Cost-Benefit Analyses for Final Production Parts

by Zach Simkin & Annie Wang

Additive manufacturing (AM) has made tremendous technological progress. Final production parts, such as jet engine fuel nozzles, custom hearing aids, and impellers, can now be printed in materials ranging from polymers to metals.

However, just because a part *can* be produced using AM does not mean that it *should* be. Prior to implementing the technology, it is essential to conduct a thorough cost-benefit analysis.

Generally speaking, it is often stated that AM is economically suitable for parts that have the following features: low volume, complex, and small. Although this can be true, it is not sufficient to only consider features of the part. Rather, when trying to determine whether a particular part can be cost-effectively produced using AM, it is critical to analyze the entire supply chain.

To start, it is helpful to consider the supply chain from a qualitative standpoint. Courtesy of Senvol, below are the seven supply chain scenarios that tend to lend themselves well to AM. If a part falls into one or more of these scenarios, then that part may be cost-effective to produce via AM. If a part does not fall into any of these scenarios, then the part almost certainly will not be cost-effective for AM given the current AM technology.

Scenario	Scenario Description
Expensive to Manufacture	Do you have parts that are high cost because they have complex geometries, high fixed costs (e.g. tooling), or are produced in low volumes? AM may be more cost-efficient.
Long Lead-Times	Does it take too long to obtain certain parts? Are your downtime costs extremely high? Do you want to increase speed-to-market? Through AM, you can often get parts more quickly.
High Inventory Costs	Do you overstock or understock? Do you struggle with long-tail or obsolete parts? AM can allow for on-demand production, thus reducing the need for inventory.
Sole-Sourced from Suppliers	Are any of your critical parts sole-sourced? This poses a supply chain risk. By qualifying a part for AM, you will no longer be completely reliant on your current supplier.
Remote Locations	Do you operate in remote locations where it is difficult, time consuming, or expensive to ship parts to? AM may allow you to manufacture certain parts on-site.
High Import / Export Costs	Do you pay substantial import/export costs on parts simply because of the location of your business unit and/or your supplier? On-site production via AM can eliminate these costs.
Improved Functionality	AM can enable a part to be redesigned such that its performance is improved beyond what was previously possible.

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For parts that fall into one or more of the above scenarios, a detailed, quantitative cost-benefit analysis is warranted. To conduct such analyses, an algorithm, courtesy of Senvol, was used to determine what types of parts can be more cost-effectively manufactured using AM versus the status quo. The algorithm analyzes an array of variables that span the entire product life cycle.

The following pages detail two analyses that Senvol has conducted. The first details an example of a part that can be cost-effectively produced using AM, and the second details an example of a part that is not cost-effective for AM. For the part that is not cost-effective, the analysis shows why the part was not cost-effective, and what AM variables (e.g. machine cost, build speed, material cost) would need to improve in order for the part to *become* cost-effective.

