A Thesis

entitled

An Experimental and Theoretical Analysis of Additive Manufacturing and Injection Molding

by

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Submitted to the Graduate Faculty as partial fulfillment of the requirements for the Master of Science Degree in Mechanical Engineering

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An Abstract of

An Experimental and Theoretical Analysis of Rapid manufacturing Versus Injection molding

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As additive manufacturing has grown over the past several years it has displaced traditional methods. In the rapid prototyping field, 3D printer have grown to occupy the entire market. As this and other instances have shown, additive processes have successfully entered new markets and gained market majority. In this paper we explore the application of additive manufacturing and the feasibility of the disruption of traditional methods like injection molding. The feasibility is determined by an analysis of the cost to make parts as per batch basis. We then determined the break-even point and the relationship to the overall cost structure.
For Sabrina, You’ve helped me believe that anything can happen, and proved it so.

For Caffeine, for all of those long nights we’ve shared recently.
Acknowledgments

This thesis would not have happened without the support of my family. Because of their encouragement I have been able to realize my future as an engineer. Their patience and wisdom throughout my life has been the greatest influence on my life so far. Although I will never be able to fully repay them for their years of advice and care, I hope to show my appreciation for many years to come.

I could not have become an engineer without the guidance and help of my advisor, Dr. Franchetti. Working and learning under his lead has made the difference in my education. For every point in my academic career, Dr. Franchetti has been there to help. The greatest realization of any student is that college was not for the paperwork, but for the ability to learn. With this realization, I will always be a student ready and eager to learn.
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Chapter 1

Growth of Additive Manufacturing

1.1 Recent Movement in the AM Field

Additive manufacturing is one of the fastest growing industrial sectors in the United States. In the year 2014, there was an estimated $1.065 billion spent on additive manufacturing of production grade parts\(^1\). This technology has grown at an average rate of 76% over the last 14 years. The ability to rapidly design and build models with minimal lead times has been well adopted by companies producing small batches of parts. With low cost of individual production, additive processes are a key asset to reduce tooling costs. As the decreasing cost of production continues, the feasibility of additive manufacturing replacing traditional processes like injection molding is increasingly probable. The graph below is an estimated growth model for additive manufacturing globally. The most notable part of this graph is the direct part section. This section increases in size until 2020, in which it contributes the largest portion of the additive manufacturing market.
To determine the likelihood of this scenario, we examined the relative cost of additive manufacturing versus injection molding. Because of the large variance caused by different parts and their respective masses, we built a cost model based on experimental data. This model was then used to simulate the total cost of a batch as per part basis. This cost structure is then refined to determine the breakeven point between an additive method and injection molding.
1.2 Features of Additive Manufacturing over Traditional Methods

Additive manufacturing offers several distinct advantages unattainable with other manufacturing methods. It is named after the process of how it deposits material. In traditional methods, like machining and tooling, the material is removed from a solid block of material. An additive process is the polar opposite, it adds material to the model to produce a solid part. In the following section, several advantages have been chosen to demonstrate the advantages of additive that cannot be obtained in any other manner.

1.2.1 Flexibility of Design and Production

The most notable of these advantages is the added flexibility in design. Utilizing additive processes, it becomes possible to make components that are hollow in certain cross sections. Because the material is added in layers and patterns, the material density of the core can be manipulated. The ability to actively change the core properties in the part allows for design flexibility in the unseen characteristics of the model. This same flexibility allows for unique sections of the component to be reinforced. Because the process is considerably more controlled per cubic millimeter of material, the parts are not only significantly reduced in weight but also magnitudes stronger. Because of the controlled process of adding material, ideal material conditions per location is now dictated in design, not by a post process method. This design criteria is well documented by Boeing, and is used to reduce manufacturing lead time as well. The graphic below shows how Boeing was able to implement additive into their design process. The upper
component was made using traditional methods, whereas the lower was made using an additive process. In this particular example, the component is about 125% stronger, and the reduction in weight to the airplane can save around $3000 in fuel annually.

Figure 1.2: Above are the two hinge parts developed by Boeing to look at the feasibility of an additive made part. The top component is traditional made, while the lower parts are made additively.  

