

Does Material Choice Drive Sustainability of 3D Printing?

Jeremy Faludi, Zhongyin Hu, Shahd Alrashed, Christopher Braunholz, Suneesh Kaul, Leulekal Kassaye

Abstract—Environmental impacts of six 3D printers using various materials were compared to determine if material choice drove sustainability, or if other factors such as machine type, machine size, or machine utilization dominate. Cradle-to-grave life-cycle assessments were performed, comparing a commercial-scale FDM machine printing in ABS plastic, a desktop FDM machine printing in ABS, a desktop FDM machine printing in PET and PLA plastics, a polyjet machine printing in its proprietary polymer, an SLA machine printing in its polymer, and an inkjet machine hacked to print in salt and dextrose. All scenarios were scored using ReCiPe Endpoint H methodology to combine multiple impact categories, comparing environmental impacts per part made for several scenarios per machine. Results showed that most printers' ecological impacts were dominated by electricity use, not materials, and the changes in electricity use due to different plastics was not significant compared to variation from one machine to another. Variation in machine idle time determined impacts per part most strongly. However, material impacts were quite important for the inkjet printer hacked to print in salt: In its optimal scenario, it had up to 1/38th the impacts coreper part as the worst-performing machine in the same scenario. If salt parts were infused with epoxy to make them more physically robust, then much of this advantage disappeared, and material impacts actually dominated or equaled electricity use. Future studies should also measure DMLS and SLS processes / materials.

Keywords—3D printing, Additive Manufacturing, Sustainability, Life-cycle assessment, Design for Environment.

I. INTRODUCTION

3D printing is revolutionizing some fields of manufacturing, especially prototyping [1]. It is sometimes assumed to be a more sustainable way to manufacture, but such blanket statements are unrealistic for any manufacturing technology, as production methods for different kinds of finished products vary so widely. For some kinds of products it can be a great improvement, and indeed it enables the production of some products that could not be economically produced any other way. GE is printing jet engine nozzles predicted to save millions of gallons of fuel per year due to geometries enabled by 3D printing, which were not economically viable through previous manufacturing methods [2]. Many people assume 3D printing virtually eliminates waste, but this is only true for some circumstances, such as FDM machines not using support material; other 3D printers can produce as much as 43% material waste, even before support material is counted (see Results section). Many people also assume that 3D printing is

more sustainable because it can eliminate transportation of consumer goods [3]. Unfortunately, this is misguided because transportation only represents a small fraction of lifetime ecological impacts for most products [4], even ignoring the fact that 3D printers still require raw materials to be transported. On the other hand, Markus Kayser's "solar sinter" demonstrated 3D printing of glass from desert sand, an abundant, non-toxic, local material fused together directly by sunlight in a printer run entirely from solar power [5]. One could hardly ask for a more sustainable manufacturing method (assuming the resulting printed objects are robust). As a result of all these issues, there is not one simple answer. Recent studies [6], [7] have shown that even for the relatively limited scope of prototyping plastic parts, 3D printing can be either better or worse than status-quo methods such as machining, depending on multiple factors.

To drive the 3D printing industry toward a future where it does become an inherently more sustainable manufacturing method than other options, we should study where the biggest impacts of 3D printing lie and how to minimize them. Moreover, we should communicate these results in a way that is easy for industry to understand and make decisions based on it. This study examined whether material choice was the most important factor determining the sustainability of 3D printing, or if other factors such as machine size or utilization frequency were dominant. Some types of 3D printing allow for very "green" material choices—ones which are renewable or abundant, non-toxic, recyclable or compostable, and which have little embodied energy or resources. A modest example is PLA bioplastic (an improvement compared to ABS); more daring examples include salt, sugar [8], starch [9], or sawdust [10]. Some of these materials also enable low-energy printing processes, because they rely on chemical adhesion as opposed to melting plastic or curing photopolymers with UV light. This study also measured such factors, as they are usually inextricable from material choice. An SLA machine can only print in photopolymers, an inkjet machine cannot melt plastics, and so on. So for a complete picture, whole-system printer performance must be considered, as well as the different materials.

