Integrating Additive Manufacturing into Operations at Middle Market Companies

by

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B.S. Mechanical Engineering, United States Military Academy, 2010

Submitted to the MIT Sloan School of Management and the Mechanical Engineering Department in Partial Fulfillment of the Requirements for the Degrees of

Master of Business Administration
and
Master of Science in Mechanical Engineering

In conjunction with the Leaders for Global Operations Program at the Massachusetts Institute of Technology

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Abstract

Ascent Aerospace's leadership recognizes the transformative potential of additive manufacturing (AM) to the aerospace tooling industry. As a middle market company, Ascent required a deliberate approach to identifying areas with the highest potential for value creation. Without the research and development budget of an aerospace OEM, the best path forward for Ascent is to leverage existing AM technologies and those requiring minimal further development.

The motivation for this project is to identify the best path forward for Ascent in leveraging AM as a value creation tool. Ascent had no AM capability at the beginning of this project, using a supplier when AM components when specifically requested by a customer. The thesis describes a methodology and results for identifying where to integrate AM into operations. It discusses the data and analysis used to find impact areas. The thesis also addresses some of the barriers impacting the adoption of AM.

The analytical methods and organizational factors for additive adoption provide a holistic view of how to integrate AM into regular operations. Abstracted away from the case studies, the method should be actionable at any capitally constrained company to generate value through the adoption of AM. Recommendations on future work on how to approach the adoption of AM will be discussed, along with specific future work related to the thesis.

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Many thanks to all the Leaders for Global Operations faculty, staff, students. Learning from and with you inside and outside the classroom was a pivotal part of my MIT and internship experience.

Most importantly, I must acknowledge the immense contributions and sacrifices of my wife, Esther (LGO '15). More than anyone she demonstrates selfless leadership and what it means to be an operations professional. Over the past two years, she has provided patient guidance, support, and love even when I ignored her council. We are a few days away from meeting our first child, I pray she waits until this document is submitted.

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1. Project Motivation and Problem Statement

Ascent Aerospace is a Michigan based aerospace tooling and equipment manufacturer. The rapid advancement of additive manufacturing (AM), colloquially referred to as 3D printing, in the past decade has largely been ignored by tooling manufacturers due to perceived low quality and high price. In the last twelve months Ascent realized that AM technologies have developed far enough to be highly relevant, and perhaps revolutionary, for the aerospace tooling industry.

Ascent has a broad product portfolio including automated fastening systems, layup molds, trim and drill fixtures, work platforms, and the accompanying capability to design and integrate entire assembly lines. Ascent has deep expertise in traditional manufacturing methods from manual processes like bump forming to large numerically controlled (NC) machines.

Until recently Ascent lacked the capability to produce parts using AM. AM easily delivers complex shapes traditional manufacturing struggles with. Often times, the tools required to build aerospace parts exhibit the same complex features and surface as the components they are used to build.

A broad range of 3D printing technologies is commercially available. The diversity of printers and materials can be daunting to the uninitiated. Large OEMs like Boeing, BMW, and SpaceX have devoted millions in research and development dollars to investigate 3D printing. Niche cases have been found but there is no “killer app” for additive yet. As a result, many suppliers are slow in the uptake of 3D printing despite the technology’s potential. What these suppliers, and likely the OEMs, lack is a framework for identifying where to best apply the technology in their current and future product portfolios.

This project is ultimately motivated by the desire to integrate additive manufacturing into Ascent's operations in the way that drives the most value for the business and its customers. The underlying problem is the lack of a comprehensive framework for anyone to apply when evaluating what to print.

2. Background

2.1. Aerospace tooling

Aerospace tooling is a broad category of products centering around the production of air- and spacecraft. Essentially any piece of equipment found in a OEM's factory that is not intended to be part of the flight vehicle is an aerospace tool. This includes everything from small handheld locating fixtures to fully automated fastening systems capable of holding and rotating the entire fuselage. In addition to the assembly of the airplane, aerospace tooling also encompasses the equipment used to make parts of the aircraft. Typical examples of these tools include layup molds for composites and the accompanying trim and drill fixtures. Another category of aerospace tooling consists of large, often moveable, work stands used to access various parts of the airplane.

The most common theme among the disparate categories of aerospace tools is the complexity of the final product they are used to create. Modern aircraft are built to precise tolerances, often varying only a few thousandths of an inch over large areas. This necessitates that the tools used to make the aircraft are capable of achieving these exacting standards as well. Furthermore, the surfaces and geometries of parts are highly complex, driven by aerodynamics, space, and weight constraints. The tools must match this complexity as well. Aerospace tools are tightly toleranced for both large and highly complex geometries. This thesis will center on the production of layup molds and trim and drill fixtures for composites.

2.2. How it's made now

Complex surfaces with tight tolerances are not easily achieved, especially over large areas. Manufacturing aerospace tooling requires state of the art machinery and a highly skilled labor force. Some of the most highly skilled and paid workers in aerospace make the complex surfaces for composite tooling. These tools are produced at very low volumes, six of the same tool in a year is considered high volume, so there is minimal investment in the tooling to create the tool. Instead, the process of bump forming is performed by a skilled workforce to create the complex surfaces.

2.2.1. Bump Forming

Bump forming is essentially modern day black smithing. At its heart bump forming is bending sheet metal with a hydraulic press to make an aerospace surface. The most common materials used are steel, aluminum, and Invar, a nickel based steel alloy. The operator responsible for the forming and a production engineer jointly segment the surface into manageable pieces based on size and complexity. Portions of the tools with multiple diverging contour lines are parceled into smaller sections than gently contoured surfaces. For example, the gently sloping contour of a wing can be done in relatively large sections while heavily contoured engine nacelles contain sections no larger than a dinner plate. After the forming process, the pieces are welded together.

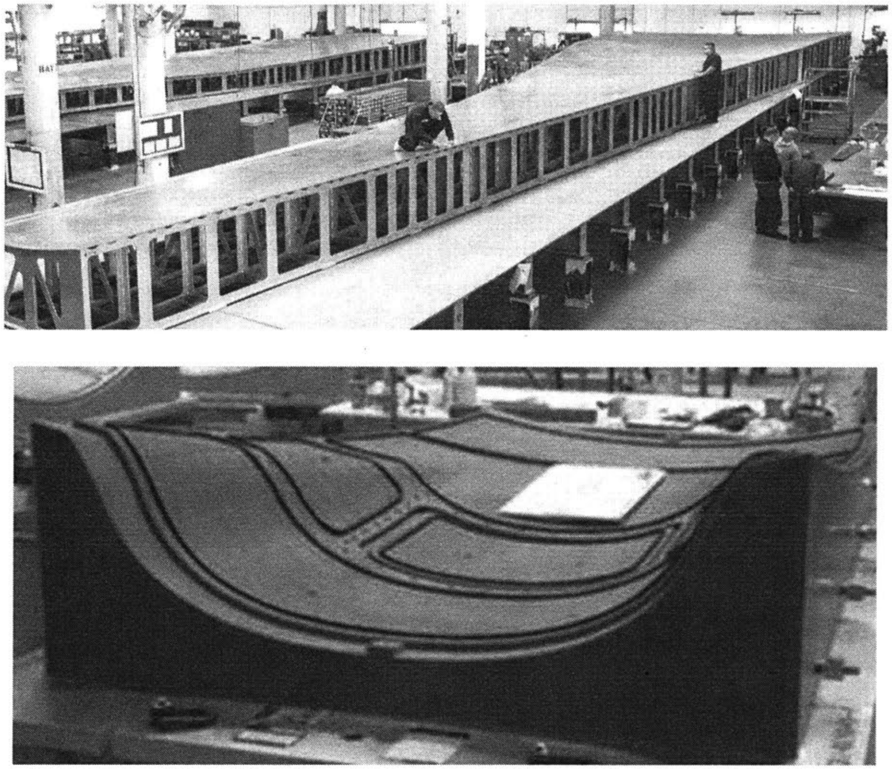

Figure 1. Large (above) and Small (below) Scale Tools [1].

During the forming process, the operator uses a combination of custom stencils and drawings to guide his work. Though best practices are shared among the operators, there is much variation in throughput and rework rates. Some operators work at seemingly half speed making no mistakes, while others have high scrap rates at a faster pace. Yet others work with unmatched pace, rework, and scrap rates. The variation in throughput and quality makes estimating the cost of a tool difficult. Bump forming is also the bottle neck in producing layup molds.

