collaborative Working Group EREE [5] and IMS (Intelligent Manufacturing System) as Manufacturing Technology Platform (MTP) Theme [6].

Based on a systematic taxonomy of manufacturing unit processes, a worldwide data collection effort is introduced. A large number of research institutes and associated industrial partners in different continents have already joined the CO2PE!-Initiative and share the required expertise and facilities among each other. A centralized overview and coordinating effort will allow to avoid undesirable redundancy in data collection efforts and facilitate direct communication between parties with overlapping interests and expertise needs. Therefore a data-exchange platform has been launched [1] and a methodology to systematically collect, treat and distribute data is in preparation by the initiative consortium.

3 METHODOLOGY

In this section, the proposed LCA-like methodology, as shown in Figure 1, is summarized. Each of the four steps will be explained briefly in the next paragraphs.

3.1 Goal and scope definition

First the goal and scope of the study should be clearly defined and must be consistent with the intended unit process. The most important parts of the scope definition that should be considered are the system boundaries and the functional unit of the intended process. Furthermore the machine tool architecture will be investigated and all sub-processes (subunits) are identified and located within the machine tool.

3.1.1 System Boundaries

The system boundary determines which unit process shall be investigated and which sub processes (at which level of detail) of the selected unit process will be investigated individually. All included in- and outputs from techno- and ecosphere must be listed as shown in Figure 2. For our type of studies, the system boundaries are set to include only the operating phase of one isolated manufacturing unit process, disregarding materials processing, production, maintenance and disposal of the machine tool itself.

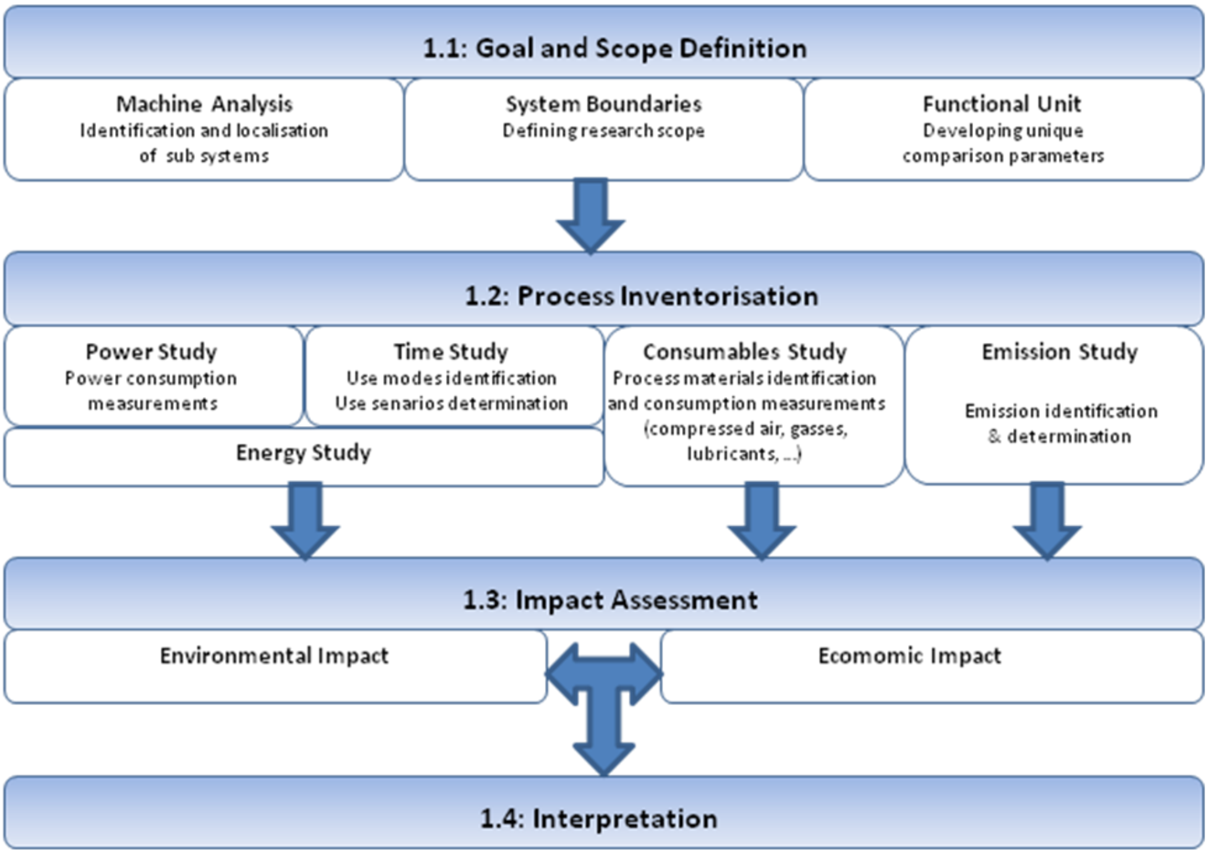

Figure 1: Methodology overview.

