# The Additive Manufacturer Green Trade Association in Collaboration with Delft University of Technology Presents:

## State of Knowledge on the Environmental Impacts of Metal Additive Manufacturing

by Jeremy Faludi, Ph.D. and Corrie Van Sice

November 17, 2020

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## Introduction

Metal additive manufacturing (AM) is a large and growing market, estimated at $1 billion in 2020, and predicted to grow over 27% per year for the next several years (Grand View Research, 2020). Compared to conventional manufacturing (CM), it can enable the production of new complex shapes, can consolidate assemblies into single parts, and can enable lighter or functionally optimized designs. For example, GE notably used AM to reduce a turboprop engine from an 855-part assembly to the only 12 part Catalyst™ engine with improved power and fuel efficiency over its predecessors, shown in Figure 1 (Dusen, 2017). Metal AM also enables manufacturing with advanced materials, such as the cobalt chromium ceramic alloy used to print a jet engine nozzle which could not be produced by conventional methods (Beyer, 2014). AM shows clear functional and economic advantages over CM for some circumstances; does it also show environmental advantages? And if so, are these advantages in the same circumstances with economic or functional advantages? How can organizations plan responsible strategies for AM in a world increasingly affected by climate change and resource scarcity? What research is still needed to ensure a sustainable future for metal AM?

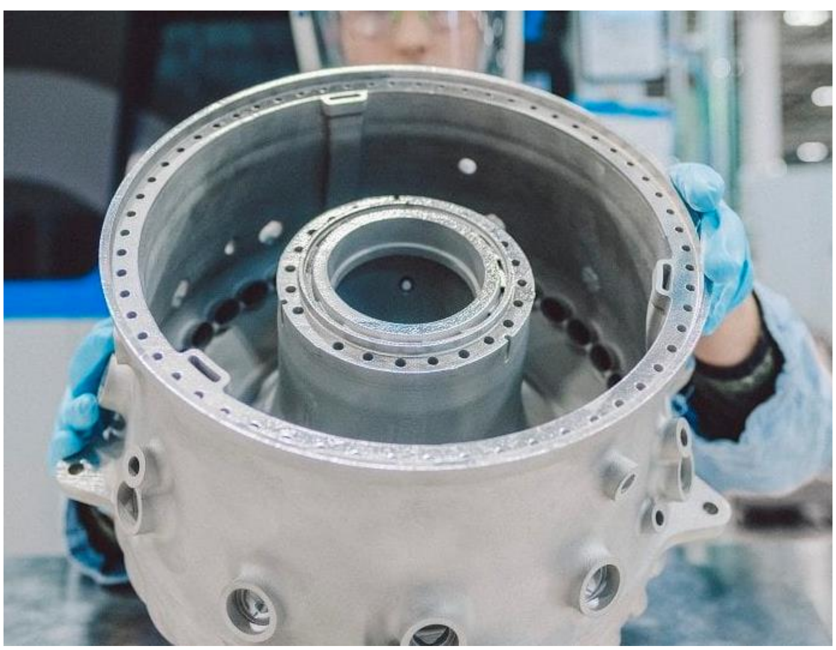

*Figure 1. A 3D printed component of the GE Catalyst™ engine used in Cessna Denali aircraft that was reduced from 855 parts to just twelve (Hurm, 2019). Photo courtesy of Nick Hurm, GE Additive.*

This report synthesizes existing academic literature comparing the environmental impacts of metal AM with conventional manufacturing methods and provides context with impacts of common metals and processing methods found in a materials database. Its goal is to summarize current knowledge and identify areas where information is sparse, unclear, and much needed. Life-cycle assessments were especially sought, as they can provide a comprehensive picture of the impacts of manufacturing technologies, measuring multiple types of environmental impacts from cradle to grave. The report's structure is as follows: The Methods section describes how the literature review and material database knowledge was gathered and analyzed. The Results and Discussion section discusses the data from the database and literature, comparing AM and conventional manufacturing by life cycle stage, including embodied material impacts, processing impacts, the change in product usage impacts due to light-weighted AM designs, and other considerations. It also compares AM to conventional manufacturing by industry sector, including aerospace, automotive, and medical devices. Finally, the Conclusion summarizes key takeaways for decision-makers considering what technologies, assessment tools, and research areas to pursue.

# Methods

Two methods were used for this report: gathering data on conventional manufacturing processes and materials from the Granta CES Edupack materials database, and reviewing academic literature of metal AM. Data from these two methods were then combined for broader comparison across manufacturing methods and materials.

## Database

Granta CES Edupack (Granta Design, 2020) was chosen as the database for CM information because it is the largest, most thorough, and most credible materials database in the world. It features sophisticated tools for visualizing and comparing materials and manufacturing methods. It was used to find greenhouse gas emissions intensity (kg $CO_2$ equivalents per kg material) and Cumulative Energy Demand intensity (source energy, in MJ per kg material).

