A Comparative Evaluation of Energy Consumption of Selective Laser Sintering and Injection Molding of Nylon Parts

Cassandra Telenko and Carolyn Conner Seepersad
Mechanical Engineering Department
The University of Texas at Austin
Austin, TX

Additive manufacturing is often advocated as a sustainable alternative to competing manufacturing technologies. This research study focuses on estimating and comparing the energy consumption required for different production volumes of nylon parts using either selective laser sintering (SLS) or injection molding (IM). For IM & SLS, energy consumption is estimated for nylon material refinement and part fabrication. For IM, energy consumption is also estimated for manufacturing the injection molds and refining their metal feedstock. A paintball gun handle serves as a representative part for calculating and normalizing material flows and processing times. For different sets of assumptions, cross-over production volumes are calculated, at which the per-part energy consumption of the two processes is equivalent. These energy-based cross-over production volumes are compared to similar economic cross-over production volumes available in the literature.

1. Introduction

Selective laser sintering (SLS) is a prominent technology for additive manufacturing (AM) of functional parts. SLS and competing AM technologies are generally assumed to be more environmentally sustainable than conventional manufacturing methods because the additive process minimizes tooling, material waste, and chemical fluids. Quantitative support for many of these hypotheses is not publicly available (Drizo and Pegna, 2006); accordingly, a 2009 NSF-sponsored workshop identified multiple research needs relating to sustainability, including material performance data, measures of process sustainability, and comparisons with other manufacturing methods (Bourell *et al.*, 2009). The research presented in this paper addresses some of these challenges by evaluating the energy consumption required to fabricate nylon parts using SLS and comparing it with that required for injection molding (IM) the same parts.

Estimates of energy consumption are obtained from life cycle inventories (LCIs) of SLS and IM. An LCI is an important part of life cycle analysis (LCA), an accepted method for quantifying the environmental impacts of a product or process throughout its life cycle (ISO, 1997). A traditional product life cycle, shown in Figure 1, starts with procurement of materials from the earth and ends with return of materials to the environment or re-processing plant. In the context of the life cycle, an LCI entails tracking the flows of energy and/or materials between a technical system and its surroundings. In this research, LCI data are collected and evaluated for energy consumption during two stages of the SLS and IM life cycles: material refinement and part fabrication. Specifically, energy consumption is estimated for refinement of nylon feedstock material, use of SLS and IM equipment for part fabrication, and fabrication of an injection mold for a representative part.

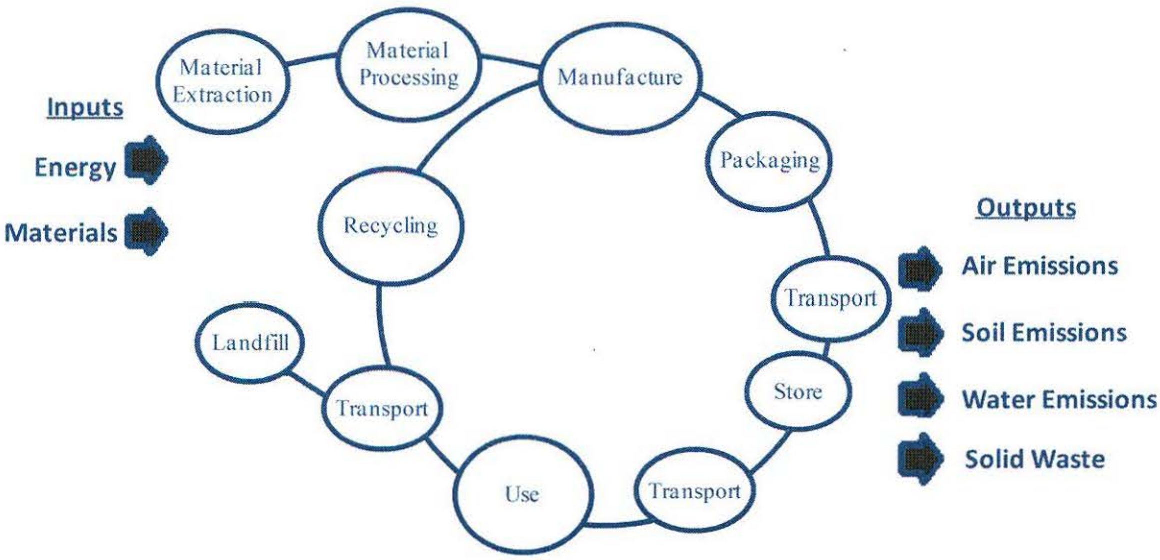


Figure 1: Inputs, outputs and processes included in a product's life cycle

A comparative study of SLS and IM is interesting because several differences between SLS and IM manufacturing systems affect their energy consumption. An SLS machine consumes a significant amount of energy while fabricating parts, but SLS does not require tooling. IM machines consume less energy while fabricating parts, but IM requires metal molds. These metal molds require significant amounts of energy investment as a result of the metal feedstock and machining operations used to fabricate the mold. For both IM and SLS, the energy consumed per part depends on the number of parts fabricated. IM requires large numbers of parts to justify the investment in the mold. SLS energy consumption per part depends on the density of its build and related factors such as part orientation. All of these factors are considered in this study.

Previous work has included quantification of the material and energy use of laser sintering (Luo *et al.*, 1999; Mognol *et al.*, 2006; Kellens *et al.*, 2010; Sreenivasan and Bourell, 2009; Baumers *et al.*, 2010; Dotchev and Yusssof, 2009), IM (Thiriez and Gutowski, 2006), and die manufacture (Dalquist and Gutowski, 2004; Morrow *et al.*, 2007), but SLS and IM have not been systematically compared in an LCI. Hopkinson and Dickens (2003; 2006) and Atzeni *et al.* (2010) compared the monetary costs of SLS and IM, but not the energy costs. Morrow *et al.* (2007) compared the energy consumption for machining and Direct Metal Deposition of a simple steel die, but they did not consider the significant material refinement costs of metals (Dahmus and Gutowski, 2004) nor did they consider IM or SLS processes. The goal of this paper is to build from these findings and create a comparative study of IM and SLS energy requirements for material refinement, tooling, and nylon part production. The scope of the study is defined in Section 2, followed by the details of the LCI in Section 3 and the results in Section 4.