2.2.2. Chip Forming

At times, surfaces become too complex for even the most skilled operators to form. In this case the smallest possible portion of the surface is segmented and milled from a block. This is unfavorable for two reasons: (1) mills are expensive to run and (2) much material is wasted. The block of material being machined is taken down to the same thickness as the sheet metal used in bump forming, between 0.25 and 0.75 in. For a surface with a large, complex contour, this could mean up to 90% of the material is machined away. This is not only wasteful from a material standpoint, but also means that the NC will be running for an extended period of time even when the optimally small block is chosen for the job. Additionally, the complex surface must be machined on all sides, necessitating multiple set ups for the same job. This reduces the operational availability of the factory's most valuable machines.

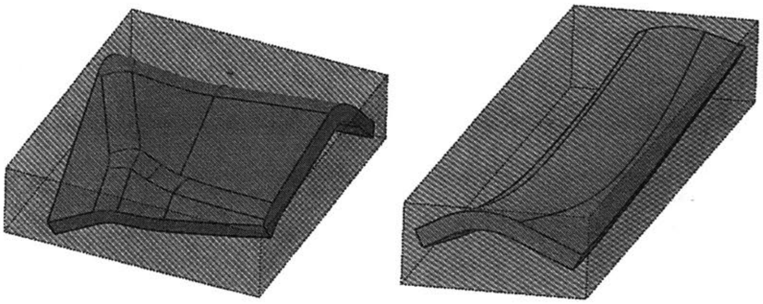

Figure 2. Representative Chip Formed Inserts.

2.2.3. The Support Structure

The substructure supporting the aerospace surface is relatively easy to manufacture compared to the surface itself. It is made of pieces of sheet metal cut to be quickly assembled like building blocks and then welded together. The pieces are made sparse with a laser cutter or water jet, a relatively inexpensive and fast process. Afterwards welders quickly assemble the substructure, commonly referred to as an "egg crate." The egg crate serves the dual purpose of providing the template for assembling the bump and chip formed pieces of the surface.

Hollowing out the substructure serves two main purposes. A lighter tool is cheaper to ship and easier to move around production facilities. The smaller mass also allows for faster heating and cooling for autoclave tools, reducing cycle time for curing composites. Making the substructure sparse does lead to material waste at rates similar to that of chip forming. However, the process of laser cutting out a large section is much faster and less expensive than milling layer by layer. While it can take weeks to form a surface, creating the substructure for a medium sized tool can take less than a day.

2.2.4. Post Processing

Once the surface is welded and joined to the egg crate, the tool is heat treated for stress relief and annealing. Afterwards the final surface and features are machined onto the tool. The manual forming process and assembly of parts is not accurate enough to meet aerospace tolerances, necessitating the extra machining step. Small details are also added in this step. The egg crate is sanded and painted while the surface is hand finished for a good polish. Additional components like vacuum tubes and control boxes are added to finish the tool in final assembly. Once complete, the tool is inspected and shipped to the customer.

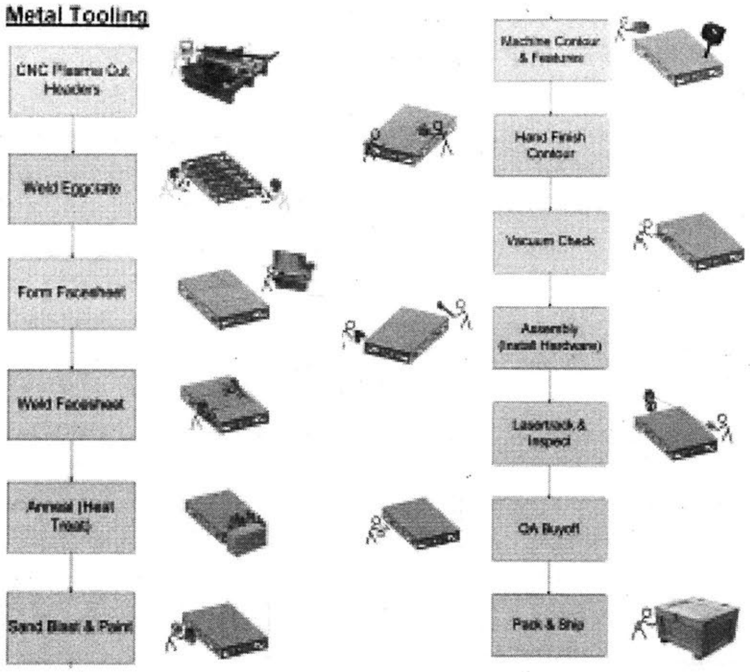

Figure 3. Steps for Creating Metal Layup Molds and Drill and Trim Fixtures.

3. Additive Manufacturing

Additive manufacturing is best understood in comparison with traditional manufacturing methods. EOS, a market leader in AM, defines the technology as "a process by which digital 3D design data is used to build up a component in layers by depositing material" [2]. The definition contains two aspects, the 3D design data and depositing material layer by layer. The inclusion of digital data differentiates AM from manual processes like cladding which may or may not be digitally guided.

AM contrasts with traditional manufacturing methods which can be grouped into two broad categories: subtractive and formative. Either of these can be guided by 3D models or done by hand while AM is always digitally guided. Subtractive methods refer to manufacturing methods which remove material, like milling. Formative methods are those by which material is shaped through any of a multitude of processes such as injection molding.

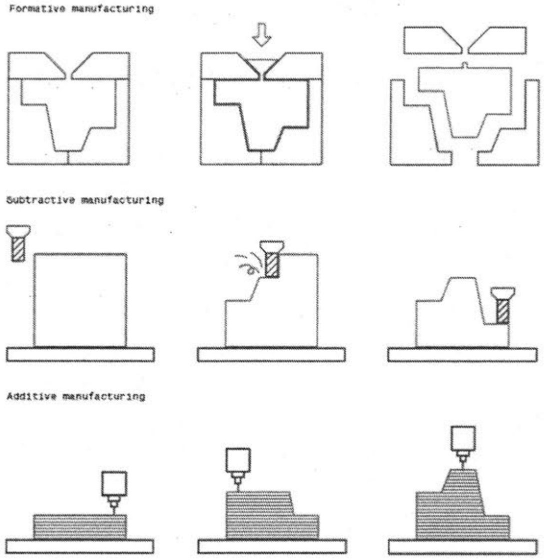

Figure 4. Comparison of main manufacturing technologies [3].

3.1. The benefits of AM

Additive manufacturing has multiple value propositions for manufacturers. In general, the value derived from using AM can be divided into three categories: design freedom, time, and cost.

Design freedom with AM typically refers to the ability of AM to make geometries impossible or incredibly costly to make with traditional processes. Lightweighting components with interior cavities or lattices is a common example from the aerospace industry. In the case of reducing component weight the benefit is easy to quantify, each pound saved on an aircraft leads to a set amount of fuel savings over the life of the aircraft. Another example of light weighting is with tooling, some traditional tools require lift assists while the hollow AM tool is easily handled by one operator.

A harder to quantify example of increased design freedom is the inclusion of ergonomic and other design features in parts. While it is possible to calculate the cost of making a part designed for AM (DfAM) with traditional methods, the benefit of the features themselves are difficult to quantify. Attaining the perfect fit for a hip implant to increase patient comfort and quality of life is something many are hesitant to put a price on.

A third design advantage of AM is the reduction of parts. Many products are assemblies largely due to the limitations of manufacturing processes. With AM, a complex assembly can be printed as one piece. Since joints and interfaces are typical points of failure, product life is increased by moving to AM. Eliminating the need for assembling multiple parts together, sometimes laboriously done by hand, also helps reduce the time to manufacture a product.

Inventory reduction is closely linked to part reduction. Inventory management is simplified by the need to only maintain a stock of one part instead of each part of an assembly. Additionally, the capacity of flexible 3D printers can be used as a substitute for holding inventory. Slow moving inventory for old equipment can be stored as a digital file and printed on demand. Utilities and other businesses with equipment of lifespans of 20 or more years maintain warehouses where some spare parts have not moved for decades. There is a high cost to holding these parts while the cost of maintaining a digital model is near zero.

AM can significantly reduce lead times for some types of parts. This is particularly true for prototypes and small batches. Prototypes that may take several days or weeks to make in a machine shop can be printed overnight. This accelerates the product development cycle. Increasing the productivity of any department is obviously beneficial to a company, though the benefits are hard to quantify outside of reduced labor hours to develop each iteration. AM is also able to bypass the requirement for tooling. An injection mold machine may be able to produce 100 parts faster than a 3D printer. If only 100 parts are required though, the printer may finish the run of 100 pieces before the mold is ready. In 2018 this was exhibited by the production of a collector's edition can cozy for the hit movie *Black Panther* [4].