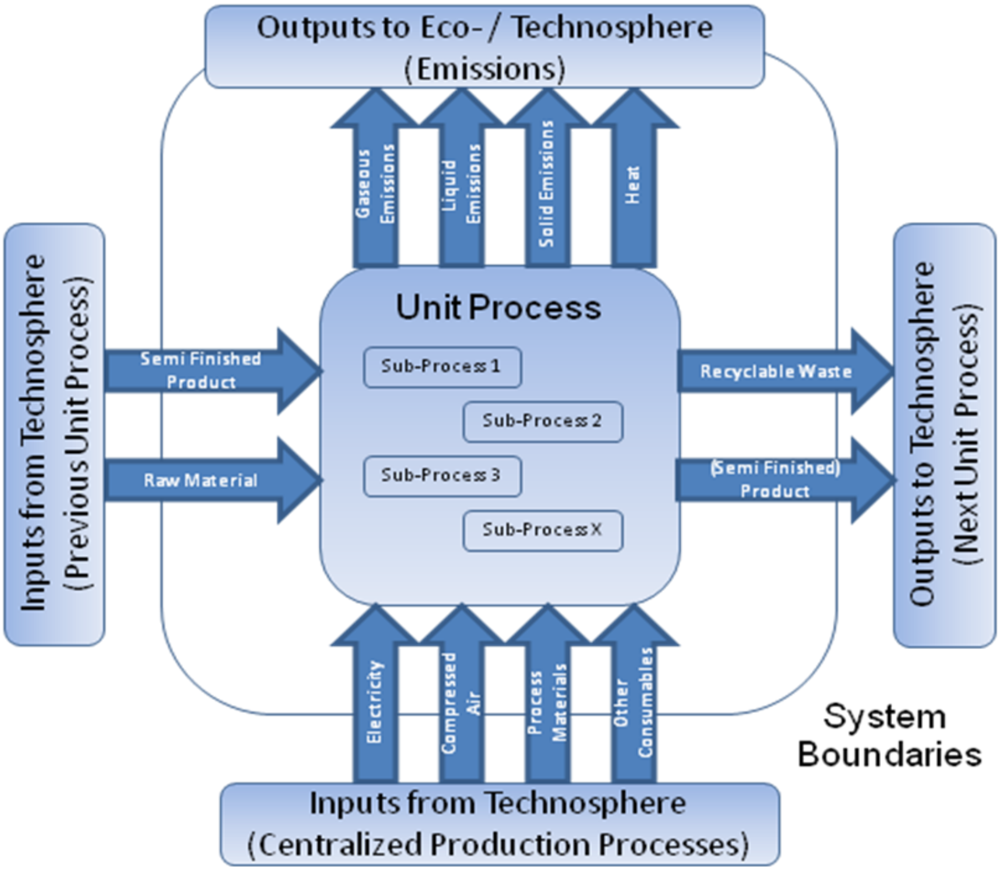

Figure 2: System boundaries.

3.1.2 Functional Unit

The most important function of a functional unit, which must be clearly defined (quantitatively as well as qualitatively) and measurable, is to provide a reference flow to which all other input and output flows of the process quantitatively relate. Therefore, a unit time of active processing under a specified operational load, including energy and resource consumption in productive as well as non-productive modes, is preferable.

3.1.3 Machine Analysis

Finally, the machine tool architecture is investigated before an inventarisation of all selected mass and energy flows through the machine tool takes place. The typical use scenarios of the machine tool are considered and the energy and resource consuming units as well as the emission generating sub processes of the machine tool under investigation will be identified together with their functionality and location

3.2 Process inventorisation

As shown in Figure 3, the process inventarisation includes a time, power, consumables as well as an emission study. Data needed depend on the goal and scope of the study, and may include a mixture of measured, calculated or estimated data.

3.2.1 Time study

During the first step of the process inventarisation, time studies are performed in order to identify the different use modes of a machine tool and their respective share in the covered time span. The identified time modes start from the machine tool start-up, over the use phase to finally switching off the machine, but are determined for periods of full machine occupancy (no idle time due to a lack of orders).