1.2.2 Consolidation of complexity through AM

By manufacturing using additive methods, parts have also been shown to reduce complexity, by consolidating components and/or features. This reduction in complexity effects the time it takes to effectively maintain a particular system. Because of the added flexibility of design, parts can be manufactured with features and fittings already included in the component. This flexibility allows for more ergonomically designed parts
that reduce the number of mechanical fasteners. Because of this reduction, if possible, some mechanical fasteners are reachable in a more effective manner. Simple reductions in design allow for easy to install/uninstall components. Another major feature of additive manufacturing is the ability to manufacture without consideration to complex machines and/or tooling. This ability has also been well documented by Boeing as they now use 3D printers to make replacement parts in depot. By manufacturing parts as per necessity, time and money can be saved via overhead and shipping. In additive processes there is no additional cost for complexity.

1.2.3 Reduction of Tooling Costs

One final and notable advantage of additive processes is the ability to make revisions to parts without redesigning or rebuilding tooling. In comparison to traditional molds, additive methods do not experience the cost associated with product iteration. Because additive requires virtually zero tooling cost, the design process can be accelerated to making individual parts as per needed basis.

1.3 Recent Growth of Additive Manufacturing over the Past Ten Years

3D printing and additive manufacturing as a whole have grown tremendously over the past decade. One major factor to this growth is the low cost approach provided by companies like MakerBot Inc. or Ultimaker Inc. These companies have been providing the consumer with a considerably lower cost to produce 3D printed parts. With companies like Stratasys and 3D Systems, a median priced 3D printer during the early 2000’s could cost over $100,000. The cost barriers to enter a market were consistently
high until 2010, when the market began to grow into low cost systems. The growth of affordable systems was likely caused by a decrease in the cost of computing processors and the expiration of certain patents protecting existing systems. In the year 2005, there was approximately $800 million spent on additive manufacturing in the US\textsuperscript{1}. In the Year 2010, there was approximately $1.8 billion amount spent on additive manufacturing in the US. And foremost, in 2015, there was $4.2 billion amount spent on additive manufacturing in the US. This increase, as stated above, is likely caused by the increase of low cost 3D printing.

The demand for engineers and technicians to operate additive machines are increasing as well. An analysis conducted in 2014 shows the growth of technical positions for 3D printing in manufacturing settings. As more operations take rapid prototyping in-house, the availability of having an additive engineer increases the likelihood of using additive instead of traditional processes. This growth is shown below.
Figure 1.3: The above graph shows the growth of AM over the past several years. This graph is in new hires per month.  

As 3D printing continues to grow globally and decrease in cost to use, the potential feasibility of using additive processes to replace injection molding in special cases is certainly more theoretical. This paper will examine the feasibility of implementing 3D printers into rapid manufacturing as opposed to injection molding. This comparison will be based on cost comparison analyses starting at the purchase of the system. For this analysis, we will examine material cost, initial capital cost, time constraints, energy costs, waste percentage, depreciation, and labor costs. This LCA will be based primarily on the cost implications, with special consideration given to time.

1.4 Complexity and Cost

Complexity and the relationship of cost are not very well documented in additive manufacturing. As traditionally defined, the cost of a part increases with complexity until the part is no longer economically viable. This particular concern in traditional methods of production is not effected in 3D printing. Because 3D printing adds material, selective shapes and design do not impact the overall time of production significantly. The added manufacturing flexibility caused by additive manufacturing has unknown cost benefits to the overall production value of the component.

To determine the added cost of complexity for additive methods, we first had to determine the cost of geometry in relation to the mass and print time. The mass of the part does not dictate the required time to produce the part. However, we have determined there is a relationship between the two that determines the complexity of the part. The
first graph below demonstrates the mass in kilograms versus the time required for production.

![Graph showing mass vs. time required for production](image)

**Figure 1.4:** Complexity with the mass of the part compared to the time required to produce that part. The corresponding Adjusted R value of this graph is .961.

As seen above, we built a calibration curve in an attempt to identify the likely time required to print a part if the mass is known. Initially we had believed the complexity to magnify as the part mass increased, but as we tested, we determined that
complexity is more apparent in small parts as opposed to large parts. Our conclusion is based upon the process the computer prepares the part for the machine. In large parts the computer slices, a process in which the model is separated in the z-axis, in such a way that is often a more efficient. To determine the efficiency and or complexity of the printer, we looked at the deviation from the calibration curve of Figure 1.4. In observation of that deviation, we determined the maximum to be 15.4% deviation from the calibration. From this deviation, we were able to identify the combined effects of complexity and wasted material. In an effort to remove waste (operational inefficiency) from the complexity curve, we conducted an experiment on the efficiencies of the printer for varying mass. This experiment used the same regular shape at different sizes to create an efficiency per mass graph that would allow us to remove that variance. Below we have identified the inefficiency factor.