3.2. The limits of AM

AM techniques hold many promises. One of the greatest is the ability to create complex shapes prohibitively difficult or expensive to manufacture with conventional techniques. Most AM products suffer from two competing drawbacks: build rates and mechanical properties. Build rate affects the accuracy of material placement and consequently the resolution and spacing between deposited material. This translates directly into mechanical properties. For a given process, a slow build rate for high resolution will result in a more mechanically sound part. The material used also affects build rates. Melting or sintering metals is more energy intensive and time consuming than for plastics. The limits on AM have led to its use primarily in low volume non-structural components. An additional constraint on size is the build volume of the AM machine, with many processes requiring a controlled environment [5]. Even the fastest commercial systems cannot produce parts faster than 0.6 L/hr, acceptable only for small items produced at low volume. Many quality processes are an order of magnitude slower [6].

As with any new technology, price is not the only hurdle AM must overcome. Quality and repeatability are significant barriers to AM adoption. The meaning of quality depends largely on the product and application. AM technologies have come a long way from their initial inception over 30 years ago. Quality issues with AM also largely depend on the printer, material, and settings for any given job. Still, some common themes resonate across groups of technologies and all of AM.

Durability of AM products is one of the largest concerns many have, especially when compared to time proven production techniques. Some AM processes suffer from delamination between layers, notably under stress, preventing their use in any load bearing or critical application. Similarly, processes using powders often exhibit porosity in the final product. This is particularly troublesome for any part experiencing fatigue loading. Ultimately poor layer to layer adhesion and porosity reduce a parts ultimate strength to below that of the parent material in potentially unpredictable ways. Layer to layer issues further complicate design by causing the part to exhibit nonisotropic properties. Post processing techniques, like hot isostatic pressing, exist to mitigate some of these concerns, though this can greatly increase the cost of a part.

Surface finish is another quality problem that plagues nearly all AM parts. Depending on the process the printed layers can be highly visible or the surface may simply be rough like sand paper. The implications of these imperfections vary by application. For interior, non-load bearing products appearances are largely nonconsequential. Other applications may require a smooth surface finish for any number of reasons, necessitating costly post processing.

Dimensional accuracy and inconsistency between printed parts is a major area of concern. In precision machines, parts must meet exacting standards for tolerance over large scales. Many AM processes cannot achieve these tolerances. Furthermore, dimensional consistency between prints is also not stable on many printers. If the same dimensional errors were consistently reproduced, they could be compensated for in serial production. Dimensional accuracy is continuously improving and highly dependent on the printing process being used. One off, highly accurate parts without the need for post processing are still out of reach.

This bleak picture leads to the perception that AM is only good for prototypes. What it truly means is that AM is not the panacea to manufacturing issues many wish for. One must be selective and strategic about what parts to print, how to design them, and which material and printer to use.

3.3. Types of AM technologies

An explosion of innovation has led to many types of 3D printers. 3D printers are becoming faster, less expensive, and bigger as the field advances. Material choice continues to expand from standard plastics and metals to more exotic ones. ASTM F42 recognizes 7 AM methods.

Vat Photopolymerization

Vat photopolymerization uses light to cure a photosensitive resin. Stereolythography (SLA) and digital light processing (DLP) are the most common forms of this printer. It is common for SLA parts to require support structures which are removed during post processing. The Formlabs Form 2 is a common example of a SLA printer.

Material Jetting

Material jetting deposits drops of material in the same way an inkjet printer does. The drops are used to build the part. HP's multijet fusion is an example of this type of printer. Currently available material jetting printers are for plastics only.

Binder Jetting

Binder jetting uses a bonding agent to essentially glue together a powder. The binder material is deposited using inkjet like nozzles onto a powder bed of either plastic or metal. Some form of post processing is required to fuse the powder into a solid object, sintering for metals or a fusing agent for plastics.

Material Extrusion

Material extrusion is what most picture as AM. Here a material, typically a polymer, is melted and extruded through a nozzle which places the material.

Sheet Lamination

Sheet lamination is a less common form of AM. Here sheets are bonded together to build up the part.

Powder Bed Fusion

Powder bed fusion is used for both polymers and metals. An energy source, like a laser, is used to fuse powder together.

Directed Energy Deposition

Directed energy deposition (DED) also uses a powder. Instead of a bed of powder, the powder is dispensed only where needed and immediately fused. DED is often seen in the context of repairing or augmenting up existing parts.

3.4. AM applications today

In spite of the costs and limitations of AM, companies have found many uses beyond prototyping. Examples of successful AM implementation abound across industries. One of the earliest adopters of AM was the aerospace industry. AM continues to penetrate the aerospace industry in part because aerospace parts are already very costly to make. Weight savings in aviation also leads to significant reduction in the cost of ownership of an aircraft, largely due to a reduction in fuel consumption.

GE is using AM to print a large portion of the fuel injection nozzle for the Leap engine. GE consolidated 20 parts into one. This eliminates many joints, a large point of failure in many systems, and extend the parts durability by a factor of five. The redesign also reduced weight by 25% [7]. The part is now in serial production.

The armed forces are also finding innovative ways to incorporate AM into their operations, especially for spare parts. Recently the Marine Corps printed a replacement part for the F35 landing gear using a hobby grade printer. The component was rapidly designed and printed on site, and cost less than $1 to manufacture. Replacing the entire assembly through the OEM entailed a cost of $70,000 and weeks of lead time [8]. The armed forces continue to use AM to save money, and more importantly, maintain the operational readiness of key platforms like the F35.

AM is also being used beyond aerospace applications. AM has made significant inroads in tooling. The low volumes typically associated with tooling means they are made in more labor and machine intensive processes, increasing both price and lead time. AM processes are nearly indifferent to a tools complexity, allowing AM to often print tools faster than they would be made with traditional methods. Volvo Trucks was able to reduce lead time for tools from 36 to two days using Stratasys printers [9]. Penske is also using a Stratasys printer for tooling. Penske prints multi-purpose tools otherwise prohibitively expensive to manufacture using traditional methods due to their intricate features and complexity [10]. In both cases, the tools also benefited from a significant reduction in weight, making them more user friendly.

AM is increasingly penetrating both the aerospace and tooling industries. However, examples from aerospace tooling are noticeably absent. Two main factors contribute to the absence of AM tools in aerospace. The first is scale, many tooling applications today are for small hand held tools. Aerospace tooling, especially the type made at Ascent, is orders of magnitude larger than the tools printed by Volvo and Penske. The other factor is the difference in aerospace and automotive tolerances. Many printers are capable of achieving the tolerances required for automotive parts but not those for aerospace applications. Thus, a post processing step is necessary which can tip the scales towards traditional methods from a cost and time perspective. Another factor, though more mental than capabilities based, is that most automotive tools are replaced with every model year. Thus, the tools only need to last for a period of 12 months or so. Aerospace redesigns occur much less often, with some tools remaining the same for the 20 plus year life of an aircraft. The perception among many aerospace tooling engineers is that AM parts are not durable enough.

4. Costs of AM

Direct costs associated with additive manufacturing are the easiest to quantify and compare with traditional manufacturing costs. Direct costs with AM include material, machine cost, and post processing.

Material costs are a major consideration for many AM processes. AM materials can cost 3-10 times as much as their conventional counterparts. In extreme cases materials can be two orders of magnitude more expensive. The relatively high costs of AM materials is due to the amount of processing required to produce them.

At the low end of cost for polymers, some 3D printers use the same bulk materials as injection molding machines. At the higher end of cost are precise filaments and powders. The more consistent the input, the better the resulting product. The high fidelity of the inputs is achieved through more expensive production processes.

The low end of cost for metal 3D printers uses weld wire. Weld wire is on the order of 3-5x the cost of the metal stock it is replacing. At the extreme of the cost spectrum, metal powders with a tight distribution of grain size is used. Uniform grain size is essential for achieving consistent melt pools when using a laser in a powder bed. Newer metal printers, such from Desktop Metal, use the same powder as metal injection molding. Using the mass produced powder reduces the material cost.