3.2.2 Power study

The energy consumption of the machine tool is obtained by measuring the power consumption over a specified time period. By measuring individual power consumption patterns for all relevant active energy consuming units (ECU's) in each mode, energy and corresponding ecological footprint optimization potential can be identified.

3.2.3 Consumable study

Parallel to the time and power measurements the flow of consumables is measured for each process material (consumable) in each production mode. In this study, the consumption of process materials (inputs from the technosphere) such as compressed air, lubricants, process gasses (N2, O2,…), process filters, … are investigated. Despite the raw-material flow is not relevant for a unit process study, the created amount of waste is process depending and included as consumable.

3.2.4 Emission study

Finally, also an emission study takes place where relevant (e.g. mass balance showed abnormalities, nature of the used substances,…). This study could include gaseous, liquid, solid as well as heat emissions.

3.3 Impact assessment

By combining the results of all previous studies, the energy and resource consumption pattern of the involved process (machine tool) is determined. The environmental as well as economic aspect of these consumption patterns are analyzed in this step.

3.4 Interpretation

After analyzing the energy and resource consumption patterns, the interpretation of the results takes place. Based on peak as well as operating energy and resource consumptions as well as produced emissions during each production mode, environmental and economic optimizing opportunities could be identified and further investigated by machine builders.

4 SLM / SLS - CASE STUDIES

In the first part of this section, the functioning principle of Selective Laser Melting (SLM) and Selective Laser Sintering (SLS) will be briefly explained. Further on the general approach, as described in Section 3, is applied in two case studies, respectively for an SLS and an SLM machine tool.

SLS and SLM are additive fabrication techniques that allow generating complex 3D parts by selectively consolidating successive layers of powder material on top of each other, using the thermal energy supplied by a focused and computer controlled laser beam [7,8]. Different binding mechanisms can be responsible for the consolidation of the powder such as: solid state sintering, liquid phase sintering, partial melting or full melting [9].

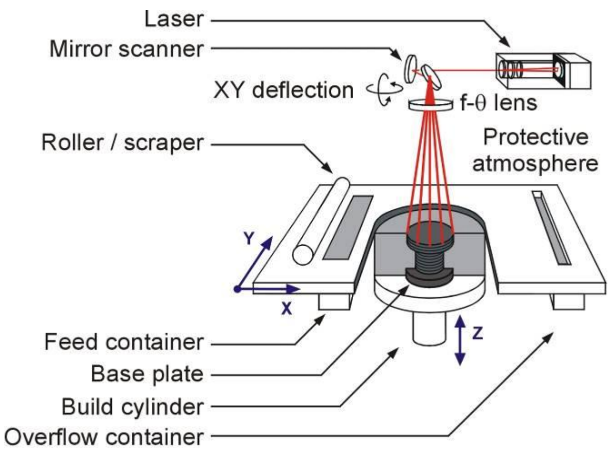

Figure 3:Functioning principle of SLS/SLM processes [10].

As depicted in Figure 3, the main components of an SLM machine tool are a laser source, a scanning system, a building platform (or build cylinder) where the part is generated, a feed container where the powder is stored and a roller/coater to lay a powder layer homogenously on the already solidified layer. Depending on the machine tool configuration, there may be two feed containers; one at each side. After a powder layer is laid on the base plate where the component is produced, the laser beam selectively scans the powder bed tracing the layer geometry. Then the build cylinder is lowered with an amount equal to the pre-specified layer thickness. The coater puts a new layer of powder and the laser scans the new slice. This process continues until the part is completely produced by SLM/SLS.

Afterwards, the component is removed from the base plate and cleaned. Often a post-processing step is applied to the component for different purposes depending on whether the process was SLS or SLM. For SLM, sand blasting and ultrasonic filing can be easily employed as post-processing techniques to remove the loosely sticking powders on the outside of the part whereas more post-processing steps are required for SLS parts.

4.1 CASE STUDY 1: Selective Laser Melting (SLM)

The first case study is performed on a Concept Laser M3 Linear machine (Figure 4), using 316L stainless steel (X5CrNi18-10) and a layer thickness of 30 µm.

Figure 4: Concept-Laser M3 Linear [11].

4.1.1 Goal and scope definition

For this case study, the system boundaries and functional unit are set as described in section 3.1.1 and 3.1.2 respectively.

During the machine analysis, 8 different subsystems were identified: laser unit (including the laser cooling unit), powder dosage chamber, building platform, coater, compound table system, nitrogen circulation unit, cabinet cooling and the computer unit. During the inventarisation step, the energy and resource consumption of all these subunits are investigated during each different production mode. Furthermore, the emission study is performed.