In the figure above, we demonstrated how we were able to account for the inefficiency. After building this curve, and including it into the original calibration model, we determined that the overall maximum inefficiency of the printer was 2.5% of the overall predicted mass to actual mass. This finding also allow for us to conclude that the maximum effect of complexity on the part is around 14% of the mass. In essence, the complexity value can add up to 14% of the original time value to the overall time required to produce a part.
Chapter 2.

Data Collection & Analysis

2.1 Material cost of plastic

Plastic cost in the United States have dropped 150% over the last 10 years. In 2005, the average cost of ABS per kg, a slightly modified version, cost around $600. Now the cost of that same ABS from an industrial additive manufacturer is around $400 per kg. As the market consolidates, the cost of proprietary materials has decreased. In the consumer/prosumer market, the cost of ABS per kg is around $35. This material is roughly 1/10 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. The lowering cost of plastics has allowed for replacement of parts that were traditionally wooden or metal. As additive manufacturing developed in the 1990’s, a plethora of plastic based materials were developed to be used in SLS and 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 consumer 3D printing was adopted around 2012, the cost of certain materials has fallen. Yet some proprietary materials still have extensive costs. This unusual relationship is shown in the table below. As you can see some materials are fraction of the cost to their proprietary counterparts. Based on our FDM model, we chose ABS plastic, 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. Being a reliable thermoplastic that has a relatively low cost gave us a chance to compare if material cost of ABS for an additive process were lowered.

<table>
<thead>
<tr>
<th>Cost of Material</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ABS Plastic</strong></td>
</tr>
<tr>
<td>Traditional ABS for Additive manufacturing (Kg)</td>
</tr>
<tr>
<td>Modern Professional-grade ABS for 3D printing (Kg)</td>
</tr>
<tr>
<td>Cost of raw ABS used in Injection Molding (Kg)</td>
</tr>
<tr>
<td><strong>Various Plastics and Resins</strong></td>
</tr>
<tr>
<td>Range for FDM Plastics (Kg)</td>
</tr>
<tr>
<td>Range For Additive Polymer Resins (Kg)</td>
</tr>
<tr>
<td>Range for ABS Filament (Kg)</td>
</tr>
<tr>
<td>Range for Injection Grade ABS (Kg)</td>
</tr>
</tbody>
</table>

Table 2.1: The above graph highlights the cost of material in the U.S. for FDM processes
2.2 Initial Capital Cost

The initial capital cost of acquiring a 3D printer has also fallen dramatically. The cost of a 3D printer in 1998 is over 4000% lower the cost of buying one today. This high cost was inhibitive enough to stagnate the market until the late 2000’s, when consumer systems were available for several thousand dollars. A consumer/pro-sumer 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. Attached below is the costs of several systems available on the market.
## Capital Cost Structure

### Additive Machines

<table>
<thead>
<tr>
<th>Machine</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratasys Fortus Series 250</td>
<td>$40,000</td>
</tr>
<tr>
<td>Stratasys Fortus Series 400</td>
<td>$300,000</td>
</tr>
<tr>
<td>MakerBot Replicator 2X</td>
<td>$3,500</td>
</tr>
<tr>
<td>Ultimaker 2</td>
<td>$2,500</td>
</tr>
<tr>
<td>PrintrBot Metal Plus</td>
<td>$1,200</td>
</tr>
</tbody>
</table>

### Injection Molding Machines

<table>
<thead>
<tr>
<th>Machine</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milacron 250T Injection molding machine</td>
<td>$300,000</td>
</tr>
<tr>
<td>Milacron 100T Injection Molding Machine</td>
<td>$90,000</td>
</tr>
<tr>
<td>Arburg 30T Injection Molding Machine</td>
<td>$30,000</td>
</tr>
<tr>
<td>Boy 15T Injection Molding Machine</td>
<td>$6,000</td>
</tr>
</tbody>
</table>

Table 2.2: The above table details the capital required to purchase various systems. With a special note on the large variance between system costs.