Impact data was gathered for several CM processes: machining, casting, extrusion and foil rolling, roll forming and forging, and wire drawing. Metal types investigated for these production processes were mild steel, stainless steel, aluminum, and titanium. However, mild steel data was later discarded when insufficient AM literature was found to compare it to. Each material and manufacturing method included roughly 50 – 100 variants in the database, including different alloys and variants on manufacturing processes.  The mean value was calculated for each, as well as maximum and minimum recorded values.  Data was also gathered on the embodied impacts of these metals, i.e. the impacts of mining and refining them into ingots for manufacturing.  It also included impacts for metal powder forming, a necessary step to make the metal ingots usable for the AM processes studied here.  It is unknown whether these powder forming processes are the same as those used for AM, but since they were a small percentage of total impacts, further precision was not deemed necessary.

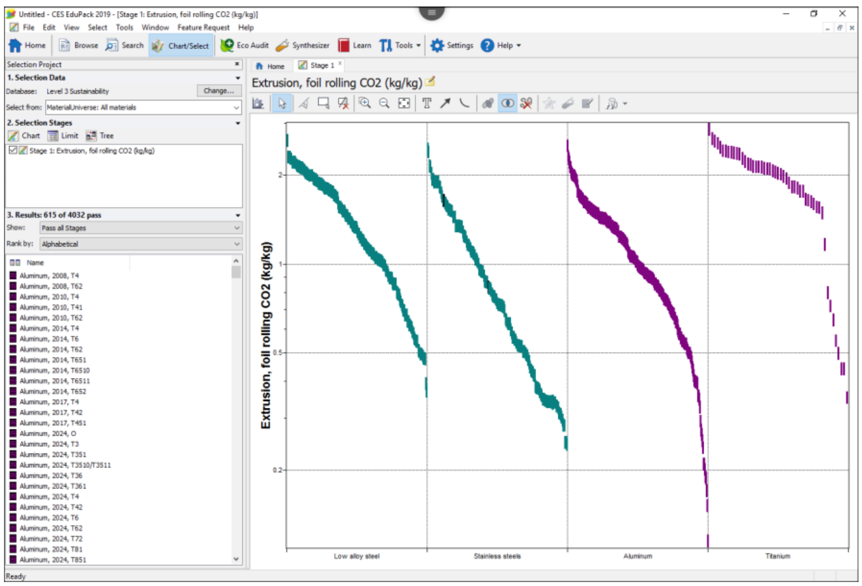


*Figure 2. Screen shot from Granta CES EduPack showing carbon footprint of extruding the four metals investigated.*

## Literature Review

While the Granta database was an excellent resource for conventional manufacturing, it lacks data on AM processes due to the lack of existing research on AM impacts.  Thus, data was sought in academic journal articles, books, conference papers, and other sources with quantitative life cycle assessments of AM; especially papers directly comparing AM and CM.  Climate and energy impacts were primarily sought, but toxicity and other health hazards were also sought.  The AM processes investigated were selective laser melting (SLM), electron beam melting (EBM), and directed energy deposition (DED); the latter also includes direct metal deposition (DMD) and laser engineered net shaping (LENS), but this report refers to them all as DED.  SLM is a powder bed fusion method that employs a laser to melt and fuse layers of fine metal powder.  Printing is done in an enclosed atmosphere of inert gas, such as argon.  EBM is also a powder bed fusion method, using an electron beam instead of a laser.  It keeps the build chamber under vacuum during printing.  DED does not use a powder bed but uses a laser to melt a metal wire or powder stream and deposit material along a build path. DED machines are often five-axis machines reminiscent of CNC mills, and can be used to repair conventionally manufactured metal parts.

Literature searches were performed in Google Scholar and Clarivate Analytics' Web of Science index using keywords for relevant methods, including: metal additive manufacturing; metal 3D printing; SLM; DED; DMD; LENS; EBM; machining; sustainability; LCA; life-cycle; CO2; energy; embodied energy; energy intensity; Cumulative Energy Demand; toxicity; hazard; and combinations thereof. Note that the AM process of Binder Jetting was also searched for, but insufficient papers were found with usable data to include in the results.

Papers were sought to include as much of a product's full life cycle as possible: raw material extraction, manufacturing, transport, product use, and end of life. Unfortunately, few papers included all these life cycle phases, and only one included the production of the AM printers or CM machines as well; the industry requires further study. Papers were also sought to include multiple industry sectors, especially aviation / aerospace, automotive, and medical devices, since those are the primary applications of metal AM today. Papers were also sought to find where AM is a more environmentally sustainable option than CM, where it is worse, and where further research or technological development is required. Note that social sustainability was not examined, as it is a complex issue, difficult to measure, and for which there is scant AM literature.

## Synthesis

Because few papers directly compare AM to CM, Granta data was combined with data from literature to enable comparison. These comparisons were made using kg of $CO_2$ equivalent per kg of material processed. This metric is a widely-used compromise—it is not as accurate as comparing the impacts to produce the same specific part, since impacts per kg vary by part geometry, but there are no studies quantifying the environmental impacts per part across several metal AM materials and printing processes. Therefore, the only available option to compare impacts across many studies with no standardization of parts is to compare impacts per kg. This is the same functional unit used in the Granta database, for the same reason. Even if it is not as accurate as counting impacts per specific reference part, it allows intuitive comparisons of how manufacturing method and material choice influence sustainability.

