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ORIGINAL ARTICLE

An economic analysis comparing the cost feasibility of replacing injection molding processes with emerging additive manufacturing techniques

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Abstract Additive manufacturing (AM) has proliferated in recent years and is displacing traditional manufacturing methods in numerous applications due to improvements in process efficiencies and cost reductions related to the evolving AM processes. This study explores the cost structure and break-even points of AM versus traditional methods. The comparative analysis examined the cost requirements of AM versus injection molding to manufacture various lot sizes of parts. Break-even points based on lot sizes and the relationship to the overall cost structure were also calculated. This research concludes that break-even points may be calculated based on part mass, density, and lot size.

Keywords Additive manufacturing · 3D printing · Injection molding · Cost analysis

1 Introduction

Additive manufacturing (AM) is one of the fasted growing industrial sectors in the USA and has been considered the next industrial revolution [1]. In 2014, there was an estimated $1.065 billion spent on the AM of production grade parts and the industry has grown at an average rate of 76 % over the last 14 years [2]. The ability to rapidly design and build models with minimal lead times has been readily adopted by companies producing smaller batches of parts or parts that may be customized by batch. With a low cost to create an individual part or for small lot size production, AM processes are able to significantly reduce tooling costs. As decreasing costs of production continues, the feasibility of AM replacing traditional processes like injection molding is becoming increasingly probable.

AM offers several distinct advantages that are not attainable with traditional manufacturing methods. AM is named after the process of how it deposits material. In traditional methods, like machining, the material is removed from a solid block of material. An additive process adds material to the model to produce a solid part. The key advantages include [3] flexibility of design, consolidation of complexity, and reduction in tooling costs.

The field of AM has grown tremendously over the past decade [4]. One major factor to this growth is the low cost approach provided by companies including MakerBot Inc. and Ultimaker Inc. These companies have been providing the consumer with a considerably lower cost to produce 3D printed parts [5]. With companies such as Stratasys and 3D Systems, a median priced 3D printer during the early 2000s could cost over $100,000 [6]. The cost barriers to enter a market were consistently high until 2010, when the market began to transition and included low cost- and consumer-based systems. The growth of affordable systems was caused by a decrease in the cost of computing processors and the expiration of certain patents protecting existing systems. In 2005, there was approximately $800 million spent on AM in the USA [2]. In the year 2010, there was approximately $1.8 billion amount spent on additive manufacturing in the USA. And foremost, in 2015, there was $4.2 billion amount spent on AM in the USA [2]. A contributing factor to this increase was the proliferation of low cost 3D printing.

The demand for engineers and technicians to operate additive machines is increasing as well. An analysis conducted in

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2014 shows the growth of technical positions for 3D printing in manufacturing settings [6]. As more companies consolidate rapid prototyping as an in-house operation, the availability of having an “additive engineer” increases the likelihood of using AM instead of traditional processes. As AM continues to grow globally and decrease in cost to use, the potential feasibility of using AM processes to replace injection molding in special cases is certainly more theoretical.

Several recent studies have examined opportunities and obstacles in AM [7, 8], the environmental impacts and life cycle assessments (LCA) for AM [9, 10], but few have examined break-even points and comparisons between traditional manufacturing and AM. In fact, most studies that have examined the economic impact of AM tend to focus on filament costs and recycling of the filament [11]. These studies have provided environmental impact and production cost insights into 3D printing but have not comprehensively examined AM versus traditional methods from a cost perspective. An analysis focusing on comparative costs and break-even points would be novel in this field and assist manufactures in their decision making processes to balance production cost and production time. The intent of this study was to create a model to assist manufacturers in making these types of decisions based on part complexity and lot sizes. This model and comparative analysis were based on cost comparison analyses that included the purchase of the manufacturing equipment, material, labor, and overhead costs. For this analysis, material cost, initial capital cost, time constraints, energy costs, waste percentage, deprecation, and labor costs were included to establish break-even points.

A previous white paper prepared by a private company in France considered a similar operating scenario of transitioning from injection molding to AM; the study’s ultimate outcome identified that the amount of 3D printed parts that can be made optimally before it is more cost effective to switch to injection molding [12]. Sculpteo determined the relative cost of the initial setup and the overall cost of the batch size. The study identified a break-even point between 300 and 400 units depending on complexity and part size [12]. Sculpteo identified higher labor cost and tooling for injection molding but lower material costs. The study did not provide strong references to published literature nor strong elaborations on the mathematical modeling used for the comparison.