II. BACKGROUND

Some specific environmental impacts of 3D printing have been studied in depth—usually energy use [11], [12], [13], but occasionally also toxicity [14]. Even when researchers do specifically study health impacts from 3D printing, such as evaporated plastic particles in the air [15], they rarely compare these to energy use or other impacts to find top priorities for

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sustainability. Only one study was found to have measured multiple kinds of ecological impacts together to balance the effects of material use, waste, toxins, and other factors against energy use in a life-cycle assessment (“LCA”) with combined single-score measurements, comparing several 3D printer types [16]. That study was from 1999, so even without the current project’s new focus on materials, the older study should be updated for changes in 3D printer technology, available 3D printing materials, and LCA tools. Several of the machine types and materials measured here were not in use then.

III. METHODS

A. LCA Scope and Functional Units

This project extends the work of recent studies [6], [7] by measuring more machines and testing variations in material choice. For this study, the printers measured were a large commercial-scale Dimension 1200BST fused-deposition modeling (“FDM”) machine, a small desktop-scale Afinia H480 FDM machine, a small desktop Type A Machines Series 1 FDM machine, an Objet Connex 350 polyjet machine, a 3D Systems Projet 6000 stereolithography (“SLA”) machine, and a Zcorp 310 inkjet machine.

LCAs were conducted in SimaPro software, with data primarily from the EcoInvent database, but some data coming from US Franklin LCI and other standard databases. ReCiPe Endpoint H methodology [17] was used to combine 17 different categories of ecological impact (including climate change, toxicity, resource depletion, and other factors) into unified single scores. LCA scope was cradle-to-grave, including electricity used to print parts, material comprising the parts printed, and waste material generated during printing, as well as electricity use while machines idle or start up, embodied impacts of raw materials and manufacture of the machines themselves, transportation of the machines to and from UC Berkeley, and disposal of the machines at their end of life, conservatively assumed to be five years, since no 3D printer manufacturer was willing to provide lifetime estimates, and estimates from an informal survey of prototypers produced few and highly varying answers.

Masses and manufacturing processes of printer components were not provided by the manufacturers, so they had to be estimated by measuring the dimensions of every one of the dozens of components that could be accessed, and calculating their masses by standard densities of steel, aluminum, glass, polyurethane, ABS, copper wire and motor windings, etc. Electronics were estimated by area of circuit board, length of cable, or by approximate equivalence to existing items in the databases (for example, 1 desktop computer for the SLA machine’s control and interface electronics, since the actual electronics were inaccessible). These component estimates are uncertain, but environmental impacts of the entire machines’ materials and manufacturing was usually less than 10% of lifetime impacts, so further precision was not deemed necessary. Electricity use was measured with a WattsUp Pro ES power datalogger, except where raw data was already

available from previous studies. Ecological impacts from electricity were modeled as average US electricity grid mix. Disposal was modeled with a standard combination of landfill and recycling, the EcoInvent process “Durable goods waste scenario/US S.”

These different printers work in very different ways, with different kinds of environmental impacts, so to create a fair “apples-to-apples” comparison, ecological impacts of different materials and printers were compared per object printed. The functional unit was the printing of a single thin-walled part, designed to be representative of a typical prototyping job—see Fig. 1. Industry representatives told us that roughly “90%” of their customers’ prototyping jobs were thin-walled plastic enclosures for consumer products.



Fig. 1 Two units of the printed part, showing inside and outside

B. Materials

The Dimension (large FDM) and Afinia (one of the desktop FDMs) printed in ABS plastic. The Type A (the other desktop FDM) printed in PET plastic and PLA bioplastic. These are all fairly standard plastics today. LCAs and toxicological studies alike have found that PLA has the lowest health and environmental impacts of the three, followed by PET and then ABS [18], [19]. PLA is notable because it is a bioplastic, made from agricultural sources such as corn rather than fossil fuels, and it has a significantly lower melting point, allowing printers to extrude it with less energy use. In addition, neither PLA nor PET requires a 3D printer to have a heated bed to avoid curling as ABS does [20], which should save significant energy.