Since some literature did not report $CO_2$, but only reported source energy or site energy, SimaPro life cycle assessment software was used to translate site MJ/kg and source MJ/kg to kg $CO_2$eq./kg. Note the difference between source energy and site energy: A power meter reading the electricity used by a machine at the plug measures site energy. But if the source of that electricity is a coalfired power plant that is 33% efficient, then the source energy is three times the site energy. Site energy is sometimes reported because it is easy to measure, but source energy is required for comparing electricity to heat and the embodied energy of materials. Source energy still does not represent environmental impacts, because 1 MJ generated by coal power has very different environmental impacts from 1 MJ generated by solar power, but it is closer than site energy, and is often reported because it is easier to calculate by hand than actual environmental impacts such as kg $CO_2$ equivalents. Proper LCA software automatically calculates such impacts, including not only $CO_2$ but acidification, eutrophication, land use, water use, resource depletion, and many other factors, but most AM researchers do not have professional LCA software and are unaware of the free options available. Here, the impacts of using 1 MJ of site electricity were modeled as an average of five regional US electric grid sources: Western Electricity Coordinating Council (WECC), Midwest Reliability Organization (MRO), Texas Reliability Entity (TRE), South East Reliability Corporation (SERC), and Northeast Power Coordinating Council (NPCC), all using EcoInvent 2.0 data.

# Results and Discussion

## Comparing Database and Literature Findings

Comparing CM data from the Granta database to AM data from literature showed that metal AM generally has much higher carbon footprints per kg of material processed than CM, when considering the direct manufacturing process itself. For example, Granta data on casting, extrusion and foil rolling, roll forming and forging, and wire drawing of stainless steel at mass-manufacturing scale varied in impacts from 0.8 to 9.5 kg$CO_2$eq./kg material, while literature data on SLM (AM) of stainless steel (Kellens et al., 2017; Baumers et al., 2011; Baumers et al., 2010) ranged from 13 - 68 kg$CO_2$eq./kg material. Since Granta's embodied impacts for stainless steel material itself ranged from 1.8 - 12 kg$CO_2$eq./kg with powder forming impacts ranging from 1 – 3.6 kg$CO_2$eq./kg, the total impacts for these manufacturing processes plus their material ranged from 2.6 to 22 kg$CO_2$eq./kg material, while the literature's data on SLM ranged from 16 – 84 kg$CO_2$eq./kg material. Granta's impacts for machining stainless steel plus the material's embodied impacts were 1.9 – 13 kg$CO_2$eq./kg, but it is important to note that this is per kg of material *removed*, not per kg of material remaining in the final part. As later discussion will show, these numbers cannot be directly compared to AM or other CM impacts per kg.

Similar results were found for aluminum and titanium. For aluminum, Granta's CM impacts ranged from 11 – 27 kg$CO_2$eq./kg including the material's embodied impacts, while literature's impacts of SLM (Kellens et al., 2017; Faludi et al., 2017a) ranged from 61 – 212 kg$CO_2$eq./kg. For titanium, Granta's CM impacts ranged from 28 – 77 kg$CO_2$eq./kg including material impacts, while literature's impacts of EBM (Baumers et al., 2017; Priarone et al., 2017; Paris et al., 2016) ranged from 40 – 131 kg$CO_2$eq./kg.

Other literature corroborates this: in a review of many AM methods, Gutowski et al. found that the electrical energy intensity of AM generally (not only metal) was 1-2 orders of magnitude higher than conventional machining and injection molding, and processing speeds were 3 orders of magnitude smaller (Gutowski et al., 2017). Gutowski's differences are more extreme because they do not include the embodied impacts of materials as in the results above. This suggests AM is usually a less sustainable choice than casting, extrusion, rolling, forging, or wire drawing. To beneficially replace those processes, situations must be found where AM greatly reduces part mass, combines multiple CM processes, avoids tooling for short production runs, or provides other benefits discussed later. This correlates with AM being more expensive than those processes for mass-manufacturing, however, AM most often replaces machining, not those other processes, and there the comparison is more complicated, requiring more direct study.

## More Direct Comparisons Needed

A fair comparison between machining and AM is complicated by measuring impacts per kg processed, as mentioned above, since machining impacts are determined per kg removed and for AM they are determined per kg added. Thus, impacts depend greatly on part geometry—a solid cube will be much lower impact to produce by machining, while a hollow shell or lattice can be lower impact to produce by AM. It would be helpful for industry or academia to adopt a standard reference part (or parts) to easily compare different AM and CM processes in different materials. An example of such a fair comparison from literature is shown in Figure 3, excerpted from Priarone et al. (2017), which compares impacts of machining versus EBM of titanium for three different part geometries.