In 2012, Atzeni and Salmi examined the economics of AM versus traditional die casting for the production of metal parts [13]. The study examined part sizes, lot sizes, part densities, material costs, machine costs, labor costs, and setup time to determine break-even points versus selective laser sintering and high-pressure die casting for the manufacturing of airplane landing gear. In a case study presented in this paper, the authors identified a break-even point of 42 units between the two methods with tooling/die costs as a major expense for traditional methods and machine depreciation as the major expense for AM [13].

2 Methodology and analysis

2.1 Material cost of plastic

The cost of plastics in the USA has declined by 150 % in the last 10 years [6]. In 2005, the average cost of acrylonitrile-butadiene-styrene (ABS) per kg, a slightly modified version, cost around $600 [14]. Now, the cost of that same ABS from an industrial additive manufacturer is around $400 per kg [14]. As the market consolidates, the cost of proprietary materials has decreased. In the consumer market, the cost of ABS per kg is approximately $35 [14]. This material is roughly one tenth the cost of traditionally available additive plastics. This can also be compared to cost of raw ABS plastic in pellet form, which has a cost of about $1.50 per kg [14]. The lowering cost of plastics has allowed for replacement of parts that were traditionally wooden or metal. As AM developed in the 1990s, a plethora of plastic based materials were developed to be used in selective laser sintering (SLS) and fused deposition modeling (FDM) methods. Because of the proprietary nature of using designated material, the costing structure associated with these new materials was considerably higher than virgin plastic. As the consumer use of 3D printing has significantly increased, the cost of AM raw materials has dropped. Yet, some proprietary materials still have extensive costs. Based on the FDM model, ABS plastic was chosen as the material for this research, as it has a reliable cost per kg. ABS is considered the most widely used material for 3D printing, and its use in injection molding has been well known. ABS, being a reliable thermoplastic that has a relatively low cost, provided an opportunity to meaningfully compare material costs of AM versus traditional manufacturing methods.

2.2 Initial capital cost

The initial capital cost of acquiring a 3D printer has also fallen dramatically. This high cost was inhibitive and stagnated the market until the late 2000s, when consumer systems were available for several thousand dollars. A consumer system can typically range anywhere from $900 to around $5000. As low cost methods have been introduced into the market, the relative cost of high grade systems has also fallen. In the past several years, there has been a definite trend for the market to equalize and produce a quality system at around $5000. This cost, however, will take several years to consolidate in price. The costs of several consumer systems available on the market are displayed in Table 1.

From a capital standpoint, systems from Stratasys represent industrial 3D printers that are extremely capital intensive. They are on par with the cost associated with traditional manufacturing systems. In the scenario, section of this study examines the implication of a lowered capital cost and its overall effect on the simulation.

Table 1 Capital costs required to purchase various manufacturing systems

Additive machines	
Stratasys Fortus Series 250	$40,000
Stratays Fortus Series 400	$300,000
MakerBot Replicator 2X	$3500
Ultimaker 2	$2500
PrintrBot Metal Plus	$1200
Injection molding machines	
Milacron 250 T injection molding machine	$300,000
Milacron 100 T injection molding machine	$90,000
Arburg 30 T injection molding machine	$30,000
Boy 15 T injection molding machine	$6000

2.3 Setup time

The setup time and the associated cost between additive processes and injection molding are a unique scenario. The cost to produce and prepare a mold for injection molding may range from 2 to 6 days depending on the complexity. The initial setup time required for injection molding can severely limit the capability of manufacturing in a short timeframe. Whereas, additive process requires virtually zero tooling and minimal labor.

2.4 Energy cost of systems

The relative cost of energy consumed per method is varied. For additive processes, the amount of energy consumed is significantly less than injection molding because of the minimal area required for heating and the subsequent losses. The mass of the printed object is the largest factor in determining the energy cost for additive, whereas the total run time is the largest factor with injection molding. This relationship is shown below in the following two equations.

$$E_{\text{Additive}} = \sum_{n=N} \frac{0.001(w)\left(t_{\text{warmup}}\right)}{3600} + \frac{0.001(w)\left(t_{\text{Runtime}}\right)}{3600}$$

$$E_{\text{Injection}} = \frac{0.001(w)\left(t_{\text{setup}}\right)}{3600} + \frac{0.001(w)\left(t_{\text{runtime}}\right)(N)}{3600}$$

Where E represents total energy usage in watts, w part mass in kg, t represents time in seconds, and N represents the total number of parts to be produced in a single run.

