LOW COST ADDITIVE MANUFACTURING PRODUCTION/INTEGRATION MODELS

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PROJECT INTRODUCTION

Additive Manufacturing (AM) technology is continually making headlines in a variety of media, and showing significant trends of adoption within industries such as aerospace, biomedical, automotive and industrial tooling. These industries are known for their lower production volume and higher customization applications. Other industries such as those related consumer goods products, still rely almost exclusively for convention manufacturing techniques for production and do not consider AM at this time to be a viable production method. Such industries may employ AM for prototyping and early stage development, but not for final end use products.

Likewise, for industries more accepting of AM applications, there is often a heavier focus on industrial AM equipment and its applications for end use production, than there is consideration for lower cost AM equipment. Such equipment, costing $5000 or less per unit cost, is often overlooked as a viable application of AM in general.

This project focuses on a concept that is completely revolutionary in terms of existing manufacturing and is now only possible due to advances in AM technology, expiration of previous patents, and consumer access. Specifically, the use of lost cost AM equipment to produce end use products, omitting conventional manufacturing processes altogether, even for products that are considered general consumer goods. This project includes case studies of startup or small business companies that are interested in bypassing the conventional manufacturing model and going directly to low cost additive production. Addressing considerations of startup costs, design mentality shifts, material options, post-processing techniques, finishes, and lead time.

This project also includes research in to existing small companies, 100 employees or less, that already have moved to this model of production, evaluating their performance and some of the long term benefits of this business model. Including study of samples of these AM produced end use products in terms of user experience and manufacturing quality.

This project reveals a manufacturing opportunity of significant economic interest. Demonstrating a potential shift in the startup costs necessary for a new, small company to begin production of their idea with only a fraction of the typical investment needed. Being able to reduce prototyping and first run production costs down from tens or hundreds of thousands of dollars to merely a few thousand. Representing an opportunity for a tremendous shift in conventional business mentality, and a significant manufacturing barrier removal for inexperienced innovators. Leading to a significant influx of new products and innovations from entrepreneurs simply due to newfound production accessibility via low cost AM.

Additionally building from a previous project on low cost AM integration, this project will also include an example of a larger manufacturer utilizing low cost AM for internal tooling and maintenance part replacements. Demonstrating the potential return on investment of low cost AM integration when compared to conventional manufacturing or even higher cost AM equipment.

Overall, this project demonstrates that low cost AM technology represents a more significant manufacturing potential than many currently recognize. It not only provides means and access to successful prototyping, but also an avenue for production and a completely new manufacturing business model that has never before been practically available.

EXISTING RESEARCH

Searches were made for any existing research along the lines of this project. Many articles were found involving the concept of AM being used for production methods, even as far back as 2003. Terms such as “Next Industrial Revolution” or “Direct Digital Manufacturing” were often found. Even entries associated with the ideal framework for the use of AM in production were discovered. Others addressed the significance of it and the need for better standards, a larger variety of AM materials, improved equipment production capabilities. And there are numerous publications involving additive as a production method, typically pointing out the overarching themes of higher product complexity, low volume production, customization without added cost, etc.

But none were found with a focus of the practical advantages of using low cost AM equipment as a production model. Nor any regarding its ability to remove multiple barriers faced by small startup companies and entrepreneurs.

CASE STUDY 1: NAPIER, COSMOTOLOGY INVENTION

INTRODUCTION

After decades in the cosmetology industry as a stylist and instructor, Mr. Napier had an inspiration to create a device that could dry hair via suction and natural humidity removal as opposed to the application of significant heat to evaporate the moisture. His concept is related to a typical Psychrometric process where the wet hair is exposed to a strong airstream of lower humidity at room temperature, thus dehumidification of the hair occurs without having to introduce heat to evaporate the moisture within the hair. This device would allow professionals to achieve the majority of the desired drying results without the hair damaging effects of heat-based drying devices.

CONVENTIONAL BARRIER

Mr. Napier has had this idea since the late 1980's, but the conventional barrier was primarily the cost to develop it as well as potential cost to produce, coupled with ergonomic design. Napier spent approximately $500 to design and produce a convention prototype made of metal that was not ideally functional to the application he conceived nor very ergonomic. In theory it could work, but the shape and performance were not that suitable for practical use. Due to further costs to development and no practical guarantees that he could market the product, Napier was not willing to take the investment risk. He therefore tabled the project for many years.

AM PROCESS & SOLUTION

After learning of Napier's idea and situation, an opportunity was extended to him for his project to be used as a case study for a low cost AM solution. Initially Napier provided his one prototype and was under the impression that the AM solution would be similar in design but produced more economically. This was not to be the case, as a key advantage of AM is its ability to produce designs that were conventionally impossible.

In fact it has been found that the best approach for AM solutions within this research is to determine the desired outcome of a design, but then to completely eliminate any preconceived notions, designs, or related prototypes. Essentially remove the project inventor or owner from the design process, as they often will inhibit the ideal AM design solution due to conventional mentalities.