The Zcorp printer generally uses a proprietary plaster powder bonded with proprietary inkjet ink. However, measurements here were performed with a Zcorp printer hacked to print in many alternative materials, including salt, sawdust, and concrete. Such hacking is done by a small but growing community of people pursuing both eco-friendly materials and cheaper materials than the proprietary ones sold by printer manufacturers. The Zcorp machine measured was hacked by UC Berkeley architecture professor Ron Rael and his students, working with their own proprietary formulations, so a public-domain recipe was taken from an internet forum where people trade recipes for do-it-yourself 3D printer materials [21], and Rael stated it was similar enough for accurate modeling. This “salt” printing recipe was a powder mixture of 88% fine-ground salt and 12% maltodextrin, bonded with a liquid mixture of 280 mL isopropyl alcohol, 920 mL distilled water, and 45 mL food coloring per inkjet bottle. (One bottle lasts for many print jobs, so the actual amount of liquid per print is a fraction of this.) Since this

material by itself is fragile, parts are very often strengthened after printing by soaking epoxy, cyanoacrylate, or other bonding agents into the salt printout. Since the ecological impacts of epoxy are roughly 47 times larger than the salt / dextrose / isopropyl material (as measured in ReCiPe Endpoint H points per unit mass), LCA scores with and without epoxy were both calculated for each scenario of the inkjet. This range of scores with and without epoxy should cover the whole range of materials the inkjet printer is likely to use, from proprietary plaster formulations to hacker formulations of sawdust or concrete or other materials.

The Projet used a proprietary SLA resin called Accura ABS White SL7810, a polymer that hardens with exposure to UV light. Despite its name, it was not ABS. Its somewhat vague Materials Safety Data Sheet (MSDS) said it was composed of hydrogenated bisphenolA epoxy resin, 3-ethyloxetane-3-methanol, propylene carbonate, "sulfonium salt mixture," and bisphenol A epoxy resin. While epoxy resin was in the EcoInvent database, the other chemicals largely did not match chemicals in the EcoInvent or other LCA databases available to this team, so a sensitivity analysis compared 15 different chemicals considered most likely to match these ingredients' environmental impacts. Extreme high and low ReCiPe point values were eliminated, and final LCAs included two scenarios each—a high estimate assuming the material was entirely epoxy resin, and a low estimate using "acrylic acid, at plant". Resulting differences in total ReCiPe Endpoint H points per part printed in the four different SLA machine utilization scenarios ranged from 16% (running 24 hrs/day, 7 days/wk, printing 4 parts at a time) to a 0.2% difference (printing 1 part/wk but left idling when not in use). Final results shown later in the Results section use the high estimates, as the MSDS did explicitly list epoxy resin as comprising 30–60% of the material.

The Objet used a proprietary "polyjet"UV-curing polymer called Fullcure 720, whose MSDS listed the ingredients exo-1,7,7-trimethylbicyclo[2.2.1]-hept-2-yl acrylate, acrylic monomer, urethane acrylate oligomer, acrylate oligomer, and epoxy acrylate. Again, exact matches for all these chemicals were not available in the databases, but sensitivity analysis was performed, so each scenario had a high estimate (epoxy resin again) and low estimate ("acrylic acid, at plant" again) for material impacts. Resulting differences in total ReCiPe Endpoint H points per part printed ranged from 9% (running 24 hrs/day, 7 days/wk, printing 4 parts at a time) to a 0.2% difference (printing 1 part/wk but left idling when not in use). Final results shown here use the high estimates, for consistency with the SLA machine. High estimates were also chosen because the purpose of this study was to see how large variations due to material choice could be, and even the lower-impact scenarios for these materials these materials were at the higher-impact end compared to salt and dextrose.

While all of these machine types (FDM, polyjet, inkjet, and SLA) can print in different materials, the materials listed above were the only materials made available to us by the machine operators. Only the Type A machine was measured using two different materials; for all other machines, the type

of machine was tied to one type of material, and any variation was from theoretical calculations of sensitivity analysis. While this is certainly a limitation of the study, we believe the results show that this does not affect the validity of the conclusions (see Results section).

C. Machine Utilization

3D printer utilization varies widely in industry—some machines run nearly 24 hours/day, 7 days/week, especially those used for manufacturing finished parts (as opposed to prototypes), or those run by contractors who print for hire ("job shops"). Other machines may go for days or weeks (even months) between print jobs, especially small inexpensive desktop units used by design firms for occasional prototypes, or used by home hobbyists. An informal utilization survey sent to nearly a thousand product design practitioners provided little insight, with few responses and a wide range of answers, so no defensible "average" utilization could be determined. Therefore, a range of scenarios was calculated. Maximum utilization was defined as printing parts 24 hrs/day, 7 days/wk, for a machine's entire life (which is not actually possible, but represents the asymptotic "best case" scenario).

