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**Authors**

Faludi, Jeremy
Bayley, Cindy
Bhogal, Suraj
et al.

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# Comparing Environmental Impacts of Additive Manufacturing vs. Traditional Machining via Life-Cycle Assessment

Jeremy Faludi[1], Cindy Bayley[1], Suraj Bhogal[1], Myles Iribarne[1]
[1] University of California, Berkeley, department of Mechanical Engineering

## Introduction

Additive manufacturing ("AM" or "3D printing") is revolutionizing prototyping and even small-scale manufacturing (Anderson, 2013). Many people presume that it has environmental benefits compared to traditional manufacturing processes, but there have been no comprehensive life-cycle assessment ("LCA") studies providing a fair and quantitative comparison for these presumptions. Studies have measured either the impacts of machining, or of additive manufacturing, but not both together in a way that captures all major impacts (energy use, waste, toxins, etc.) This is worth investigating, because even slight improvements in manufacturing could have a significant impact on greenhouse gas emissions and other environmental impacts. According to Diaz et al. (2010), “manufacturing activities are responsible for 19% of the world’s greenhouse gas emissions and 31% of the United State’s total energy usage.” In addition, the cutting fluid used by CNC machines is said to pose notable health and environmental threats--it is usually a naphthenic or paraffinic oil with various emulsifiers and additives such as biocides, and it is slightly alkaline (Childers, 1994). Additive manufacturing eliminates the need for cutting fluids, but introduces new chemicals for its

model materials and support materials, whose potential health and disposal problems have not been compared to machining standard engineering plastics, cutting fluid, energy use, and other ecological impacts. Finally, many people assume AM eliminates waste, though the results here will show this is not necessarily true, nor is it necessarily a dominant factor environmentally.

The goal of this research was to conduct a comprehensive comparison across all major sources of ecological impacts (energy use, waste, manufacturing of the tools themselves, etc.) as well as all major types of impacts (climate change, toxicity, land use, etc.), so that prototypers and job shop owners can make an informed decision about which technology to purchase or use, and so the makers of 3D printers can understand their priorities for improving environmental impacts.

## Background

Many studies have been done on the life cycle impacts of milling machines and 3D printers; however, no one (to our knowledge) has published what prototypers and job-shop owners need: a comprehensive cradle-to-grave life cycle assessment that tracks all major impact types, and compares machining to additive manufacturing on that basis. Of the 50 publications we read, most studies are quite narrow in scope; most focus on energy use (Dahmus 2004, Behrendt 2012, Diaz 2011, Diaz 2012, Kara 2011, Helu 2011, Sreenivasan 2009, Baumers 2011, Telenko 2012, and more), while some studies consider embodied energy, water, waste, and/or

toxins (Muñoz 1994, Avram 2011, Ogaldez et al. 2012, Duflou 2012, and more). A few broader studies consider all of these as well as other factors, such as social impacts (Huang 2012, Bezerra and Gomes 2012). However, even most of these studies do not measure true environmental impacts, they merely measure raw inputs and outputs, such as kWh of energy used, or kg of waste produced. These are not meaningful environmental impacts--obviously 1kg of mercury in a river has a much greater health impact than a 1kg block of steel on the ground, and 1kWh of electricity generated by photovoltaics has a tiny fraction of the impacts of 1kWh generated by a coal plant. Environmental impacts are things which cause damage to human health and ecosystems, and which deplete non-renewable natural resources; these include climate change, ozone depletion, deforestation, toxicity as measured in Disability-Adjusted Life Years, etc. To make intelligent decisions, we must measure the things that matter, even if they seem less concrete than raw data such as kg of waste or kWh of energy use. As we will see later, this can be achieved by life-cycle assessment using multiple types of impacts normalized and weighted to produce single-score metrics. A couple papers exist using such metrics (Luo 1999, Gonzalez 2007), but none were found that compare additive manufacturing to machining, nor could the existing papers be used to extrapolate a fair comparison.

### Impacts of CNC Milling Machines in Literature

Energy use during processing is widely considered to be one of the largest impacts of machining (though our results will show this is not always true). Energy use can be complex to

measure, and to fairly attribute to different parts manufactured in different production environments. For CNC milling machines, about “85% of the energy used by machining equipment is constant, regardless of whether or not a part is being produced” and thus the electrical demand per part was inversely proportional to the material removal rate (Dahmus et al. 2004). For metal machining, Diaz et al. (2011) showed that a CNC mill cutting steel may use only 7% more energy than “cutting” empty air, though other data has shown as high as 23% increase in other circumstances (Diaz, personal communication 3/13/2013). This is because CNC machines often utilize auxiliary equipment such as coolant pumps, misters, and pressurized air, whose energy use can far exceed the actual cutting energy. Thus the percentage of tool utilization is also an important factor in its environmental impacts--to achieve low impacts, it is not enough that the machine processes a part quickly, but also that it spends as much of its time processing parts as is feasible, as opposed to sitting idle.

Embodied energy, water, toxins, and other environmental impacts of the machine tools are another consideration. No studies were found that actually measured embodied impacts the most precise way--by disassembling and weighing components of machine tools. Instead, studies have estimated the mass of each specific material comprising the machine by measuring its dimensions, using simplified geometries and known densities of materials to calculate component weights (Azevedo et al. 2011, Chen et al. 2009). While the embodied energy of machine tool manufacturing is large, approximately 18,000 MJ and 100,000 MJ per machine to manufacture a Bridgeport Series 1 and Mori Seiki DuraVertical 5060 respectively (Diaz et al. 2010), Dahmus et al. (2004) asserts that these impacts mostly amortize away, saying, “In 1989, 60% of metal cutting machines in the US were more than 10 years old... Thus, the environmental impact per part is relatively small.” Chen et al. (2009) concludes that for a simple Bridgeport Series 1 mill, “the use phase dominates, accounting for between about 90-95% of the Bridgeport’s emissions. For a Mori Seiki DuraVertical 5060, however, the figure is only 60 - 86%.” This last figure is surprisingly low, and means that embodied impacts must be taken into account for a fair comparison of life-cycle impacts.

One of the biggest health and environmental concerns for machine tools in the literature is the use of cutting fluid, because workers are directly exposed to it. It provides machine tools with cooling, lubrication, chip removal, corrosion protection, and tool cleaning, but also causes multiple environmental impacts. One of these is a significant water footprint (Ogaldez et al. 2012). More troublesome, however, is toxicity. Some papers on machining measure nothing but impacts of the cutting fluid waste (Avram 2011). According to Avram, “even though cutting fluids have been seen traditionally as a solution rather than a problem, they have a variety of environmental liabilities associated with human chronic diseases and costly schemes applied for their disposal.” He continues, “These pollutants raise issues at both local and global levels. While some of the chemicals used in these processes can be harmful to workers, such as some additives to cutting fluids, other chemicals, such as TCA, are associated with high-level ozone depletion.” However, the results of this study show these concerns may be overblown.

Another concern for CNC machining workers is injury. Sheehy and Chapman (1988) state that “the incidence of robot and CNC related accidents has not been considered a significant

occupational safety issue” but they are comparing it to manual machining, and they do acknowledge the potential for serious accidents with CNC machining. Furthermore, they argue that the danger is understudied because people assume that automation is inherently safe, even though there is human involvement, just for different tasks than manual machining.

End of life disposal and recyclability of machine tools was difficult to determine from literature. Diaz et al. (2010) acknowledges that “there is a significant uncertainty regarding the end-of-life of a machine tool since they are constantly resold in the used machine tool market.” They estimated 10 - 20 year lifetimes for different circumstances, but also noted that when tools are resold, uptime utilization at the new owners is unknown, and makes a crucial difference in the environmental impact per part processed.

## Impacts of Additive Manufacturing in Literature

There are many different types of AM processes, constructing parts in different ways. The techniques analyzed in this paper are Fused Deposition Modeling (FDM) and Inkjet Printing (IJP, or “polyjet”), though literature was also examined on other processes.

Some of the perceived advantages of additive manufacturing are material efficiency, part flexibility, and production flexibility (Huang et al. 2012). However, as mentioned above, literature searches revealed that the environmental impacts of 3D printing are not adequately studied. Drizo et al. (2006) observed that aside from the study by Luo et al. (1999), the literature on this topic is very limited. In Luo, three case studies were presented:

Stereolithography (“SL” or “SLA”), Selective Laser Sintering (“SLS” or “LS”), and Fused Deposition Modeling (“FDM”). A holistic view was taken, considering material extraction, energy consumption, process wastes, and disposal, but only for the processing stage of life, not the manufacturing or end of life of the machines themselves.

Most research to date has focused primarily on energy use. Mognol et al. (2006) compared various manufacturing parameters of three rapid prototyping systems in order to identify a set of parameters that could reduce electrical energy consumption. The systems tested were Thermojet (3DS), FDM 3000 (Stratasys) and EOSINT M250 Xtended (EOS); it was revealed that electrical energy consumption is directly dependent on the duration of the job. The manufacturing time is the most important parameter, and recommendations were made for minimizing this for each system. Another study, by Baumers et al. (2011) determined that “the LS energy consumption is dominated by the time-dependent energy consumption” and that cooling and heating were the greatest contributors to energy used. Luo et al. (1999) determined the system energy usages in terms of the energy consumption rates (kWh/kg of part geometry) for LS, FDM, and SLA. Telenko et al. (2012) observed that “it is difficult to prescribe a specific energy consumption constant for SLS, because of the variance in build density and height” and therefore chose to use the accepted value of 130MJ/kg that resulted from the work by Sreenivasan et al (2009).

Some of the environmental impacts that are mentioned in research to date are related to material toxicity. Huang et al. (2012) and Drizo et al. (2006) investigate the toxicological and

environmental hazards that result from handling, using, and disposing of the materials used in additive manufacturing processes. Drizo et al. (2006) observes that “one of the most pressing issues in estimating the environmental impact of RP [rapid prototyping] and RT [rapid tooling] technologies is to evaluate the potential toxicological health and environmental risks that can occur from handling, using and disposal of the RP and RT materials.”

It has been suggested that AM minimizes manufacturing waste. Huang et al. (2012) argue that rapid prototyping contributes to raw material reduction because a common pool of material is used to create parts. However, Drizo et al. (2006), quoting an earlier study by Wohlers and Grimm, counter that “most of the material used in RP processes cannot be completely reclaimed. ...in the case of SLA, the cumulative exposure to UV can cause a whole vat of resin to become unrecoverable. SLS process requires a ratio of 20- 50% of virgin material to recycled powder and therefore waste is generated with each build.” Calculations by Telenko et al. (2012) revealed that “up to 44% of the material that enters the SLS process might be wasted and that SLS has a likely range of yields from 56-80%.” It has also been debated whether the proliferation of one-off goods that will result from the inevitable increase in additive manufacturing will result in positive or negative environmental impacts (Drizo et al. 2006).

## AM vs. CNC Comparisons

The impacts of AM and traditional CNC machining can be directly compared in some ways, and not in others. Both use significant amounts of electricity, as shown earlier. In both cases, the electricity use is largely time-dependent and is also dependent on part geometry or finish quality, primarily through their effects on processing time. However, strategic choices in tool operation can reduce these times. For AM, Mognol et al. (2006) found that "With [a] good set of parameters, it is possible to save 45% of electrical energy for the Thermojet, 61% for the FDM and 43% for the EOS."

Both CNC and AM cause a certain amount of material waste (from the original material being cut away, from support material, or supply cartridge leftovers), which is directly comparable once adjustments are made for the resource intensiveness and toxicity of different materials. "Estimates of scrap production in machining range from 10% to 60%. While these chips and scraps can be recycled, the machining process itself requires the inflow of a large amount of pure material...Given that Al from virgin sources requires around 270 MJ/kg to produce, while Al from recycled sources requires only 16 MJ/kg, this is an important process requirement that must be considered when evaluating machining" (Dahmus 2004). Petrovic et al. (2011) quoted Reeves 2008, saying "For some applications, especially in the metal sector, case studies show that the waste of raw material is reduced by up to 40% when using additive technologies instead of subtractive (machining) technologies... Also, 95% to 98% of the remaining material (powder that is not fused) may be recycled." However, this was for laser sintering; for the Objet printer studied here, none of the waste polymers are recyclable.

Recycling should be possible for unused FDM material, but reliable statistics on recycling rates for the industry sector were not found.