With such high material costs, it may be a wonder why some would opt to use AM over traditional manufacturing methods. A holistic view of the costs is required to understand where AM is preferable over traditional methods. The most dominating factors for AM costs after material are the machine costs (depreciation, maintenance, power, etc.) and post processing costs. Post processing includes anything done to the printed part to finish it. A common examples include the labor required to remove any support material and heat treatment for metal parts. Traditional methods have a very similar cost structure, but also include the cost of any tooling (molds, fixtures, etc.) to make the part.

$$\mathrm{COST}_{\mathrm{AM}} = \text{material} + \text{equipment} + \text{post processing}$$

$$\mathrm{COST}_{\mathrm{TM}} = \text{material} + \text{equipment} + \text{labor} + \text{tooling}$$

While the AM cost equation has fewer terms, material, machine, and post processing costs can vary greatly between production methods. As discussed earlier, material costs in AM can exceed 10 times that of standard materials. Since there is no tooling though, there are virtually no economies of scale for making a small batch or a very large number of parts with AM. The below graph illustrates the tradeoff between volume and cost for additive, subtractive, and formative technologies.

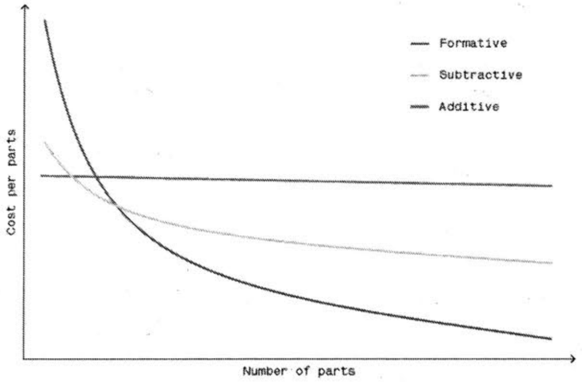

Figure 5. Volume-Unit Price Tradeoff for Manufacturing Techniques [11].

For some applications the comparison of production costs is not enough to justify using AM. In these cases, the value AM brings to the product must also be considered. This is where AM has the ability to be truly transformative. The value AM brings is the difference between the values of the traditional product and the one designed for AM.

4.1. Proposed check criteria

Engineers, designers, production managers, and others weighing the costs of additive manufacturing tend towards extremes when evaluating candidate parts. At one end they want to include every conceivable cost in the analysis from the start. This causes those unfamiliar with the technology and cost structure to balk. The other extreme, largely used by those unfamiliar, is to consider only the change in material costs. While material costs can dominate in AM, the cost to produce a traditional part can be an equally powerful force.

In this section we propose a quick check anyone can perform when evaluating potential candidate parts for AM. Done properly, it can guide the decision making process by identifying strong candidates and eliminating weak ones. The checks are highly applicable to products that do not derive ancillary benefits or where those benefits are hard to quantify. Essentially, we are conducting a first pass check on the leanness of a process. The ability to create a more streamlined factory and increase productivity is one of the key advantages of AM over traditional methods.

The check we derive uses simple ratios based on current traditional manufacturing and estimated AM costs to produce goods. Using unitless ratios, we avoid the often tiresome calculations necessary to conduct a full analysis. While this is eventually necessary, we can screen candidates using simpler methods. This cuts down on the analysis and data required when evaluating a portfolio. It also allows for quick decision making in meetings.

The checks follow a two step process:
Step 1. Initial check including material and production costs.
Step 2. Compare per unit costs using print speed as a proxy.

If a part passes the above two checks, an in-depth analysis of the entire process is required in most cases. The benefit of using this method is that it screens out many undesirable candidates before conducting the in depth analysis.

4.1.1. Typical Method

The first check many perform when evaluating an AM candidate is material cost. This simplistic view ignores additional production costs. At its heart, this view assumes that productivity gains cannot outweigh the increased material costs. Below we derive a simple inequality using this analysis method.

Additive material cost x material used < traditional material cost x material used

$$C_{m,A}m_A < C_{m,T}m_T \qquad \text{Equation 1}$$

$$\frac{C_{m,A}}{C_{m,T}}\frac{m_A}{m_T} < 1 \qquad \text{Equation 2}$$

$$C_{m,R}m_R < 1 \qquad \text{Equation 3}$$

C_m = material cost for additive (A) and traditional (T) on the same unit basis
m = total material used for additive (A) and traditional (T) on the same unit basis
R = subscript denoting ratio of additive to traditional cost or material

If the above inequality holds true, the part is considered a potential candidate. This test is valid but creates many false negatives by ignoring current production costs. Production costs can easily tip the scale in favor of AM. In Equation 3 the manager simply asks, if material costs increase by a factor of 4 and the now hollow parts weigh 50% of the original, am I better off? The answer is "No" ($.5 \times 4 < 1$ is False). However, the above inequality does not account for other factors like labor and machine time, some of which could be eliminated by AM.

A better, but harder test is comparing the entire production cost. We will ignore ancillary benefits and focus purely on the cost of goods sold. Ideally we would capture the entire value stream for both AM and traditional methods. Instead, our proposed method captures all traditional costs and assumes post processing is negligible. This is for simplicity as many candidates can be eliminated before considering post processing requirements. Negligible post processing is also a reasonable assumption for some AM technologies and parts. After conducting the initial test, post processing will require a more thorough investigation.

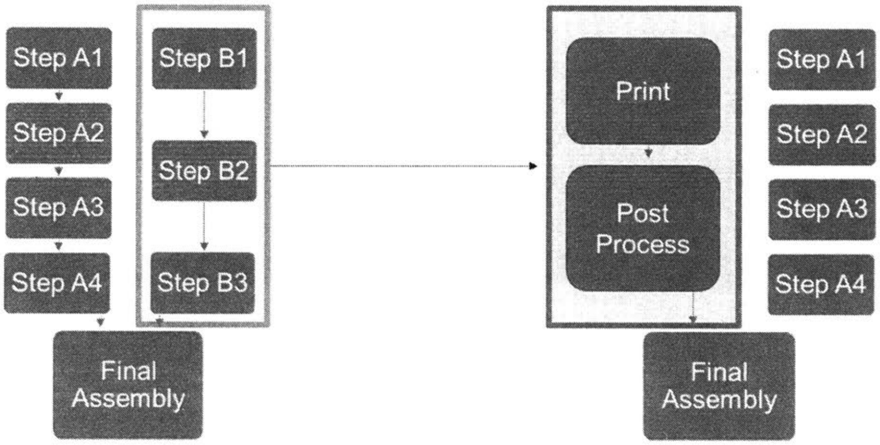

Figure 6. VSM analysis example.

4.1.2. Proposed Method

Our proposed check, derived from the comparison of total traditional production and material costs to the equivalent printed costs, makes a slight but meaningful adjustment to the inequality in Equation 3 above. It also simplifies some of the calculations required for comparing total manufacturing costs. Traditional manufacturing costs are required, but additive costs are temporarily suspended. Calculating the cost per unit for an AM process often involves an elaborate spreadsheet. Instead, we will later use printer speed as a proxy for cost per part.

$$C_{m,R}m_R < \frac{C_{P,T}}{C_{m,T}} + 1 \qquad \text{Equation 4}$$

$C_{P,T}$ = total production cost for the traditional or current method including labor, machine, and tooling costs

$\frac{C_{P,T}}{C_{m,T}}$ is a measure of process to material intensity in a production system. In the current example, if the 10 worker hours cost \$60/hr while the material cost is only \$500, $\frac{C_{P,T}}{C_{m,T}}$ is 6. We now account for the intensity of the production effort in relation to the material costs. Parts that previously looked like bad candidates for AM now seem like they could be viable candidates. Continuing with the same example, we can see below how the part transitions from being rejected for AM to remaining a candidate for further evaluation.

Example 1. Check 1 for process intensive part.

Simple method: $0.3 \times 4 < 1$ is False, and therefore not worth printing.

Proposed method: $0.3 \times 4 < 6 + 1$ is True, and further investigation is required.

For processes where material costs dominate, the adjustment is less significant in identifying good candidates. It is still required to gain an accurate estimate of print speed (our proxy for production cost per unit) in proceeding steps. Material costs typically dominate in wasteful processes such as creating thin contoured surfaces from a block of material. In some applications the final part can be less than 20% of the stock material. In Example 2 below we will assume that we print to the exact shape required (20% of the stock material). Production cost is \$600 and material costs are \$800; $\frac{C_{P,T}}{m_T}$ is 0.75. Our AM material price is 4 times the traditional material price.

Example 2. Check 1 for material intensive part.

Simple method: $0.2 \times 4 < 1$ is True, and further investigation is required.