Some printers can only print one part at a time (large and small FDM machines), but some printers can print several parts in almost exactly the same time it takes to print a single part, without using noticeably more energy (polyjet, inkjet, and SLA machines). Therefore, maximum utilization for polyjet, inkjet, and SLA machines is not only printing parts 24 hrs/day, 7 days/week, but also printing multiple parts at once. The number of parts that can be printed at once without adding more print time (thus adding energy use and higher environmental impacts) was not clearly defined for any of the machines, and surely varies from machine to machine, since the SLA machine can print parts throughout its entire print bed without adding much more time, while the inkjet and polyjet machines can only print parts within the width of their moving print heads without adding more time. Budget and time constraints did not allow the printing of large numbers of parts to test the limits of these improved efficiencies, nor did any of the company representatives provide hard data on the number of additional parts printed before print times increased, but informal discussions with machine operators indicated that for the scale of parts being used as the functional unit here, at least four parts could be printed in almost the exact same time, with almost the exact same energy use, as one part. Perhaps even more parts may be printed simultaneously before the additional time and energy use would become appreciable (one company representative suggested ten parts or more at a time), but such changes would create such extreme improvements to the ecological impact scores that they should be backed by real empirical data, not mere estimations.

Here, "minimum" utilization was defined as printing one part per week, since results of the utilization survey indicated that was a common (if not necessarily typical or dominant) rate around the low end of professional use. However, this minimum utilization was split into two separate scenarios, because the amount of electricity used by idle machines left on

has an enormous effect on ecological impact scores. Some of the machines measured use nearly as much power when they are sitting idle as they do when they are printing (at worst, 260 watts idle vs. 280 watts running). Even for those that do not (the majority), the sheer number of hours spent idle will greatly multiply electricity impacts. Therefore, one scenario was for each printer to print one part per week but be shut off when not in use, the other scenario was for each printer to print one part per week and be left on for the remaining idle hours. Other utilization rates could be calculated by the reader from the data shown in the Results section, using a method described there.

IV. RESULTS

A. Ecological Impacts per Part

As mentioned earlier, one of this study's goals is to measure not merely one kind of environmental impact (e.g. kg of CO₂ equivalent emissions), but to measure several, so that impacts from energy use can be meaningfully compared to impacts from resource use and waste, material toxicity, and other factors.

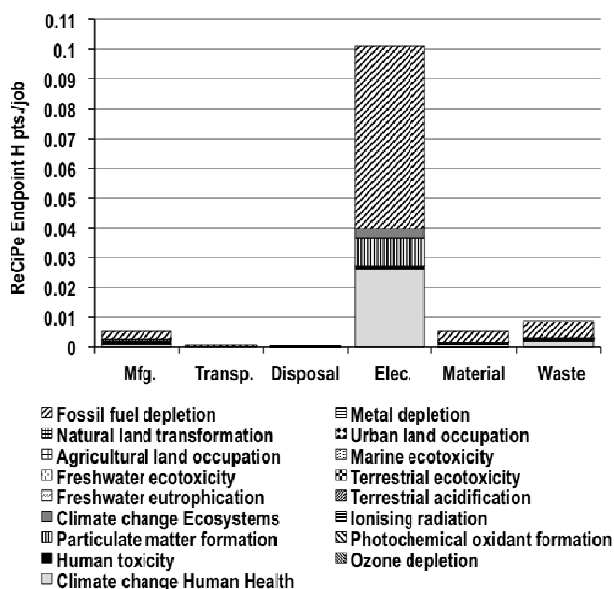


Fig. 2 Ecological impacts per job for the large FDM machine printing ABS, operating at maximum utilization. Different types of impacts are normalized and weighted into ReCiPe Endpoint H points

