Sustainability Study in Selective Laser Sintering – An Energy Perspective

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Abstract

This paper presents a sustainability analysis of Selective Laser Sintering (SLS) from an energy standpoint. Data of electrical power consumed by the system over an entire build were acquired using a LabVIEW 8.6 circuit. The power drawn by individual subsystems were also measured, and an energy balance was performed. These data were then used to arrive at a Total Energy Indicator of the process with the help of a specific type of Environmental and Resource Management Data (ERMD) known as Eco-Indicators, which indicates the level of sustainability of the process.

1. Introduction

Sustainability is defined as a measure of degree with which the material and social conditions for human health and the environment are maintained or improved over time without exceeding the ecological capabilities that support them. Sustainability is usually thought of as the goal and sustainable development, a means to achieve it. According to United Nations' World Commission on Environment and Development in their report "Our Common Future", 1987, sustainable development is defined as that which meets the needs of the present generation without compromising the needs of future generations [1].

Sustainability centers on global conditions of ecology (i.e., environment), economic development (i.e., by technologies), and societal equity as illustrated in Figure 1. Engineering processes generally occupy the economic development portion of the spectrum. With respect to a manufacturing process, the two driving factors of economic development are material and energy consumption. Therefore the main purpose of a sustainability study in a manufacturing process is to restrain material and non-renewable energy consumption [2].

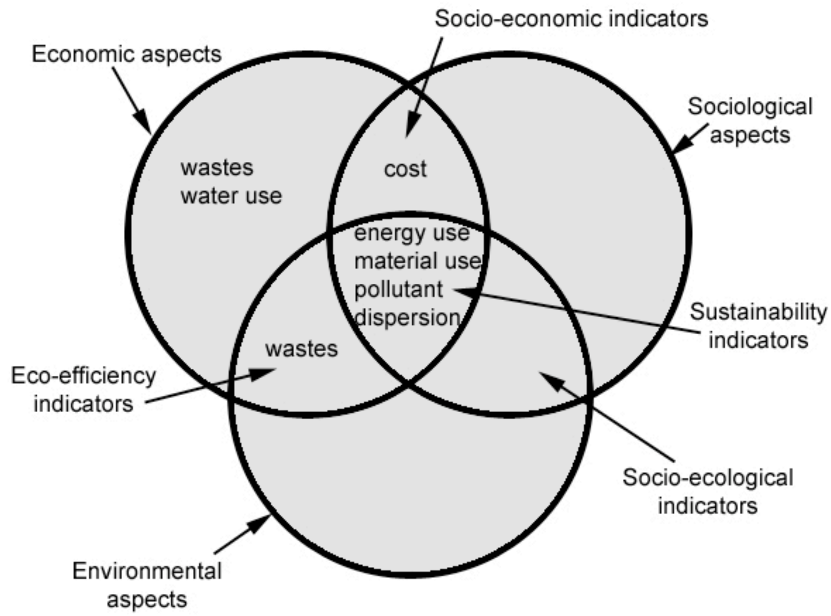

Figure 1. Three intersecting circles to illustrate sustainability [2]

Solid Freeform Fabrication (SFF) processes have experienced tremendous growth and development since their introduction in the mid 1980s. SFF has evolved and is generally considered to be both a manufacturing process and a prototyping process. Therefore it is reasonable to analyze and study the sustainability aspects of SFF. There has not been much research done in this regard and the literature on this topic is fairly limited [3]. In general, SFF processes possess good environmental characteristics. The waste streams are much less in SFF processes than in conventional manufacturing processes such as machining or molding. Worn tools and scrap can be minimal in SFF. Cutting fluids, which are the major source of hazard in the manufacturing waste stream, are not required in SFF processes. However compared to conventional manufacturing processes, SFF processes have their distinguishing features in terms of materials, functionality, quality, system complexity, operating style and so on. It is still necessary to understand the essence of these processes, apply a systematical method to evaluate their environmental property, and derive quantitative assessment of environmental performance for different SFF processes [3].

Materials and energy consumption are the governing factors of sustainability in a manufacturing process. In a powder-based SFF system such as Selective Laser Sintering (SLS), the focus of this research, the scrap rate is usually very low. Therefore it would be more pertinent to analyze the energy consumption to evaluate the sustainability of the process.

The bulk of the energy consumption in a manufacturing process, almost 80%, occurs in the material refining/production process [8]. This paper deals with a sustainability study of SLS using Nylon-12 as the material. Energy consumption during the process is targeted without regard to the refining/material production stage.