Proposed method: $0.3 \times 4 < 0.75 + 1$ is still True, and further investigation is required.

Using the adjusted ratio allows one to quickly calculate required print speed. As mentioned above, this is used as a proxy for a cost per unit comparison. If the required speed is less than the printer's actual speed, then printing is a viable option.

We will use the inequality from Equation 4 for this calculation. The right hand side will be referred to as r_1 and left hand side as r_2. With this convention, used mainly to avoid redundant calculations, the required print speed is:

$$s_P = \frac{C_P m_R}{(r_1 - r_2) m_T} \qquad \text{Equation 5}$$

s_P = the required print speed
C_P=price per hour to operate the printer
$r_1 = \frac{C_{P,T}}{C_{m,T}} + 1$ (right hand side of equation 4)
$r_2 = C_{m,R} m_R$ (left hand side of equation 4)

s_P gives us the minimum print speed for printing to be cost competitive with our traditional process. If s_a is less than the actual speed of the printer, we are reasonably confident that printing this part is a good course of action. This is contingent on any required post processing and should be the subject of further analysis.

Two reasons lead us to use print speed as a proxy for price. Ease of use and flexibility. For ease of use, print speed is quickly derived from our initial check. As long as costs across various printers under consideration are approximately the same, we will be able to eliminate printers that are too slow. On the flexible side, we can compare printers with different cost basis by establishing relationships between different costs. For example, required print speed scales linearly with printer cost.

In fact, r_1-r_2 alone is often a good guide to the feasibility of printing a part. Since r_1-r_2 is in the denominator of Equation 5, as the difference approaches zero, the required speed increases rapidly. This intuitively makes sense, as the gap between material and production costs closes (roughly what r_1-r_2 measures) the printer cost needs to be amortized over more parts. This is only accomplished through increased print speeds.

Print speed works as a proxy because it is directly tied to the cost of a part. Specifically, it captures the overhead costs of a printer. Printer costs are calculated as (cost/hr)*(hr run). The number of hours the printer is in operation can be approximated as directly proportional to the printers speed and material printed. As long as printer utilization says the same, cost per hour and therefore speed increase in lock step. Utilization rates and printer life vary, reasonable costs for first pass estimates are $50/hr for small units and $150/hr for large units. Hobby grade printers can operate for less than $10/hr.

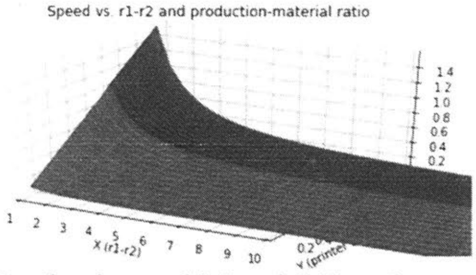

Figure 7. Production and Material Cost Impact.

We already discussed the effect the difference between r_1 and r_2 has on the feasibility of printing a part without ancillary benefits. Traditional material costs also find themselves in the denominator of the equation for print speed. Intuitively this makes sense: as material costs increase, production costs carry proportionally less influence on the total cost of a part.

Weight savings is accounted for in the required print speed. At first glance Equation 5 suggests print speed and weight savings have a linear relationship. This is not the case as w also features in the denominator as part of r_2. The non-linear relationship between weight savings and print speed means that small gains from design can have a significant impact on the economics of printing a part.

Similar to weight savings, the relationship between m and print speed is nonlinear. m is also in r_2. Since reductions in r_2 can significantly impact the required print speed, reducing the price of material for an additive process can greatly increase how widely a printer can be used. Switching to a less expensive material has the same effect. With modest reductions in the price ratio can, the required print speed can exponentially decrease.

For designers, two main levers exist to increase the attractiveness of printing a part: material efficient designs and proper material selection. Material efficient design impacts material savings compared to the conventional part and material selection reduces the price ratio. Manufacturers have two additional levers: print speed and printer price.

5. State of the Art for Large Scale AM

Large scale AM faces the same tradeoffs and challenges as smaller scale AM processes. With large scale AM though, the issues are more pronounced due to scale. The tradeoff between speed and resolution is critical in large scale AM. To obtain a near perfect surface finish, small layer sizes are required, resulting in prohibitively long build times for large pieces. Larger layers, which can be deposited faster, result in a coarser surface finish. As a consequence of this trade off, most large scale AM processes print to near net shape instead of to net shape. The print is then machined in a post processing step. The machining serves the dual purpose of achieving an appropriate surface finish and eliminating dimensional errors arising from the stacking of tolerances between layers. As an illustrative example, a 500 lb printed part may take 6 hours to print and an additional 12 hours to machine with a large near net printer. The same piece would take over 500 hours to print at the speeds used for high resolution printers. The concept of near net printing at larger scales applies to both polymer and metal printers.

5.1. Large scale polymer AM

Big Area Additive Manufacturing (BAAM) differs from other AM technologies most noticeably through scale as the name implies. Oak Ridge National Laboratory (ORNL) achieved build rates of 5 L/hr [12]. By using carbon reinforced polymer pellets, the mechanical properties of the resulting build are sound enough to be used in tooling applications. BAAM achieves high build rates by combining several ideas in a novel way, all enabled by materials selection [6].

BAAM uses a carbon fiber reinforced polymer pellet. ORNL tested variants of acrylonitrile butadiene styrene (ABS) infused with carbon fibers. The carbon fiber provides two advantages over pure ABS. The first is that the carbon fiber enhances rigidity and strength. Second, the carbon fiber enhances thermal properties. Carbon fiber infused polymers also demonstrate a higher coefficient of thermal expansion and higher thermal conductivity. Better mechanical and thermal properties allow for the manufacture of larger structures [13].

The improved rigidity and strength mean that carbon fiber reinforced polymers produced through AM can be used for load bearing applications. While exhibiting significant improvements over ABS, doubling strength and quadrupling of Young's modulus, the material lends itself best to tooling applications. Parts still suffer from reduced performance in the z-direction due to the layer by layer deposition process and resulting interlayer adhesion. Performance is above that of ABS but below carbon fiber. Table 1 contains a detailed comparison [13].

Table 1. Young's modulus and strength for in-plane samples (Ex, Sx) and vertically built samples (Ez, Sz) [13].

Platform	Sx (MPa)	Sz (Mpa)	Ex (GPa)	Ez (GPa)
Makerbot replicator 2X	21.04 ± 0.62	20.95 ± 1.3	1.22 ± 0.10	1.42 ± 0.05
CubeX	29.31 ± 0.68	7.61 ± 2.91	1.69 ± 0.21	1.31 ± 0.23
Afina	28.09 ± 0.53	14.91 ± 0.96	1.48 ± 0.07	1.18 ± 0.05
Solidoodle 3	24.08 ± 1.12	16.75 ± 4.56	2.05 ± 0.23	1.55 ± 0.07
Solidoodle 3 with 13% CF/ABS	70.69 ± 4.01	7.00 ± 2.59	8.91 ± 0.97	1.52 ± 0.10

Strong parts naturally lend themselves to tooling applications. Large tools require large build volumes and rates. Thermal stresses caused by thermal gradients plague many

AM processes when scaled. The larger the part, the worse the stresses and resulting distortion. Improving the thermal conductivity and coefficient of thermal expansion over regular ABS through carbon fiber reinforcement plays a dual role in increasing part size. Higher thermal conductivity allows for smaller temperature gradients across the entire material, reducing stress and distortion. It also allows for manufacture at ambient room temperatures. Unconstrained by an enclosure for environmental control, the extrusion head can be attached to a gantry system of any size. Reduced thermal expansion further reduces stress and distortion as the material cools. A comparison of thermal expansion and conductivity is contained in Table 2. The deflection at one end of a sample 102mm curl bar was almost an order of magnitude lower for carbon fiber reinforced ABS versus regular ABS [13].

Table 2. Coefficient of Thermal Expansion and Thermal Conductivity Comparison [13].

	CTE (μm/m°C)	Conductivity (W/m K)
ABS	87.32 ± 6.17	0.177
ABS/CF 13% parallel to deposition	9.85 ± 0.84	0.397
ABS/CF 13% perpendicular to deposition	106.3	0.156

While many extrusion based AM processes use a polymer filament, BAAM uses pellets similar to those in injection molding. The ORNL team chose pellets because they can be melted faster than the polymer filament, a limiting factor on similar filament deposition modeling (FDM) systems. Instead of melting a uniform filament, a single screw extruder both melts and controls material flow. This unique application allows for build rates one to two orders of magnitude larger than other AM techniques [6].