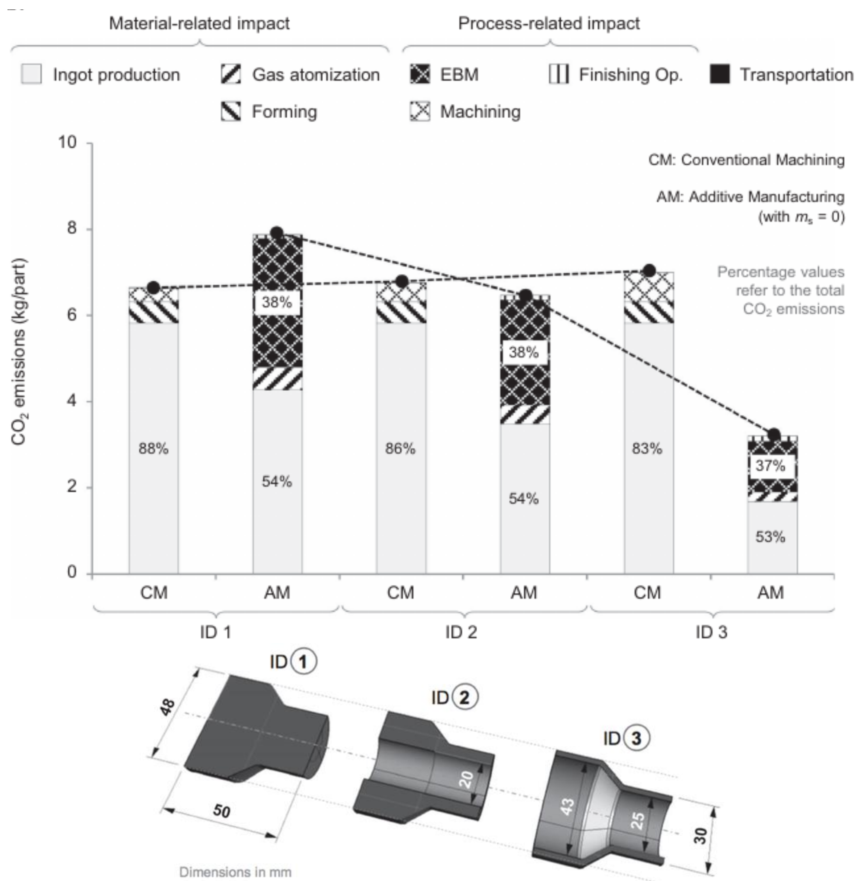


*Figure 3. Greenhouse gas emissions per part for three part geometries (ID1, ID2, ID3), using machining (CM in figure only) and EBM (AM) of titanium. Reproduced from Priarone et al., 2017.*

Figure 3 shows that AM process energy was higher than machining in every case, and total impacts were higher for the solid part; but for thin-walled parts (ID2 and especially ID3), AM was a more sustainable option overall because of saved material impacts. This would likely be true even if all machining waste titanium scraps were recycled, because that still requires energy and chemical processing, but this was not investigated in the paper. Priarone's study provided a fair comparison across three different types of parts, which enables estimation of the crossover point where EBM becomes environmentally better than machining for titanium. However, no such studies were found for stainless steel or aluminum to determine where their environmental crossover points might be. More studies are required to test different materials and different AM processes, such as SLM and DED.

The reference parts chosen for such comparisons should represent typical parts produced by metal AM. A balance may need to be struck between using a universal reference part printed on all AM machines to compare impacts across printing technologies, such has been performed for plastic AM (Shi and Faludi, 2020; Faludi et al., 2015), versus using different reference parts more relevant to the specific applications of different printer technologies. Or, as in Priarone (2017), a set of parts varying from solid to hollow might be used to establish environmental benefit crossover points. One reference part should include internal channels as shown in Figure 1, because AM is often used for such features and they are very difficult to create with CM, generally requiring assemblies and multiple processing steps as noted in that figure. One reference part should require high precision tolerances and surface finishes, as this is often a disadvantage of AM that requires post-processing to achieve, which would increase processing impacts compared to conventional machining. The more data, the better, but limits of time and resources will apply. All parts should be relatively small, both to avoid burdensome print time and money, and to enable testing of print bed utilization efficiency. Ideally a set of reference parts would be agreed upon by a broad coalition of industry and academic representatives.

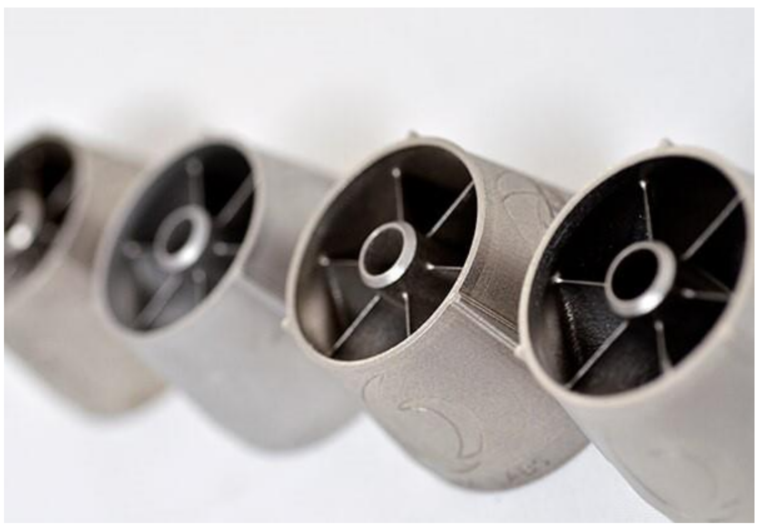

*Figure 4. Reference parts to fairly compare impacts of AM and CM might require several variants. Photo courtesy of Sigma Labs Inc.* www.sigmalabsinc.com