The primary difference between AM and CNC in types of impacts is that machining generally uses cutting oil for lubrication, which is an additional source of waste. Huang et al. (2012) state "The pollution of terrestrial, aquatic, and atmospheric systems is much less in AM than in conventional manufacturing processes" and they claim "the main health risk generated by traditional manufacturing processes is oil mist resulted from metalworking fluid." Thus it is important to measure not just energy use, or material waste, but also toxicity and as many other factors as possible. The best-informed decisions come from the most comprehensive data. Luo et al. (1999) showed ecological impacts for different AM machines varying by up to a factor of ten, and machining most plastics does not require lubricant. Finally, Kara et al. (2011) showed that faster cutting speeds dropped the total processing energy of machining logarithmically, which could more than compensate for the impacts of waste fluid for some speed ranges in metal.

Another impact unique to machining is that it incurs wastage of tooling bits; however, these have been shown to be a relatively insignificant percentage of total impacts (Dahmus 2004) because the amount of wastage per part is extremely small. Particularly when cutting plastic, it takes an extremely long time for bits to wear down.

Finally, part geometry also matters. Because AM and machining are different processes, one process may cause lower ecological impacts for some part designs, while the other method

may be better for others. Even in machining alone, this has been shown to be true for different part designs and positioning (Muñoz 1994). As such, an important aspect of our methodology was to choose parts that did not unfairly advantage either process.

## Methodology

Three LCAs were performed, each with multiple scenarios, comparing a Haas VF0 CNC mill to a Dimension 1200BST FDM machine and an Objet Connex 350 inkjet machine. Because there are so many differences between these tools and how they manufacture, it is important to make an apples-to-apples comparison. Therefore the functional unit was chosen to be one "job" comprising the manufacturing of two different parts in plastic--one with complex curvature as people often make by additive manufacturing, and one with simple planes and holes as people often make with traditional milling machines. Both parts are shown below in Figure 1, as printed by the inkjet.

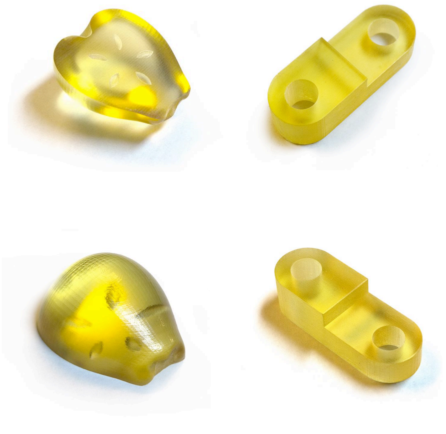

*Figure 1. Different views of the two parts used for the functional unit of one "job".*

Metal parts were not considered, as the FDM and inkjet printers tested do not print in metal. Ideally the same plastic would have been used in all cases, but this was not possible due to the limitations of materials used by the FDM and inkjet machines. (A detailed discussion of material impacts is included later in this section.) Different levels of quality were also not considered--since quality cannot be changed in either of the AM machines, it was assumed that their quality is acceptable, otherwise they would not be considered a contender by the prototyper or job shop owner. (See Results for more discussion.) The LCA was limited to environmental impacts; societal impacts were only considered qualitatively. Methodologies for measuring social impacts are not as detailed or agreed-upon as environmental metrics, and while some have analyzed machining with both (Bezerra and Gomes 2012), it was considered too complex for a single-score decision metric here.

The LCAs were conducted using the ReCiPe Endpoint H methodology in SimaPro software. This method measures fossil fuel depletion, mineral depletion, human toxicity, marine ecotoxicity, freshwater ecotoxicity, terrestrial ecotoxicity, freshwater eutrophication, marine eutrophication, photochemical oxidants, particulate matter, climate change ecosystem impacts, climate change human health impacts, ozone depletion, terrestrial acidification, ionizing radiation, natural land transformation, urban land occupation, and agricultural land occupation. It then normalizes and weighs these to provide a single combined score in units of “points” for the ecological impact per job. For those unfamiliar with LCA normalization and weighting, a full explanation is too long to include here, but can be found in Pré Consultants' published explanation of the ReCiPe normalization and weighting schemes (Pré Consultants 2009). In brief, these points are based on the annual environmental impact per person of an average European; many variables are first normalized to disability-adjusted loss of life years for humans, probable loss of species per year for environmental impacts, and loss of resource availability as measured in financial cost of resources, before the final normalization to points. The authors chose this methodology because they believe it to be highly credible based on the

published explanation of its normalization and weighting schemes, its endorsement by the Dutch ministry of environment, and its authorship by the makers of SimaPro software.

Almost no studies were found on CNC or AM that attempt to balance this many ecological impacts; most are content with one indicator (usually CO2 emissions), or a few indicators separately listed, such as energy, solid waste, and water (Choi et al. 1997). Bringing different impact types together into single scores allows for easier decision-making and allows results to simultaneously display many different scenarios and life-cycle stages.

The scope of this analysis was cradle-to-grave; it included the embodied impact of the tools themselves (raw materials and manufacturing), transportation of the machines to and from UC Berkeley, energy use during the processing of parts, energy use while idling and in standby, material used in the final parts, waste material generated during processing, cutting oil for the CNC mill, and disposal of both process material waste and the machines themselves. Tool wear and replacement parts were not considered, nor was compressed air, pressurized water, or other systems used to clean support material from 3D printed parts or to clean chips off the bed of the CNC mill. Assumptions for the life-cycle inventory are below.

### Manufacturing of the Machines

The manufacturers were not willing to release bills of materials with weights listed, as they believe that the mass of steel, glass, and plastic in their machines is “proprietary” information, even though it is trivial (though time-consuming and tedious) to simply measure. This can be

done most precisely by disassembling the machines and weighing all components, then entering the data into LCA software with estimates of materials and the manufacturing processes used to make each part. In the interests of not unduly disrupting the workflow of the machines, or possibly breaking them, we did not disassemble the machines, but instead measured the dimensions of all parts accessible, and calculated the masses of parts using the densities of materials from reference sources such as Engineering Toolbox online. Estimating the mass of copper in motors was assumed to be necessary, because even though the mass is a small percentage of the whole machine, copper has much higher environmental impacts per kg than steel. From previous experience in the motor industry, we know motors are commonly 10-18% copper, so an estimate of 13% copper by volume was used. This is not precise, but analysis results showed it was not a significant enough part of even the manufacturing, let alone the full life-cycle, to warrant further precision.

To check accuracy, the sum of all component weights were compared with the mass of each whole machine listed in the manufacturer’s specification pages. In the case of the Objet machine, the calculated mass was only 3% below the listed mass, so no corrections were made to the calculations. In the case of the Dimension FDM machine, the calculated mass fell short of the listed mass by 20%, which was deemed significant. To compensate, dummy inventory items were added. It was assumed that the missing mass came from steel, plastic, and electronic components not visible or adequately estimated; 63% of the measured mass was steel, 26% of the measured mass was plastic, 7% of the measured mass was copper (estimated from motor windings and cables), and the remaining 4% was from miscellaneous materials such

as glass and aluminum. It was assumed that these ratios would be similar for the missing mass, but with more steel taking the place of miscellaneous materials. Therefore dummy inventory items were created for 22kg of steel, 8.8kg of plastic (assumed to be polycarbonate, as was the main case material, in order to withstand the high temperature inside the machine), and 2.2kg of copper. This is not a very precise measurement, but results showed that in two of the three scenarios studied, the FDM machine’s embodied impacts were insignificant, so further precision was not deemed necessary. For a full list of masses entered into the life cycle inventory, see Appendix 1, Manufacturing-Stage LCA Data.

For the CNC mill, the calculated mass was only 3% below the listed mass (as with the Objet machine), so no corrections were made to the calculations. A direct measurement of the main spindle motor was not possible, but based on the Haas specification sheet, it was assumed the main motor is similar to a Baldor 5.6kW motor weighing 73 kg (Thomasnet.com 2013). Other motors' masses for steel and copper were estimated by dimensions and percent copper, as described above.

### Transportation & End of Life

Transportation for all machines was assumed to be from their respective manufacturing locations to UC Berkeley and back again at the ends of their lives; the assumption of a return trip magnifies the impact of transport, but results showed it to not be a significant percentage of total lifetime impacts. Future studies might improve precision by not assuming a return trip and using a geographically average US location, but results showed that transportation was so small an impact it was not deemed necessary here.

Lifetimes of the tools were not known. Manufacturers of the 3D printers gave estimates of 10-15 years, which seemed unrealistically high given the rapid pace of improvement and obsolescence. Published data was not found. A survey to determine average lifetime, end-of-life, and usage data of additive manufacturing tools was distributed to over a thousand product designers through multiple email lists and a blog post on the Autodesk Sustainability Workshop, but unfortunately there were only four respondents, not enough for a statistically significant finding. The average from the few respondents was three years. Thus a lifetime of five years was assumed for both of the 3D printers, as a hedge between this number and the manufacturer numbers. The CNC mill was assumed to have a life of ten years. While conservative, this is based on the results of interviews from Chen et al. (Chen 2009) listing the average life of a CNC mill in a job shop to be 10 years, with a range of 8 to 25 years. Results showed that lifetime was only a significant factor in the final total impacts when the utilization was low (one job per week scenarios), and even then was only a dominant factor for the CNC machine if it was always powered down when not in use. In all other cases, both for the CNC and additive manufacturing machines, the machines' usage impacts were dominant. Thus, a sensitivity analysis of lifetime was not deemed necessary.

For end of life, the US EPA disposal scenario for durable goods was used (EcoInvent process "Durable goods waste scenario/US S"). It assumes recycling of materials such as steel and glass

which are commonly recycled, and landfill or incineration of less commonly recycled materials, such as many plastics. This is certainly a conservative assumption, because as discussed earlier, most machine tools are resold when their original purchasers no longer find them useful; the same may be true of 3D printers as well, but as mentioned above the survey did not provide adequate information. However, disposal was a negligibly small portion of all the machines' life-cycle impacts, so refinement of this assumption was not investigated.

### Energy Use During Life

Each of the machines studied used energy not only when "running" (either printing or cutting), but also when "idle" (while users are programming the next job to be produced, or cleaning up from the previous job, or in the case of the CNC machine, fixturing parts). In addition to these, the Dimension FDM machine had a "warmup" mode it required if it had been sitting idle long enough for its model and support materials to cool, and had a low-power "standby" mode. The FDM and CNC machines could be powered entirely off when not in use, but the inkjet machine is never powered off for fear of its lines clogging with model or support material. Its users reported that the procedures for flushing the lines for safe machine shutdown are onerous enough that they would only shut down the machine if it were to lie unused for several weeks, and perhaps not even then. Other Berkeley researchers had already measured the power usage of each machine in all of these states; much of their results are

published (Diaz 2011), and their raw data was available to us as well. Thus we had credible power values for each state of each machine, and only needed to measure the amount of time processing and idle to run each job.

Time spent in warmup and standby for the FDM machine were calculated based on machine utilization. This becomes a complex question, as it requires allocating a certain amount of idle time to the manufacturing of each pair of parts (as well as powered-off time for the CNC, and for the FDM machine sometimes warmup time, standby time, and powered-off time). The survey described above was also intended to determine average machine utilization percentage, but as mentioned there were not enough respondents. Instead, a sensitivity analysis was performed, dividing the question of ecological impacts per job into three different scenarios:

- Minimal utilization (1 job/wk), idling

  Here, each machine is in "idle" power mode when not in use (except the FDM machine, which is in "standby" and then goes through "warmup" time to be ready to print, only being "idle" for programming and a short post-printing time).

- Minimal utilization (1 job/wk), low-power

  Here, the inkjet machine is in "idle" power mode when not in use, but the CNC and FDM machines are fully powered off when not running or being programmed (other than the "warmup" time needed by the FDM machine).

- Maximal utilization (running 24 hrs/day, 7 days/wk).

  Here, the only "idle" time is to program jobs and perform minimal cleanup (not full cleanup of the CNC bed).