To deliver this high volume of material, the BAAM extrusion head produces a bead from 4 to 7.6mm in diameter compared to 0.1 to 0.3 mm for typical FDM processes

[12]. BAAM deposits up to 100 lbs of material per hour. The controls system is capable of tolerances of 0.002 in [6]. The convergence of improved mechanical and thermal properties allows for these increased build rates. The significantly improved build rate enables the production of large structurally sound components.

Printers based on the same principals of BAAM are now also offered by competitors, most notably Thermwood's Large Scale Additive Manufacturing (LSAM) and Ingersoll's Wide and High Additive Manufacturing (WHAM). Each of these printers shares the same fundamental characteristics of BAAM, though differ slightly in their execution. All suppliers are working on increasing both print quality and speed, which some tests reportedly in excess of 1,000lbs/hr. Demonstration projects abound with some larger OEMs and startups installing printers for both experimental and production purposes.

The first large tooling projects for the ORNL team included a layup mold for wind turbine blades and a trim and drill fixture for the 777X. BAAM is sold by Cincinnati Inc.

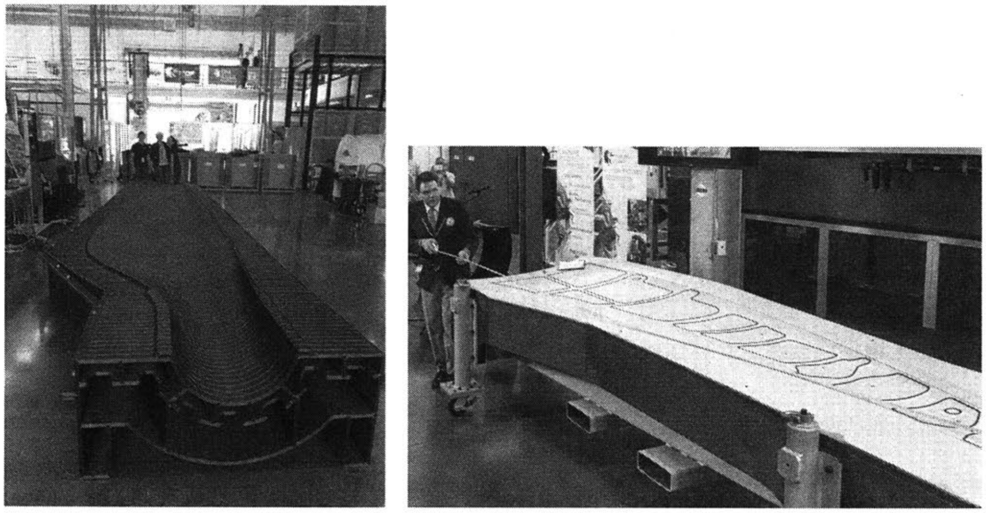

Figure 8. Wind Turbine Blade Mold [14] (left) and 777X Trim and Drill Fixture (right) [15].

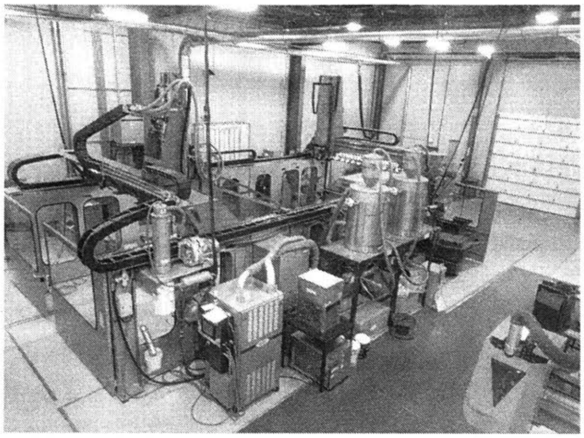

Figure 9. Thermwood LSAM Printer with 40 ft print bed [photo by author].

5.2. Large scale metal AM

Large scale metal AM is also being pursued by ORNL and Wolf Robotics, as are several other companies. Anyone familiar with welding will recognize the most common processes for printing large scale metal parts. In fact, many large metal printers incorporate off the shelf or modified weld guns. These are then attached to a CNC machine or robotic arm. The software and controls system powering the printer is what sets it apart from a typical automated welding operation. This process does not fall neatly into any of the ASTM AM categories.

Figure 10. Wolf Robotics Large Scale AM Print Cell exterior (left) [16] and interior (right) [17].

Large scale metal AM essentially continuously welds one layer onto another until the part is complete. As with BAAM type processes, using already commercially available feed stock – weld wire in this case – significantly reduces the material cost of printing. This is key in larger applications. Weld wire costs around three times the amount of the base material, compared with 10-100 times for AM metal powders. Additionally, the practice of using layers of weld to repair parts is already widely used, making adoption more likely as users in the field are already comfortable using the technology. Cladding and "buttering up" are common names for this operation. Often done manually, it is used to build up areas for repairs or rework.

Another benefit of using weld wire is that nearly any formula a customer may want already exists. Process parameterization for a specific type of wire is the only real hurdle to adoption. This is a low barrier to adoption since much of welding process is already characterized and robust simulation software already exists.

Wolf Robotics and ORNL have collaborated extensively on large scale metal AM with great success. In initial phases of the collaboration, mechanical properties of the printed material were already within 5% of the properties of the equivalent bulk material [18]. These results allowed ORNL and Wolf Robotics to print a functional excavator arm. The arm incorporated internal channels for hydraulic fluids, eliminating the need for traditional hydraulic lines. Furthermore, the cab of the excavator was printed on the Cincinnati BAAM. This project demonstrated the capability of large scale metal AM to create parts durable under extreme conditions.

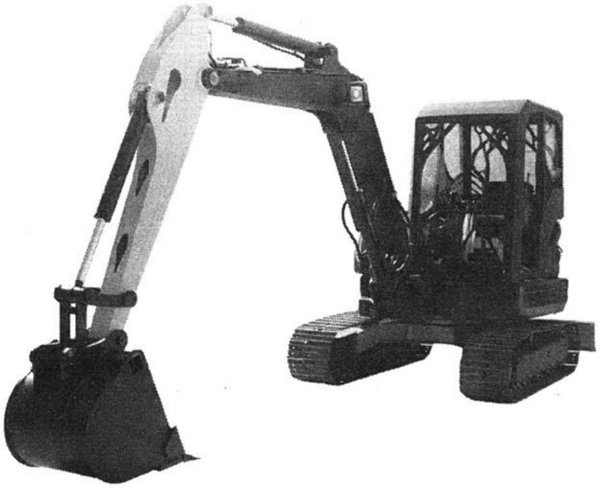

Figure 11. ORNL Excavator Arm (white section) [19].

6. AM and Part Selection Process

6.1. General approach

The road to identifying how to best incorporate AM into aerospace tooling manufacturing was not immediately clear from the onset. While AM can be used to make incremental changes in many products, to get real momentum in an organization a meaningful application is required. The main line of effort was in identifying where AM could demonstrate its ability to be transformative to an organization. Secondary efforts included educating design and manufacturing engineers on the capabilities and value of AM along with empowering them to experiment with designs.

Ascent had previously hosted outside AM subject matter experts (SME) for an onsite factory visit. During this visit, the SMEs were giving a tour of the factory and production facilities. They identified many parts AM could easily replicate or make some improvements to. This exercise generated a relative amount of excitement within the engineering and R&D organizations at Ascent. Following the SME visit, an economic analysis was done on the proposed parts, all would be at least an order of magnitude more expensive to print. The excitement quickly cooled and many adopted the mindset that AM was just too costly to make a difference.

The SME visit points to a problem that plagues AM adoption. AM is prohibitively expensive when applied to the wrong products. AM experts tend to focus on the size and shape of products when identifying what they *can* print. They use shape and complexity as a proxy for the cost of manufacturing. Instead, one must focus on what one *should* print. A company should print components where AM adds value through cost reduction, process improvement, or feature enhancement. They can print anything that fits into the build envelope of a printer, but that does not mean they should.

The proper way to identify which parts a company should print is to begin with the value gained through leveraging AM. This value could take any of the many forms discussed in Section 3.1. In addition to the value per part, the aggregate value to the enterprise is also important to consider. Saving $1 on a high volume part could be worth significantly more compared to $100 on a low volume part.

The approach used at Ascent was to focus mainly on cost reduction. In an environment where a number of products are produced in volume, focusing on each particular part is a viable option. Ascent however makes many product families, but rarely makes the exact same part twice. Instead of focusing on a part, the analysis concerned improving the production process for different product families.