2. Goal and Scope of the Life Cycle Inventory (LCI)

The goal of this study is to understand whether SLS is more energy efficient than IM, and if so, under what circumstances and for what production volumes. The scope of this study is limited to material refinement and part fabrication stages of the life cycle of a functional nylon part. Specifically, the scope is limited to evaluating the energy consumed for refining nylon feedstock, fabricating parts with SLS and IM equipment, and fabricating injection molds for IM. These processes and corresponding reference flows are depicted in Figures 2 and 3. This energy study does not include packaging, storage, transportation, or use of the functional part; nor does it include recycling of the functional part, treatment of waste streams from the material refinement or part fabrication stages, or the energy consumption of the infrastructure (e.g., climate control) surrounding the SLS or IM machines. Parts are assumed to be fabricated from nylon on a 3DSystems® Sinterstation® HiQ™ + HiS™ SLS machine.

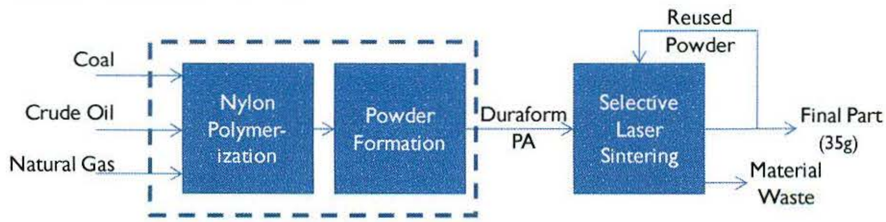


Figure 2: The scope and reference flows of the SLS LCI

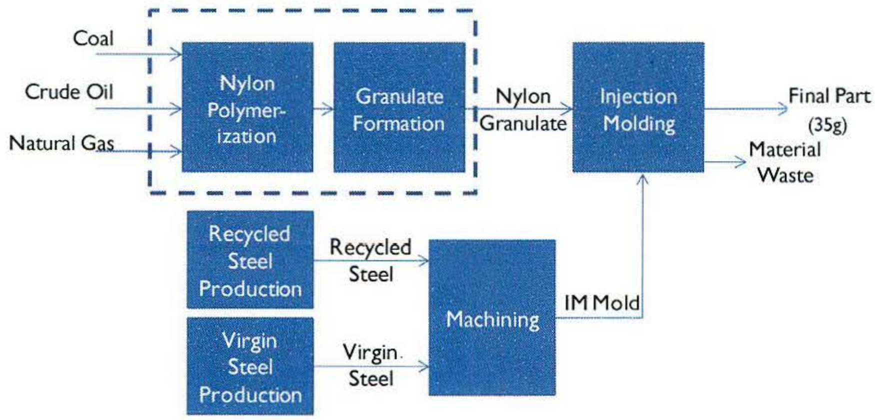


Figure 3: The scope and reference flows for the IM LCI

A representative part was selected as the basis for the functional unit of the LCI. As shown in Figure 4, the representative part is a paintball gun handle created by undergraduate and graduate students in a Solid Freeform Fabrication course taught by one of the authors (Bazan *et al.*, 2009). As shown in Figure 4, the part is created in two halves and encloses the metal frame of a paintball gun handle. This part was selected for its moderate size and complexity and suitability for additive manufacturing. For example, using 3D scans of molds of customers' hands, form-fitting grips could be added to the handles, along with personalized names or insignia. In this study, however, the part is assumed to be mass-produced so that only one injection mold must be designed and fabricated.

The functional unit used in the LCI is the number of representative parts manufactured, also referred to as the production volume. The handles are small enough, approximately 3.2cm by 2.54cm by 12.7cm per half, that a single 3DSystems® Sinterstation® HiQ™ + HiS™ SLS machine could produce 300 halves or 150 units within the machine's build volume of 381mm(W) by 330 mm (D) by 457mm (H). This estimate allows for 12.7 mm of spacing around the edges of the build chamber. The spacing between halves is assumed to be 2.54 mm on all sides, with each half oriented with its longest dimension parallel to the height axis of the build chamber to increase packing density. In this configuration, 50 units (or 100 halves) can be fabricated in a single row, approximately 130 mm high, in the SLS build chamber, with 3 rows constituting a full build of 150 units. A small or partial build is defined as a single row of 50 units.

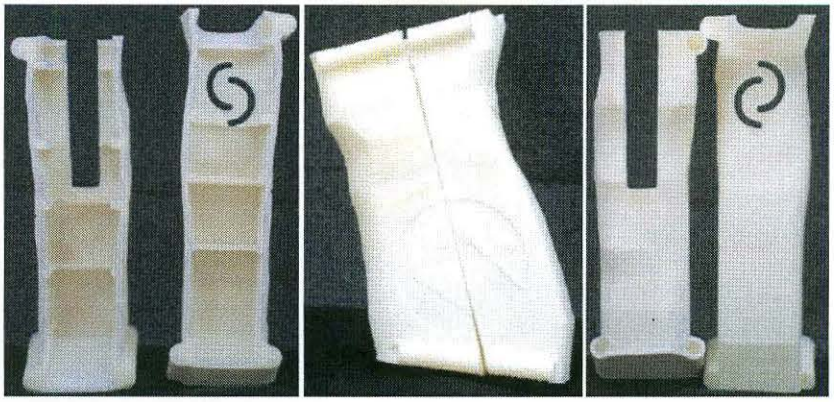


Figure 4: The paintball gun handle consists of two halves per part

3. Life Cycle Inventory Methodology

Based on the assumptions described in Section 2, an LCI is performed for SLS and IM. The total energy consumed by each process is quantified by Equations 1 and 2:

$$E_{AM} = E_{nylon} + E_{SLS} \qquad (1)$$

$$E_{IM} = E_{metal} + E_{machining} + E_{nylon} + E_{M} \qquad (2)$$

where E_{AM} denotes the total energy required to create SLS parts; E_{nylon} denotes the energy consumed during the processing of nylon feedstock for the final part; E_{SLS} denotes the energy consumed by the SLS unit manufacturing process; E_{IM} denotes the total energy required to create IM parts; E_{metal} denotes the energy consumed during the processing of steel or aluminum feedstock for the injection molds; $E_{machining}$ denotes the energy consumed during machining of the injection molds; and E_M denotes the energy consumed by the IM unit manufacturing process. The following subsections describe the process for calculating the input parameters for Equations 1 and 2.

3.1 Energy Consumption of Nylon Production

Both processes are assumed to use the same Nylon 12 material and refining processes. These processes are surrounded by dashed lines in Figures 2 and 3. Equation 3 is used to determine the energy consumption of material refinement:

$$E_{nylon} = m_{feedstock}\left(\frac{1}{Y_{nylon\_production}}\right)\left(k_{nylon}\right) \qquad (3)$$

where $m_{feedstock}$ is the mass of nylon required by the IM or SLS manufacturing process; $Y_{nylon\_production}$ is the material yield of nylon production measured as the mass fraction of nylon feedstock that is successfully converted to nylon powder or granulate; and k_{nylon} represents the specific energy consumption (SEC) of the nylon production process.

The SEC is the amount of energy, in megajoules, consumed during the processing of a single kilogram of nylon feedstock. The Plastics Europe life-cycle inventory (GaBi, 2006; Hischier, 2007) for nylon 6 granulate production provided an SEC for nylon production, k_{nylon}, of 116 MJ per kilogram of nylon produced. The difference in SEC between Nylon 6 and Nylon 12 was assumed to be negligible.

The nylon production yield, $Y_{nylon\_production}$, was estimated separately for IM and SLS. Material loss during nylon production differs for nylon granulate and nylon powder, utilized by IM and SLS, respectively. Since the estimate for k_{nylon} incorporates the yield of the granulate production process, the material yield of IM nylon granulate production, $Y_{nylon\_production}$(IM), was assumed to be 100%. In contrast, the material yield for SLS nylon powder production, $Y_{nylon\_production}$(SLS), was assumed to be 98%. This assumption was based o the details of U.S. Patent 4,334,056, which describes the process of creating nylon powder for SLS (Meyer *et al.*, 1982; Zarringhalam *et al.* 2006). The patent suggests that 2% of particles yielded by this process are outside of the acceptable size range for SLS.

The total amount of feedstock is calculated according to Equation 4:

$$m_{feedstock} = n_{parts} m_{part} \left(\frac{1}{Y_{SLS\ or\ IM}}\right) \tag{4}$$

where n_{parts} is the number of parts; m_{part} is the mass of each part (35 g for the representative part); and $Y_{SLS\ or\ IM}$ is the process material yield for either SLS or IM.

A yield rate, Y_{IM}, of 90% is assumed for IM. Waste varies by shop and is created during machine start-up, purging, and maintenance. Olmstead and Davis (2001) cite a "standard reject rate" of 5%. Michaeli and Greif (2001) cite that waste content of material can be 5-50%, presumably by weight. A 90% yield rate is based on the work of Thiriez and Gutowski (2006), who performed an energy LCA of IM using data from over 100 sources and estimated a scrap rate of 10% for IM manufacture.

The yield rate of SLS is estimated from best practice and powder utilization data. Best practice requires that the powder for each build contain at least 30% virgin material, assuming that the powder is not infinitely recyclable. Furthermore, depending on the density of the build, Dotchev and Yussof (2009) report that as little as 12.8% of the powder is sintered into final parts, indicating that some of the used powder is eventually discarded to accommodate the virgin material requirement and the powder losses experienced during part breakout. Based on powder utilization data reported by Dotchev and Yussof (2009) and the 30% virgin material requirement, the authors calculated that between 40% and 80% of the material in a single build is sintered into a final part in the initial build or subsequent builds. In Equation 4, a material yield, Y_{SLS}, of 60% (40% material loss) is assumed, which agrees closely with values suggested by a local service bureau.

3.2 Energy Consumption of SLS

As reported in Equation 1, the energy required to fabricate an SLS part, E_{AM}, is the sum of the energy embedded in the nylon feedstock, E_{nylon}, and the energy consumed during the SLS process, E_{sls}.

It is difficult to prescribe a specific energy consumption value for SLS in terms of part volume or mass, because energy consumption varies with build density and height. For example, Mognol *et al.* (2006) built the same metal sintered part in multiple orientations and found that the difference in build height corresponded to a range of 115-187 MJ of energy consumption for the build. Orientation alone accounted for a 60% increase in energy use, because changes in orientation can cause changes in the height and duration of the build and therefore increase the energy consumption of the layer-based SLS process.

Accordingly, the energy consumption of the SLS unit process, E_{SLS}, was calculated by summing the product of average pre-heating power consumption and preheat time with the product of the build time and average build power consumption as shown in Equation 5:

$$E_{SLS} = t_{build}\dot{E}_{build} + t_{preheat}\dot{E}_{preheat} \quad (5)$$

where $\dot{E}_{build}$ is the average power required during the build stage; t_{build} is the build time; $\dot{E}_{preheat}$ is the average power required to preheat the build chamber; and $t_{preheat}$ is the time required to preheat the build. Equation 5 is further refined into Equation 6:

$$E_{SLS} = n_{layers}t_{layer}\dot{E}_{build} + t_{preheat}\dot{E}_{preheat} \quad (6)$$

where the time to build is calculated as the time to build each layer, t_{layer}, multiplied by the number of layers in a build, n_{layers}.