The third scenario brings up the question of what "maximum utilization" is for each machine--they manufacture parts at very different speeds, and thus cannot be fairly compared by having each machine spending 24 hours per day 7 days per week creating the apples and linkages used for the functional unit. (Recall that our functional unit measures impacts per job per year, where one job is one apple plus one linkage.) If the Objet is printing with 100% model material, printing one part at a time (as it would for separate individual users who do not coordinate with each other), it takes six hours to print both parts, thus it can run a maximum of 27 jobs per week. However, if it is printing with 10% model material and 90% support material, it takes significantly less time, and if both parts are printed at the same time, the job takes almost exactly half as long, so it can print 27 pairs of apples and linkages (27 jobs) per week while still having 50% of its time available for other jobs. The CNC machine is much faster--it can run 69 of these jobs per week, and thus can print 27 jobs in less than 40% of its time, leaving over 60% of its time available for other jobs. The FDM is slow when printing at 100% solid fill, but relatively fast when printing at "sparse fill" (90% hollow). To make a fair comparison, then, we assume that maximum utilization is a theoretically perfect 24 hrs/day, 7 days/wk (time for maintenance, repair, tool-switching or material-switching are ignored), but that only a certain percentage of that time will be spent on this job; the rest will be spent on other jobs. This percentage is used to determine what percentage of the machines' manufacturing, transportation, and end-of-life impacts is allocated to this job vs. other jobs. A graph of the percentages is below, in Figure 2. Note that no scenario fully reaches 100%, because only an integer number of jobs can be processed. For a full table of power use and times spent in all energy states, see Appendix 2: Tables of Energy, Material Use, and Waste.

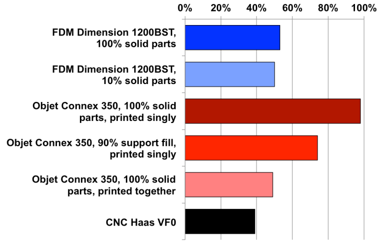

*Figure 2. Allocation of time to this job for different scenarios of each machine, if operating at maximum utilization (24 hrs/day, 7 days/wk).*

Users of the FDM machine often use an additional sonic bath machine to remove support material, though they often do not. Such extra processing causes extra energy use and water use that is expected to add significantly to the ecological impacts of FDM. It was considered outside the scope of this study and thus not measured, but future studies could include it for additional completeness.

The ecological impacts of electricity use were modeled as the US average electricity mix. The actual impacts at UC Berkeley are lower, since California's electricity mix is significantly cleaner than the national average, but the authors believe that the average value is more general, and thus provides better decisions for most prototypers.

### Material Types And Masses

To make fair comparisons, similar materials were used as much as possible between all three machines; however, it was not possible to use the exact same materials, due to limitations on the materials usable by the AM tools. The model material for the FDM is called "ABS plus"; while the actual chemical composition of the material is not published even in material safety data sheets (MSDSes), it is assumed to be chemically similar to ABS, and was modeled as such in SimaPro. To match this, blocks of actual ABS were used as the model material for the CNC mill. The model material for the inkjet was formerly called "ABS-like", now called "Fullcure 720". Its MSDS revealed that it is only like ABS in mechanical properties, not chemically. The databases in SimaPro did not have a material matching it, nor did they have matches for the constituent ingredients listed in the MSDS (Objet 2001), namely exo-1,7,7-trimethylbicyclo[2.2.1]-hept-2-yl acrylate, acrylic monomer, urethane acrylate oligomer, acrylate oligomer, and epoxy acrylate. To estimate a reasonable material substitution, a sensitivity analysis was performed to compare fifteen different materials that appeared most likely to be chemically similar to these ingredients. The ReCiPe Endpoint H eco-impacts were calculated, and extreme high and low values thrown out; the final LCA was performed with two scenarios--one estimating high eco-impacts for Fullcure 720 (using "epoxy resin, liquid" as a substitute, scoring roughly 50% worse than ABS per kg) and one estimating low eco-impacts (using "acrylic acid, at plant", scoring roughly 40% better than ABS). See Appendix 3: Material Sensitivity Analysis for a graph of the 15 materials' impact scores.

Support materials were another case where the additive manufacturing materials differ from milling, because milling generally does not use consumable support material, only fixturing blocks which are reused. (Exceptions exist, but not for the parts tested here.) However, the impacts of support material were easier to determine, because their chemistry better matched items in the LCA databases used. The Dimension FDM support material "SR-30" was comprised of a terpolymer of methacrylic acid, styrene, and butyl acrylate. No database item was available for "terpolymer", but similar chemicals were, and the MSDS (Stratasys 2012) did not list the mass ratios of ingredients, so it was assumed that the material was composed of equal parts of butyl acrylate, styrene, and methyl acrylate. A sensitivity analysis showed that all three materials were within 25% of the same ecological impact, roughly centered around the impact of ABS as measured by ReCiPe Endpoint H points, so it was deemed that further precision was not necessary. See Appendix 3: Material Sensitivity Analysis for a graph of these materials compared to ABS and possible ingredients of the Objet model material. The support material for the Objet, "SUP705", was comprised of ingredients available in the LCA database. Its MSDS (Stratasys 2011) did not specify mass ratios of ingredients to any precision, so it was assumed the material was 30% propylene glycol, 30% ethylene glycol, 30% acrylic acid, and 10% glycerin. Each of these has fairly low impact compared to ABS and other model materials listed above, so further precision was not deemed necessary.

Both the mass of waste material and the material ending up in the final parts were considered as impacts, because of the variation both in material chemistries and part mass. For the CNC machine, the only possibility was that the final part was 100% solid ABS; however, for the FDM machine, one scenario produced 100% solid "ABS plus" while the other produced a 90% hollow part, obviously reducing material impacts greatly. The inkjet machine could not produce hollow parts, but it could vary between producing a part of 100% model material and a part of 10% model material with 90% support material (which had lower eco-impacts per kg). See Appendix 2: Tables of Energy, Material Use, and Waste for all masses.

Waste mass for the CNC process was measured simply by weighing the blocks of raw material before processing, and weighing the final parts after processing. The initial blocks of ABS were significantly larger than the final parts, resulting in 70% of the original material being cut away for the linkage and 81% for the apple; this could be reduced by choosing stock material closer to the size of the desired final parts. Interviewing machine operators and other prototypers to determine how closely their initial blocks match final parts did not yield conclusive results; they did not track this data, and said there was a wide range, based on what they had on hand at the time, or what stock sizes are available to order conveniently, compared to the size of parts desired. The levels of waste for our parts were not uncommon at all, but there was no clear "normal". LCA results showed that material waste impacts were a large portion of the CNC machine's impacts at maximum utilization, so future studies should attempt to measure the percentage of waste from large samples of parts in a wide variety of shop environments, in order to have statistically valid numbers. The theoretical minimum waste possible for these two parts, assuming rectangular blocks of raw material that are exactly the outer dimensions of the apple and linkage, would be 37% for the linkage and 46% for the apple. Obviously this is a rare occurrence, but it reduces the total mass of waste ABS by 78% (65g waste for 89g of parts, as opposed to 209g waste for the same mass of parts), which shows the potentially extreme range for this variable.

Waste mass for the FDM process was measured by collecting and weighing the (miniscule) leftover waste filaments after processing, as well as using the as-yet unpublished data gathered by Mickey Clemon, another Berkeley researcher investigating the impacts of additive manufacturing. Measurement of the mass of uncured liquid waste from the inkjet machine was also supplemented by one additional datapoint from Clemon. No attempt was made to measure the volume of water used to wash support material off parts, as it was assumed to be a low impact relative to the chemicals involved in the material use and waste, but future studies could measure this as well.

### Cutting Fluid

Cutting fluid for the CNC was not required, due to the model material being plastic. However, some CNC machines use cutting fluid by default, and operators often do not bother to change default settings; therefore, it was included for the sake of comprehensiveness in the analysis. The operators of the CNC machine studied reported that the machine uses a mix of 5% TRIM C320 lubricant and 95% water. The TRIM C320 MSDS (Master Chemical Corp. 2006) reports that it is composed of 10-20% triethanolamine (for the LCA, 20% was assumed) and 1-10% monoethanolamine (for the LCA, 10% was assumed); these were the only chemicals identified in the MSDS, despite obviously not adding up to 100%. The other 70% of the product was assumed to be water, in addition to the water it is mixed with to become the final cutting fluid. Future studies could refine this assumption if studying machining and printing in metal rather than plastic, but for this study it was not deemed necessary since cutting fluid is not a requirement here. The cutting fluid mixture is continuously recycled, but it slowly evaporates and/or is aerosolized into the air. The machinists interviewed do not keep strict records of fluid replacement, but they estimated replacing 19 L of cutting fluid annually and 270 L of water annually to keep the proper mix ratio. Amortizing this by the machine's estimated uptime, this translates to .29 L of water and 14 mL of TRIM C320 per job at max utilization. This sounds high, but results showed cutting fluid was not a significant impact, so further precision was not pursued.

## Results

Figure 3, Figure 4, and Figure 5 show the LCA breakdown of impacts by type for one set of scenarios: all three machines making one pair of parts per week but left idling the rest of the time (24 hrs/day, 7 days/wk); the FDM machine is printing parts at 100% fill, the inkjet machine is printing parts at 100% model material rather than support material and printing parts one at a time. Impacts are shown in ReCiPe endpoint H points per year per job (one pair of parts).

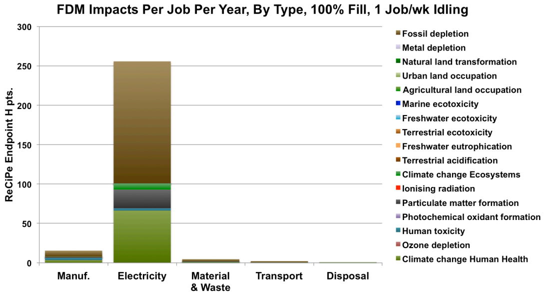

*Figure 3. Ecological impacts by life-cycle stage, showing individual types of impacts, for FDM machine printing with 100% fill, printing one pair of parts per week and left idling the rest of the time.*

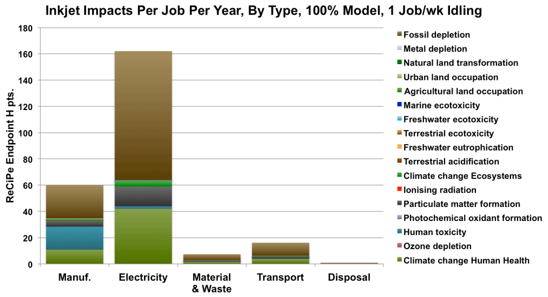

*Figure 4. Ecological impacts by life-cycle stage, showing individual types of impacts, for inkjet machine printing with 100% model material, printing one pair of parts per week, one part at a time, and left idling the rest of the time.*

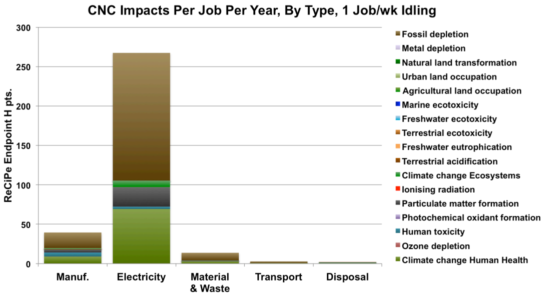

*Figure 5. Ecological impacts by life-cycle stage, showing individual types of impacts, for CNC mill cutting one pair of parts per week and left idling the rest of the time.*

Note that of the 17 types of impacts measured, five are dominant for all the cases above: fossil fuel depletion, climate change damage to ecosystems and human health, particulate matter (smog), and human toxicity; other impact types (metal depletion, land use, marine / freshwater / terrestrial ecotoxicity, freshwater eutrophication, terrestrial acidification, ionizing radiation, photochemical oxidant formation, and ozone depletion) are negligible in the scenarios studied here. This is because the impacts are primarily from energy use, production of metals and electronics (also very energy-intensive), and plastics. If it appears surprising that the manufacturing impacts of the CNC mill are smaller than the inkjet machine, despite the mill being a far more massive machine, recall that these impacts are per job per year--since the mill's lifetime was conservatively assumed to be twice as long as the 3D printers, the impact per job is cut in half.

However, the utilization of machines shown above will only be true for a few users. As mentioned previously, this study compares the machines across three kinds of scenarios: Minimal utilization (1 job/wk) idling; Minimal utilization (1 job/wk) at low power (off when not in use if possible); and Maximum theoretical utilization (running 24 hrs/day, 7 days/wk).

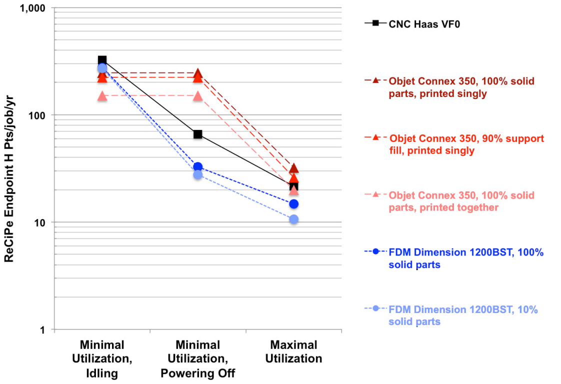

*Figure 6. Total eco-impacts for three scenarios of all machines, on a log scale. For a linear scale and breakdown of impacts by source, see Figure 7 and Figure 8.*

Figure 6 shows that at minimal utilization, the inkjet has the lowest overall impact score if the machines are left idling when not in use. In fact, when the inkjet uses 100% model material and prints both parts together, the impact score is nearly 50% less than the FDM and CNC. This is mainly due to the FDM and CNC using more energy than the inkjet while idle.