Based upon these two equations, the model considered varying sizes of parts to be produced. The relative energy cost is based on the overall running time versus the part mass. Based on physical testing, the AM machine consumed roughly 1200 W in a 12-min warm-up and 300 W during runtime. The injection molding machine consumed roughly 3000 W throughout the runtime, with an average setup of 120 min. This variance was tested with several samples, and the model was refined with the abbreviate cost per Kw/H. Overall, the research team determined the cost per Kwh is approximately $0.12. This cost is based on the rough cost of energy in Toledo, Ohio taken from the Energy Information Agency.

$$C_{E\text{Additive}} = (\$0.12)\left(\sum_{n=N}(0.000333)(12) + \frac{1}{360}(300)\left(t_{\text{runtime}}\right)\right)$$

$$C_{E\text{Injection}} = (\$0.12)((0.000833)(120)) + \left(\frac{1}{360}(3000)\left(t_{\text{runtime}}\right)\right)$$

2.5 Waste percentage of production

Waste is typically an unavoidable aspect of any manufacturing operation, and additive processes have very low waste percentage. Over the past year, the research team collected data on the typical waste percentage of additive parts. Overall, the team found that the average waste percentage of additive manufacturing using FDM technology is around 12.8 % of total mass.

Although additive processes have low wastes, injection molding also has significantly lower waste percentiles. Typically in injection molding, the waste percentile is around 18 % by mass. This number also varies greatly because of mass and can be controlled with mold design and part orientation.

2.6 Depreciation of systems

The high cost of some industrial systems offers the incentive to deprecate the system at market rates to benefit from the tax system. Unfortunately, because of the large gap in the cost of additive systems, the incentive to depreciate lower cost systems is low, while the higher cost systems are typically in the range to deprecate by unit rather than lifetime.

2.7 Cost of labor

AM and injection molding manufacturing used for this analysis demonstrated similar and low labor costs of operation. Most injection molding machines run continuously without direct labor, once it is setup. The same is true with most additive processes as well. For this section, the team examined at the labor cost in setting up the machines and a low amount of observation during processing. For most additive processes, the machine can be setup in less than half an hour, whereas injection molding requires significant setup. As described later in this paper, the process for setting up the injection molding machine requires significantly more labor. The production of a mold may take up to 50 h, and preparing the machine could be well over 10 h. This time cost of labor in this model is $20 an hour. This represents the cost of skilled labor to operate the machine and/or make the mold. Because of the implications of using different costs for each process, the research team decided that the cost of labor will remain consistent throughout the model to compensate for differences between each individual manufacturer.

2.8 The variance in setup and operation between the two methods

This section examines the setup and operational time differences between AM and injection molding. The scenario examines a manufacturer's choice to utilize AM or injection molding for a new product to be produced on site. The manufacturer is considering whether to buy and install an injection molding machine or 3D printers. The primary goal is concerned with the ability to produce parts at the lowest cost and in a timely manner that are consistent with just-in-time production. The comparison between the methods examines the individual cost per part, the total cost of the production run, and the relative break-even point. The expected outcome of this simulation is to define the conditions in which AM is cost/time effective versus traditional methods.

2.8.1 Additive manufacturing

First, as with the production of most parts, the component must be reviewed for manufacture. For an additive process, reviewing that consists of verifying the model is correctly designed for additive construction. The model must be examined for cross-sectional integrity to ensure that the parts will be reinforced in certain areas. The model must also be placed in the printer to verify optimal surface conditions, orientation strength, and support structures. After reviewing the model, the printer must be prepared for the process. In most printers, checking for material and running a brief calibration is enough. Many higher costing systems will perform this on their own. After preparing the machine, the model must be rendered in the printer software and verified. After submitting the model to the printer, the printer builds the component. After completing the build, the part is removed. In some cases, the part has post-processing, which consists of refining the surface finish using chemicals or abrasives. In some cases, holes are reamed using traditional machining to provide superior tolerances. Table 2 summarizes the cost structure by line item for AM processing. The cost table was adapted from Atzeni and Salmi [13].