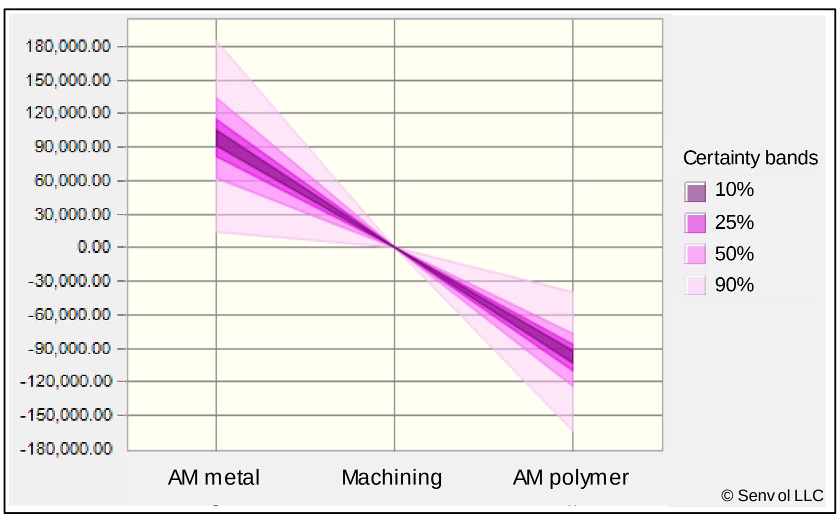
Cost-Effective Use Case

The part analyzed in this case was for General Electric's Measurement & Control division (GE). The part measures 5cm x 5cm x 9cm and is currently produced in an aluminum alloy via machining. Most customers require a custom variation of the part. The quantity of units that the customer orders is highly variable, ranging from a dozen units to several hundred. The part was redesigned for AM in order to achieve better functionality. Interestingly, all engineering specifications were able to be met by both an AM metal process as well as an AM polymer process. (Note: Further details about the part, including the specific AM materials analyzed, cannot be disclosed due to confidentiality).

Three production options were analyzed:

1. Machining (the status quo)
2. AM metal
3. AM polymer

The total cumulative cost over 10 years (net present value of 2014-2023) was computed for the three production options. The total cumulative cost for machining was set to $0. The total cumulative cost for AM metal and AM polymer were then compared relative to machining. On average, over the 10 year period, producing the part via AM metal is approximately $99,051 *more* expensive than via machining, but producing the part via AM polymer is approximately $100,534 *less* expensive than via machining.

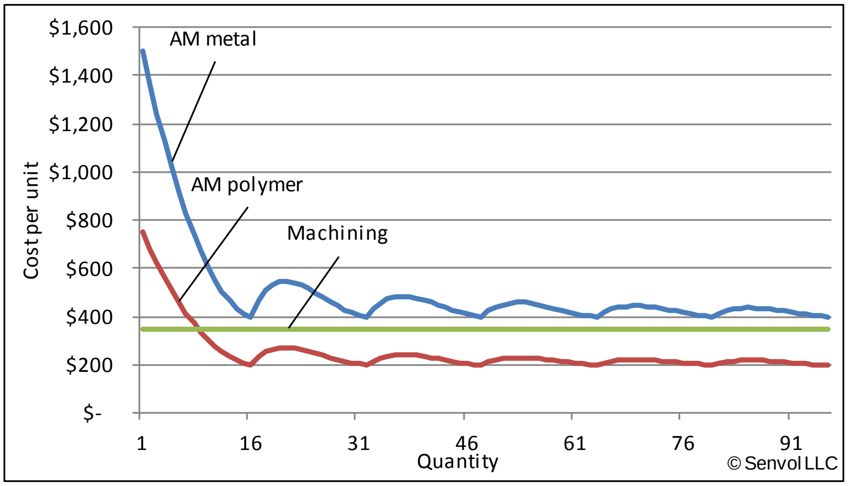


Comparison of AM metal & AM polymer total cumulative cost over 10 years (in 2013 U.S. Dollars) relative to machining cost.

The algorithm used is based on Monte Carlo simulations to account for variability of the inputs. The above graph shows that with 90% certainty, AM metal would be $14,444-$188,823 more expensive than machining and

AM polymer would be $41,479-$165,227 less expensive than machining over 10 years.

The graph below shows the cost per unit for the three production options as a function of the quantity of units produced.



Note: The "wave pattern" seen on the two AM cost curves is caused by the addition of inefficient print batches (i.e. batches that do not fill the print bed). The machining cost curve is flat and does not reflect economies of scale because cost per unit was taken as an average across a wide range of quantities.

Relating this part back to the seven supply chain scenarios detailed above, the part falls under the "Expensive to Manufacture" scenario. Due to a complex geometry, it is difficult and therefore expensive to machine the part, whereas AM polymer can produce it more cost-effectively. AM was able to leverage geometry and redesign to make a polymer part as strong as the original machined metal part, which led to significant cost savings.

Non-Cost-Effective Use Case

The part analyzed in this case was for Johnson Controls, Inc.'s Automotive division. The part measures 25cm x 12cm x 5cm and is currently produced in polypropylene via injection molding. Approximately 8,500 units are sold each year. The part was redesigned for AM, and no finishing or post-processing is required. (Note: Further details about the part cannot be disclosed due to confidentiality).

Four production options were analyzed:

1. Injection molding (the status quo)
2. In-house production via one 3D Systems sPro™ 230 AM machine
3. In-house production via eight 3D Systems ProX™ 500 AM machines
4. Outsourcing to an AM service bureau

All three AM production options were considered with the 3D Systems DuraForm® EX Black material.