A significant change in the overall impact becomes apparent during the minimal utilization, low power case. This represents a more realistic scenario for responsible tool owners. Since the inkjet machine is not turned off, its impact scores remain constant. In

contrast, much less electricity is used by the FDM and CNC; thus the FDM impacts fall by roughly a factor of eight, and CNC by almost a factor of 5. Even when comparing these to the inkjet's best case scenario (printing both parts together using 100% model material), the inkjet has double the impact score of the CNC and five times that of the FDM.

During maximum utilization, the impact per job of all the machines plummets to nearly 1/10th the impacts of the low utilization idling scenario. It appears that the way a machine is used matters much more than the type of machine used. Regardless of the model material density, the FDM machine has the lowest impact score here. By comparison, the best-case impact score of the inkjet (printing both parts at the same time) is twice that of the FDM printing at 10% model material density and around 25% more than the FDM printing at 100% model material density. The CNC impact is double the best-case FDM impact; comparing CNC and inkjet is less clear, however--it scores better than two of the three inkjet scenarios, but worse than the third. Even these results are not as reliable as they appear, given the margins of error.

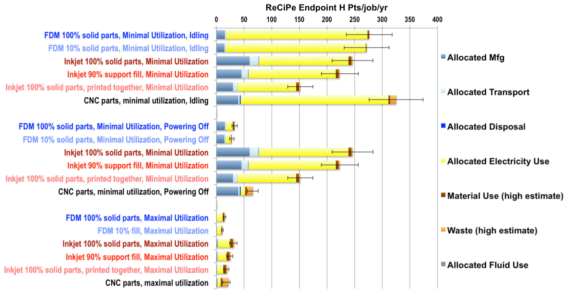

*Figure 7. LCA results broken down to show contributions by life-cycle component, with uncertainty ranges.*

To further delve into the specifics and the margins of uncertainty of these results, Figure 7 provides a detailed look at each usage scenario examined, showing the contributions by life-cycle component. It also shows error bars--these assume the uncertainty for all total impact scores is at least ±15%, and larger for some high utilization scenarios (see description of Figure 8). This range is an assumption based on four factors: first because measurements of emissions are almost never better than ±10% (Ashby 2009), second because average data from databases was used rather than empirical measurements of impacts, third because only one job of two kinds of parts were created by each machine, rather than a broad statistical sampling of many jobs involving many different kinds of parts, and fourth because of the many simplifying assumptions described above.

In the minimal utilization idling scenario, by far the greatest contribution to the total ReCiPe endpoint H score for all machines is allocated electricity use; the (distant) second greatest contributor for all machines is allocated manufacturing (the embodied impacts of the machines). In the minimal utilization low-power scenario, embodied impacts are the dominant impact for the FDM and CNC machines, with electricity use the second greatest contributor. Material use and waste are insignificant for most minimal utilization scenarios, except for the CNC machine if turned off when not in use. The scenarios shown here for the inkjet are the high-eco-impact materials estimate; the low-eco-impact scenarios are even less significant.

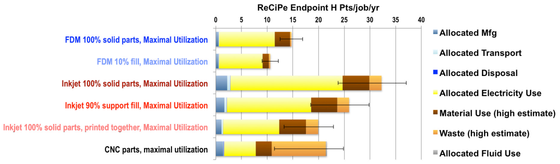

*Figure 8. LCA results for the Maximal Utilization scenario for all machines and part types.*

Figure 8 is simply the bottom third of Figure 7, expanded for readability. Exceptions to the ±15% error rule become visible in Figure 8 where they were not in Figure 7--these exceptions are the lower bounds for inkjet and CNC machines in maximal utilization. For each of these, the upper bound of error is the high-impact scenario plus 15%, while the lower bound of the error is the low-impact scenario minus 15%; the graph bars themselves show the high-impact scenarios. For the inkjet, sensitivity analysis of the "ABS-like" material for the inkjet machine showed that the material composition does matter for maximum-utilization cases. Total life-cycle impacts of the high-impact material assumption are 22% higher than the low-impact material assumption for the scenario with maximum utilization, printing both parts together, with 100% model material. For the scenario at max utilization printing 100% model material but printing one part at a time, the difference was only 13%, because the slowness of processing made electricity use very dominant. For max utilization printing 10% model material and 90% support material, printing one part at a time, the difference was 16%, because the printing speed (and thus electricity impact) was in between the other two scenarios. For the CNC mill, sensitivity analysis of the amount of waste material showed that it matters a great deal. As mentioned earlier, the parts studied here and the initial blocks of ABS caused 70-81% waste, due to poor matching between stock sizes and part sizes, while a theoretically ideal minimum-sized block for each part would generate 78% less waste. This would lower the total impacts for CNC machining by 38%. Though interviews with prototypers showed that the amount of waste here is not extreme, many jobs are likely to have less waste. Thus the low ends of the inkjet and CNC error bars are extended to show the best case of the low material impact scenarios.

At maximal utilization, the FDM machine printing 90% hollow parts is the clear winner over all other scenarios; only the CNC machine comes close at the extremes of all error bars. Even when comparing the FDM machine at minimum utilization to the other machines at maximum utilization, the FDM does well if powered off when not in use. The FDM printing one job per week at 10% solid fill and powered off instead of idling has eco-impacts within error bars of the CNC and inkjet impacts at maximal utilization.

The relative portion of impacts from energy, manufacturing, and material use / waste change significantly between minimal utilization and maximal utilization. In all max utilization cases, embodied impacts of producing the machines have become insignificant, while FDM and CNC manufacturing impacts are very significant in the case of low utilization with powering off. Electricity use is still dominant for both 3D printers in all scenarios, but materials have a larger relative impact than at low utilization. For the FDM machine, waste impacts are always small, because only 1 - 2% of model material is wasted, and even adding support material brings the total waste percentage to 19% for 90% hollow parts and 9% for 100% solid parts. For the inkjet machine, however, 40-45% of liquid ink was wasted, including support material. For the CNC mill, waste becomes the dominant impact at maximum utilization, though it holds a high degree of uncertainty, and could be lower than impacts of material in the final part if stock is well-chosen. As mentioned above, cutting fluid use is included for CNC for the sake of comprehensiveness, but is not required for plastic parts; in any case, it is never a significant percentage of total impacts. Note that although the major sources of impacts change from 3D printing to CNC milling, the distribution of impacts by type of ecological damage remain fairly constant--fossil fuel depletion and climate change remain dominant, with notable contributions from particulates and human toxicity. This is because plastic production (the largest impact for CNC) and average US electricity production (the largest impact for FDM and inkjet) are both fossil fuel industries.

As described above, FDM clearly beats inkjet and CNC at maximum utilization, but the contest between inkjet and CNC is not clear. Inkjet is worse than CNC for two scenarios and better for the third, but the uncertainty ranges on all of them are so large that the comparison is inconclusive. The bottom of the uncertainty range for the worst inkjet scenario is below the top of the uncertainty range for CNC, and the bottom of the uncertainty range for CNC is better than any of the inkjet scenarios, even at the bottoms of their uncertainty ranges. Once again it appears to matter more how the tools are used than which is used.

To check the credibility of the ReCiPe Endpoint H normalization and weighting scheme, the same analysis was also performed using another leading LCA methodology, the IMPACT 2002+ method, shown in Figure 9. While the absolute numbers of points in the IMPACT 2002+ results differed greatly from ReCiPe Endpoint H points, the relative scores of the different scenarios were so similar as to be nearly indistinguishable. The IMPACT 2002+ results support all of the conclusions listed above, with no modifications of any kind. These results also reinforce the credibility of both methodologies.

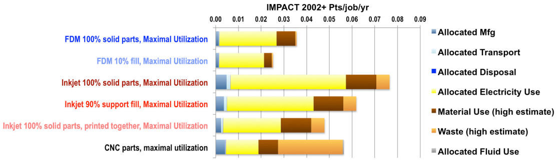

*Figure 9. LCA results for the Maximal Utilization scenario for all machines and part types, using IMPACT 2002+ methodology.*

### Quality

The quality of the products was not a specific requirement of the LCA, as mentioned before. The surface finish of the CNC part, shown in Figure 10, was the smoothest and thus had the highest overall quality out of the three machining techniques, though it was not able to resolve as sharp corners of the "apple" part's seed details as both 3D printers did. The surface finish of the inkjet was smooth but faceted on curved surfaces, implying that the limitation to smoothness was actually the CAD model rather than the printer. (If this were known in advance, a model with more polygons would have been used.) The quality of the FDM, shown in Figure 11, was distinctly worse than either CNC or inkjet, with the layers of deposition clearly seen and felt.

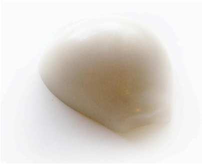

*Figure 10: CNC test part*

*Figure 11: FDM test part*

Changing quality levels might change environmental impacts. The quality level of the FDM and inkjet are not adjustable, but it is possible to have the CNC parts machined at a lower quality level similar to the printed parts. In this case, the CNC would have used less energy, because less processing time would have been required, but the difference in waste impacts would be negligible because the difference in grams of material removed would be insignificant, and any reduction in waste would be an addition to final model material. Increasing the quality of the FDM parts would most likely use a manual sanding process, which would increase worker exposure to plastic particulates. Power sanders would also add impacts through electricity use. Another processes for improving surface finish is to use an acid solution to dissolve the FDM surface to a smoother state; this would definitely add environmental and health impacts (depending on the toxicity). As mentioned before, however, this study assumes the quality for all of the three machines is acceptable, thus these variations were not pursued.

### Characterizing Social Impacts of Additive Manufacturing vs CNC Machining

While the goal of this study was to quantitatively compare environmental impacts, social impacts were also briefly considered in a qualitative manner, inspired by the Global Reporting Initiative guidelines. Results were not conclusive. Only the use phase (operation of the machines) was considered. For worker exposure to toxins, FDM appeared best, as there was no direct worker exposure, while CNC had aerosolized cutting fluid and the inkjet machine had potential (though unlikely) exposure to liquid inks whose MSDSes showed HMIS and NFPA health ratings of 1. Worker safety appeared good for all three, but likely best for the inkjet, since it has neither the high-speed parts of the CNC nor the high temperatures of the FDM. Toxin exposures to local communities from waste is likely to be minimal for all three, but is probably best for FDM because the inkjet machine has the potential for liquid ink spills and the CNC has potential for liquid cutting fluid spills. The additive manufacturing tools required very little worker skill compared to the CNC mill, but arguments can be made for this being positive or negative, since lower-skill jobs are easier to get but higher-skill jobs pay more and are more secure. Both AM tools also required a tiny fraction of the worker time needed by CNC, but again, arguments can be made for this being positive or negative--reduction in labor time may increase quality of life for workers, or may increase unemployment.

## Conclusion

The results of this comparative LCA indicate that the relative sustainability of additive manufacturing vs CNC machining depends primarily on the usage profiles, and then on the specific machines. It cannot be categorically stated that 3D printing is more environmentally friendly than machining, or vice-versa. If machine utilization is low (1 job/week), powering the machines off when not in use results in a large drop in overall environmental impacts. However, the best way to optimize ecological impacts per job is by maximizing tool usage: doing so reduced impacts by nearly a factor of ten for all machines from the low-utilization idling scenarios. Thus the best strategy for sustainable prototyping is to share tools, to have the fewest number of machines running the most jobs each. This means it is usually better to contract jobs out to dedicated job shops than it is to have your own in-house machine, until you have enough demand to keep the tool operating at high utilization. In cases like this, job shops can legitimately argue that they not only provide economic advantage to customers, but also environmental advantage.

To the extent that any one tool was the winner, it was the FDM machine. It had the lowest impacts both in maximal utilization and in minimal utilization if machines were powered off when not in use. The FDM machine scored so well that even at low utilization (if powering off) it is nearly as sustainable as the other machines running at maximum utilization. This also provides an argument for the acceptability of hobbyist-scale desktop FDM machines, as opposed to job shops (as long as the greater convenience of such tools does not cause spurious prototype-making as desktop printers caused spurious paper use). Uncertainties were too high to declare definitively whether machining was better than inkjet at maximal use; it depended on the inkjet machine usage scenario, and even then did not have as clear-cut a winner as the FDM. At minimal utilization, CNC was better than inkjet if responsibly turned off when not in use, but worse if left idling constantly.