2. Experimental Setup

The SFF machine used in this research was an SLS Vanguard™ HiQ+HS machine. The material used for the experiments was commercially available DuraForm® PA (Nylon-12). Two “full chamber build” prosthetic parts were built in this experiment. The machine was operated with the following parameters: the laser scan speed was 10 m/s; the powder layer thickness was 0.15 mm; the power of the laser used was 50 W. The warm up height was 12.7 mm; the build height was 340 mm; the cool down height was 2.5 mm. All the four heater zones were initially set at 100^o C. The part heater had a build zone temperature of 186^o C, and the right feed heater and left feed heater were set to 142^o C. The part cylinder heater zone had the lowest build zone temperature of 138^o C. The cool down zone temperature of both the feed heaters was 45^o C, whereas the part heaters had a temperature of 60^o C.

The major power drains of the SLS Vanguard™ HiQ are represented in Figure 2.

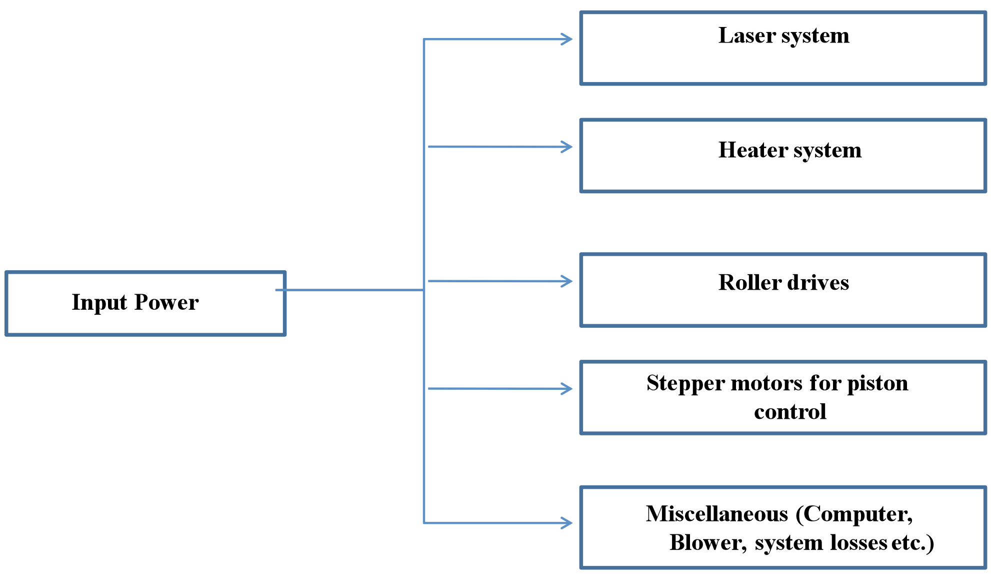

Figure 2. Power drains of the SLS Vanguard™ HiQ+HS Machine

Three single phase clamp-on ammeters were used to measure the currents flowing across the input electrical connections to the three-phase ac machine. A LabVIEW circuit was designed to acquire the power data over lengths of time from the start to the end of the build. A NI-DAQ USB 6251 device was used as the DAQ (Data Acquisition) interface to gather the data. The sampling frequency was set in such a way that data were collected every two minutes from the start to the end of the build. This enabled acquisition of enough data to observe the trends in power consumption during the various stages of the process. The same method was used to measure the power consumption of individual subsystems.

3. Results and Discussion

3.1. Power Measurement

The total power input to the machine was calculated across the three phases of the connection. The results are shown in Figure 3.

The average values of current flowing across the three phases were measured to be 51 A, 47.99 A and 45.6 A. The line voltage (V_L) of the system was 235 V. Therefore, the power, P of the system can be calculated as follows [4]

$$P = (V_L/\sqrt{3}) * (I_1+I_2+I_3)$$

where I_1, I_2 and I_3 are the currents flowing in phase 1, phase 2 and phase 3 respectively. The power was calculated to be 19.6 kW. However this is the average power value obtained during the entire build. The original power values were found to vary from 12 kW to 24 kW as shown in Figure 3. These fluctuations were attributed to individual components of the system that switch on and off at various stages during the build process.