4.1.2 Process inventorisation

As described in the methodology section, the process inventarisation starts with a time study of the process, in which all different production modes and their share in the total production time are determined. The identified different modes are listed in table 1. The share of each mode is based on a sample batch with a total production time of 4 hours.

Nr:	Production mode	%
1	*Start-up:* pre-heating and generation of an inert atmosphere (nitrogen).	12
2	*Melting*: the laser is melting powder particles or moving the scan head.	68
3	*Sweeping*: a new layer is deposited.	5
4	*Product removing + Machine tool cleaning*	15

Table 1: Production modes.

Besides the time study, also an energy, consumable and emission study were performed. Figure 5 shows the power consumption at machine tool level as well as at subunit level during the production of 3 layers.

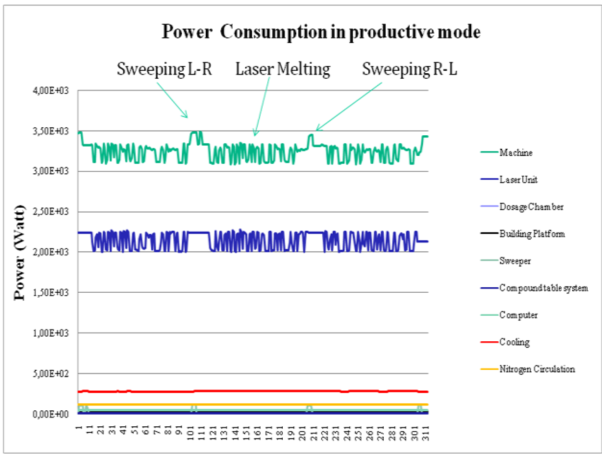

Figure 5: Power consumption during 3 layers.

As expected, the laser unit (2.24 kW for an output power of 100W), is with 68% the most energy consuming subunit. Furthermore, the cabinet cooling (282W) and nitrogen circulation (122W) are the most important consumers. Taking into account the energy consumption during the start-up mode (1.125 kWh) and product removal and machine tool cleaning mode (0.4 kWh), the share of all different modes in the total energy consumption (11 kWh) of the sample batch is shown in Figure 6.

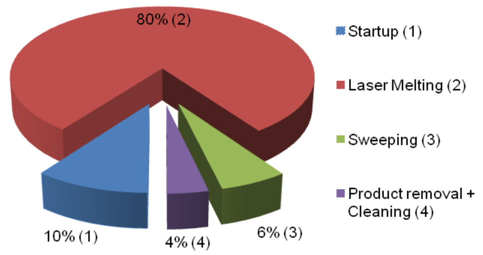

Figure 6: Energy consumption during productive mode.

Since nitrogen is used to create an inert atmosphere in the process chamber, this should be taken into account as consumable. A pre-flushing rate of 6.5 m³/h during the start-up mode (30 minutes) is followed by a continuous flow rate of 3.5 m³/h of nitrogen during the actual production phase.

Another so called consumable is the created waste material. Based on a test case of 5 consecutive batches (with rather small parts) of the same material (X5CrNi18-10) and 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.

For the emission study, we used data of the Laser Safety database of the Laser Zentrum Hannover e.V. [12].

4.1.3 Environmental impact assessment

Table 2 shows an overview of all environmental impacts created during the production of the sample batch with a weight of 409 gram and a total production time of 4 hours. The impacts are calculated based on the eco-indicator99 (H,A) method using the ecoinvent database and expressed in millipoints (mPts) [13,14].

		Impact (mPts)	%
Energy	11 kWh	286.6	41.6
Process Gas (N_2)	15.5 m³	308.3	44.8
Waste Material	0,084 kg	93.9	13.6
Emissions	1.3 mg NO_2 1.6 mg NO 3.3 mg Aerosols	~0	~0
Total		**688.9**	

Table 2: Overview ecological impacts [13,14].

4.2 CASE STUDY 2: Selective Laser Sintering (SLS)

The second case study took place on four EOSINST P760 machine tools, which uses a double-laser system (2x50W) for plastic laser-sintering [15].

Figure 7: EOS P760 Machine Tool [15].

4.2.1 Goal and scope definition

Also for this case study, the system boundaries and functional unit are set as described in section 3.1.1 and 3.1.2 respectively.

During the machine analysis, 10 different subsystems were identified: heating (process chamber heating + frame heating + bottom heating), laser unit, laser cooling unit, scanners, servos (e.g. coater, ...), Machine tool lightning, machine tool cooling (e.g. cabinet cooling, ...), lens heating, computer unit and the 24-voltage units.