The analytical methods used to evaluate processes at Ascent is transferable to analyzing many SKUs in higher volume production environments. At Ascent the average costs and times of various production steps were normalized to a per unit basis (typically pounds of material or square feet of surface area). In a production environment, the units analyzed would be per part or lot.

Ascent's enterprise resource system (ERP) is still undergoing a normalization process of its own. Once run as separate companies, data was captured in different ways at each manufacturing facility even when using the same ERP system. Thus, a high level first pass using the aggregate data was impractical. Using the method in Section 4.1.2 as a sieve to identify the most promising parts would not work.

This impediment to an "easy" high level analysis was actually beneficial to the low volume production environment at Ascent. The high level analysis is well suited for printing an entire component or part. However, the manufacture of many sub components by hand is not explicitly captured in some ERP systems. This was the case at Ascent. Instead, these processes are often identified by comments in the ERP system. And each site has its own colloquial names for the processes.

The ERP system contained a wealth of data, though it was impenetrable to anyone not intimately familiar with the workings of each site and how each type of tool was made. An arm's length analytical sieve was not a practical option to begin the analysis. Something else had to guide the search for value.

Anyone familiar with process improvement will agree that the best place to start is with the problem. From there, you can further investigate the root cause and eventually find a solution. The same thing can be done when identifying which parts to print. Inevitably all manufacturing plants experience problems: cost over runs, bottle necks, a shortage of skilled labor, and more.

I conducted interviews with engineering, production, and general managers of the various factories in order to begin identifying product families that may benefit from AM. There were many ideas floated in this initial phase that were promising applications for AM: light weighting handheld tools and robotic components, consolidating parts in complex assemblies, and nearly anything conforming to a complex surface.

Over the course of multiple interactions, a recurring theme was the difficulty in creating parts, especially large ones, with complex surfaces. Many tools from hand held locating jigs to wing sized molds fell into this category. Ascent often times takes on work packages with all these tools, keeping the larger and more complex ones in house while outsourcing smaller ones. Large tools like layup molds and trim and drill fixtures represent a large enough portion of Ascents revenue that even a relatively minor improvement in cost would have a meaningful impact on the organization.

6.2. Educating the work force

Over the course of multiple interactions, it became clear that many managers and engineers were not familiar with the benefits, limitations, and current applications of AM. The most damaging of these was design engineers not understanding the benefits of AM. This lead many to discount the applicability of the technology to their work. Not understanding the limitations of AM is less important since it allows for more creative ideas and the possibility of incorporating nascent AM technology instead of "main stream" printers.

Many components not tracked separately in ERP systems due to their relative insignificance can benefit from AM with minimal redesign. This is particularly true for part consolidation. Design engineers create their parts with a particular manufacturing process in mind. Educating the designers is a way to work around a lack of production data. Designers already weigh various production techniques when creating new parts. Adding AM to their tool box enables them to leverage the new technology as they create new customer solutions. Giving them easy access to printers further encourages innovation.

Exposure to AM across the enterprise varied greatly. I developed a short introductory course on AM tailored to the work Ascent does. While my interviews and data analysis were instructive, clean sheet designs were an entry point for AM I could not access directly. My work was merely process improvement with AM as the main lever.

The main objective of the training was to encourage engineers to begin using AM as a tool to solve problems they encountered in clean sheet designs. A guiding principle was: “If you are having trouble visualizing how to build the part, you can probably print it easier.” This message was repeated in various permutations throughout the 90-minute introductory course.

A constant form of resistance was “our customers will not accept printed parts.” Engineers in most industries tend to be conservative. They rely on design principles that have withstood the test of time. Conducting a finite element analysis of every part is impractical, so they simply chose a material of a standard thickness that has always worked. When asked “Why is this bracket made of ¾ in aluminum plate?” A typical response is, “Because I know it will work and it’s easy to make.” That is a credible answer coming for an aerospace engineer with 30 years of experience. It is also a hard mindset to overcome.

The best method for overcoming a bias against AM is to show the engineers applications relevant to them. Demonstrating that Boeing, Airbus, GE and others are using AM in serial production on aircraft is a very powerful message to tooling engineers: “Not only are your customers using a technology you deem inferior, but they are using it in an application with more risk than your product.” This quickly wins over most critics, many of whom had not realized how far AM has come over the past five to ten years.

The question of cost must also be addressed in the training. The method discussed in Section 4.1.2 is an easy rule of thumb for engineers to use when designing parts. They already have a general idea of costs for the traditional processes used. An easy mental check on the efficacy of AM can help guide them in initial design phases.

Once engineers understand the value, limits, and applications of AM, they will surprise you with their ingenuity. Ascent purchased a Form 2 printer and accompanying accessories (approximately $5,000) for two different facilities. A small handful of prints paid for the printers in less than four months.

The importance of getting printers and printed parts into the hands of engineers cannot be overstated. One engineer printed a prototype to see if it would behave as expected. Once in hand, he realized that the plastic component was adequate for the customer. We conducted a joint cost analysis of the part he printed and the process for making the metal part. All in, the printed part cost less than $6 when accounting for material, print time, and post processing. The material cost alone for the original aluminum design exceeded $10. Accounting for labor and machine time, the cost exceeded $450.

This would be a significant cost reduction if the part in question was being sold on its own. However, it was one small piece of a low volume production system priced at over $20,000. In this context $450 of savings accounts for 2.25% of the overall cost. This, and many similar robotic systems, have many small components that could be printed. Finding ten components with comparable savings could reduce the system price by over 20%. AM begins to offer a competitive advantage over competitors who still rely on costlier production methods.

The path to the first internally generated use case with the Form 2 flowed in six stages, education occurring throughout. (1) We placed the printer in a prominent area and (2) encouraged engineers and designers to print. (3) We demonstrate the printer's ability through intricate and meaningful parts. (4) Engineers and designers began printing parts meaningful to them (mainly miniatures of past work and vanity projects). (5) Eventually one printed a prototype test product. (6) After evaluating the prototype, the engineer deemed it field ready as printed.

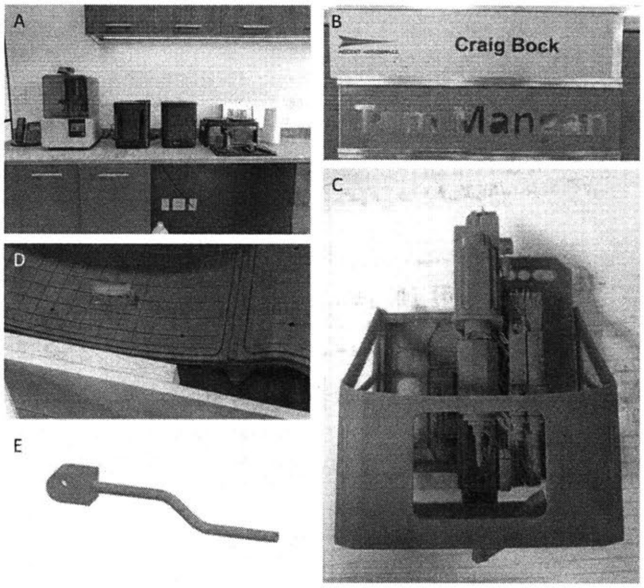

Figure 12. Journey to the first AM production part.
(A) Printer with free access, (B) Early experiments, (C) Intricate and relevant demonstration part, (D) User generated vanity projects testing the limits, (E) Prototype water tube that became a production part [photos by author].

AM also reduced the product development cycle of some parts at Ascent. A design engineer used the Form 2 to print a prototype of a fastening system. All in the prototype cost $23 to print in ten hours. The machine shop estimated 2-3 weeks and a cost of over $1,500. This is a clear savings both on cost and time. The engineer was able to complete three design iterations in the time the machine shop would have made one.

While the exact material used for the prototype was not suitable for the end user (but appropriate for a prototype), the engineer realized that a slightly different printed material would be appropriate. This was a powerful value proposition to the customer because a significant portion of the actuator consisted of wear components. Printing significantly reduced the cost and lead time of the wear components without compromising system performance.

One could imagine that instead of Ascent continuing to make the wear component as a replacement part in the machine shop, they could license the part file to a print shop or their customer. This creates a recurring revenue stream without tying up Ascents assets. Ascent can instead use its engineering and manufacturing expertise to create new, more value added products.