Table 2 Cost model by line item for AM processing per part

Number of part produced per lot		N
Material cost per kg	$/kg	M
Part volume	mm3	V
Density of printed material	g/mm3	D
Mass of material per part	kg	U = D*1.1*V
Material cost per part	$	MP = U*M
Machine operator cost per part	$/h	O
Setup time per build	h	A
Pre-processing cost per part	$	AP = O*A/N
Depreciation cost per year	$/year	
Hours per year	$/h	4000
Machine cost per hour	$/h	C/h
Build time	h	T
Machine cost per build	$	CB = CH/H
Processing cost per part	$	CP = CB/N
Machine operator cost per hour	$/h	O
Post-processing time per build	$	B
Heat treatment cost per build	$	HT
Post-processing cost per part	$	BP = (O*B*HT)/N
Total cost per assembly	$	P = MP + AP + CP + BP

2.8.2 Injection molding

Injection molding is much more suited for mass production than individual runs. Once the machine is setup and hot, the process for production per part is very fast. To setup an injection molding production run, there are quite a few considerations. The first of these considerations is mold design and use. After designing and fitting the mold, the correct operating parameters of the mold must be established. Because there are about 150 variables to production, there is typically some down time ensuring the operating conditions. After checking the operating conditions, the system is heated and calibrated. The system is optimized for continuous operation, after testing with a few individual cycles. While the machine is running, an operator is typically watching the system to ensure the parts are of quality, feeding the hopper, and removing any snags in the mold. After the production run, parts are selected to verify accuracy and process controlled features. Lastly, if there are any parts that require post-processing, they are machined to tolerance. Table 3 summarizes the cost structure by line item for injection molding. The cost table was adapted from Atzeni and Salmi [13].

3 Case study

This case study scenario examines the current market and the cost relationship between AM versus injection molding. The cost to purchase an AM system has been lowered further to approximately $5000. At that price point, an AM system can utilize a wide range of all FDM materials options. The raw

Table 3 Cost model by line item for injection molding processing per part

Production volume	Pcs	V
Material cost per kg	$/kg	M
Part weight	kg	W
Material cost per part	$	MP = W*M
Standard component cost	$	SC
Mold cavities and sides cost	$	K
Ancillary cost	$	A
Mold cost per part	$	KP = (SC + K + AO)V
Machine cost per part	$	P
Cycle time	h	T
Labor cost per hour processing	$	PL
Percentage of operating time	%	PT
Processing cost per part	$	CP = (P + PL * PT) * T
Heat treatment cost per part	$	HT
Machining operations cost	$	MO
Labor cost per hour post-processing	$/kg	AL
Operator time	h	AT
Post-processing cost per part	$	AP = AT + MO + AL * AT
Total cost per part	$	P = MP + KP + CP + AP

FDM material, ABS, now costs roughly $28 per kg, and although this cost is still considerable higher than virgin material prices for injection molding, the decreasing cost of plastic is advantageous in favor of AM.

The model for injection molding has not varied significantly over the past decade. With stable plastic prices and an abundance of quality machines for application based usage, the overall model has shown strong stability.

3.1 Part overview

The part selected for the cost comparison scenario was an internal housing for automotive applications. The part is 20 cm by 8 cm by 10 cm and is not a structural component subject to heavy loading. The part has print time of about 2.4 h for AM and a mold cool time of 0.5 min. The housing is displayed in Fig. 1.

3.2 Break-even calculations

By applying the models developed in Section 3, the break-even points based on the established cost structures were calculated for AM and injection molding. LINGO software was used to perform the break-even calculations based the data provided for the case study. To perform the analysis, all of the parameters for AM and injection molding were held constant and the unknown variable, lot size, was determined as the break-even point.

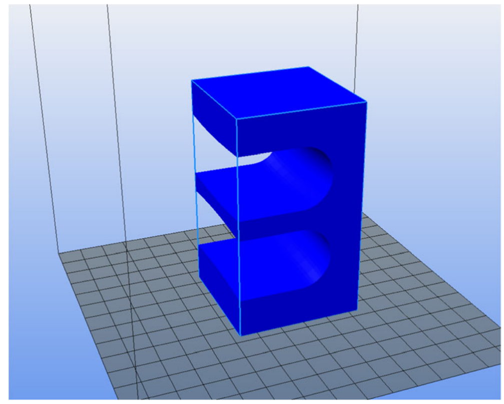


Fig. 1 Drawing of automotive housing used for case study

The results of the analysis indicated a break-even point of 187 units as displayed in Fig. 2.