From a capital standpoint, systems from Stratsys represent industrial 3D printers that are extremely capital intense. They are on par with the cost associated with traditional manufacturing systems. In the scenario section of this paper we will examine the implication of a lowered capital cost, and its overall effect on the simulation.
2.2 Time Value

The time cost between additive processes and injection molding is a unique scenario. The cost to produce and prepare a mold for injection molding can be anywhere 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 processes require virtually zero tooling, and minimal labor.

2.3 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 two equations.

\[
E_{Additive} = \sum_{n=N} \frac{0.001(w)(t_{\text{warmup}})}{3600} + \frac{0.001(w)(t_{\text{runtime}})}{3600}
\]

\[
E_{Injection} = \frac{0.001(w)(t_{\text{setup}})}{3600} + \frac{0.001(w)(t_{\text{runtime}})(N)}{3600}
\]
Based upon these two equations, we build a model for varying sizes of parts produced. As you can see the relative energy cost is based on the overall running time vs the part mass. As we tested our additive system, we concluded that is consumed roughly 1200 watts in a 12 minute warm-up, and 300 watts during runtime. We also determined that the injection molding machine consumed roughly 3000 watts throughout the runtime, with an average setup of 120 minutes. This variance led us to test with several samples, and refine the model with the abbreviate cost per Kw/H. Overall, we determined the cost per Kwh is around $0.12. This cost is based on the rough cost of energy in Toledo, Ohio taken from the Energy Information Agency.

\[ C_{EAdditive} = ($0.12)(\sum_{n=N}^{(0.000333333)}(12)) + \frac{1}{360}(300)(t_{runtime}) \]

\[ C_{Einjection} = ($0.12)((0.000833333)(120)) + (\frac{1}{360}(3000)(t_{runtime})) \]

2.4 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, we have collected data on the typical waste percentage of additive parts. Overall we have 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.

2.5 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 deprecate lower cost systems is low, while the higher cost systems are typically in the range to deprecate by unit rather than lifetime.

2.6 Cost of Labor

Both methods of manufacturing used for this analysis are virtually labor free in operation. Most injection molding machine run continuously without direct labor, once it is setup. The same is true with most additive processes as well. For this section we looked at the labor cost in setting up the machine. 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 more labor. The production of a mold may take up to 50 hours, and preparing the machine could be well over 10 hours. 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, we decided that the
cost of labor will remain consistent throughout the model to compensate for differences between each individual manufacturer.
Chapter 3.

The Variance in Setup and Operation between the Two Methods

In the next section, both methods are dissected by step to further understand time constraints. In this particular scenario we intent for it to be laid out such that a new production part needs to be made, and two processes are available. In our particular scenario, the factory is taking an operation from a supplier to an in-house job. The factory is considering whether to buy and install an injection molding machine or 3D printers. Their major concerns are the ability to produce parts at the lowest cost, and in a timely manner consistent with just-in-time production. For this scenario, we will look at the individual cost per part, the total cost of the run, and the relative break-even point. Of the these factors listed below, we hope to learn how certain variables effect the overall ratio of how many parts can be made using additive methods before the switch to injection molding. The expected outcome of this simulation is to define the conditions in which additive processes are cost/time effective. This idea has been discussed for a decade, and as costs lower for additive manufacturing, a simulated model is ideal. This relationship is best shown by the graph below
Figure 3.1: The figure above shows the idealized model of the cost comparison between the two methods describe in this paper.

3.1 Additive Manufacturing

The procedure for additive manufacturing is typically simple. Firstly, as with any production part, the component must be reviewed for manufacture. For an additive process, reviewing consists of verifying the model is correctly built 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, orientational 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.

3.2 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.
Chapter 4.

Revision of other work

4.1 Sculpteo

A company based in France considered this same operating scenario of moving from injection molding to additive manufacturing. Their ultimate outcome labels the amount of 3D printed parts that can be made optimally before switching to injection molding. Their outcomes are designated below in the following graphs taken from their website. In the process of verifying the simulation, we recreated their results with our model.

The first model used to verify our calibration is shown below. It is a modified handle for the product GoPro. This handle is can be made easily with either additive or injection methods. This part has roughly a volume of 78.54 cubic centimeters and has a mass of about 81.68 g. Based upon their model, they predicted that rough break-even point occurred at 486 units, at a cost of €17 a piece. The total order cost is roughly €8,260 or about $8960.
Figure 4.1: This was a model and cost structure built by Sculpteo to demonstrate the break-even costing structure in a GoPro handle.