The conventional wisdom that additive manufacturing is more sustainable than subtractive manufacturing because it does not waste as much material (and in fact can use less model material by making hollow parts) was partly confirmed, because waste is a much smaller percentage of the impacts for AM. However, it was partly contradicted, because impacts from AM's greater energy use can overwhelm savings in material impacts, and because one of the 3D printers still had significant material impacts--both from it producing roughly 40% waste, and from its model material having higher ecological impacts per gram than traditional ABS plastic due to higher toxicity of ingredients.

Measuring many kinds of impacts and comparing them via a normalized weighted scheme proved vital to making an informed decision about which tool is the most sustainable choice. If the study only measured energy use, the CNC machine would appear to have the best impacts of all three tools at maximum utilization; however, if the study only measured waste, the CNC machine would appear the worst of the three in the same situation. Most studies on the environmental impacts of CNC machining only measure energy use, while results here clearly show that these impacts are less important than material waste (at high machine utilization, when machining ABS plastic, with a high percentage of material removal). Cutting fluid use, while shown by previous studies to be the biggest direct worker health risk, were found to be negligible in comparison to the fossil fuel depletion, climate change, and toxicity from electricity production and waste that cause health risks both to workers and the world at large. Having a credible scientific method to compare these different impact types saves a job shop owner, prototype lab manager, or other decision-maker (none of whom are environmental scientists) from comparing these environmental and health impacts by uneducated guesswork.

These conclusions assume the quality of surface finish and tolerances for all three machines are acceptable; additional processing to raise quality of FDM parts, or less processing by the CNC mill to reduce impacts in exchange for lower quality, could change results. If these three

processes are all acceptable choices, the results from this study can be used to help prototypers and job shop owners make informed decisions about which tool to use, and how to use it.

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## References

Anderson, C. (2013). The Makers Revolution. *Seminars About Long-Term Thinking*. Lecture conducted from the Long Now Foundation, San Francisco, CA.

Ashby, M. F. (2009). *Materials and the environment: eco-informed material choice*. Butterworth-Heinemann, p.267.

Avram, O., Stroud, I., Xirouchakis, P. (2011). A multi-criteria decision method for sustainability assessment of the use phase of machine tool systems. *International Journal of Advanced Manufacturing Technology*, Mar 2011, Vol. 53 Issue 5-8, p.811.

Azevedo, M., Oliveira, M., Pereira, J.P., and Reis, A. (2011). Comparison of Two LCA Methodologies in the Machine-Tool Environmental Performance Improvement Process. *Glocalized Solutions for Sustainability in Manufacturing*: 575-80.

Baumers, M., Tuck, C., Bourell, D.L. et al. (2011). Sustainability of additive manufacturing: measuring the energy consumption of the laser sintering process. *IMechE Part B: J Eng Manuf* 225:2228– 2239

Behrendt, T., Zein, A., & Min, S. (2012). "Development of an energy consumption monitoring procedure for machine tools." *CIRP Annals-Manufacturing Technology*, 61(1), 43-46.

Bezerra de Araujo, J., Gomes de Oliveira, J.F., (2012). Evaluation of Two Competing Machining Processes Based on Sustainability Indicators. *Proceedings of the 19th CIRP Conference on Life Cycle Engineering*, University of California at Berkeley, Berkeley, USA, May 23 - 25.

Chen, Y., Diaz, N., Helu, M., and Jayanathan, S. (2009). *Environmental Analysis of Milling Machine Tool Use in Various Manufacturing Environments*. Unpublished report for UC Berkeley class CE 268E, Dec 8 2009. p.34.

Childers, Jean C. (1994). The Chemistry of Metalworking Fluids. *Metalworking Fluids*, ed. Jerry P. Byers, Marcel Dekker, Inc., New York, New York.

Choi, A.C.K., Kaebernick, H., Lai, W.H. (1997). Manufacturing processes modeling for environmental impact assessment. *Journal of Materials Processing Technology*, 70(1), 231-238.

Dahmus, J., & Gutowski, T. (2004, November). An environmental analysis of machining. In *ASME International Mechanical Engineering Congress and RD&D Exposition, Anaheim, California, USA.*

Diaz, N., Helu, M., Jayanathan, S., Chen, Y., Horvath, A., Dornfeld, D. (2010). *Environmental Analysis of Milling Machine Tool Use in Various Manufacturing Environments.* UC Berkeley: Laboratory for Manufacturing and Sustainability.

Diaz, N., Redelsheimer, E., Dornfeld, D. (2011). *Energy Consumption Characterization and Reduction Strategies for Milling Machine Tool Use.* UC Berkeley: Laboratory for Manufacturing and Sustainability.

Diaz, N., Ninomiya, K., Noble, J., & Dornfeld, D. (2012). Environmental impact characterization of milling and implications for potential energy savings in industry. *Procedia CIRP*, 1, 518-523.

Drizo, A., & Pegna, J. (2006). Environmental impacts of rapid prototyping: an overview of research to date. *Rapid prototyping journal*, 12(2), 64-71.

Duflou, J. R., Sutherland, J. W., Dornfeld, D., et al. (2012). Towards energy and resource efficient manufacturing: A processes and systems approach. *CIRP Annals-Manufacturing Technology*, 61(2), 587-609.

Gonzalez, A. (2007). Machine Tool Utilisation Phase: Costs and Environmental Impacts with a Life Cycle View. (Student paper). KTH.

Helu, M., Vijayaraghavan, A., & Dornfeld, D. (2011). Evaluating the relationship between use phase environmental impacts and manufacturing process precision. CIRP Annals-Manufacturing Technology, 60(1), 49-52.

Huang, S. H., Liu, P., Mokasdar, A., & Hou, L. (2012). Additive manufacturing and its societal impact: a literature review. *The International Journal of Advanced Manufacturing Technology*, 1-13.

Kara, S., Li, W. (2011). Unit process energy consumption models for material removal processes. *CIRP Annals - Manufacturing Technology*. 60(1):37-40.

Luo, Y., Ji, Z., Leu, M. C., & Caudill, R. (1999). Environmental performance analysis of solid freedom fabrication processes. In *Electronics and the Environment, 1999. ISEE-1999. Proceedings of the 1999 IEEE International Symposium on* (pp. 1-6). IEEE.

Master Chemical Corp. (2006), Material Safety Data Sheet for TRIM C320. Accessed 3/10/13 from http://www1.mscdirect.com/MSDS/MSDS00024/80105463-20070621.PDF .

Mognol, P., Lepicart, D., Perry, N. (2006). Rapid prototyping: energy and environment in the spotlight. *Rapid Prototyping Journal*, 12(1):26-34.

Muñoz, A. A., & Sheng, P. (1994). An analytical approach for determining the environmental impact of machining processes. *Journal of Materials Processing Technology*, 53(3), 736-758.

Objet inc. (2001). Material Safety Data Sheet for Fullcure 720. Accessed 3/10/13 from http://www.laserlines.co.uk/images/m2_13/objet/materials/DOC-06118_A1_Objet%20FullCure720%20RGD720_Version%202_Eu.pdf .

Ogaldez, J., Barker, A., & Zhao, F. (2012). Water Footprint Quantification of Machining Processes. In *Lecture Notes in Applied and Computational Mechanics: Leveraging Technology for a Sustainable World: Proceedings of the 19th CIRP Conference on Life Cycle Engineering, University of California at Berkeley*. Berkeley, USA, May 23-25 2012 (p. 461). Springer.

Petrovic, V., Vicente Haro Gonzalez, J., Jorda Ferrando, O., Delgado Gordillo, J., Ramon Blasco Puchades, J., & Portoles Grinan, L. (2011). Additive layered manufacturing: sectors of industrial application shown through case studies. *International Journal of Production Research*, 49(4), 1061-1079.

Pré Consultants. (2009). *ReCiPe 2008, (First Edition)*. Amersfoort, Netherlands: Goedkoop, M. et al.

Sheehy, N.P., Chapman, A.J. (1988). The Safety of CNC and Robot Technology. *Journal of Occupational Accidents*, Volume 10, Issue 1, June 1988, pp.21–28.

Sreenivasan R., Bourell, D.L. (2009). Sustainability Study In Selective Laser Sintering – An Energy Perspective. *The 20th Solid Freeform Fabrication Symposium*, UT Austin, pp 3-5.

Stratasys inc. (2012). Material Safety Data Sheet for SR-30 Soluble Support Material. Accessed 3/10/13 from http://www.stratasys.com/~/media/Main/Secure/MSDS/SR-30_Support/MSDS_US_SR-30_Soluble-Support-Material.pdf .

Stratasys inc. (2011). Material Safety Data Sheet for SUP705 Objet Support Material. Accessed 3/10/13 from http://www.stratasys.com/materials/material-safety-data-sheets/polyjet/~/media/Main/Secure/MSDS/Support-Materials/DOC-06136-Objet-Support-SUP705-EU.ashx

Telenko, C., Seepersad, C. (2012). A Comparison of the Energy Efficiency of Selective Laser Sintering and Injection Molding of Nylon Parts, *Rapid Prototyping Journal*, Vol.18 Iss: 6, pp.472 - 481.

Thomasnet.com specification sheet, Baldor BM3710T brake motor. Retrieved 3/10/13 from http://ps.thomasnet.com/productsearch/itemdetail.html?cid=10004116&cncat=1825&cnprod=3001002&cnitem=1146&WTZO=Product+Search+Flattened&searchpos=3 .

# Appendix 1: Manufacturing-Stage LCA Data

### Data & Assumptions for LCA of FDM Dimension 1200BST

**Raw Materials & Manufacturing & Disposal**

| Part name / number | Mass / Unit (g) | Units | Total Mass (g) | Material | Manufacturing proce | Disposal Method | Notes / Assumptions |
|---|---|---|---|---|---|---|---|
| **Steel Components** | | | | | | | |
| Front door steel | 2,027 | 1 | 2,027 | Steel, mild | sheet bending, stampi | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, possible heat treating, etc. |
| Air ducts | 9,432 | 1 | 9,432 | Steel, mild | sheet bending, stampi | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, possible heat treating, etc. |
| interior steel rear wall | 3,111 | 1 | 3,111 | Steel, mild | sheet bending, stampi | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, possible heat treating, etc. |
| interior steel floor plate | 2,712 | 1 | 2,712 | Steel, mild | sheet bending, stampi | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, possible heat treating, etc. |
| steel drive shafts | 4,148 | 1 | 4,148 | Steel, mild | extruding | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, possible heat treating, etc. |
| steel lead screws | 453 | 1 | 453 | Chromium steel | Turning, mostly dressi | Durable goods | |
| steel support beams | 2,144 | 1 | 2,144 | Steel, mild | Average Metal Workin | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, possible heat treating, etc. |
| FDM Print head steel | 8,284 | 1 | 8,284 | Steel, mild | sheet bending, stampi | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, possible heat treating, etc. |
| Brackets holding shafts | 8,784 | 1 | 8,784 | Steel, mild | cast | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, possible heat treating, etc. |
| Platform table (steel) | 10,408 | 1 | 10,408 | Steel, mild | Hot rolling, machining | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, possible heat treating, etc. |
| Platform table beam | 2,870 | 1 | 2,870 | Steel, mild | Cold rolling | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, possible heat treating, etc. |
| Drive Motors - steel | 4,595 | 1 | 4,595 | Electric steel | Sheet rolling (half) cas | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, possible heat treating, etc. |
| Fasteners (all) | 120 | 1 | 120 | Steel, mild | Extrusion, machining | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, possible heat treating, etc. |
| Upper box | 1,591 | 1 | 1,591 | Steel, mild | sheet bending, stampi | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, possible heat treating, etc. |
| Rear plate | 11,149 | 1 | 11,149 | Steel, mild | sheet bending, stampi | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, possible heat treating, etc. |
| (Missing mass, steel) | 22,694 | 1 | 22,694 | Steel, mild | sheet bending, stampi | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, possible heat treating, etc. |
| **Plastic Components** | | | | | | | |
| External enclosure | 22,234 | 1 | 22,234 | polycarbonate | injection-molding | Durable goods | db didn't have roto-molding, so used injection-molding. |
| Foam insulation | 2,300 | 1 | 2,300 | polyurethane foam | (included) | Durable goods | |
| box for reading height | 187 | 1 | 187 | polycarbonate | injection-molding | Durable goods | db didn't have roto-molding, so used injection-molding. |
| FDM print head plastic | 142 | 1 | 142 | polycarbonate | injection-molding | Durable goods | |
| Material/Support Cartridges | 1,340 | 1 | 1,340 | polycarbonate | injection-molding | Durable goods | |
| Platform (plastic) | 51 | 1 | 51 | ABS | injection-molding | Durable goods | |
| Wiring (plastic) ---- DON'T USE | 1,570 | 1 | 1,570 | PVC | Extrusion | landfill | used extrusion for plastic pipes (only other choice was extrusion for films). |
| Power cable (plastic) ---- DON'T USE | 105 | 1 | 105 | PVC | Extrusion | landfill | |
| (Missing mass, plastic) | 8,776 | 1 | 8,776 | polycarbonate | injection-molding | Durable goods | |
| **Electronic Components & Motor Windings** | | | | | | | |
| display electronics | --- | .2 p | --- | LCD Flat Screen, 17 ir | --- | Durable goods | |
| optosensors | 9 | 1 | 9 | PCB | (included) | Durable goods | |
| LED Lighting | 200 | 1 | 200 | LED | (included) | Durable goods | |
| Main electronics | --- | 1 p | --- | Desktop computer (no | (included) | Durable goods | |
| Wiring, internal | --- | 6 m | --- | network cable (cat 5) | (included) | Durable goods | |
| Power cable | --- | 2 m | --- | Cable, connector for c | (included) | Durable goods | |
| Fans | 2,217 | 1 | 2,217 | Computer Fan | (included) | Durable goods | |
| Wiring (copper) ---- DON'T USE | 4,887 | 1 | 4,887 | Copper wire | (included) | Durable goods | |
| Power cable (copper) ---- DON'T USE | 326 | 1 | 326 | Copper wire | (included) | Durable goods | |
| Drive Motors - copper | 912 | 1 | 912 | Copper wire | (included) | Durable goods | |
| (Missing mass, copper) | 2,220 | 1 | 2,220 | Copper wire | (included) | Durable goods | |
| | | | | | | Durable goods | |
| **Misc. Components** | | | | | | Durable goods | |
| Front door glass | 3,114 | 1 | 3,114 | glass | (included) | Durable goods | |
| Rubber drive belts | 77 | 1 | 77 | Synthetic rubber | (included) | Durable goods | |
| Aluminum drive gears | 139 | 1 | 139 | Aluminum | cast | Durable goods | |
| **Packaging --- not included** | --- | --- | --- | --- | --- | --- | |