3.3 Sensitivity analysis

A sensitivity analysis was performed to identify the variables that have the largest impact on the break-even point between AM and injection molding. To perform the sensitivity analysis, each variable was increased by 10 % while holding the other variables constant to measure the impact on the break-even point. A total of 20 variables for AM and a total of 19 variables for injection molding were evaluated as displayed previously in Tables 2 and 3, respectively. LINGO was utilized to perform the calculations.

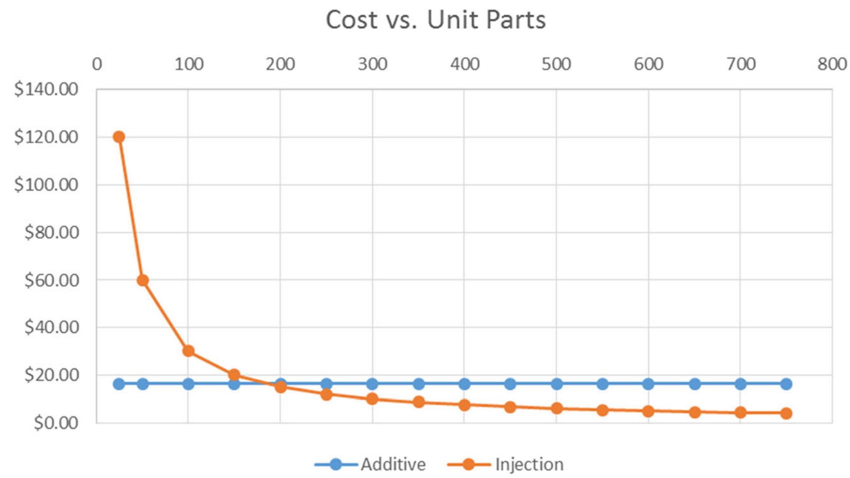
The findings from the sensitivity analysis are displayed in Tables 4 and 5 for AM and injection molding, respectively.

As displayed in the tables, for AM, variables related to material cost (9.8 % increase) and part density (9.6 increase) had the highest sensitivity to change, while other variables had a 3 % or less change. For injection molding, material cost (9.0 % increase) and mold cost per part (7.3 % increase) had the highest sensitivity, while other variables had a 3 % or less change. Not surprisingly, material costs have a large sensitivity for both AM and injection molding.

4 Conclusions

Based upon the results analysis, a lot size approaching 200 units is the break-even point when deciding between AM and injection molding. Injection molding is a better cost effective choice for higher batches of parts. Also, from a production time perspective, injection molding can produce larger quantities of parts much faster than current AM technology. In that

Fig. 2 Break-even analysis



respect, AM does not have the ability to completely replace injection molding but offers cost effective options when running small or customize production runs under 200 units. AM may lack the benefits of faster production runs versus injection molding, but AM offers additional benefits such as the ability to create rapid prototypes, single unit production, and highly complex parts. As designers and engineers take advantages of AM, the likelihood of small-scale production methods increase and become more cost effective versus traditional methods.

The ultimate cost differential between these two methods is the cost of the mold for injection molding. For the injection

Table 4 Sensitivity analysis for AM (10 % in each variable)

AM variable	% change in break-even point
Material cost per kg	9.8
Part volume	8.7
Density of printed material	9.6
Mass of material per part	9.4
Material cost per part	9.4
Machine operator cost per part	2.0
Setup time per build	0.1
Pre-processing cost per part	0.2
Depreciation cost per year	0.3
Machine cost per hour	0.8
Build time	1.0
Machine cost per build	2.0
Processing cost per part	3.0
Machine operator cost per hour	0.8
Post-processing time per build	1.3
Heat treatment cost per build	0.2
Post-processing cost per part	0.3

Table 5 Sensitivity analysis for injection molding (10 % in each variable)

Injection molding variable	% change in break-even point
Production volume	1.0
Material cost per kg	9.0
Part weight	1.1
Material cost per part	2.5
Standard component cost	1.3
Mold cavities and sides cost	0.0
Ancillary cost	0.5
Mold cost per part	7.3
Machine cost per part	0.0
Cycle time	0.0
Labor cost per hour processing	0.0
Percentage of operating time	0.9
Processing cost per part	0.0
Heat treatment cost per part	0.4
Machining operations cost	0.0
Labor cost per hour post-processing	0.0
Operator time	0.0
Post-processing cost per part	1.0

mold, a typical price may range from $3000 to 10,000. This cost is circumvented in AM as there is no tooling required. Additionally, material costs are a key factor when considering production options for both methods based on the sensitivity analysis.

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