Cost Component	Injection Molding	sPro™ 230	ProX™ 500	Service Bureau
Unit Purchase Price	$1.99			
New Tooling	$0.36			
Tooling Maintenance	$0.14			
Excess Operational Cost	$0.15			
Material Cost		$26.65	$26.65	
AM Annual Services Cost		$1.69	$12.68	
Redesign Cost		$0.01	$0.01	$0.01
AM Machine Cost		$9.42	$29.90	
Qualification Cost		$1.50	$11.25	
Labor Cost		$0.15	$2.89	
Service Bureau Unit Cost				$147.50
Service Bureau Shipping Cost				$0.84
Total Cost per Unit	**$2.64**	**$39.42**	**$83.38**	**$148.35**

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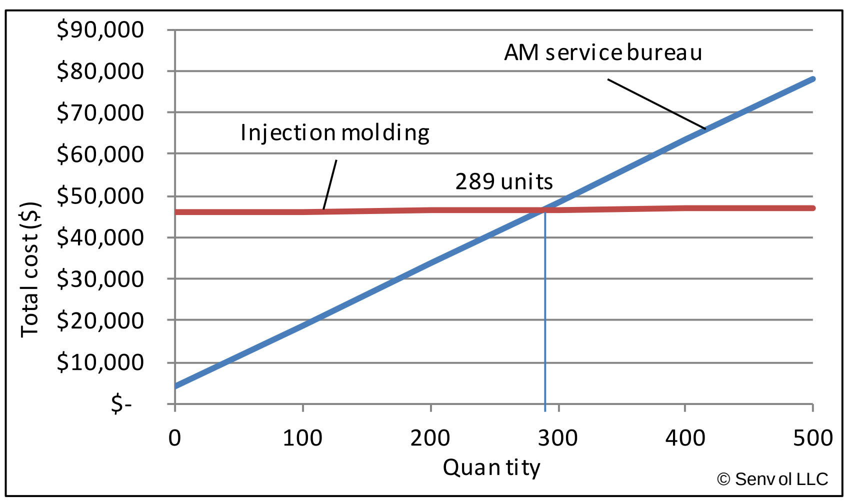
Cost per unit (broken down by cost component) for the four production options.

At $2.64 per unit, injection molding is substantially less expensive than any of the AM options. The sPro™ 230 is the most cost-effective AM option at $39.42 per unit.

If the current injection molding tool breaks, however, Johnson Controls will have a decision to make: Should it invest in new injection molding tooling, or should it start producing the parts via AM? As the graph below shows, AM would be more cost-effective for very low volumes.



Specifically, if Johnson Controls were to need 289 units or fewer, then outsourcing production to AM service bureaus is the most cost-effective option. However, if the company were to need more than 289 units, then it would be more cost-effective to invest in a new injection molding tool.

Given the current state of the technology, AM is not cost-effective for this part if high volumes (i.e. greater than 289 units) are needed. That said, further analysis was conducted in order to determine which AM variables will need to improve – and by what magnitude – in order for AM to *become* cost-effective.

Producing the part via the sPro™ 230 yields a cost per unit of $39.42. The algorithm analyzed what would happen to cost per unit if certain variables were to improve. Each variable improvement was considered in isolation (i.e. holding all other variables constant). Below is a heat map showing how impactful each variable improvement would be on cost per unit (green cells mean that the variable change was not very impactful on cost per unit, whereas red cells mean that the variable change was very impactful on cost per unit).