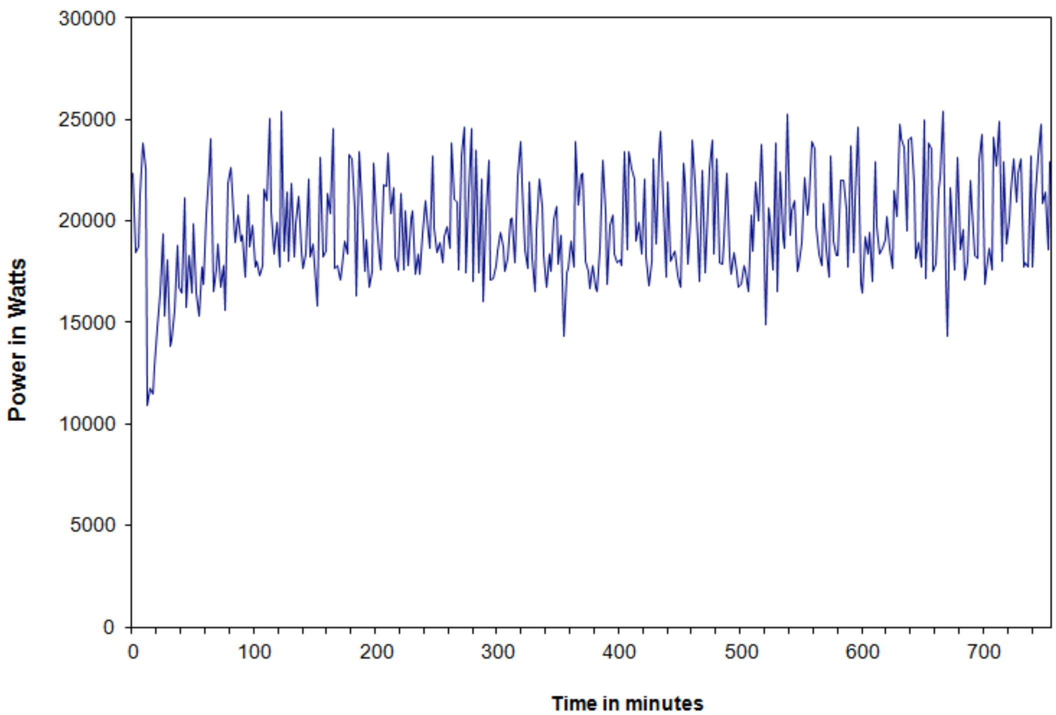

Figure 3. Power consumption (Watts) of SLS Vanguard™ HiQ over the entire build.

The power drawn by various sinterstation components was also measured and computed. The heater system which was used for heating the powder bed was the largest accumulator of electricity draw, followed by the stepper motor system which controls the piston motion of the powder bed, then the roller system which spreads the powder across the bed, and finally the laser system. The difference between the total power consumption and the power acquired by these four individual components was attributed as unaccounted losses which included the computer interface, the blower system, etc. The approximate values of power consumed by the individual components are given in Figure 4.

Heating, which normally is considered a power intensive process, is done by four heater systems in an SLS Vanguard™ HiQ machine. Therefore the power consumed by the heater zones accounted for a significant portion of the total power consumed by the machine. The high power consumption of the stepper motor system was attributed to the reciprocating action in lifting heavy loads of powder on the feed cylinders. The efficiency of laser was approximately 5% and hence the power consumption by it accounted for 16% of the overall consumption.

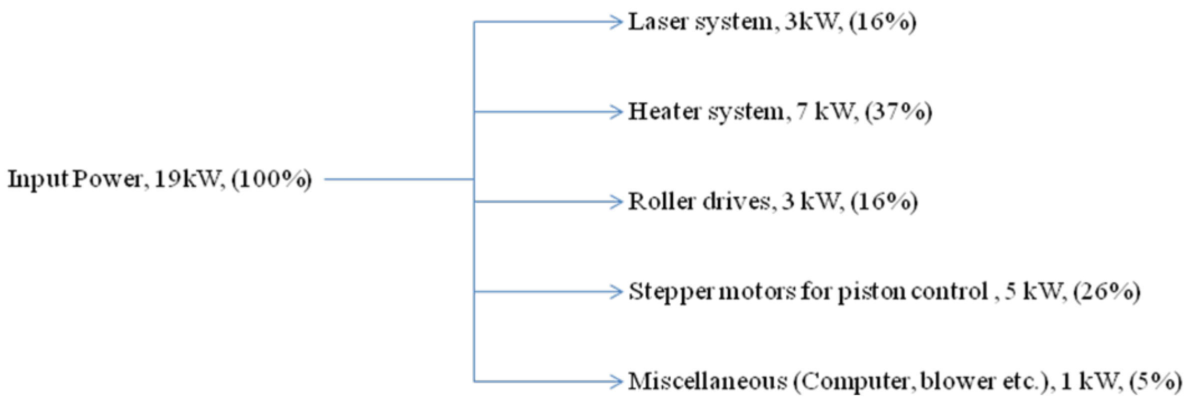

Figure 4. Power drawn by individual components

3.2. Sustainability Analysis

To perform a sustainability analysis to determine the total energy factor, unambiguous measures of environmental impact for certain materials, energy, etc. are needed. Environmental and Resource Management Data (ERMD) define what the environment actually is and how to quantify the consequences of impairment of the environment. In this study, the ERMD data, Eco-indicator, collected and calculated by PRe Consultants of Netherlands [5] were used. The higher the indicator, the greater is the environmental impact. The eco-indicator for a certain material or a process can be obtained as follows. First, inventory of all environmental effects and damages are made. Then a normalization is applied to obtain some equivalent effects. Finally weighting factors are used to scale the effects. Setting equivalents and weighting factors are subjective choices.