For this study, average power consumption and build and preheat times were measured from three builds on a 3DSystems® Sinterstation® HiQ™ + HiS™ SLS machine. A Fluke 1750 3-phase power meter was used to measure the voltage and current drawn by the machine during two builds and by the laser chiller during a third build. As reported in Table 1, build densities and heights ranged from 9% to 13% and 60 to 152 mm, respectively. The warm up time for these builds ranged from 2 hours to 2 hours and 45 minutes. Layer scan and preparation time required an average of 45 seconds during the first two builds. The machine was found to draw an average of 4 kW during the warm up stage and 3.5 kW during the build stage. The chiller was found to operate at a nearly constant 2 kW for both stages. During the third build of a pyramid-like structure of layers ranging from 90-20% density, layer preparation and scan time was found to range from 60-25 seconds as density of the scan area decreased.

Table 1: Results for power and chiller measurements using a Fluke 1750, 3 phase power meter and a 3DSystems® Sinterstation® HiQ™ + HiS™ SLS machine

		Warm Up Stage		Build Stage				
Build	Chiller	Duration	Power	Duration	Power	Packing Density	Build Height	Avg Layer Time
1		2 hours	3.9 kW	13h	3.5 kW	9%	152 mm	46 s
2		2h 45m	3.8 kW	8h 12m	3.6 kW	13%	97 mm	45 s
3	2 kW	2 hours		3h 45m		13%	35 mm	56 s

From these experimental observations, the machine and chiller were assumed to operate at a combined average of 6 kilowatts while preheating the build, $\dot{E}_{preheat}$, and 5.5 kilowatts during the build, $\dot{E}_{build}$. Each build was assumed to incur a warm up time of two hours, $t_{preheat}$, and each layer was assumed to require 45 s for preparation and scanning, t_{layer}. As explained in Section 2, the build chamber accommodated 150 representative parts, arranged in 3 rows of 50 parts per row. Each part row was approximately 130 mm high and included 860 layers, n_{layers}, each of which required approximately 45 seconds to build and prepare. Energy was calculated for two scenarios, partial builds of a single row of 50 parts and full builds of three rows of parts, for a total of 150 parts.

The experimentally determined values of power and energy consumption for the 3DSystems® Sinterstation® HiQ™ + HiS™ SLS machine are similar to those published in the literature for comparable applications. Previous studies (Luo *et al.*, 1999; Baumers *et al.*, 2010; Mognol *et al.*, 2006; Kellens *et al.*, 2010; Sreenivasan and Bourell, 2009) of metal and plastic sintering have measured power draws ranging from 3 to 19 kW during the build stages of plastic and metal sintering machines including the EOS EOSINT P760, EOSINT M250 Xtend, 3DSystems® Sinterstation® HiQ™ + HiS™ SLS machine, and DTM Sinterstation 2500. Luo *et* *al.* (1999) and Kellens *et al.* (2010) fabricated polymer parts on a Sinterstation 2000 and an EOSINT P760, respectively, and report SLS machine energy consumption that can be expressed as a specific energy consumption value ranging from 108 to 144 MJ per kilogram of fabricated part. Based on Equation 6 and the assumptions reported in this section, the specific energy consumption of the 3DSystems® Sinterstation® HiQ™ + HiS™ SLS system is approximately 130 MJ/kg for fabrication of the representative part.

3.3 Energy Consumption of IM

Mold Production

As reported in Equation 2, the total energy required to make an IM part, E_{IM}, includes the energy consumed to produce the mold ($E_{metal}+E_{machining}$), the energy required to refine the material, E_{nylon}, and the energy consumed by the IM process itself, E_M. Calculation of energy consumption for nylon refinement, E_{nylon}, was described in Section 3.1. To calculate E_{metal} and $E_{machining}$, the two-plate injection mold for this study is assumed to fit two copies (four halves) of the paintball handle. Equation 7 was used to calculate E_{metal}, the energy required to create the necessary volume of tool steel entering the machining process:

$$E_{metal} = m_{metal}\left((1-r)k_{virgin} + rk_{recyc}\right) \qquad (7)$$

where m_{metal} is the mass of metal required for the injection molds before machining; r is the fraction of recycled content of each metal; and k_{virgin} and k_{recyc} denote the specific energy consumption (SEC) or megajoules of energy required to refine a kilogram of metal from virgin and recycled sources, respectively.

The required mass of metal was calculated using dimensioning and tolerancing guidelines from the text by Kazmer (2007). Each mold plate was assumed to contain cavities or cores for two complete representative parts (i.e., four halves of paintball gun handles). The dimensions of each mold plate allowed for perimeter spacing equal to the depth of the cavities and minimal diameter cooling channels. The total volume of steel or aluminum for each plate was estimated to be approximately 4,000 cm^3, resulting in approximate masses of 31 kg for steel or 11 kg for aluminum.

The SECs for steel and aluminum production are cited from Dahmus and Gutowski's (2004) study of machining. The SEC of a metal varies significantly with recycled content. For example, virgin aluminum embodies approximately 270 megajoules per kilogram, k_{virgin}, and recycled aluminum embodies approximately 16 MJ/kg, k_{recyc}. The recycled contents for steel and aluminum can be as high as 80% and 20%, respectively. For steel the recycled material requires 9 MJ/kg, k_{recyc}, and the virgin material requires 31 MJ/kg, k_{virgin}. Three possible materials are considered for the molds: aluminum with 20% recycled content, steel with 80% recycled content, and 100% virgin tool steel.