## Literature Findings by Life Cycle Phases

While it would be ideal to quantify impacts from all phases of a product's life, from mining raw materials to end of life, most AM literature only considers the impacts of process energy, with some incorporating material embodied impacts and end-of-life scenarios (Ingarao et al., 2018; Paris et al., 2016; Priarone et al., 2017). Very few consider toxicity during processing (Arrizubieta et al., 2020). Some studies consider the product use phase (Huang et al., 2016; Kellens et al., 2017; Mohd Yusuf et al., 2019); this is especially important for aerospace and automotive applications. An increasing number of studies consider part geometry and the benefits of process optimization (Ingarao et al., 2018; Priarone et al., 2017; Yi et al., 2020). Embodied impacts of metal AM machines themselves were only considered in one publication (Faludi et al., 2017a), though they have been considered in more plastic AM studies (Shi and Faludi, 2020; Faludi et al., 2017b; Faludi et al., 2015). In all of these studies, process energy was found to dominate the environmental impacts of AM for all technologies measured.

### Material Extraction & Production

Embodied impacts of materials can be very significant, indeed dominating the impacts for machining, as demonstrated in Figure 3 and noted in other studies (Paris et al., 2016). This is not only true for titanium, but also lower-impact materials like aluminum (Ingarao et al., 2018). Thus, material choice can be as important as manufacturing method choice in some circumstances. Indeed, it can determine manufacturing method. Processing energy is affected by a material's melting point and other properties—aluminum's high reflectivity and thermal conductivity has caused its SLM to use more energy than EBM of titanium (Ingarao et al., 2018). One possible key to reducing the environmental impacts of metal AM is to replace the metals, which require melting, with new materials that bond chemically at ambient temperature. However, such replacements would require great advances in material development to match metal's functionality.

### Process Energy

Process energy of AM is much higher than CM, as shown above, but there are still scenarios where metal AM is a more environmentally sustainable choice, as shown in Figure 3 and other literature. Compiling recommendations from metal AM literature (Gutowski et al., 2017; Ingarao et al., 2018; Kellens et al., 2017; Priarone et al., 2017; Wilson et al., 2014), AM is environmentally beneficial where:

- Tooling is avoided for low part quantities.
- High-embodied-impact materials (like titanium) are saved.
- Design optimization improves performance in the use phase, and that use phase dominates lifetime impacts.
- Remanufacturing extends the life of high-value components.

Processing energy per part and per kg of material can be greatly improved by maximizing machine utilization; this is one of the OECD's primary policy recommendations for more sustainable AM (Faludi et al., 2017b). This means using fewer printers that are shared, printing many parts at once to fill the print bed, and printing constantly to minimize idle energy. In fact, most studies assumed high utilization when comparing AM to other manufacturing processes, regardless of actual industry practice.  Utilization's importance in minimizing environmental impact has been demonstrated repeatedly in literature (Baumers et al., 2016, 2013, 2011; Faludi et al., 2017a; Shi and Faludi, 2020), making up to a 5x difference in impacts per part for metal, and far higher for polymers.  The aforementioned studies were SLM, where parts must connect to a build platform, but EBM parts can be free-floating, which enables even denser part-packing for high utilization.

### Post-Processing and Print Failures

Metal AM parts often require post-processing before they are used in products, but the environmental impacts of these steps are frequently ignored in literature.  The performance and appearance of AM parts are affected by porosity, surface roughness, anisotropy, residual stress and other factors.  Post-processing can include finish machining to smooth surfaces, improving aesthetics, reducing friction in sliding parts, and removing imperfections that seed fractures.  It can also include cold rolling and heat treatments to reduce residual stresses, and hot isostatic pressing and infiltrating increase part density (Gisario et al., 2019).  Avoiding such post-processing can shorten part lifetimes by causing higher fracture and fatigue failure rates than in CM parts.  EBM parts do not have residual stresses, a benefit over SLM and DED, but they are more often post-processed because of their rougher surface finish (Liu and Shin, 2019).  If standardized methods are developed to measure metal AM environmental impacts, they should include post-processing.

Metal AM can also have far higher failure rates than CM, which would increase the environmental impacts per final part used if it were measured.  Failure rates may be as high as 25%, but published data is difficult to find (Mohd Yusuf et al., 2019).  Industry and researchers should publish failure rate data for different AM processes and materials, to enable more accurate impact assessments.

### Print Process Hazards

Metal AM powders are made up of titanium, aluminum, chromium, nickel, iron, cobalt and other elements.  Some of the powders pose serious toxicity risks, including cancer.  Most metal powders studied have the potential for causing allergic skin reactions, damage to organs after prolonged exposure, cancer, and are harmful to aquatic life.  Workplace health hazard of metal AM powder is an area needing more research, though a few studies have been performed focused on fine particles. Nanoscale particles can be generated, and while general dust inhalation hazard seems to be low given machine enclosures and ventilation, smaller particles may pose toxicity risks to workers because of their ability to pass biological barriers.  A comparison can be made to welding, where nanoparticles are also a risk (Arrizubieta et al., 2020).