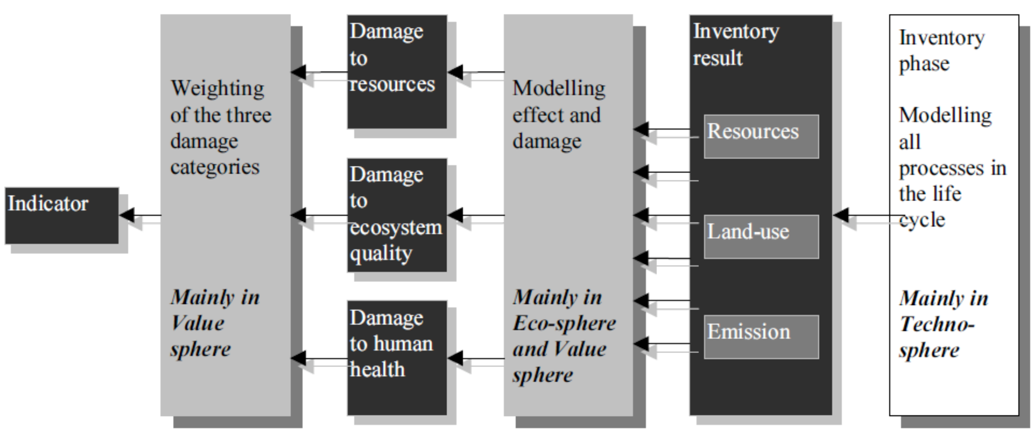

Figure 5. Principle of Eco-indicator [6]

Leo, et al. [3] devised a process model to compare the total energy factors of several SFF processes. The ERMD data, the Eco-indicator, were employed to provide quantitative measures for the total energy consumed during the process.

For the analysis, the following process parameters were used: V, scanning speed (mm/s); W, road width size (mm); T, layer thickness (mm); ρ, material density (kg/mm3); P, power rate (kW); and k, process overhead coefficient (0.6-0.9).

The Process Productivity (PP) and the Energy Consumption Rate (ECR) may be determined according to the principle of layered fabrication as

$$PP\ (kgh) = V \times W \times T \times \rho \times 3600 \times k$$

and

$$ECR\ (kWhr/kg) = \text{Power rate} / \text{Process Productivity}$$

3.3. SLS Total Energy Indicator:

The total energy indicator was obtained by the product of ECR and Eco-Indicator for electricity which is 0.57 [4]. The specific gravity of Nylon-12 was taken as 1.04.

Table 1 shows the total energy indicator of SLS Vanguard™ HiQ. The overhead factor was taken as 0.6 [3]

Parameters	**SLS Vanguard™ HiQ**
V (mm/s)	10000
W	0.4
T	0.15
Specific gravity	1.04
K	0.6
P (kW)	19.6
Process productivity(kg/hr)	1.35
Energy consumed rate (kWhr/kg)	14.5
Eco-indicator (/kWhr)	0.57
Total Energy Indicator	**8.275**

Table 1. Sustainability Analysis of SLS Vanguard™ HiQ

The Total Energy Indicator value for the SLS Vanguard™ HiQ sinterstation with Nylon-12 was calculated to be approximately 8 which compared competitively with that of SLA 5000 and FDM 1650 [3].

4. Conclusions

Sustainability considerations, specifically power consumption, were applied to Selective Laser Sintering, an additive manufacturing process. For a Nylon-12 full chamber build, the average total power consumption in a 3D Systems Vanguard™ HiQ+HS sinterstation was 19.6 kW. Most of the energy was consumed by the chamber heaters (37%), followed by the stepper motors for the piston control (26%), the roller drives (16%) and the laser (16%). The Total Energy Indicator was approximately 8 which is competitive with other additive manufacturing processes. Energy savings for SLS are best achieved by operating the build process at room temperature, although for materials such as Nylon-12, part integrity will suffer. Overall, SLS holds promise from a sustainability perspective due to its low energy consumption, favorable Total Energy Indicator, minimal creation of waste products and low material scrap rate.

5. Acknowledgement

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