The energy for machining the injection molds, $E_{machining}$, is also evaluated using values from Dahmus and Gutowski (2004). The total machining energy is then calculated using Equation 8:

$$E_{machining} = k_{machining}\left(v_{cavity} + v_{core}\right) \qquad (8)$$

where v_{cavity} denotes the volume of material removed to create the part cavities in the mold; v_{core} denotes the volume of material removed to create the cores in the mold; and $k_{machining}$ denotes the SEC of the machining process.

To manufacture two paintball gun handles in a single mold, 270 cm^3 would be removed to create the four cavities, and 2,500 cm^3 would be removed to create the four cores. Manufacture of the cooling channels and runner system are not considered. The SEC for machining, $k_{machining}$, changes with the hardness of the material being machined. Steel requires more machining energy than aluminum. Dahmus and Gutowski (2004) report four average SEC values for machining. The modal values for aluminum, 5 kJ/cm^3, and steel, 20 kJ/cm^3, are used in this study.

<u>IM Process-Related Energy Consumption</u>

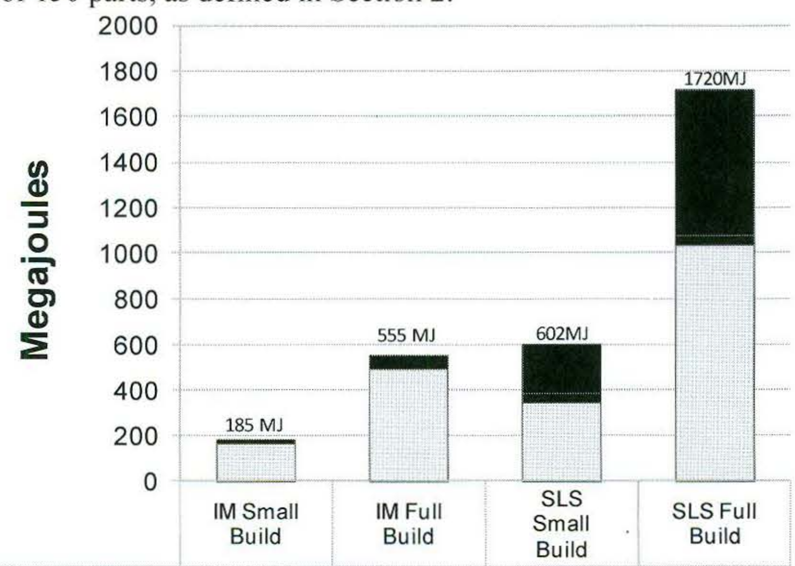
The energy consumed by the IM machine itself is calculated as follows:

$$E_M = m_{feedstock} k_{IM} \tag{9}$$

where k_{IM} is the SEC of the IM manufacturing process. Thiriez and Gutowksi (2006) report a wide range of SEC values for IM. They identify three types of IM machines in use in the United States: electric, hydraulic, and hybrid. They report average, high and low values of SEC for each machine type, and they assume that 70% of the machines in use are hydraulic. Therefore, the average SEC value, 11 MJ/kg, for hydraulic IM machines is used in Equation 9.

4. Energy Comparison of SLS and IM

Equations 1 through 9 are used to calculate the energy required to fabricate different quantities of representative parts with SLS or IM. Figures 5 and 6 illustrate total energy consumption, excluding and including mold production, respectively. Each column in the figures represents the energy calculated using Equations 1 and 2 for SLS and IM, respectively. These columns are decomposed into "Nylon Production" from Equation 3 for both SLS and IM, "Build Preheat" from the second term of Equation 6 for SLS, and "Part Manufacture" from the first term of Equation 6 for SLS and from Equation 9 for IM. Energy consumption is calculated for two different production volumes of representative parts: either a partial/small SLS build of 50 parts or a full SLS build of 150 parts, as defined in Section 2.

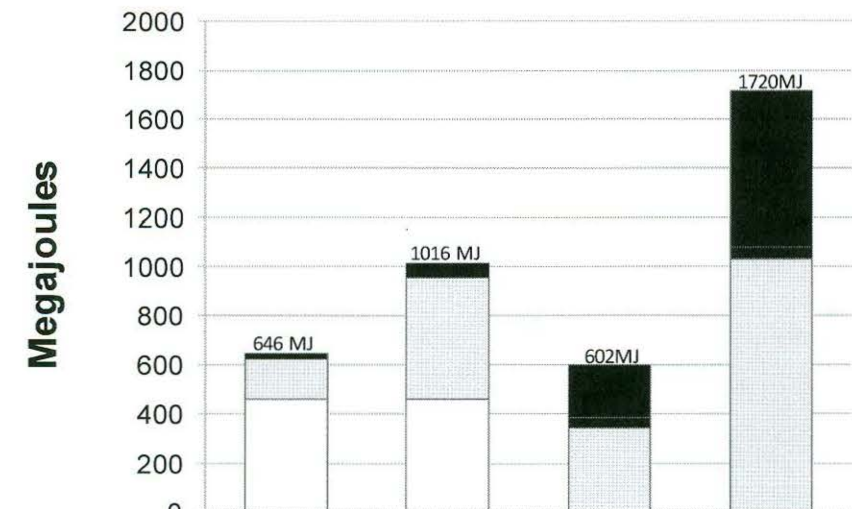


	IM Small Build	IM Full Build	SLS Small Build	SLS Full Build
■Part Manufacture	20 MJ	59 MJ	214 MJ	641 MJ
■Build Preheat			43 MJ	43 MJ
□Nylon Production	165 MJ	496 MJ	345 MJ	1036 MJ

Figure 5: The energy breakdown for IM and SLS of small (n_{parts} =50) and full (n_{parts} =150) builds of a representative part. The IM energy totals exclude mold production.