**Transportation**

| Transportation mode | Distance (km) | Mass shipped (kg) | Ton-km | Notes / Assumptions |
|---|---|---|---|---|
| Truck | 6400 | 148 | 947.2 | Shipping from Minneapolis, MN to Berkeley, CA and back at end of life |

**Lifetime of Items**

| Item | Lifespan (years) | Notes / Assumptions |
|---|---|---|
| Whole machine | 3 | Preliminary survey results |
| Whole machine | 10 | Mcor claimed 10-year lifespan |

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### Data & Assumptions for LCA of Haas VF0 CNC Mill

**Raw Materials & Manufacturing & Disposal**

| Part name / number | Mass / Unit | # of Units | Total Mass (kg) | Material | Manufacturing process | Disposal Method | Notes / Assumptions |
|---|---|---|---|---|---|---|---|
| **Cast Iron** | | | | | | | |
| Main spine | 1,177.15 | 1 | 1,177.15 | Iron, cast | (included) | Durable goods | didn't add mfg process, but added powder coating for 4m^2 |
| Spine arm for Tool | 53.94 | 1 | 53.94 | Iron, cast | (included) | Durable goods | |
| Spine arm for spindle | 74.22 | 1 | 74.22 | Iron, cast | (included) | Durable goods | |
| Spine foot under mill | 510.48 | 1 | 510.48 | Iron, cast | (included) | Durable goods | |
| **Steel Components** | | | | | | | |
| main steel box | 185.51 | 1 | 185.51 | Steel, mild | sheet cutting, bending, painting | Durable goods | didn't add mfg process, but added powder coating for 8m^2 |
| grey skirt | 47.06 | 1 | 47.06 | Steel, mild | sheet cutting, bending, painting | Durable goods | didn't add mfg process, but added powder coating for 4m^2 |
| front doors | 26.53 | 1 | 26.53 | Steel, mild | sheet cutting, bending, painting | Durable goods | didn't add mfg process, but added powder coating for 2m^2 |
| Spindle box (hollow | 35.62 | 1 | 35.62 | Steel, mild | sheet cutting, bending, painting | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, |
| Spindle (solid steel) | 30.19 | 1 | 30.19 | Steel, mild | sheet cutting, bending, painting | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, |
| Spine arm for control | 31.15 | 1 | 31.15 | Steel, hot-rolled | drawing of pipes | Durable goods | |
| Tool changer shell | 15.76 | 1 | 15.76 | Steel, mild | sheet cutting, bending, painting | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, |
| chucks / bits (steel | 40.26 | 1 | 40.26 | Steel, mild | Machining | Durable goods | Using Chromium steel and "Steel product mfg, average metal working/RER S" |
| X-slide plate for tool | 11.66 | 1 | 11.66 | Steel, mild | sheet cutting, bending, painting | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, |
| Tool changer vertical | 5.46 | 1 | 5.46 | Steel, mild | sheet cutting, bending, painting | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, |
| Tool changer tool | 52.81 | 1 | 52.81 | Steel, mild | Machining | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, |
| Rear electronics box | 71.07 | 1 | 71.07 | Steel, mild | sheet cutting, bending, painting | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, |
| x axis platform | 134.55 | 1 | 134.55 | Steel, mild | sheet cutting, bending, machining | Durable goods | Using "Steel product mfg, average metal working/RER S" because lots of processes |
| y axis platform | 46.13 | 1 | 46.13 | Steel, mild | sheet cutting, bending, machining | Durable goods | Using "Steel product mfg, average metal working/RER S" because lots of processes |
| central platform base | 13.95 | 1 | 13.95 | Steel, mild | machining | Durable goods | |
| central platform | 78.30 | 1 | 78.30 | Steel, mild | machining | Durable goods | |
| Vise top large block | 12.11 | 1 | 12.10987643 | Steel, mild | sheet cutting, bending, machining | Durable goods | Using "Steel product mfg, average metal working/RER S" because lots of processes |
| Vise top small block | 7.40 | 1 | 7.400480038 | Steel, mild | sheet cutting, bending, machining | Durable goods | Using "Steel product mfg, average metal working/RER S" because lots of processes |
| Vise base (steel) | 34.60 | 1 | 34.59964693 | Steel, mild | sheet cutting, bending, machining | Durable goods | Using "Steel product mfg, average metal working/RER S" because lots of processes |
| Vise Dowel (steel) | 3.22 | 1 | 3.220681381 | Steel, mild | sheet cutting, bending, machining | Durable goods | Using "Steel product mfg, average metal working/RER S" because lots of processes |
| Plate at Back (steel) | 16.40 | 1 | 16.40279558 | Steel, mild | sheet cutting, bending, machining | Durable goods | Using "Steel product mfg, average metal working/RER S" because lots of processes |
| Cutting fluid Box | 37.79 | 1 | 37.79 | Steel, mild | sheet cutting, bending, painting | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, |
| **Electronic** | | | | | | | |
| fan in top of spindle | 2.14 | 1 | 2.14 | Fan | (included) | Durable goods | |
| Control box | --- | 1 | pieces | Desktop PC | (included) | Durable goods | |
| CRT monitor | --- | 1 | pieces | CRT, 12-inch | (included) | Durable goods | used .7 of a 17" CRT monitor |
| Electronics in rear | --- | 1 | pieces | Power electronics? | (included) | Durable goods | used 20 PC power supplies |
| Power cables (total | --- | 26.2128 | meters | power cable | (included) | Durable goods | |
| Control cables (total | --- | 21.336 | meters | signal cable | (included) | Durable goods | |
| **Motors (incl. Windings)** | | | | | | | |
| Z-drive motor | 27.72 | 1 | 27.72 | Steel, electric | Machining | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, |
| Z-drive motor | 5.50 | 1 | 5.50 | Copper wire | (included) | Durable goods | |
| X- and Y-drive motors | 21.72 | 1 | 21.72 | Steel, electric | Machining | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, |
| X- and Y-drive motors | 4.31 | 1 | 4.31 | Copper wire | (included) | Durable goods | |
| Spindle motor | 136.88 | 1 | 136.88 | Steel, electric | Machining | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, |
| Spindle motor | 27.15 | 1 | 27.15 | Copper wire | (included) | Durable goods | |
| Tool changer motor | 10.48 | 1 | 10.48 | Steel, electric | Machining | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, |
| Tool changer motor | 2.08 | 1 | 2.08 | Copper wire | (included) | Durable goods | |
| Oil pump motor | 33.88 | 1 | 33.88 | Steel, electric | Machining | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, |
| Oil pump motor | 6.72 | 1 | 6.72 | Copper wire | (included) | Durable goods | |
| Other oil pump motor | 8.38 | 1 | 8.38 | Steel, electric | Machining | Durable goods | Using "Steel product mfg, average metal working/RER S" because no process for stamping, and should also include painting / powder coating, |
| Other oil pump motor | 1.66 | 1 | 1.66 | Copper wire | (included) | Durable goods | |
| **Misc. components** | | | | | | | |
| Windows polycarb | 8.35 | 1 | 8.35 | Polycarbonate | sheet extrusion | Durable goods | |
| Aluminum cylinder for | 0.65 | 1 | 0.65 | Aluminum | Extrusion, Turning | Durable goods | |
| Vise Aluminum | 1.59 | 1 | 1.59 | Aluminum | Extrusion | Durable goods | |
| Plastic Tubing (total | 1.48 | 1 | 1.48 | PET | Extrusion | Durable goods | |

**Transportation**

| Transportation | Distance (km) | Mass shipped (kg) | Ton-km | Notes / Assumptions |
|---|---|---|---|---|
| Truck, 32-ton diesel | 1160 | 2,955 | 3,427.27 | From Oxnard, CA to Berkeley, CA and back again at end of life |

**Lifetime of Items**

| Item | Lifespan (yrs) | Notes / Assumptions |
|---|---|---|
| whole machine | 10 | from Diaz et al. 2010 |
| whole machine | 10 | Dahmus et al. 2004 says "In 1989, 60% of metal cutting machines in the US were more than 10 years old. |

**Usage Impacts**

| Energy or Material | Amount | Unit | Notes / Assumptions | | | |
|---|---|---|---|---|---|---|
| Electricity use | see elsewhere | | | | | |
| lubricating oil use | 0.106198416 | kg/yr | | | | |
| **Cutting fluid** | | | | | | |
| triethanolamine | 3.78541178 | kg/yr | | | | For Etcheverry, not allocated |
| monoethanolamine | 1.89270589 | kg/yr | | | | For Etcheverry, not allocated. |
| water in C320 itself | 0.013248941 | m^3/yr | 13.24894123 | L/yr --> | 0.014343583 | L/part allocated at max utilization (27 parts/wk, 52 wks/yr, 38% time on this job, Etcheverry runs at 25% utilization) |
| water added | 0.270386556 | m^3/yr | 270.3865557 | L/yr --> | 0.292726186 | L/part allocated at max utilization (27 parts/wk, 52 wks/yr, 38% time on this job, Etcheverry runs at 25% utilization) |