Fig. 2 shows that just three to five categories of ecological impacts dominate for the large commercial FDM machine printing in ABS, operating at its theoretical maximum utilization. Fossil fuel depletion, climate change damage to human health, particulate matter formation (a kind of smog causing both human and ecosystem health damage), climate change damage to ecosystems, and human toxicity are the largest types of impacts, in order. Most other impact categories (such as ionizing radiation, ozone depletion, etc.) are so small as to be invisible. Climate change, fossil fuel

depletion, and smog largely dominate because they are the dominant impact categories of status-quo US electricity use. Fig. 2 also shows that electricity use during the printing of parts is the dominant cause of ecological impacts, which may be expected, since 3D printing uses a significant amount of energy but by comparison causes little direct toxin exposure to users. The ultrafine plastic particles exposure mentioned in [15] may not be adequately captured by the LCA model here, but even if human toxicity and particulate impacts were multiplied tenfold, they would still not dominate the impact categories. Even for machine manufacturing, the material used in the final products printed and material waste produced by the machines, these impact categories remain dominant. It could be argued this is due to bias in the weighting method, but a previous study by some of the authors [6] checked ReCiPe Endpoint H results against IMPACT 2002+ normalization and weighting [22]; they were nearly identical.

Combining all the different categories of impacts into single scores, we get Figs. 3 and 4. Each stacked column in Fig. 2 becomes one segment in the new stacked bars: "Allocated mfg" includes all the climate change, pollution emissions, resource use, toxicity, and other ecological impacts due to manufacturing (both raw material extraction and their processing into the bent steel struts, glass plates, injection-molded plastic parts, and electronics that comprise the machines). These manufacturing impacts were "allocated" in the sense that they are amortized across the life of the machine, so only the correct fraction of them were allocated to each 3D printed part. Likewise, "allocated transport" and "allocated disposal" include transportation and end-of-life disposal of the machines (not the printed parts), with only the appropriate fraction allocated to each part printed. As stated in the Methods section, printer lifetime was conservatively assumed to be five years; since many users keep their printers longer than this, readers are welcome to make their own estimates of printer lifetime and reduce the allocation of these impacts accordingly. (For instance, assuming a printer life of ten years would mean all the "allocated" impacts shown in this study are divided by two.) "Material use" includes the material in the printed parts themselves, as well as its raw material extraction and disposal at the end of the parts' lives (conservatively assumed to always be landfill). "Waste" includes both support material and any model material used in printing that does not end up in the finished part, but is disposed of instead. (This was primarily an issue for the polyjet printer.) "Electricity use" includes energy used to print parts, as well as to sit idle, power up, and power down, depending on the scenario.

Fig. 3 compares ecological impacts of different printers printing with different materials, in two different scenarios: printing one part per week but with the printer left powered on and idling for the rest of the time, and printing one part per week but powering completely off between prints (including appropriate startup and shutdown times). The exception is the polyjet printer, which is shown in both areas of the graph printing one part per week but left idling, not turned off. This is because operators informed us that the machine is never

shut down between prints, even if two weeks pass between print jobs, due to the hassle involved in purging fluid lines to avoid clogs from resin potentially hardening in the lines. (When the machine sits idle powered on, pumps run fluid through the lines to avoid clogs.) Also note that the Type A machine is shown twice in each area of the graph—once for printing in PET, once for printing in PLA.

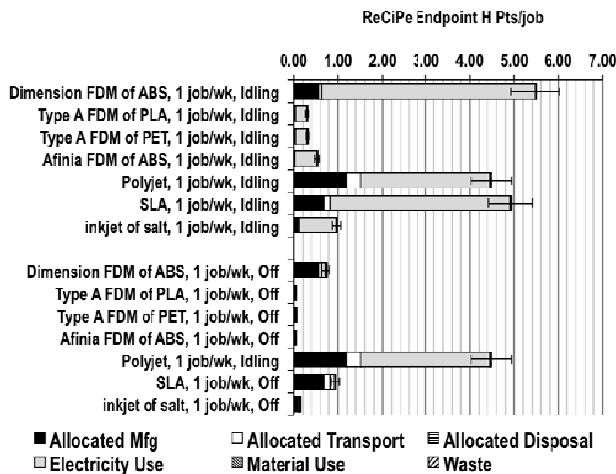


Fig. 3 Ecological impacts per job for low utilization, either with machines left idling or turning machines off when not in use

Fig. 3 shows that the ecological impacts of material use are not dominant for any of the scenarios pictured—in fact, electricity use and allocated impacts of manufacturing the printers themselves are so dominant that material use and waste impacts are hardly even visible on the graph. Choice of materials can also change the amount of electricity used and the bulk of the machine required to print the materials; but this appears to be a minor effect. The difference between PLA and PET in the same desktop FDM machine is almost invisible compared to the difference between that machine and a large commercial FDM machine. Likewise, the difference between a small desktop FDM of ABS and the other desktop FDM scenarios is miniscule compared to the large FDM printing ABS. The difference between printing by FDM vs. printing by polyjet, SLA, or inkjet is unclear, because machine size is a confounding factor—the polyjet, SLA, and inkjet machines are larger commercial-scale units like the large FDM machine. The most obviously dominant factor in Fig. 3, however, is that each of these printers has far larger impacts per part when left idling than when turned off between prints.