As shown in Figure 5, SLS consumes more energy per part than IM when mold fabrication is not considered. A full or partial build in SLS consumes more than three times the energy required to IM the same number of parts. Material inefficiency results in SLS requiring approximately twice the nylon production of IM; furthermore, the part manufacturing process requires more than 10 times the energy of IM manufacturing. Taller builds of SLS are marginally more efficient per part because build preheat energy requirements are assumed to be equivalent for partial and full builds. It is important to remember that both full and partial builds are packed densely in the build chamber, as described in Section 2, and that less dense SLS builds would consume more energy per part, with energy consumption proportional to the height of the build during the build stage.

When injection mold fabrication is included in the energy consumption calculations, SLS consumes less energy than IM for small production volumes. Figure 6 summarizes the energy consumption of SLS and IM, including the fabrication of a recycled steel injection mold. The energy investment in mold fabrication is calculated from the sum of Equations 7 and 8, which comprise the first two terms in Equation 2.



	IM Small Build	IM Full Build	SLS Small Build	SLS Full Build
■Part Manufacture	20 MJ	59 MJ	214 MJ	641 MJ
■Build Preheat			43 MJ	43 MJ
□Nylon Production	165 MJ	496 MJ	345 MJ	1036 MJ
□Recycled Steel Mold Production	461 MJ	461 MJ		

Figure 6: The energy breakdown for IM and SLS of small (n_{parts} =50) and full (n_{parts} =150) builds of a representative part. The IM energy totals include mold production.

Injection mold fabrication requires significant energy consumption when compared to builds of SLS parts. The 80% recycled steel injection mold shown in Figure 6 is the least energy intensive of the three mold types considered, but it alone requires approximately 460 MJ of energy or 75% of the total energy required for a small SLS build of 50 representative parts, including SLS part manufacture and nylon production. Mold fabrication from virgin steel or 20% recycled aluminum requires approximately 2000 or 2300 MJ of energy, respectively—more than the total energy consumed for a full SLS build of 150 representative parts. When the energy consumption of nylon production and part manufacture are added to that of mold fabrication, the tradeoffs favor SLS even more.

Although SLS uses significantly more energy than IM during part manufacture, the initial energy investment for IM mold plate manufacture creates a fixed energy investment that is not present in SLS. This fixed energy investment allows SLS to be more energy efficient per part for small production volumes. Crossover production volumes, for which IM and SLS use equivalent amounts of energy, are illustrated in Figure 7. The horizontal markings in Figure 7 highlight the initial energy investment required to fabricate the mold, and show that a significant number of SLS parts could be manufactured with less total energy than that required to fabricate the mold alone for IM. Depending upon the metal used for the mold, SLS uses less energy than IM when production volumes can be serviced by only a few builds. For the representative part, the energy consumption per part for the aluminum injection mold scenario is similar to the SLS energy consumption per part for production volumes of approximately 300 parts. The virgin steel injection mold scenario is only slightly less energy intensive and incurs similar crossover production volumes. In contrast, the recycled steel injection mold substantially reduces the crossover production volume to approximately 50 parts. These results indicate that only products with very small production volumes can be manufactured more energy efficiently using SLS.

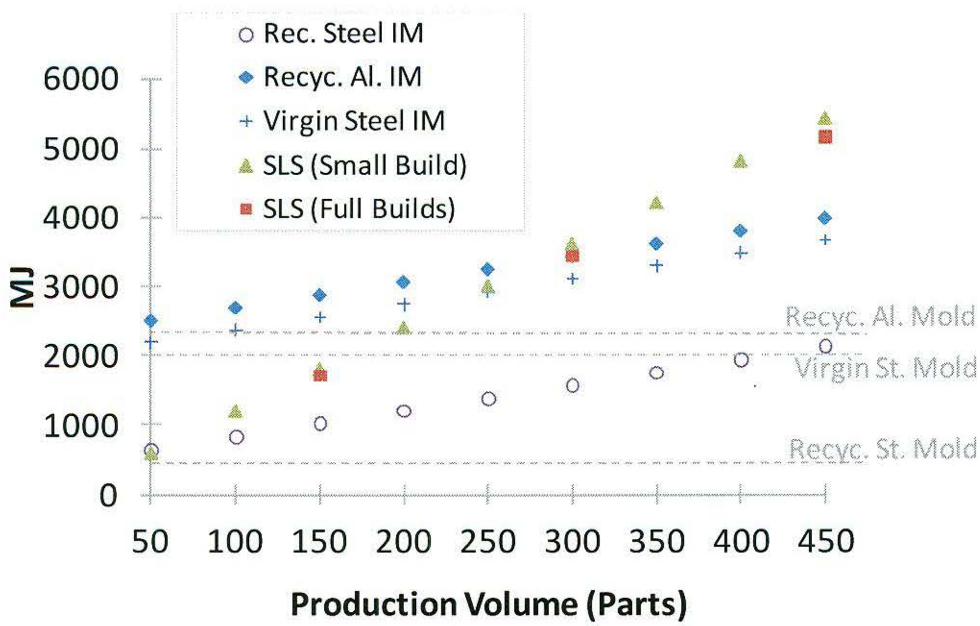


Figure 7: Total energy use versus production volume for SLS and IM of the paintball handle.

The results of this energy analysis can be compared with previous economic analyses. In Figure 8, energy consumption is displayed on a per part basis to facilitate this comparison. As shown in Figure 8, the IM energy consumption per part decreases with production volume, while

SLS energy consumption per part is relatively constant.[1] Atzeni *et al.* (2010), Ruffo *et al.* (2006), and Hopkinson and Dickens (2003; 2006) observed similar trends in monetary cost comparisons of SLS and IM. However, the magnitudes of the crossover production volumes differ significantly between those monetary cost studies and the energy study reported in this paper. Hopkinson and Dickens (2003; 2006) calculated machine, labor, and material costs for IM and laser sintering of a small part with maximum bounding dimension of 35 mm. They calculated a monetary crossover volume of approximately 14,000 parts. Monetary crossover volumes dropped by more than 80% for larger parts (44g and 210 mm maximum bounding dimension), more equivalent to the geometry of the representative part in this study. Ruffo *et al.* (2006) modified the Hopkinson and Dickens study to account for powder recycling and other costs and to adjust costs for low production volumes, less than a full build. They calculated crossover volumes as low as approximately 9,000 parts for the 35 mm part. Atzeni *et al.* (2010) redesigned a multi-part assembly to reduce part count in SLS and added assembly costs to their monetary cost comparison of SLS and IM. With assembly costs, crossover volumes reached as high as 60,000 or more parts (Atzeni *et al.*, 2010). Although these studies differ in scope, the large discrepancy between monetary and energy crossover volumes indicates that SLS may be more cost effective than energy efficient within the boundaries of this study.