## Data & Assumptions for LCA of Inkjet 3D Printing (Connex 350)

**Raw Materials & Manufacturing & Disposal**

| Part name / number | Mass / Unit (g) | # of Units | Total Mass (g) | Material | Manufacturing process | Disposal Method | Notes / Assumptions |
|---|---|---|---|---|---|---|---|
| **Steel Components** | | | | | | | |
| Front Door Hinge | 8,525 | 1 | 8,525 | Steel, low-alloyed, at plant/RER S | Steel product manufacturing, average metal working/RER S | Durable goods | |
| Front Door Bracket | 360 | 1 | 360 | Steel, low-alloyed, at plant/RER S | Steel product manufacturing, average metal working/RER S | Durable goods | |
| Front Steel Panel | 9,803 | 1 | 9,803 | Steel, low-alloyed, at plant/RER S | Steel product manufacturing, average metal working/RER S | Durable goods | |
| Odor Filter Compartment | 3,562 | 1 | 3,562 | Steel, low-alloyed, at plant/RER S | Steel product manufacturing, average metal working/RER S | Durable goods | |
| Top Lid Air Shocks | 591 | 1 | 591 | Steel, low-alloyed, at plant/RER S | Steel product manufacturing, average metal working/RER S | Durable goods | |
| Top lid metal hinge (Z-shape) | 10,612 | 1 | 10,612 | Steel, low-alloyed, at plant/RER S | Steel product manufacturing, average metal working/RER S | Durable goods | |
| Rear steel supporting frame (in rear supporting lid (tube)) | 16,350 | 1 | 16,350 | Steel, low-alloyed, at plant/RER S | Steel product manufacturing, average metal working/RER S | Durable goods | |
| Steel frames, rear verticals (tube) | 17,548 | 1 | 17,548 | Steel, low-alloyed, at plant/RER S | Steel product manufacturing, average metal working/RER S | Durable goods | |
| Steel frame vert side plates | 28,014 | 1 | 28,014 | Steel, low-alloyed, at plant/RER S | Steel product manufacturing, average metal working/RER S | Durable goods | |
| Bottom side bumper (steel C) | 55,934 | 1 | | Steel, low-alloyed, at plant/RER S | Steel product manufacturing, average metal working/RER S | Durable goods | |
| Bottom side floor beam (steel tube) | 8,915 | 1 | 8,915 | Steel, low-alloyed, at plant/RER S | Steel product manufacturing, average metal working/RER S | Durable goods | [side floor beam in SimaPro] |
| Bottom floor (steel) | 22,030 | 1 | 22,030 | Steel, low-alloyed, at plant/RER S | Steel product manufacturing, average metal working/RER S | Durable goods | |
| Back case panel | 16,163 | 1 | 16,163 | Steel, low-alloyed, at plant/RER S | Steel product manufacturing, average metal working/RER S | Durable goods | |
| Stage (steel) | 7,874 | 1 | 7,874 | Steel, low-alloyed, at plant/RER S | Steel product manufacturing, average metal working/RER S | Durable goods | |
| platform around stage (steel) | 4,280 | 1 | 4,280 | Steel, low-alloyed, at plant/RER S | Steel product manufacturing, average metal working/RER S | Durable goods | |
| Steel frame for platform: front and rear beams (L-shape) | 3,757 | 1 | 3,757 | Steel, low-alloyed, at plant/RER S | Metal working machine operation, process heat from light fuel oil/RER S | Durable goods | |
| Side Bits (L Shape) | 4,134 | 1 | 4,134 | Steel, low-alloyed, at plant/RER S | Metal working machine operation, process heat from light fuel oil/RER S | Durable goods | |
| Side Steel Mount for the Track | 1,273 | 1 | 1,273 | Steel, low-alloyed, at plant/RER S | Metal working machine operation, process heat from light fuel oil/RER S | Durable goods | [side steel mount] |
| Steel Plate at Back of the Track (Bent) | 2,162 | 1 | 2,162 | Steel, low-alloyed, at plant/RER S | Metal working machine operation, process heat from light fuel oil/RER S | Durable goods | |
| Steel Plate at the Back of the Track | 936 | 1 | 936 | Steel, low-alloyed, at plant/RER S | | Durable goods | |
| Steel Lead Screws | 575 | 1 | 575 | Chromium steel 18/8, at plant/RER S | Turning, chromium steel, CNC, average/RER S | Durable goods | [made this the same as for the FDM] |
| Print Heads | 201 | 1 | 201 | Steel, low-alloyed, at plant/RER S | | Durable goods | |
| Material/Support Holder | 7,125 | 1 | 7,125 | Steel, low-alloyed, at plant/RER S | Steel product manufacturing, average metal working/RER S | Durable goods | |
| Side Doors - steel | 7,359 | 1 | 7,359 | Steel, low-alloyed, at plant/RER S | Steel product manufacturing, average metal working/RER S | Durable goods | |
| Print head frame | 5000 | 1 | 5,000 | Steel, low-alloyed, at plant/RER S | Steel product manufacturing, average metal working/RER S | Durable goods | |
| Drive Motor - steel | 4595 | 1 | 4,595 | Steel, electric, un- and low-alloyed, at plant/RER S | Steel product manufacturing, average metal working/RER S | Durable goods | |
| **Aluminum Components** | | | | | | | |
| Aluminum Side Bar (running along the side of the platform) | 1,668 | 1 | 1,668 | Aluminum, cast, semi-permanent mold (SPM), at plant/kg/US | (included) | Durable goods | |
| Aluminum track Bar (raising and lowering the stage) | 445 | 1 | 445 | Aluminum, cast, semi-permanent mold (SPM), at plant/kg/US | (included) | Durable goods | |
| Aluminum printer head track- track that the Printer Heads Move Along | 2,771 | 1 | 2,771 | Aluminum, cast, semi-permanent mold (SPM), at plant/kg/US | (included) | Durable goods | |
| Aluminum Bar | 2,902 | 1 | 2,902 | Aluminum, cast, semi-permanent mold (SPM), at plant/kg/US | (included) | Durable goods | |
| Aluminum Bar Calibrating bar (light colored aluminum) | 1,394 | 1 | 1,394 | Aluminum, cast, semi-permanent mold (SPM), at plant/kg/US | (included) | Durable goods | |
| **Glass Components** | | | | | | | |
| Top lid glass | 5,451 | 1 | 5,451 | Flat glass, coated, at plant/RER S | (included) | Durable goods | |
| **Plastic Components** | | | | | | | |
| Top lid case | 16,444 | 1 | 16,444 | Polyurethane, rigid foam, at plant/RER S | Injection moulding/RER S | Durable goods | Corrected volume calcs, corrected in SimaPro |
| Front Doors - plastic | 25,238 | 1 | 25,238 | Polyurethane, rigid foam, at plant/RER S | Injection moulding/RER S | Durable goods | |
| Cable housing to print head | 446 | 1 | 446 | Polycarbonate E | Injection moulding/RER S | Durable goods | (not sure if injection molding should be here. made it 0 kg in SimaPro) |
| Cable housing (blue cable) | 149 | 1 | 149 | Polycarbonate E | Injection moulding/RER S | Durable goods | |
| Side Doors - plastic | 23,254 | 1 | 23,254 | Polyurethane, rigid foam, at plant/RER S | Injection moulding/RER S | Durable goods | (this is just an estimate of the empty case.) |
| Material/Support Cartiges | 3,717 | 1 | | Polycarbonate E | Injection moulding/RER S | Durable goods | |
| **Rubber Components** | | | | | | | |
| Drive Belts (within the track system) | 83 | 1 | 83 | Synthetic rubber, at plant/RER S | | Durable goods | |
| **Electronic Components & Motor Windings** | | | | | | | |
| Cables (all) | 19 | 1 | 19 | Data cable | (included) | Durable goods | (listed as "cable, print cable,...." under Connex main electronics) |
| Fans | 419.00 | 1 | — | Computer fan | (included) | Durable goods | roughly estimated from this source: http://www.frozencpu.com/products/16099/fan-1003/Phobya_120mm_x_25mm_G-Silent_12_Black_Edition_-_2000_RPM_78353.html?tl=g36c435 |
| Circuit Boards | 0.11 | 1.00 | 0.11 | Printed Wiring Board, lead-free | (included) | Durable goods | (listed directly in Connex main electronics) |
| drive motor - copper | 912 | 1 | — | Copper | Wire drawing | Durable goods | (currently estimated as the same as the FDM. Drive Motor - Copper) |
| Power Cable (2 m long) | — | 1 | — | Three-conductor power cable | (included) | Durable goods | |
| Main electronics (Desktop computer) | — | 1.5 | — | Desktop PC | (included) | Durable goods | Estimating that all the circuitry in the two boxes of the right-hand side plus the circuitry in the back wall adds up to equivalent of 1.5 PCs w/ no screen. |
| | 332,992 | | | | | | |

**Transportation**

| Transportation mode | Distance (km) | Mass shipped (kg) | Ton-km | Notes / Assumptions |
|---|---|---|---|---|
| Freighter | 12,560 | 500 | 6279.77 | Shipping from Tel Aviv to Houston, TX. Calculated using: http://www.searates.com/reference/portdistance/ |
| 32 ton truck | 3,093 | 500 | 1546.5 | From Houston, TX to Berkeley, CA |
| Total Freighter shipping(Return trip also) = | 12,560 | | | |
| Total Truck (Return trip also) = | 3093 | | | |

**Lifetime of Items**

| Item | Monthly Consumpt. (units) | Notes / Assumptions |
|---|---|---|
| (see Energy doc) | | |

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## Appendix 2: Tables of Energy, Material Use, and Waste

| | FDM Dimension 1200BST | | | | | | Objet Connex 350 | | | | | | CNC Haas VF0 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | FDM 100% solid parts, Minimal Utilization, Idling | FDM 100% solid parts, Minimal Utilization, Powering Off | FDM 100% solid parts, Maximal Utilization | FDM 10% solid parts, Minimal Utilization, Idling | FDM 10% solid parts, Minimal Utilization, Powering Off | FDM 10% fill, Maximal Utilization | Inkjet 100% solid parts, Minimal Utilization | Inkjet 100% solid parts, Maximal Utilization | Inkjet 100% solid parts, printed together, Minimal Utilization | Inkjet 100% solid parts, printed together, Maximal Utilization | Inkjet 90% support fill, Minimal Utilization | Inkjet 90% support fill, Maximal Utilization | CNC parts, minimal utilization, Idling | CNC parts, minimal utilization, Powering Off | CNC parts, maximal utilization |
| Running power (W) | 680 | 680 | 680 | 560 | 560 | 560 | 740 | 740 | 740 | 740 | 740 | 740 | 1,159 | 1,159 | 1,159 |
| Running time per unit (sec) | 11,580 | 11,580 | 11,580 | 10,980 | 10,980 | 10,980 | 21,812 | 21,812 | 10,906 | 10,906 | 16,380 | 16,380 | N/A | N/A | N/A |
| Running time per unit (hrs) | 3.21666667 | 3.21666667 | 3.21666667 | 3.05 | 3.05 | 3.05 | 6.05888889 | 6.05888889 | 3.02944444 | 3.02944444 | 4.55 | 4.55 | 0.59555 | 0.59555 | 0.59555 |
| Number of units created per week (#) | 1 | 1 | 27 | 1 | 1 | 27 | 1 | 27 | 1 | 27 | 1 | 27 | 1 | 1 | 27 |
| Total running time per week (hrs/wk) | 3.22 | 3.22 | 86.85 | 3.05 | 3.05 | 82.35 | 6.06 | 163.59 | 3.03 | 81.80 | 4.55 | 122.85 | 0.60 | 0.60 | 16.08 |
| **Running energy per week (Wh/wk)** | 2,187 | 2,187 | 59,058 | 1,708 | 1,708 | 46,116 | 4,484 | 121,057 | 2,242 | 60,528 | 3,367 | 90,909 | 690 | 690 | 18,637 |
| | | 0 | | | 0 | | | | | | | | | | |
| Idle power for setup/cleanup (W) | 460 | 460 | 460 | 460 | 460 | 460 | standby | standby | standby | standby | standby | standby | 323 | 323 | 323 |
| Idle time per unit (hrs) | 0.03333333 | 0.03333333 | 0.03333333 | 0.03333333 | 0.03333333 | 0.03333333 | | | | | | | 2.01666667 | 2.01666667 | 1.78333333 |
| Total idle time per week (hr/wk) | 0.03333333 | 0.03333333 | 2.25 | 0.03333333 | 0.03333333 | 2.25 | | | | | | | 2.02 | 2.02 | 48.15 |
| **Idle energy per week (Wh/wk)** | 15 | 15 | 1,035 | 15 | 15 | 1,035 | | | | | | | 651 | 651 | 15,552 |
| | | 0 | | | 0 | | | | | | | | | | |
| **Fraction of time on this job** | 100% | 100% | 53% | 100% | 100% | 50% | 100% | 98% | 100% | 49% | 100% | 74% | 100% | 100% | 38% |
| Total time on this job per week (hrs/wk) | 168 | 168 | 89 | 168 | 168 | 85 | 168 | 164 | 168 | 83 | 168 | 124 | 168 | 168 | 64 |
| double-checking time | | 0 | | | 0 | | | | | | | | | | |
| Warmup power (W) | 610 | 610 | N/A | 610 | 610 | N/A | N/A | N/A | N/A | N/A | N/A | N/A | 1,159 | 1,159 | N/A |
| Warmup time (sec) | 1,400 | 1,400 | | 1,400 | 1,400 | | | | | | | | 900 | 900 | |
| Warmup time (hrs) | 0.38888889 | 0.38888889 | | 0.38888889 | 0.38888889 | | | | | | | | 0.25 | 0.25 | |
| Number of warmups per week (#) | 1 | 1 | | 1 | 1 | | | | | | | | 1 | 1 | |
| **Warmup energy per week (Wh/wk)** | 237 | 237 | | 237 | 237 | | | | | | | | 290 | 290 | |
| | | 0 | | | 0 | | | | | | | | | | |
| Standby power (W) | 305 | 0 | N/A | 305 | 0 | N/A | 178 | 178 | 118 | 118 | 178 | 178 | 323 | 0 | N/A |
| Standby time per week (hr/wk) | 164.36 | 164 | | 164.53 | 165 | | 161.94 | 0.90 | 164.97 | 0.90 | 163.45 | 0.90 | 165.14 | 165.14 | |
| **Standby energy per week (Wh/wk)** | 50,130 | 0 | | 50,181 | 0 | | 28,836 | 160 | 19,530 | 107 | 29,105 | 160 | 53,340 | 0 | |
| | | 0 | | | 0 | | | | | | | | | | |
| **Annual Avg. Energy Use (kWh/yr)** | 2,734 | 127 | 3,125 | 2,711 | 102 | 2,452 | 1,733 | 6,303 | 1,132 | 3,153 | 1,689 | 4,736 | 2,858 | 85 | 1,778 |