In the following graphs we have rebuilt this model. Accounting for the changes between the euro and dollar, we were able to recreate their model. We determined the relative cost of the initial setup and the overall cost of the batch size. For the additive method, we took the initial setup cost (however minimal) and added to cost per part. Because of the low setup cost, and the constraint-less scaling factor, the cost per size batch does not increase. Injection molding as a traditional process varies greatly in cost per batch size.

The overall cost per batch size break-even point in Sculpteo model becomes more cost effective to use injection molding, rather than additive process at 486 parts. This point occurs at roughly 450 parts in the recreated model. The initial cost of a 25 unit batch was used to determine if the boundary conditions were correct. In the Sculpteo
model, the 25 unit batch cost roughly $210. In our recreated model we determined the cost per 25 unit batch to be $204. The one major definitive variance initially between the Sculpteo model and the recreated model is the cost per part in the additive section. After translating the relative cost from a FDM to SLA process used by Sculpteo, we were able to recreate this data exactly accounting for the change in material cost per kg. The largest factor of variance after accounting for the different additive process was the mark-up for sale. By contacting the company, we determined the mark-up for their product is around 300%. After making these changes, we constructed the graph below. From this data we concluded that the recreated model is accurate.

![Cost vs. Unit Parts](image)

**Figure 4.2:** The graph above shows the replicated example of Go Pro handle, in which the boundary conditions and intersect are nearly identical
Figure 4.3: The relative costs of production for each system for the Go Pro recreated simulation.

The second model we recreated from Sculpteo was a part named the Rooster. This part has probably very little technical application. The reason this component was chosen was because of its low weight to complexity. In traditional processes like injection molding, it can be made easily. Because the part is well within the complexity range of a mold and has a thin walled features, it is ideal for injection molding. The first model was much more suited to an additive process, whereas the rooster is best designed for an injection process. The Sculpteo cost analysis is shown below as well as the recreated model.
Figure 4.4: The above graph shows the break-even cost structure associated with a rooster created by Sculpteo. Note the overall low cost offered by both systems.
Figure 4.5: The graph above shows the replicated example of the Rooster of which the intersection was determined.
Figure 4.6: The relative costs of production for each system for the Rooster with a recreated simulation.

To continue to test the recreated model we compared another Sculpeo model that exemplified an ideal part for additive. The sprocket model requires an extremely detailed mold, and therefore has a large initial cost to compensate, whereas the additive process is not affected by the complexity or thickness. The results from the Sculpeo model are shown below as well as the results from the recreated model.
Figure 4.7: This was a model and cost structure built by Sculpteo to demonstrate the break-even cost structure in a Sprocket.
Figure 4.8: The graph above shows the replicated example of Sprocket, in which the boundary conditions and intersect are nearly identical.
Figure 4.9: The relative costs of production for each system for the Sprocket and recreated simulation.
Chapter 5.

Simulation Results

5.1 Scenario 1

The first scenario tested is similar to how the market would have looked in the early 2000’s. The cost to enter the additive market is extensive, the cost of the material is considerably higher than current costs. To simulate this, we increased the cost of the machine and material. We did not alter the injection molding model, as the process has not seen a considerable amount of change over the past two decades. The initial capital required to add another process in this model does not vary greatly between the additive and injection molding. Because of this close price, the market leading companies would sell additive machines as if they were comparable to an injection molding machine. In 2005, the cost of an additive machine capable of building models comparable to a 250 ton injection molding machine is around $75,000. At that point, those additive machines would have also had a considerable cost of material. For the recreated model, we used the average cost of material per kg of $450. This cost is around 10X the cost of professional grade material available today, and about 1.5X the cost of that same material today, offered from the same company. Other considerations were given to part size and complexity. To get a clear perspective on the effects of part variance, we used two parts.
The first part we ran in the simulation is tooling mold. It has a weight of 45 grams and has an overall complexity of 4 out of 10. This resulted in a print of around 3.75 hours without warm-up time. The maximum thickness is 15mm, resulting in an in-mold cool time of about a minute. The result of the simulated model using this parts are shown below.