Studies of SLM verified the presence of nanoparticles and found that recycled powders tended to have more small particles than new powder (Sousa et al., 2019). The authors suggested that workers exposed to nano-scale metals should do regular biological monitoring, such as urine analysis, to watch for toxic exposure.

### Computational Design and Process Optimization

Design optimization is an area of unique freedom for AM, allowing, for example, the minimization of part mass (see Figure 1) and tuning mechanical properties without increasing difficulty of manufacturing (Baumers et al., 2017a). Manufacturing process optimization is also a growing area of interest in AM as computational methods become more advanced and the use of AM in industry becomes more of a reality.

Simulation and live process monitoring are two areas with the potential to improve the sustainability of AM. Failure rates in AM can be high, but detailed analysis of material and processing factors plus in-situ controls can reduce errors and improve part quality (He et al., 2019; Peng et al., 2020). Efficiency and cost can also be modeled before manufacturing takes place. Yi et al. developed a model predicting the energy demand of SLM with 98.5% accuracy (Yi et al., 2020). It enabled energy optimization by varying laser speed, layer thickness, and machine utilization. Liu et al. developed a cloud-connected framework “MANUELA” for optimizing design, process, and post-processing using web-based and on-site analytics, including machine learning (Liu et al., 2020). It was tested on a distributed network including EBM and DMLS machines. It enabled operators to balance energy use with part performance, cost, production volumes, and more. Further development in AM process optimization is expected, which could provide valuable data for understanding the sustainability of AM, especially from a systems perspective.

### Product Use

The use phase is often left out of AM LCA studies because part use is generalized, yet there are studies showing some applications where AM parts enable major improvements to performance. Aerospace applications are the most notable, where it is estimated that every kilogram of aircraft mass saved could save 134 - 200 gigajoules of fuel energy over a typical 30-year commercial aircraft lifespan (Mohd Yusuf et al., 2019). Kellens (2017) calculated the savings per kg of weight reduction for several vehicle types and multiple environmental metrics—see Table 1. One study considered replacing 9 - 17% of fleet-wide aircraft mass with lightweight AM parts made from aluminum-, nickel-, titanium- and steel alloys. Cumulative savings in GHG emissions were estimated at 92 - 215 million metric tons of $CO_2$ through the year 2050 because of a 6.4% fuel reduction (Huang et al., 2016).

Interestingly, the net change in environmental impacts were not only from fuel savings: 2-5% were from manufacturing impact reductions due to the dramatic difference in "buy-to-fly" ratio, or the mass of materials used to that of finished parts, even with a CM model that included forging and casting, not only machining. Where CM commonly has buy-to-fly ratios of 12:1 to 25:1 for aluminum and titanium alloy parts, AM can have ratios closer to 1.5:1.

| Transport system | Energy source | FRC [26] | Service life | Eco-Impact (ReCiPe H/A) | Life time savings (ReCiPe H/A) | Equivalent electrical energy |
|---|---|---|---|---|---|---|
| Gasoline car | Gasoline | 0.5 l / (100kg*100km) | 200000km | 0.121 Pts/l | 1.21 Pts/kg | 85 MJ |
| Diesel car | Diesel | 0.24 l / (100kg*100km) | 200000km | 0.141 Pts/l | 0.68 Pts/kg | 48 MJ |
| Short distance train | Electricity | 300 kJ / (1000kg*km) | $3.5*10^6$ km | 0.051 Pts/kWh | 14.88 Pts/kg | 1050 MJ |
| Long distance train | Electricity | 100 kJ / (1000kg*km) | $10*10^6$ km | 0.051 Pts/kWh | 14.17 Pts/kg | 1000 MJ |
| Short distance aircraft | Kerosene | 12.5 ton / (100kg*year) | 25 year | 0.134 Pts/l | 335 Pts/kg | 23647 MJ |
| Long distance aircraft | Kerosene | 103 ton / (100kg*year) | 25 year | 0.134 Pts/l | 2760 Pts/kg | 194852 MJ |

*Table 1. Fuel consumption reduction coefficients for different vehicle types and related lifetime impact savings per kg of weight reduction. From Kellens et al., 2017.*

While saving fuel in aerospace applications is so valuable that manufacturing impacts are nearly irrelevant, even if they are higher than conventional manufacturing, that is not the case for all industries. Product lifetimes and their contribution to GHG emissions are important parts of the equation, as Table 1 shows. For passenger cars, higher impacts of AM versus CM were not offset within any reasonable product lifespan (Ingarao et al., 2018; Kellens et al., 2017). One study of a throttle component for a passenger van comparing a CM assembly to a topologically optimized and consolidated AM part found that AM only improved total lifetime impacts if the part lifetime was increased by 200% and at least 30% of the mass was removed (Yang et al., 2019). Another study found similar results for a 5-liter truck engine, but found that replacing high impact metals like nickel alloys and stainless steel with low-alloy steel would improve total impacts (Bockin and Tillman, 2019).

One seldom-considered aspect of product life is repair of existing parts with AM (specifically DED), where new material is deposited and fused to the existing part to patch gaps. This is quite rare, but can reduce lead times on repairs by 50% and reduce maintenance and repair costs (Mohd Yusuf et al., 2019). One study of patching cracked turbine airfoils using DED with nickel alloy resulted in lower impacts than producing a new blade by investment casting when the repair volume was less than 18% (Wilson et al., 2014).