Changes in ecological impacts due to material choice only become visible in the maximum utilization scenarios (where parts are being printed 24 hours per day, 7 days per week). This is shown in Fig. 4. It was not included in Fig. 3 because the difference in scale is so large—note the ReCiPe Endpoint H points per job go from a maximum of 5.5 in Fig. 3 to 0.25 in Fig. 4. The smallest four bars in Fig. 4 are repeated in a breakout box for readability, so the minimum score of .002 pts/job is visible.

Fig. 4's graph of impacts at maximum utilization parallels

the material and machine scenarios in Fig. 3 running at lower utilization, but also adds four additional variations for sensitivity analysis. As mentioned in the Methods section, only one part was printed per machine, but SLA, inkjet, and polyjet machines can print several parts in nearly the same time as one part. Thus, Fig. 4 also includes scenarios where four parts are printed with the same energy usage as one part. These scenarios are denoted by (*) to indicate they are more theoretical results. These printers may be able to print significantly more parts (perhaps ten or more parts at once) in nearly the same time with nearly the same energy use, but measuring such variations in mass-printing was beyond the scope of this study. If readers wish to make their own estimates of improved eco-efficiency from more parts being printed simultaneously, they can do so easily by using the maximum utilization graph, dividing impacts from energy usage by the chosen factor of improvement, and leaving all other impact sources (manufacturing, transport, material use, waste, and disposal) constant.

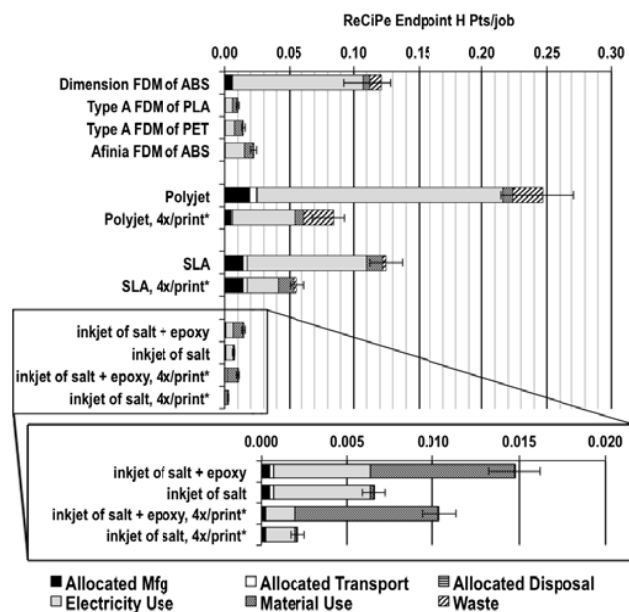


Fig. 4 Ecological impacts per job at maximum utilization scenarios. Scenarios denoted by (*) are four parts being printed simultaneously

Fig. 4 does show variation in impacts from material choice. The fairest comparison of different materials is in the small desktop FDM machines printing PLA, PET, and ABS, as these machines were most similar to each other in size and technology. However, their difference in impacts is still dwarfed by the difference between the small desktop FDMs and the large commercial FDM. Differences between FDM and polyjet or SLA cannot be ascribed to material choice alone, because the polyjet and SLA printers were large commercial units like the large FDM, not directly comparable to the desktop FDMs. While the polyjet printer had the highest impacts per part (it not only used the most energy, but also produced a large amount of waste—roughly 43% by mass of

all liquid resin), the scenario where it prints four parts at once brings its impacts to within the extreme ends of uncertainty values for commercial FDM impacts. Likewise, the SLA printer had higher or lower impacts than the commercial FDM, depending on whether it printed single parts or groups of four parts. Here again machine utilization dominates material choice or machine type.