4.2.2 Process inventarisation

Again, we started with a time study in which we studied 81 batches (more than 6500 products with an average exposure volume of 25.8 cm³) of fine polyamide PA2200 powder [16] and a layer thickness of 12 µm. As shown in Figure 8, 11.5% of the total machine time is spent on non-productive modes: machine tool cleaning (25 minutes, 1.1%), preheating (2 hours, 5.2%) and cooling down (2 hours, 5.2%). Also the productive modes could be subdivided into 3 major modes: the laser exposure mode (29%), the recoating mode (56%) and some other activities like filling the feed containers (3.6%).

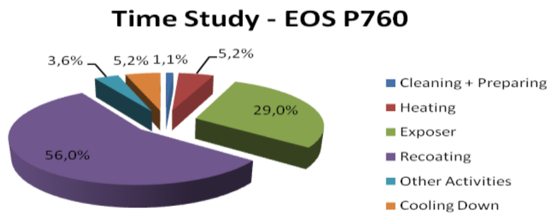

Figure 8: Production modes.

Table 3 shows the average power consumption for the total machine tool as well as for each subunit individually. Besides the heating units, the laser cooling unit is the most important consumer with a constant power of 3 kW during all modes. Figure 10 shows the energy distribution during the production phase of a sample batch of 16 products (8 small and 8 large, shown in Figure 9) with a total volume of 3598 cm³ (3.33 kg) and production time of 15 hours and 1 minute (total = 120 kWh).

Figure 9: Products of sample batch.

Power (kW)	**Standby (e.g. Cleaning)**	**Heating**	**Production**	**Cooling Down**
Heating Units (Process Chamber + Frame + Bottom)	-	4.7	2.5	-
Laser Unit	-	0.08	0.2 (0.15 -> 0.60)	0.08
Laser Cooling Unit	2.97	2.97	2.97	2.97
Servos (e.g. Sweeper)	0.12	0.11	0.20 (0.14 -> 0.24)	0.11
Scanners (Right + Left)	0.02	0.02	0.04	0.02
Machine Tool Lighting	0.06	0.06	0.06	-
Machine Tool Cooling (e.g. cabinet)	0.06	0.06	0.06	0.06
Lens Heating	0.05	0.05	0.05	0.05
Computer Unit	0.06	0.08	0.08	0.06
24-Volt Supply	0.13	0.15	0.13	0.15
Total Machine Tool	**3.52**	**8.28** **Peak >11.8**	**6.31**	**3.52**

Table 3: Average power consumptions for all subunits during each mode.

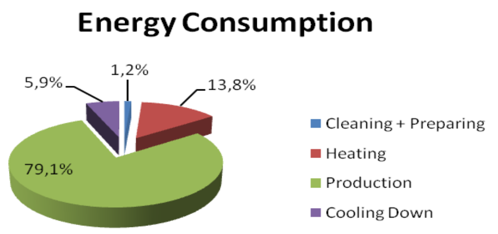

Figure 10: Energy distribution of sample batch.

EOSINT P 760 machine tools create an inert atmosphere (nitrogen) using air compressors with a constant compressed air flow rate of 20 m³/h at 6 bar [15], and based on industrial observations, half of the remainder powder (PA 2200) can be recycled. Data about air emissions is not yet available.

4.2.3 Environmental impact assessment

Based on the data collected during the process inventarisation (section 4.2.2), Table 4 shows the most important impact creating factors for our sample batch. All impacts are calculated based on the eco-indicator99 (H,A) method using the ecoinvent database and expressed in millipoints (mPts) [13,14].

		Impact (mPts)	**%**
Energy	120 kWh	3120	32.1
Compressed air	340 m³	1598	16.5
Waste Material	10.3 kg	4998	51.4
Total		**9716**	

Table 4: Overview of environmental impacts created during the production of our sample batch [13,14].

These results are in contrast with the assumed low amounts of waste for this type of processes. (Due to economic reasons?). Consequently, the environmental impact created during the production phase of our sample batch is six times higher than the corresponding impacts during the mining and production phases of the raw material (3.3kg, 1601 mPts).

5 SUMMARY

Based on the methodology summarized in section 3, the environmental performance of a SLM and SLS machine tool is investigated in this paper. It is shown that the environmental process impacts are higher than those created during the exploration and production of the raw materials, and therefore not negligible as was (is) often assumed in LCA-studies. Impact reducing measures can be found in various domains: electricity, process gasses, waste materials, ...

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