![Cost vs. Unit Parts](image)

**Figure 5.1:** The above graph shows the cost per batch size break-even point for the first scenario. In this graph it is roughly 35 parts before the transition to injection molding is cost-effective.

The second part we used in the first simulated scenario is shell component for a small plastic toy. Its weights 132 grams and has a complexity value of 9 out of 10. It also has a maximum wall thickness of 17 mm with a cool time of about one and a half minutes. This part is ideal for this simulation as it is large and complex which is idyllic for the injection molding process.
The graph above shows the cost per batch size break-even point for the first scenario. In this graph it is roughly 4 parts before the transition to injection molding is cost-effective.

Based upon the simulated results, it would be nearly impossible to produce the second part using an additive process. In these particular examples, we discovered that a batch size of less than 25 was the break even amount between traditional and additive methods. This came as a surprise as additive methods were well utilized in the year 2003. In essence, if a singular part was needed, then additive methods would be ideal.

After examining this data, we looked to determine a likely cause of product acceptance for additive manufacturing during the early 2000’s. After some communication with industry experts, the overall explanation was the added complexity and ease of use. For certain applications the added value of part complexity and complete lack of tooling were enough incentive for major manufacturers to consider
utilizing an additive methods in addition to traditional methods. In determining the overall unknown value of additive methods, the parts could be made up to 3X the cost.

5.2 Scenario 2

Scenario 2 was recreated to show what the additive market would have looked like around 2010. The market for additive is evolving quickly around the availability of cheaper 3D printers and the creation of the maker movement. At this point, the capital required to purchase a 3D printer is intense, but not nearly as expensive as just a few years earlier. In 2003, the cost of buying an additive system is around $100,000. Whereas the cost of buying a printer in 2010 was as low as $3000. The first notable company to appear in this wake is MakerBot. Although there are also a few other companies that entered this business space, Makerbot is an ideal representative as they produce a printer with similar reliability and quality as the more expensive Stratasys systems. Makerbot was making 3D printers as kits and selling them as a hobbyist tool. With a serious amount of rebuilding and upgrading, the systems would perform to the capabilities of a much more expensive system. The overall cost of these upgraded systems would be around $7000. Although hobbyist printers were available at that time for a cost that was considerably less, the quality of those systems were insufficient to meet any level of quality standards imposed by most industries. The material available for use in these printers had also seen a reduction in cost. The estimated cost for ABS in 2010 was about $60 per Kg. This is still magnitudes more expensive than current ABS prices which are around $2 per Kg in a pellet form. The estimated lifetime of printers in this scenario is also reduced as most are made from non-rated hardware. The lifetime of one of these
systems is estimated at around 5,000 hours on a per hour basis. This greatly effects the total cost of a production run as it could consume more hours that the system is built for.

The second scenario adjusts the initial cost of the additive systems, the cost of material, and the total lifetime. The cost of injection molding, as stated earlier, has not varied greatly in the past two decades. The cost of raw pellet plastic has remained stable, and the total cost to operate an injection molding device has not changed. The results are shown below.

The first part is a manifold designed for a small plane. It has a mass of 101 grams and a complexity value of 9. The overall time to 3D print is about 7.5 hours. The cooling time in the mold is about 2.5 minutes, although this is an extremely complex and large part for an additive process. The traditional process very likely could not make this part as it is far too difficult for a mold maker to design. For this scenario, we will exclude this information for the sake of the simulation.
Figure 5.3: The above graph shows the cost per batch size break-even point for the second scenario. In this graph it is roughly 90 parts before the transition to injection molding is cost-effective.
Figure 5.4: The relative costs of production for each system for the second scenario based upon the break-even point.

Based upon the results of the simulation above, the continued effectiveness of using additive methods as a replacement to injection molding are limited. In this scenario we determined a batch size of 95 had an equal cost structure per part. The result of lowering the cost of capital needed is an increase of around 90 parts. This further proves the long-term likelihood of additive processing interrupts the traditional method. One notable concern is the total time to make the additive parts. For this scenario, the total time to make the batch of components is about 700 hours. In that time, injection molding could have completed the mold and the parts two times over.
The second part for this scenario is a bracket mount inside an automobile. It has a mass of 30g and complexity value of 4. The print time is a little over 2.5 hours. The mold cool time is 6 seconds. This part was chosen to highlight the advantages of both processes as it is small, simple, and is easily made. The simulation results are below.