| | FDM | | | | Objet | | | | | | CNC | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | FDM 100% solid parts, Minimal Utilization | FDM 100% solid parts, Maximal Utilization | FDM 10% fill, Minimal Utilization | FDM 10% fill, Maximal Utilization | Inkjet 100% solid parts, Minimal Utilization | Inkjet 100% solid parts, Maximal Utilization | Inkjet 100% solid, printed together, Minimal Utilization | Inkjet 100% solid, printed together, Maximal Utilization | Inkjet 90% support fill, Minimal Utilization | Inkjet 90% support fill, Maximal Utilization | CNC parts, minimal utilization | CNC parts, maximal utilization | CNC parts, maximal utilization, min. theoretical waste |
| Number of units created per week (#) | 1 | 27 | 1 | 27 | 1 | 27 | 1 | 27 | 1 | 27 | 1 | 27 | 27 |
| Mass of Parts (g) | 85.3 | 85.3 | 35.1 | 35.1 | 100.1 | 100.1 | 100.1 | 100.1 | 97.88 | 97.88 | 89 | 89 | 89 |
| Model waste per run (g) | 0.5 | 0.5 | 0.7 | 0.7 | 38.19 | 38.19 | 38.19 | 38.19 | 37.87 | 37.87 | 290 | 290.0 | 65.0 |
| Support waste per run (g) | 7.7 | 7.7 | 7.3 | 7.3 | 13.72 | 13.72 | 13.72 | 13.72 | 11.36 | 11.36 | 0 | 0 | 0 |
| Mass of parts per week (g/wk) | 85.3 | 2303.1 | 35.1 | 947.7 | 100.1 | 2702.7 | 100.1 | 2702.7 | 97.88 | 2642.76 | 89 | 2403 | 2403 |
| Model waste per week (g/wk) | 0.5 | 13.5 | 0.7 | 18.9 | 38.19 | 1,031.09 | 38.19 | 1,031.09 | 37.87 | 1,022.60 | 290 | 7830 | 1,756 |
| Support waste per week (g/wk) | 7.7 | 207.9 | 7.3 | 197.1 | 13.72 | 370.57 | 13.72 | 370.57 | 11.36 | 306.68 | 0 | 0 | 0 |
| **Model waste per year (g/yr)** | 26 | 702 | 36 | 983 | 1,986 | 53,616 | 1,986 | 53,616 | 1,969 | 53,175 | 15,080 | 407,160 | 91,296 |
| **Support waste per year) (g/yr)** | 400 | 10,811 | 380 | 10,249 | 714 | 19,270 | 714 | 19,270 | 591 | 15,947 | 0 | 0 | 0 |
| **Mass of parts per year (g/yr)** | 4,436 | 119,761 | 1,825 | 49,280 | 5,205 | 140,540 | 5,205 | 140,540 | 5,090 | 137,424 | 4,628 | 124,956 | 124,956 |

| FDM masses | Apple, Solid | Apple, low density | Linkage, solid | Linkage, low density |
|---|---|---|---|---|
| Support Material Waste (g) | 2.8 | 2.5 | 4.9 | 4.8 |
| Model Material Waste (g) | 0.3 | 0.5 | 0.2 | 0.2 |

| Objet masses | Apple, solid | Apple, support-fill | Linkage, solid | Linkage, support-fill |
|---|---|---|---|---|
| Support Material (g) | 4.21 | 4.29 | 5.73 | 3.9 |
| Waste Not used in Part or Support (g) | 20.84 | 20.41 | 21.14 | 20.63 |
| Extrapolated Model Waste | 19.21 | 18.76 | 18.98 | 19.11 |
| Extrapolated Support Waste | 1.63 | 1.65 | 2.16 | 1.52 |

| CNC masses | Apple | Linkage |
|---|---|---|
| ABS block weight | 229 | 150 |
| Post CNC weight | 44 | 45 |
| % waste | 81% | 70% |

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| | FDM Dimension 1200BST | | | | | | Objet Connex 350 | | | | | | Haas VF0 CNC | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | FDM 100% solid parts, Minimal Utilization, Idling | FDM 100% solid parts, Minimal Utilization, Powering Off | FDM 100% solid parts, Maximal Utilization | FDM 10% solid parts, Minimal Utilization, Idling | FDM 10% solid parts, Minimal Utilization, Powering Off | FDM 10% fill, Maximal Utilization | Inkjet 100% solid parts, Minimal Utilization | Inkjet 100% solid parts, Maximal Utilization | Inkjet 100% solid parts, printed together, Minimal Utilization | Inkjet 100% solid parts, printed together, Maximal Utilization | Inkjet 90% support fill, Minimal Utilization | Inkjet 90% support fill, Maximal Utilization | CNC parts, minimal utilization, Idling | CNC parts, minimal utilization, Powering Off | CNC parts, maximal utilization |
| Manufacturing, Total | 145.29342 | 145.29342 | 145.29342 | 145.29342 | 145.29342 | 145.29342 | 306.60917 | 306.60917 | 306.60917 | 306.60917 | 306.60917 | 306.60917 | 1012.282 | 1012.282 | 1012.282 |
| Transportation, Total | 19.870163 | 19.870163 | 19.870163 | 19.870163 | 19.870163 | 19.870163 | 82.281928 | 82.281928 | 82.281928 | 82.281928 | 82.281928 | 82.281928 | 71.906071 | 71.906071 | 71.906071 |
| Disposal, Total | 1.5135032 | 1.5135032 | 1.5135032 | 1.5135032 | 1.5135032 | 1.5135032 | 3.3804473 | 3.3804473 | 3.3804473 | 3.3804473 | 3.3804473 | 3.3804473 | 41.492818 | 41.492818 | 41.492818 |
| Lifetime (yrs) | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 10 | 10 | 10 |
| Fraction of Time on This Job | 53% | 53% | 53% | 50% | 50% | 50% | 98% | 98% | 49% | 49% | 74% | 74% | 39% | 39% | 39% |
| **Annualized non-usage impacts** | | | | | | | | | | | | | | | |
| Annualized Mfg | 29.058684 | 29.058684 | 29.058684 | 29.058684 | 29.058684 | 29.058684 | 61.321834 | 61.321834 | 61.321834 | 61.321834 | 61.321834 | 61.321834 | 101.2282 | 101.2282 | 101.2282 |
| Annualized Transport | 3.9740326 | 3.9740326 | 3.9740326 | 3.9740326 | 3.9740326 | 3.9740326 | 16.456386 | 16.456386 | 16.456386 | 16.456386 | 16.456386 | 16.456386 | 7.1906071 | 7.1906071 | 7.1906071 |
| Annualized Disposal | 0.3027006 | 0.3027006 | 0.3027006 | 0.3027006 | 0.3027006 | 0.3027006 | 0.6760895 | 0.6760895 | 0.6760895 | 0.6760895 | 0.6760895 | 0.6760895 | 4.1492818 | 4.1492818 | 4.1492818 |
| **Annualized impacts allocated to this job** | | | | | | | | | | | | | | | |
| Allocated Mfg | 15.4 | 15.4 | 0.6 | 14.5 | 14.5 | 0.5 | 60.1 | 2.2 | 30.0 | 1.1 | 45.4 | 1.7 | 39.5 | 39.5 | 1.5 |
| Allocated Transport | 2.1 | 2.1 | 0.1 | 2.0 | 2.0 | 0.1 | 16.1 | 0.6 | 8.1 | 0.3 | 12.2 | 0.5 | 2.8 | 2.8 | 0.1 |
| Allocated Disposal | 0.2 | 0.2 | 0.0 | 0.2 | 0.2 | 0.0 | 0.7 | 0.0 | 0.3 | 0.0 | 0.5 | 0.0 | 1.6 | 1.6 | 0.1 |
| Allocated Electricity Use | 255.7 | 11.9 | 10.8 | 253.5 | 9.5 | 8.5 | 162.0 | 21.8 | 105.9 | 10.9 | 157.9 | 16.4 | 267.3 | 8.0 | 6.2 |
| Allocated Material Use (low estimate) | 3.0 | 3.0 | 3.0 | 1.2 | 1.2 | 1.2 | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 | 3.1 | 3.1 | 3.1 |
| Allocated Material Use (high estimate) | 3.0 | 3.0 | 3.0 | 1.2 | 1.2 | 1.2 | 5.2 | 5.2 | 5.2 | 5.2 | 5.1 | 5.1 | 3.1 | 3.1 | 3.1 |
| Allocated Waste (low estimate) | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 1.2 | 1.2 | 1.2 | 1.2 | 1.1 | 1.1 | 10.5 | 10.5 | 2.4 |
| Allocated Waste (high estimate) | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 2.4 | 2.4 | 2.4 | 2.4 | 2.3 | 2.3 | 10.5 | 10.5 | 10.5 |
| Allocated Total Fluid Use | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.2 | 0.2 |
| **Allocated Total Impacts (low estimate)** | 276.6 | 32.8 | 14.7 | 271.7 | 27.7 | 10.6 | 242.3 | 28.0 | 147.6 | 15.7 | 219.2 | 21.8 | 325.1 | 65.8 | 13.4 |
| **Allocated Total Impacts (high estimate)** | 276.6 | 32.8 | 14.7 | 271.7 | 27.7 | 10.6 | 246.5 | 32.2 | 151.9 | 19.9 | 223.4 | 25.9 | 325.1 | 65.8 | 21.6 |
| % diff. high to low | 0% | 0% | 0% | 0% | 0% | 0% | 2% | 13% | 3% | 21% | 2% | 16% | 0% | 0% | 38% |

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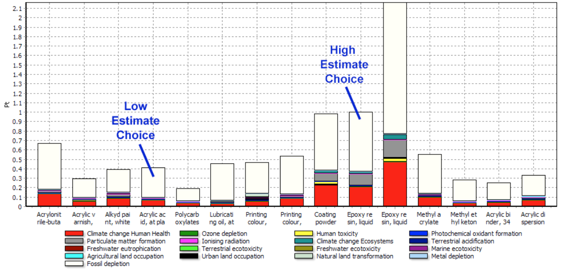
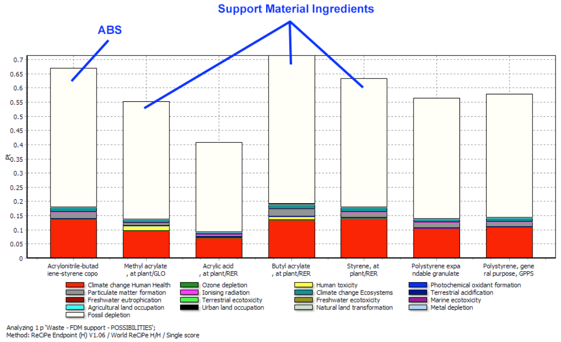
## Appendix 3: Material Sensitivity Analysis

Alternatives for Objet model material:



Analyzing 1 p 'Waste - Acrylic - POSSIBILITIES';
Method: ReCiPe Endpoint (H) V1.06 / World ReCiPe H/H / Single score

Testing impacts of FDM support material against ABS and other benchmarks:



Analyzing 1 p 'Waste - FDM support - POSSIBILITIES';
Method: ReCiPe Endpoint (H) V1.06 / World ReCiPe H/H / Single score