### End of Life, Reuse, Recycling

Material waste in metal AM is an area needing more research, as material reuse and recycling are not completely understood. Accounting for support structures, platform separation, filtering and emissions, material losses for AM have been assumed up to 20% the part mass (Kellens et al., 2011). Powders are often reused in AM machines, requiring simply to pass used powder through a sieve to remove large particles and agglomerations—about 95% of powder is thought to be reused from one job to the next.

Some questions remain about the quality of parts made form reused powders. Sartin et al. assessed 316L steel powders over 12 reuse cycles and found no statistical variation in UTS and elongation % at break (Sartin et al., 2017). While most research concluded that part material properties do not deviate significantly from those made with new powders, there is variation in results, even for the same AM method and powder type (Arrizubieta et al., 2020). In general, metal particles tend to lose their spherical shape and take on more oxygen after multiple uses, affecting powder flowability and resulting in oxidation of finished parts. Excess oxygen is known to reduce the ductility of AM Ti6Al4V (Liu and Shin, 2019). Researchers have observed changes in morphology, chemical composition, flowability, micro-structure, density, surface energy, and more (Heiden et al., 2019). A standard method for assessing recyclability of AM powders would allow for more reliable data across studies and pave the way for more powder recycling in industry.

Machining waste materials can be remelted at their end of life: 84 - 95% of aluminum is commonly recovered from machine scrap chips / swarf (Xiao and Reuter, 2002). However, the end of life for waste AM powders is not well understood, and remelting may not be efficient. Significant amounts of un-fused powder can simply be reused, but reports differ about how much is saved after quality-control filtering to remove partly-fused particles (Petrovic and Ninerola, 2015; Alamos et al., 2020). GE introduced a plasma spheroidization technique that could refine AM powders and return particles to the shape and chemical composition necessary for printing, but more research in waste powder management is needed to prevent materials from being sent to landfill (Powell et al., 2020).

## Literature Results by Industry Sector

*Figure 5. Grade 23 titanium spine, hip and knee sample implants manufactured by Tangible Solutions via Selective Laser Melting (left) and CellCore Gmbh nichrome alloy rocket engine thrust chamber made by SLM (right) (SLM Solutions Group AG, 2019).*

Roughly 40% of metal AM is used in aerospace & defense industries (Grand View Research, 2020). It is popular because complex and unique part designs can be produced to save weight without increasing tooling and processing costs (Baumers et al., 2017). In aerospace, saving weight saves great amounts of fuel, as described above in Table 1, and can improve the “buy to fly” ratio of material use. Companies pursue these strategies because they save money, and saving environmental impacts is an extra benefit. Design for AM can also save fuel through more efficient combustion, such as in the rocket engine in Figure 5. It and others like it, such as the SpaceX SuperDraco, improve efficiency with fluid channels for “regenerative cooling” inside the walls of the combustion chamber, rather than welded to the exterior as with earlier manufacturing methods (Dankhoff, 1963; Post, 2014). As mentioned earlier, GE redesigned a Cessna Denali turboprop engine from an 855-part assembly to only 12 parts via AM (Mohd Yusuf et al., 2019). These part consolidations reduce the number of processing steps in product manufacturing and simplify the supply chain.

Roughly 1/3 of metal AM is used in medical devices (Grand View Research, 2020), especially joint implants as shown in Figure 5, because AM enables customization to individual patients’ bodies. The porosity of AM parts also promotes better cell growth and integration into bone tissue. Favored processes for implants are SLM and EBM with biocompatible alloys of titanium, CoCr, and stainless steel. Examples of successful implants include cranial, mandibular, spinal, chest, lower limbs, and more (Buj-Corral et al., 2020). While these benefits give AM a clear performance benefit, environmental impacts of such implants have not yet been measured. The impacts per part are almost certainly far higher than CM, given the comparison of CM Granta data to AM literature data discussed above; those impacts would be further magnified by printing one part at a time rather than maximizing printer utilization. While medical customization does not require separate printing, the timing and low volume of surgical operations seems unlikely to allow batches of many customized parts to be printed together.