Figure 5.5: The above graph shows the cost per batch size break-even point for the second scenario. In this graph it is roughly 200 parts before the transition to injection molding is cost-effective.
Figure 5.6: The relative costs of production for each system for the second scenario based upon the break-even point.

The data reveals an even greater advantage of additive over traditional process. In this particular part, the advantages of zero tooling effect the bottom line such that 200 parts are the relative break-even. From this data, the largest costs of an additive process are material and depreciation. Whereas the largest cost of the injection molding is tooling. This trend will continue throughout the scenarios.

In reality, 2010 is the turning point for the feasibility of using an additive process producing to the scale of traditional processes. With continuing lower cost for machines and material, the trend moves towards the advantages of additive in respect to complexity.
5.3 Scenario 3

In 2015, the market for additive process has exploded overnight, as there are over 20 individual companies offering 3D printers of all qualities and costs in the U.S., and Europe. The market for industrial printers has begun consolidation and the companies selling those systems have seen a major drop in stock price and valuation. As the market does not have a visible leader, it is looking at who can provide a low-cost solution for high quality additive systems. In years past, Makerbot could have been considered a market leader, but after their buyout in 2014 by Stratasys, Makerbot systems have increased in price overnight while losing vital functionality. In 2015, the market would belong to a company that can bring a competitively priced system with the quality of an industrial system.

This scenario looks at the current market and the relationship between the proposed methods. The cost to purchase an additive system has been lowered further to around $5000. At that cost a system can utilize nearly all the FDM materials available. This system can also be built to the dimensional quality of high-price system as well. ABS now costs roughly $28 per Kg, and although this cost is still considerable higher than virgin material prices, the decreasing cost of plastic is advantageous in favor of an additive process.

The model for injection molding has not varied significantly. With stable plastic prices and an abundance of quality machines for application based usage the overall model will not likely vary overall.
The part selected for the third scenario was a mount for a fire-extinguisher. The part has a mass of 80 grams and complexity value of 3. The part has print time of about 5.5 hours and a mold cool time of 0.5 minutes.

Figure 5.7: The above graph shows the cost per batch size break-even point for the third scenario. In this graph it is roughly 200 parts before the transition to injection molding is cost-effective.
5.4 Scenario 4

The conclusive scenario looks at the conditions in which additive and injection molding are competitive on a cost basis. Ideally, this will happen around 2020 as the cost of material and machines lowers further. As the costs decrease, we anticipate the gradual increase of additive manufacturing caused by the near cost value of the two systems. With cost per part being nearly equal, the benefits of additive methods allow for a flexible operation. With the rapid growth of additive processes through the past several years, more materials and faster systems have arisen. Unfortunately, we did not predict a change in run time. For this scenario we look at continually lowering material pricing and
the effect this has on the overall part price, as well as the increasing lifetime of the additive machine, and the lowering cost of depreciation.

The part we’ve used for the simulation is a doorstop. Its simple part, weighing 35 grams. It has a complexity value of 3, with a very simple composure. It has print time of about 3.5 hours and a mold cooling time of about 1.5 minutes.

Figure 5.9: The above graph shows the cost per batch size break-even point for the second scenario. In this graph it is around 1000 parts before the transition to injection molding is cost-effective.
Figure 5.10: The relative costs of production for each system for the fourth scenario based upon the break-even point.
Chapter 6.

Conclusion

Based upon the results of the simulation and the decreasing costs of production utilizing additive manufacturing, it is my opinion that injection molding will eventually become outdated for any operation that requires less than 10,000 parts. I doubt that injection molding will ever completely be removed from the manufacturing world. From a time perspective, injection molding can produce 50,000 parts quicker than a large group of 3D printers. In that respect, I do not believe that additive manufacturing has the ability to completely replace injection molding. For what additive processes lacks in time efficiency, it will be made up in additional benefits. In the first chapter I highlight several of these advantages. The benefits of complexity and part consolidation allow for a sophisticated part with around the same cost structure as injection molding. As designers and engineers take advantages of additive methods, the likelihood of small scale production methods increase.

The ultimate cost between these two methods is the cost of the mold. For the injection mold, a typical price can be anywhere from $3000 to $10,000. This cost is circumvented in the additive process as there is no tooling is required. As shown in the fourth scenario above, the largest singular cost of the operation was the cost of the mold. In many cases, it was revealed that the total
References