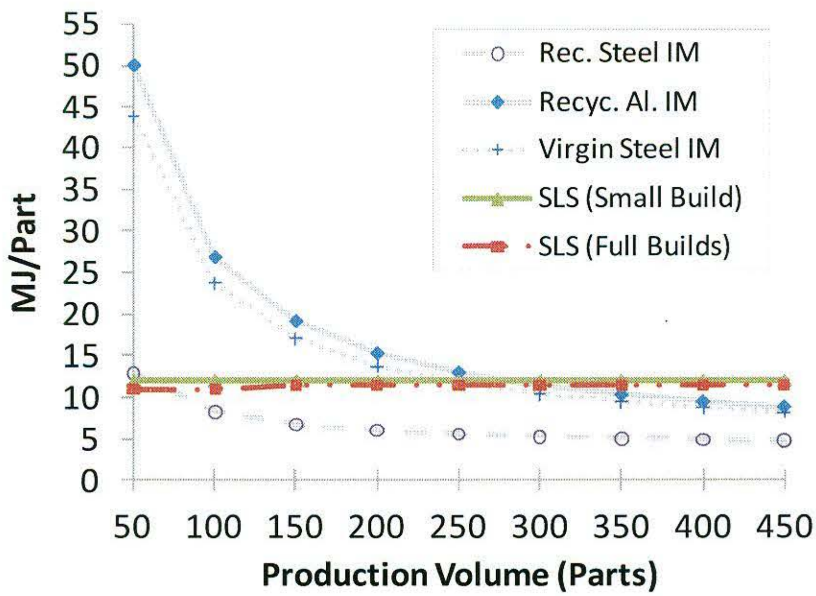


Figure 8: Total energy use per part versus production volume for SLS and IM of the paintball handle.

The results of this energy study are expected to change for different representative parts. Part size and complexity affect the energy consumption per part for both SLS and IM. A smaller, less complex part would decrease the energy required to fabricate the mold for IM, thereby tending to decrease the crossover production volume. In contrast, SLS energy consumption per part is strongly dependent on the number of parts that can be packed into a single build, with smaller

[1] SLS energy consumption per part is relatively constant when one assumes that SLS builds are always equivalently dense. In this study, production volumes are increased in increments of small builds (i.e., a fully dense row of 50 parts in a partial build) or full builds (i.e., a full build of 150 parts at maximum practical packing density).

parts typically utilizing the build volume most efficiently, tending to increase the crossover production volume.

As a point of comparison, crossover production volumes were calculated for a second representative part, the USB drive cover illustrated in Figure 9, which is smaller than the paintball handle used for the previous analysis.

Figure 9: USB case used for comparison (Blogspot, 2011).

The bounding dimensions of the USB drive cover are 4 mm by 16 mm by 45 mm, and it weighs approximately 1 g. At maximum packing density, 7524 parts can be fabricated in a single build on the 3DSystems® Sinterstation® HiQ™ + HiS™ SLS machine, with the parts arranged in 9 densely packed rows, each of which constitutes a partial build. If partial SLS builds are assumed, along with injection mold cores and cavities that can accommodate 20 USB covers, crossover volumes range from approximately 1500 to 3200 parts for virgin steel and 20% recycled aluminum injection molds, respectively. These values are much larger than the crossover production volumes for the paintball gun handle because the USB covers are much smaller and can be fabricated in larger numbers in a single SLS build. Additionally, the shallow size of the USB cover allows for thinner injection mold plates and a smaller energy investment for IM.

5. Closure

The results of this comparative LCI of SLS and IM indicate that manufacturers can save energy using SLS for parts with small production volumes. For the representative part in this study, the crossover production volume at which SLS and IM consumed equivalent amounts of energy ranged from approximately one to two full builds, or 150 to 300 parts, depending upon the material used to fabricate the injection mold. Energy crossover production volumes are much larger for a smaller representative part, indicating that specific crossover production volumes are also sensitive to the size and geometry of the representative part. In both cases, the energy crossover production volumes are much smaller than economic crossover production volumes for SLS and IM, indicating that SLS may be more efficient from a cost perspective than an energy perspective, relative to IM. The large material waste, high power draws, and long operating times of SLS make it generally inefficient to use SLS for large production volumes.

The results and analysis support three major recommendations for reducing the energy consumption of SLS. First, build volumes should be packed as densely as possible to maximize the part output per build height because SLS energy consumption is dependent upon the height of the build and the corresponding number of SLS layers. Second, material-related energy consumption could be improved by engineering infinitely recyclable powder and reducing powder loss during handling. Infinitely recyclable powder could reduce powder scrap rates from 40% to 10%, the amount of powder reported to be lost during part break-out. Third, reducing the time required to scan and prepare each layer would significantly lower the energy consumption of SLS. Although material efficiency can save money and energy, the effect of material loss is less significant than build time.

Future work is needed to refine this energy analysis and obtain a broader understanding of the relationship between part design and energy use. Studies that consider mixed part builds, a finer resolution of production volumes, and parts and builds from current manufacturing centers could provide further insight into SLS energy use. The scope of future energy studies could also be extended to include factors such as distribution, waste handling, and infrastructure that were not considered in this study.