Most notably, Fig. 4 also shows where material choice / printing technology can dominate: The inkjet printing in the “green” material of salt does in fact have far lower ecological impact scores than all other materials printed by all other printers at maximum utilization. When the inkjet is printing four parts together, it has 1/5th the impact score per job as the next-best technology, PLA printed by small desktop FDM. The inkjet has roughly 1/38th to 1/40th the impact score per job as the polyjet, regardless of whether both are printing one part at a time or four parts at a time. However, when epoxy is soaked into salt parts to harden them, ecological impacts predictably skyrocket. Printing one part at a time with epoxy, impact scores roughly double; printing four parts at once with epoxy, impact scores roughly quintuple. Neither scenario printing salt with epoxy scores better than the desktop FDM printing in PLA. As mentioned in Methods, printing other materials in the inkjet (such as sawdust, plaster, etc.) are likely to cause ecological impacts varying between the lower bound of salt and the upper bound of salt with epoxy.

As mentioned in the Methods section, the reader may extrapolate to even lower utilization scenarios by subtracting maximal utilization energy impact scores in Fig. 4 from the “1 job/week, idling” scores in Fig. 3 to find idling energy impact per week, then multiplying that by the desired idle time, and rescaling the amortized impacts of the printer (manufacturing, transport, and end of life) accordingly.

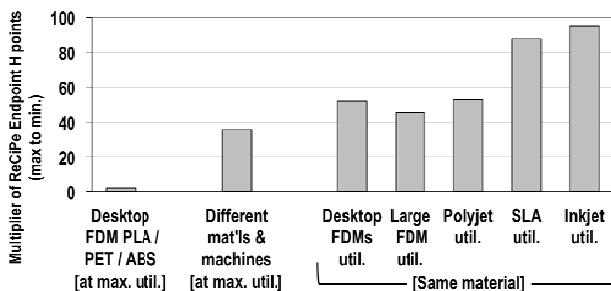


Fig. 5 Range of variation between scenarios of different materials vs. scenarios of different utilization for different machines

B. Ranges of Variation

Ecological impact scores vary greatly between different materials on different machines, but as mentioned, this variation should be compared to the variation due to machine utilization. Even without heroic improvements from printing several parts at once, machine utilization already dominates other variables in having the most influence on sustainability of 3D printing. Fig. 5 uses the data from Figs. 3 and 4 to compare the range of variation in ecological impact scores from material choice against the range of variation in impacts

from machine utilization.

As Fig. 5 shows, varying material among different plastics (PLA, PET, ABS) within the same type of machine (desktop FDM) gives a highest impact score merely double the lowest impact score. Varying the 3D printing material and machine type but operating only at maximum utilization, the highest impact score is roughly 35 times the lowest impact score. (This does not include machines printing four parts simultaneously, as that is a change in utilization, not materials.) For each individual machine, the impact scores for that machine and that material operating at minimum utilization are roughly 45 to 95 times the impact scores of the same machine and same material operating at maximum utilization. So although environmental impacts can be minimized by choosing good materials, good utilization is an even more crucial first step.

C. Print Quality

Choosing which 3D printer and material to use would be easy if environmental impact were the only consideration. Unfortunately it is not. A very important consideration is print quality, and there appears to be a roughly inverse relationship between print quality and ecological impact score per part. This can be seen by comparing Fig. 1's SLA-printed parts to Fig. 6's desktop FDM-printed PET part and inkjet-printed salt part. Polyjet and SLA prints unquestionably have the highest print quality (highest resolution and smoothest surfaces), but tend to have higher impacts per part. The large commercial FDM had midrange quality and midrange impacts. Desktop FDMs and the inkjet printing in salt had low impacts but also had the lowest quality. Their prints were all lower resolution, with less smoothness in the curved surfaces, and some prints also had errors. The Afinia FDM's parts had places where the curved surface was slightly mangled from improper detachment from support material (see Fig. 6). The machine operator said this is not very common, but is a known issue which can require multiple test prints tuning the print parameters in order to avoid such marring. The inkjet printing in salt had minor surface irregularities (see Fig. 6) in addition to its lower resolution.