6.3. Replacing vs. reinventing processes

After identifying families of products that could benefit from AM, I began using the quick check method on the products. Given the scale of even the smallest layup molds and trim and drill fixtures, large scale AM was the only viable option. The quick check method suggested that using polymer printers was economic. Large scale metal printers were at least an order of magnitude too slow to compete with our highly manual processes. This, and nearly every subsequent analysis, used approximately the last quarter's worth of production. One quarter was used mainly due to time constraints, every part had to be gone through manually to extract the relevant information. Inconsistencies between and within sites required manual sorting and interpretation among several systems and programs.

The initial screening analysis was done on the entire tool. Polymer printing is adequate for the trim and drill fixtures which remain at room temperature. The layup molds enter autoclaves where they experience extreme temperatures. While polymer parts can survive autoclave conditions, the CTE in currently available materials is not acceptable in most applications for Ascent's customers. A metal solution was required for the molds.

Further investigation led to the approach of focusing on different pieces of the overall assembly and the varied processes for producing them. While the tools under consideration are shipped as one monolithic piece, they are comprised of parts made with very different manufacturing methods as discussed in Section 2.2.

The process segmentation was done in two main ways. First, the aerospace surface was evaluated independently of the egg crate. The egg crate is constructed fast with minimal labor, negating any benefit of reduced material waste from AM. The surface however, is very labor intensive and time consuming to make. Again, the analysis revealed that bump forming is much faster and cheaper than using large scale AM.

A discussion with the GM of one facility shed light on the chip forming process after the above analysis had already been completed. None of the previous discussions on how the tools were made, and none of the company's VSMs, revealed this niche manufacturing step used to make sections of layup molds. The chip forming process was described as a major pain point in the manufacturing of some of the more complex aerospace surfaces. The description of the complexity, material waste, time, and difficulty associated with chip forms signaled a potentially transformative application of AM at Ascent.

Perfect data on chip forms did not exist. There was no code for chip forms or inserts in any of the ERP systems used, nor was there a common way to identify them through comments. A team of production and design engineers sifted through a quarters worth of data to identify every chip forming operation performed across the sites. This required going through the CAD files for every layup mold produced and matching segmented surface parts to machining operations from multiple ERP systems.

Data in hand, the criteria finally pointed to a potential candidate for large scale metal AM. The chip forming process wasted an average of 80% of the material, sometimes upwards of 90%. It was also time consuming, removing so much material and creating a contoured surface requires excessive amounts of machine time for little added value.

Replacing the chip forming process was not as clear a win as the polymer printing. At current prices and rates, printed inserts would be approximately the same cost as chip formed ones. However, printing could consolidate many chip forms into one insert. This reduces assembly time in later steps.

While the cost of printed inserts is currently at parity with chip forms, the printing technology to produce the inserts is continuously improving. Moderately increased print speeds and reduced printer costs will bring the cost of printed inserts to below that of chip forms. As the technology continues to improve from a cost and time perspective, the economics of what to print and bump form will change. Currently, it only makes sense to print the most complex parts of a surface. With time, printing will encompass an ever increasing share of the surface.

6.4. Value to customer and manufacturer

Printing tools creates for both the manufacturer and customer. The most obvious value is quantifiable savings. This creates a price advantage for early movers who can then sustain their advantage through continuously improving the integration of hybrid tools. The customer benefits from lower priced tooling. Reduced capital expenditures leads to a lower balance sheet and a higher return on capital equipment. Lower priced tooling lowers the break-even point for an aircraft program.

Both polymer and metal insert printing alleviate bottle neck of the bump forming process. By allowing workers to focus on bump forming easier parts and printing the complex components, the throughput of the plan increases. The benefit increases as the proportion of the tool printed increases and the technology progresses. Increasing throughput allows overhead costs to be spread over more tools, thus further reducing costs. Furthermore, increased throughput means reduced lead times for customers. In an industry where some customers are willing to spend ten thousand or more dollars for each week a part is delivered early, eliminating bottlenecks to increase speed represents a large benefit to the customer and huge advantage to the manufacturer.

Lastly, the skilled labor capable of producing quality bump formed parts is scarce. Potential labor relation problems aside, much of this highly skilled work force will entire retirement over the next decade with virtually no backfill. Printing ever larger sections of the surface will mitigate the effects of highly valued workers retiring. With a severely reduced work force, printing large sections or entire surfaces will be the only way to produce the tools. Learning how to properly print and integrate hybrid tools now mitigates the inevitable shift in workforce composition.

6.5. Room temperature tools

A trim and drill fixture was printed using a large format polymer printer. Figure 13 below shows the printed composite tool. The traditional tool took 12 weeks to manufacture out of aluminum. The bulk of the 12 weeks was spent on bump forming, welding the assembly together, and machining the surface. The polymer tool was printed and machined in less than 16 hours. An additional two week allows for quality inspection and adding some additional features like vacuum tubes in final assembly. The variable costs for the printed tool are roughly one third of the variable costs for the traditionally manufactured tool. This is mainly due to the reduced machine time and labor costs.

Figure 13. AM trim fixture [photo by author].

For trim and drill fixtures, using large area additive manufacturing represents an enormous time and cost savings. The longevity of the printed tools has not yet been tested. However, carbon fiber tools made with similar materials are common in the aerospace industry. The carbon fiber tools are used in high volume production environments. At one third the cost and one third the time to produce, a shorter lived tool requiring replacement may still be the more economic option. Aditionally, significantly less expensivev tooling allows for more frequent design changes to a product.

6.6. Autoclave tools

The anisotropic nature of the CTE in printed polymer tools means they are not suitable for many high temperature aerospace applications. This led to the development of printed metal tools for autoclave environments. Invar, a nickel steel alloy, is the material of choice for many high temperature layup molds. Ascent used their preferred brand of weld wire for these prints. For the initial project, an entire surface was created in steel using a large scale metal printing cell. The surface was joined to a traditionally manufactured egg crate.

As with the polymer print, the surface is near net shape. A machining step was conducted after welding the surface to the egg crate. At this time, the completed tool has not yet been delivered to the customer for final evaluation. The economics of printing the surface suggest that within a few years, printing the entire surface for complex shapes will be less expensive than bump forming. Increases in print speed should also make printing competitive from a time perspective. While inserts were not printed and integrated into a traditional assembly, the results from this print lend credence to the analysis that inserts are already cost competitive with chip formed inserts.

7. Recommendations and Conclusions

This project helped Ascent identify how to leverage additive manufacturing to make a transformative impact on the enterprise. Ascent required a disciplined and holistic approach to identifying what to print with a clear path to impact. A relatively small player compared to its OEM customers, Ascent must be judicious in its capital allocation. In essence, additive manufacturing was used as a lean manufacturing tool to eliminate bottle necks and variability in the manufacturing process. The approach of using AM as a lean tool yielded faster and superior results than identifying parts that look like the could be printed. By focusing on what should be printed, namely parts where value can be added or gained, the search for meaningful results quickly yielded fruitful. The search for pain points, bottle necks, and inefficient processes was complimented by an economic analysis used to filter out parts where the relative and absolute gains from printing were negligible.

In less than six months, Ascent went from no additive capabilities to producing large scale tools with cutting edge AM technology. Ascent also began using AM to shorten design iterations and reduce costs for components across its product portfolio. Taking cost out of an entire product portfolio requires more than one or two additive experts in R&D functions. Educating the workforce on the capabilities, benefits, and limitations of AM overcame biases towards the technology. Enabling engineers to experiment with the technology uncovered additional areas where AM can have an outsized impact on the enterprise. As engineers become more comfortable and familiar with AM, they are the ones who will truly transform the enterprise. They will begin approaching design not with the constraints of traditional manufacturing in mind, but of the ideal state for their product. AM will be the default manufacturing choice for replicating any conceived feature.

7.1. Future work

Admittedly the project uncovered more areas where AM can have an impact on the enterprise than one intern could hope to tackle over the course of six months. Both the printed polymer and metal tool must undergo field trials replicating their respective production environments. While many lessons can be gleamed from the printing and integration of an entire face sheet, the integration of printed inserts remains untested.

Ascents engineers have demonstrated a willingness to experiment with AM to create tooling. The production team should be similarly educated as it also has internal tooling requirements the design engineers are blind to. Initiative by individual design engineers has shown there is a significant amount of cost that can be removed from some of Ascent's systems. A multidisciplinary team, or perhaps future intern, could focus on taking cost out of robotics systems. These solutions are often overlooked because each part only contributes slightly to the overall cost structure, in aggregate the impact can be great.

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