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References

Atzeni, E., L. Iuliano, P. Minetola, and A. Salmi, 2010, "Redesign and Cost Estimation of Rapid Manufactured Plastic Parts", *Rapid Prototyping Journal*, Vol. 16 Issue 5 pp. 308-317

Baumers, M., C. Tuck, R. Hague, I. Ashcroft, and R. Wildman, 2010, "A Comparative Study of Metallic Additive Manufacturing Power Consumption," *Proceedings of the 2010 Solid Freeform Fabrication Symposium*, August 9-11, The University of Texas at Austin, Austin, TX.

Bazan, F., F. Concha, Z. Silva, M. VanOverloop, and R. Zavala, 2009, "Rapid Manufacturing of Custom Paintball Gun Handle," Final Report, The University of Texas at Austin, Austin, TX, May.

Blogspot (2011), "USB Flash Drive", available at: http://usb-flash-drive-guides.blogspot.com (accessed August 2011).

Bourell, D., M. Leu, and D. Rosen, Eds., 2009, "Roadmap for Additive Manufacturing: Identifying the Future of Freeform Processing", The University of Texas at Austin, Laboratory for Freeform Fabrication, Austin, TX.

Dahmus, J. and T. Gutowski., 2004, "An Environmental Analysis of Machining," *Proceedings of the 2004 ASME International Mechanical Engineering Congress and RD&D Exposition*, November 13-19, Anaheim, California.

Dalquist, S. and T. Gutowski, 2004, "Life Cycle Analysis of Conventional Manufacturing Techniques: Die Casting," LMP Working Paper LMP-MIT-TGG-03-12-19-2004, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Dotchev, K., and W. Yussof, 2009, "Recycling of Polyamide 12 Based Powders in the Laser Sintering Process," *Rapid Prototyping Journal*, Vol. 15, No. 3, pp. 192-203.

Drizo, A., and J. Pegna, 2006, "Environmental Impacts of Rapid Prototyping: An Overview of Research to Date," *Rapid Prototyping Journal*, Vol. 12 No. 2, pp. 64-71.

GaBi LCA Software 4.0, 2006, PlasticsEurope Database, PE International.

Hischier, R., 2007, "SimaPro Documentation - Part III: Plastics," Product Ecology Consultants.

Hopkinson, N., and P. Dickens, 2003, "Analysis of Rapid Manufacturing–Using Layer Manufacturing Processes for Production," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, Vol. 217, pp.31-39

Hopkinson, N., 2006 "Production Economics of Rapid Manufacture", in *Rapid Manufacturing: An Industrial Revolution for the Digital Age* (N. Hopkinson, R.J.M. Hague, and P.M. Dickens, Editors), John Wiley & Sons, Ltd., Chichester, England, pp. 147-157

ISO, 1997, *ISO 14040: Environmental Management–Life Cycle Assessment–Principles and Framework,* ISO 14040:1997(E), International Standards Organization.

Kazmer, D., 2007, *Injection Mold Design Engineering*, Hanser Gardner Publications, Cincinnati, Ohio.

Kellens, K., W. Dewulf, W. Deprez, E. Yasa, and J.R. Duflou, 2010, "Environmental Analysis of SLM and SLS Manufacturing Processes", *Proceedings of 2010 CIRP International Conference on Life Cycle Engineering*, Hefei, China, May 19-22, pp. 423-428.

Kirk, R., and D. Othmer, 2007, "Polyamides, Plastics" *Kirk-Othmer Encyclopedia of Chemical Technology*, Volume 19, John Wiley & Sons, Inc, USA.

Luo, Y., Z. Ji, L. Ming, and R. Caudill, 1999, "Environmental Performance Analysis of Solid Freeform Fabrication Processes," *Proceedings of the 1999 IEEE International Symposium on Electronics and the Environment*, May 11-13.

Meyer, K., K. Hornung, R. Feldmann, and H. Smigerski, "Method for Polytropically Precipitating Polyamide Powder Coating Compositions Where the Polyamides Have at Least 10 Aliphatically Bound Carbon Atoms Per Carbonamide Group," US Patent 4,334,056.

Michaeli, W., and H. Greif, 2001, *Training in Injection Molding: A Text and Workbook*, Hanser Gardner Publications, Munich.

Mognol, P., D. Lepicart, and N. Perry, 2006, "Rapid Prototyping: Energy and Environment in the Spotlight," *Rapid Prototyping Journal*, Vol. 12, No. 1, pp. 26-34.

Morrow, W., H. Kim, J. Mazumder, and S. Skerlos, 2007, "Environmental Aspects of Laser-Based and Conventional Tool and Die Manufacturing," *Journal of Cleaner Production*, Vol. 15, No. 10, pp 932-943.

Olmsted, B., and M. Davis, 2001, *Practical Injection Molding*, Marcel Dekker, Inc., NY, NY.

Ruffo, M., C. Tuck, and R. Hague, 2006, "Cost Estimation for Rapid Manufacuring – Laser Sintering Production for Low to Medium Volumes", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* Vol. 220, pp. 1417-1427.

Sreenivasan, R., and D. Bourell, 2009, "Sustainability Study in Selective Laser Sintering - An Energy Perspective," *Proceedings of the 20th International Solid FreeForm Fabrication Symposium*, The University of Texas at Austin, Austin, TX.

Thiriez, A. and T. Gutowski, 2006, "An Environmental Analysis of Injection Molding," *IEEE International Symposium on Electronics and the Environment*, May 8-11, San Francisco, California, USA.

Zarringhalam, H., N. Hopkinson, N. Kamperman, and J. de Vlieger, 2006, "Effects of Processing on Microstructure and Properties of SLS Nylon 12," *Materials Science and Engineering A*, Vol. 435-436, pp. 172-180.