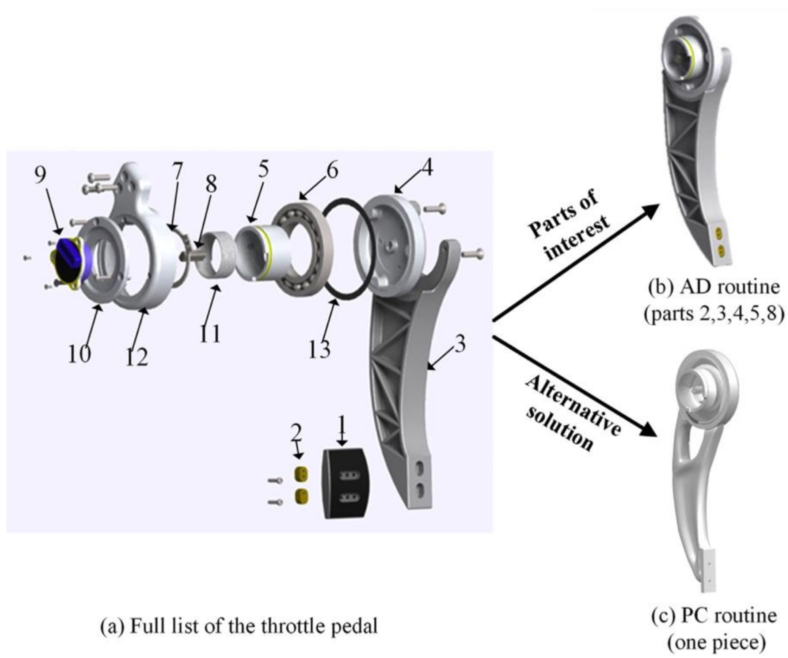


*Figure 6. Part consolidation and lightweighting of an automotive throttle component by Yang et al. that did not result in lower environmental impacts compared to CM. (Yang et al., 2019)*

Roughly 1/4 of metal AM is used in the automotive industry (Grand View Research, 2020). For car parts, AM is likely less sustainable than in aerospace parts. Yang et al. found that for the consolidated throttle design shown in Figure 6, use phase impacts and material savings were not reduced enough to make AM the better choice. Table 1 from before reveals how overall product lifetime plays a part—in Figure 6’s example, vehicle life would have to double to provide any environmental savings (Yang et al., 2019). Similarly, Bockin and Tillman found that given the present limitations on print bed size, materials, and electricity sources, the redesign of a Volvo truck engine resulted in only moderate to negligible improvements over CM (Bockin and Tillman, 2019). AM may be beneficial for metal tooling, however, if it can save significant amounts of material as in Figure 3. Experimental AM research also explores other energy-related applications like 3D printed batteries, capacitors or thermal wire from carbon nanomaterials; however, impacts of these novel applications have not yet been assessed.

## Conclusions

The environmental impacts of manufacturing process and materials for conventional manufacturing of aluminum, stainless steel, and titanium drawn from the Granta database were compared to impacts of additive manufacturing from academic literature, and found:

- More LCA studies are necessary to definitively compare metal AM to CM; especially direct comparisons of AM to machining, and especially for technologies such as binder jetting and DED. These LCAs should ideally also include more of the product life cycle.
- An assessment standard would help guide research, namely standard reference parts and standard utilization scenarios, to enable fair comparisons across process technologies.
- In direct manufacturing processes comparisons, AM had roughly ten times higher carbon footprint per kg of material than casting, extrusion, rolling, or wire drawing, even when including embodied material impacts. The increase was even greater when not including material impacts.
- When AM saves significant material mass, it can have lower manufacturing impacts than machining, especially for environmentally impactful materials like titanium.
- Part geometry heavily influenced comparisons, especially for machining, because machining impacts accrue per kg of material removed, while AM impacts accrue per kg of material added. An assessment standard would help.
- More research is necessary to determine the environmental benefits and performance risks of recycling AM powder. An assessment standard would help.
- For aerospace applications, regardless of manufacturing-stage impacts, greatly light-weighted AM parts saved so much fuel during flight lifetimes that they were a net environmental benefit over CM parts.
- For automotive applications, vehicles do not have the lifetime fuel savings per kg of weight reduction that aerospace vehicles have, so increased manufacturing impacts are harder to pay back.
- For repair applications, DED offers more opportunity to repair existing parts than SLM or EBM, but further studies are required to determine the scale of benefits and drawbacks compared to CM repair methods.

Thus, based on existing literature, metal AM would not be a more environmentally sustainable choice for many industry applications, but there are several applications where AM is a more sustainable choice, and these appear to be the industries where it is currently being used most, namely aerospace. It is an environmental benefit when resource-intensive materials such as titanium are greatly reduced, or when lightweight designs enabled by AM result in significant energy savings in the use phase. However, because it is unclear where these benefits will be strong enough to overcome the increased processing energy, much more research is required to enable modeling and prediction to support decision-making.

In addition to the comparisons of additive to conventional manufacturing, general principles were also found for improving the environmental impacts of metal AM:

- Maximizing printer utilization (using fewer printers, sharing them to avoid idle time & idle print bed space) dramatically improves environmental impacts per part.
- Reducing material embodied impacts. Though processing energy is AM's largest impact, material embodied impacts can be significant for both AM & CM, especially for titanium.
- Choosing materials to minimize AM processing energy, using factors such as melting point, reflectance, and thermal conductivity. Advanced materials might eliminate the need for melting.
- Screen printer operators for hazard exposure. AM operators appear to have low exposures with proper powder handling, but nanoparticles may pose serious health risks.
- Use design for AM and process optimization to reduce failure rates, improve print quality, and improve efficiency.

Manufacturers choosing a production technology should weigh these issues to find the most environmentally sustainable choice for their circumstances. Further studies building an extensive body of data on the environmental impacts of additive manufacturing could greatly improve this decision-making. Especially more comprehensive and standardized LCA studies, calculating multiple environmental impacts such as greenhouse gas emissions, acidification, eutrophication, land use, etc. and considering all life-cycle stages of AM parts. In the future, choosing a production technology may also become easier with computational tools to manage the complex interaction of design, material, and process parameters.

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