		Variable improvement level								
Variable	**Current AM values**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**
Material cost ($/cu inch)	$2.50	$36.76	$34.09	$31.43	$28.76	$26.10	$23.43	$20.77	$18.10	$15.44
Unit part volume (cu inch)	8.2	$36.76	$34.09	$31.43	$28.76	$26.10	$23.43	$20.77	$18.10	$15.44
AM machine cost	$780,000	$38.48	$37.54	$36.59	$35.65	$34.71	$33.77	$32.82	$31.88	$30.94
# parts/batch	60	$38.26	$37.29	$36.47	$35.77	$35.16	$34.63	$34.16	$33.74	$33.37
Non-usable scrap rate	30%	$38.81	$38.19	$37.58	$36.96	$36.35	$35.73	$35.12	$34.50	$33.89
# hours to print full bed	20	$38.86	$38.29	$37.73	$37.17	$36.60	$36.04	$35.48	$34.91	$34.35
# hours to cure full bed print	20	$38.86	$38.29	$37.73	$37.17	$36.60	$36.04	$35.48	$34.91	$34.35
AM machine Life (years)	7	$38.56	$37.85	$37.25	$36.73	$36.28	$35.89	$35.54	$35.23	$34.96
AM annual services cost	$20,000	$39.25	$39.08	$38.91	$38.74	$38.57	$38.41	$38.24	$38.07	$37.90
Qualification cost/batch	90	$39.27	$39.12	$38.97	$38.82	$38.67	$38.52	$38.37	$38.22	$38.07
Machine downtime	10%	$39.30	$39.18	$39.06	$38.94	$38.83	$38.72	$38.61	$38.50	$38.40
Labor rate ($/hour)	$17.50	$39.40	$39.39	$39.37	$39.36	$39.34	$39.33	$39.31	$39.30	$39.28
# labor hours/week	2	$39.40	$39.39	$39.37	$39.36	$39.34	$39.33	$39.31	$39.30	$39.28
Redesign cost	$4,000	$39.42	$39.42	$39.42	$39.42	$39.42	$39.42	$39.42	$39.42	$39.42

Example: The top left cell (circled in red) shows that if material cost improves by 10% (i.e. if it decreases from $2.50 to $2.25), then the total cost per unit (holding all other variables constant) drops to $36.76 (from $39.42).

As can be seen in the chart above, material cost, part volume (i.e. if the part can be redesigned to use less material), and AM machine cost are the three most impactful variables. That said, no one variable – regardless of the improvement level – can make AM cost-effective compared to injection molding, which is only $2.64 per unit.

Consequently, this means that multiple AM variables will need to improve in order for AM to become cost-effective for parts such as this.

To illustrate this point, below is a fictional scenario showing improvements to multiple AM variables for the sPro™ 230. At these levels of improvements, AM cost per unit drops to $2.63, which is cost-effective relative to injection molding ($2.64 per unit):

Variable	Current AM Values	Improvement	Improved AM Values
AM machine cost	$780,000	30%	$546,000
AM machine life (years)	7	50%	11
AM annual services cost	$20,000	90%	$2,000
Material price ($/cu inch)	$2.50	90%	$0.25
Non-usable scrap rate	30%	65%	11%
# parts/batch	60	300%	240
Unit part volume (cu inch)	8.2	10%	7.38
Labor rate ($/hour)	$17.50	0%	$17.50
# labor hours/week	2	50%	1
# hours to print full bed	20	50%	10
# hours to cure full bed print	20	50%	10
Qualification cost/batch	$90	90%	$9
Redesign cost	$4,000	0%	$4,000
Machine downtime	10%	50%	5%

Current injection molding cost/unit: **$2.64**
Current AM cost/unit: **$39.42** (using current AM values above)
Improved AM cost/unit: **$2.63** (using improved AM values above)

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Therefore, what the above chart shows is that AM can become cost-effective versus an injection molded part such as this. Accordingly, further research is recommended to better understand when AM technology will experience these improvement levels.

(Note: Energy cost was not calculated in this case and is an area that warrants further analysis).

Summary

Given current technology levels, some parts are cost-effective to produce via AM. Such parts typically fall into at least one of the seven supply chain scenarios that were outlined at the beginning of this section. In these cases, the amount of money saved from switching production to AM can be significant.

For parts that are not currently cost-effective for AM, no one variable can be singled out as the cause of AM's high cost. That said, scenarios can be constructed to show what AM variables will need to improve in order for a part to become cost-effective for AM. The most impactful AM variables (on total AM cost) are often material cost, part volume, AM machine cost and AM machine throughput.

Overall, when considering whether to implement AM, there is no substitute for conducting a cost-benefit analysis that evaluates the entire supply chain and product life cycle. Doing so may not only lead to substantial cost-savings today, but will also enable your firm to understand what AM metrics to look out for in the future. AM technology is quickly advancing, and so having a thorough understanding of when to implement the technology will enable your firm to gain a competitive advantage.