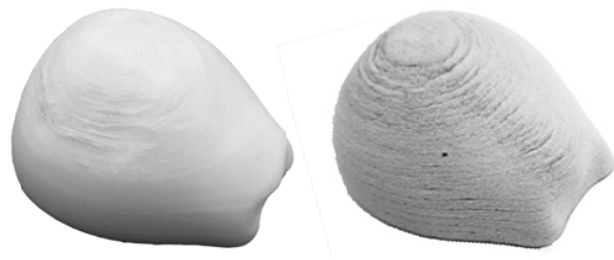


Fig. 6 Quality anomalies in a desktop FDM print (left) and inkjet salt print (right)

In addition to surface finish quality, there is also mechanical quality. Parts printed in salt alone on the inkjet were brittle, causing two small pieces of the part to break off before being infused with epoxy (not shown in Fig. 6). While many

prototypes do not need physical strength or durability, it can be a requirement for functional prototypes, so this could be a significant decision point for some users.

V. LIMITATIONS

For this study, access was available to a limited number of materials and machines compared to the vast variety that exists in the market today. We believe it does not harm the validity of conclusions here, but more data would improve confidence. The lack of a direct metal laser sinterer ("DMLS" printer) is significant, as DMLS uses significantly more energy to print parts in metal than the printers here use to print parts in plastic. This would increase the variation in environmental impacts due to material choice. Access to such machines was unavailable, but readers trying to minimize their environmental impacts per part made will be content with the data here, as DMLS will only have higher impacts compared to printing in plastic or salt. Selective laser sintering ("SLS") of plastics would also be useful to measure. For the sake of completeness, future studies should measure more machine types and machine sizes.

Machine access was also limited in the number of parts that could be printed, not allowing finer-grained study of maximum utilization in machines that could print multiple parts at once. However, as mentioned in Methods and Results, reduced eco-impacts from increases in utilization can be easily estimated by the reader.

VI. CONCLUSIONS

As 3D printing rapidly becomes a large industry, the industry's sustainability rapidly becomes important. Part of this is determining what role material choices play in the sustainability of 3D printing—whether they dominate impacts, are insignificant, or somewhere in between. Today, 3D printing does not commonly use "green" materials which cause few ecological impacts in their extraction or production. The possible exception is PLA bioplastic, which is commonly used, and which this study shows to lower printer energy use as well as having lower embodied impacts than ABS plastic. Innovative approaches, such as printing salt with an inkjet 3D printer, can lower ecological impacts per part even further. Printing this material on this machine reduced the ReCiPe Endpoint H impact score per part to as much as 1/35th the score of the highest-impact printer and material at maximum utilization (printing parts 24 hrs/day, 7 days/week). Other low-impact materials could include sawdust, plaster, or other relatively inert substances that can be bonded with low-toxicity adhesives. When higher-toxicity adhesives such as the epoxy studied here are required to give such materials adequate physical strength, they can eliminate the advantages of the "greener" material. Here, an inkjet printing salt parts later infused with epoxy scored worse than a desktop FDM printing PLA, and similar to a desktop FDM printing PET.

As much of a difference as "green" materials and printers can make, these advantages can only be realized if machine utilization is also optimized, to avoid wasting electricity

through powered-up idling between prints, or inefficient print setups. Idling is particularly important. A printer running at low utilization (printing one part per week but sitting powered-on for all its idle time) can have up to roughly 95 times the ecological impact score as the same printer running at maximum utilization (printing 24 hrs/day, 7 days/wk, 4 parts/print).

With such huge gains possible, 3D printing can be a highly sustainable manufacturing method if printer manufacturers, operators, and researchers focus their efforts. Future work should experiment with and measure the impacts of 3D printing with more alternative materials that both have low environmental impacts themselves and also enable low-energy printing processes. Industry should design printer interfaces that help maximize printer utilization to avoid idle time and amortize impacts of machines. For example, interfaces to encourage sharing printers among multiple users, interfaces to minimize material use (and thus also print time) in FDM machines, or interfaces to maximize the number of parts printed together for SLA, polyjet, and inkjet machines. Printers should also allow automatic power-saving standby modes to avoid the impacts of idle power consumption. Ideally, industry should also steer away from business models where proprietary materials are the primary profit source, with printers merely a vehicle for material demand, so that more material experimentation is enabled. 3D printing can already be a more sustainable manufacturing method for some products; with efforts such as these, it might become a greener way to make most products.

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