Typically, only well trained AM designers will be able to maximize the benefits of low cost AM production. Designers even with just a small amount of conventional manufacturing experience will often digress to conventional design mentalities and will generate part designs that are more aligned with conventional manufacturing shapes. Experience has shown, that even designers with limited experience in either AM or conventional will often deviate toward conventional features.

Therefore utilizing the true benefits of AM, the design for Mr. Napier's concept was modeled from the inside out where the internal structure was optimized for airflow but with shaped structures that would allow the client's hair to be separated and somewhat agitated in the airstream. Then the exterior shape of the part was designed for better ergonomics in terms of stylist gripping. The base of the design was then shaped to be easily attached a typical Shop-Vac sleeve to facilitate suction.

Consideration of the direction of fabrication, or printing direction, was maintained during the design process, as the overall goal was to optimize functionality and production of the device. This sometimes involves the use of asymmetrical design of holes, often referred to as inverted tear drops or triangles, resulting in the least amount of overhang potential. For this project that was not necessary as the primary holes were small enough that overhangs were not an issue. However, internal stabilizers for the interior baffles were arched to avoid overhang issues but still establish lateral stability.

The cylindrical sleeve connection of the part was selected to be the print base as that would limit curling due to residual thermal stresses within the material of choice. Likewise it has been found that vertical prints often result in the best appearance versus horizontal prints.

Multiple iterations of design were performed, with Mr. Napier reviewing each version until he felt it was suitable for market acceptance in terms of appearance and ready for functional testing.

BARRIER REMOVAL & RESULTS

Mr. Napier not only tested the design on styling mannequins, with 3 different hair qualities and textures, he also began human tests within his salon. The AM design was simply connected to a typical Shop-Vac. The results were very surprising and exciting, and in fact exceeded Napier's expectations.

One comparative test was performed for a baseline, involving a stylist hand dryer, set to high heat and medium blower fan speed, and took 30 minutes to dry wet hair that was 7 inch long. The level of dryness in this case is considered a professional's determination of "dry to the touch." The new AM product, connected to nothing more than a typical Shop-Vac, with no heat applied took only 10 minutes to dry the same hair to the same level of dryness.

Another comparative test involving a typical stylist hood dryer took 25 to 30 minutes to dry a client's hair, but the same results were achieved with Napier's AM product, again within 10 minutes and no damaging heat.

A test involving an African American woman's hair, with Napier as well as other professionals noting that such hair is often the most difficult to dry and work, comparatively took 30 to 45 minutes with a conventional stylist hair dryer to achieve what he referred to as "kind of dry." However, Napier's invention again only took approximately 10 minutes to become dry to the touch.

Napier also noted that the AM part was capable of being used as a cooling tool when dealing with the effects of a flat iron, which can heat hair to temperatures of over 400 degrees F. During his tests, his product was able to cool the hair down to below 100 degrees F in under 5 minutes. This cooling application of the tool is apparently very professionally significant as well.

FINAL COSTS

Although the project is still ongoing, Napier is in the application process for a provisional patent, and the design is currently being modified to allow for typical brush and comb attachments.

Thus far, two AM equipment units have been used to produce Napier's tool. Both are typical desktop 3D printers, one currently costs approximately $600 (Prusa I3 MK2) and the other $500 (Creality CR-10). Both are available for online purchase often with a lead time of less than 3 weeks, and arrival in a kit form for some assembly.

Current estimates show that a single machine can produce 4 units every 22 hours. Resulting in over 60 units a week when utilizing 3 low cost AM machines resulting in an approximate equipment investment of $1800. Stock material consumption would equate to 12 units per 1 kg of filament, resulting in a $1.51 per unit cost for production in PLA, possibly $2.00 per unit if produced in PETG. Note that no overhead, energy, equipment depreciation, or labor costs are factored into these estimates. Comparatively, using an online AM service instead of internally producing it himself, the costs would be $37.87 per unit, plus shipping.

For a larger weekly production quota, 4 machines could be purchased for approximately $2400 and a total of 96 parts could be produced over a 6 day span.

And although conventional manufacturing of this AM optimized design is not possible, the owner estimates that the original design produced in the late 1980's would cost $50 to $100 per unit at that time. At the target retail price point of $100 per unit, conventional production of the design is not very optimistic.

Although not factored into the expenses, the overall the project involved 15 hours of actual computer modeling design time over a 4 month period, and could be equated to $750 of consulting fees.

OUTCOMES AND CONCLUSIONS

Obviously this project has been considered a success and to say that Mr. Napier is thrilled is an understatement. As mentioned, his market research has placed his tool at a retail price of $100 per unit and he is diligently working in preparing his marketing strategy. This is an important fact to consider as experience has shown that there exists inherent problem for entrepreneurs that must split their attention between the physical production aspects of their product and the marketing of their product. It has been noted that the best scenario for this model is that the inventor focus on the marketing the product versus its manufacturing. However, since the conventional manufacturing approach typically involves much more expense, inventors have a tendency to split their attention too much. Within this production model, the AM costs were so low, and the development so smooth, that Napier was able to essentially stay focused on marketing, which will increase his likelihood of success.

What is also gratifying with this project case study, is that Mr. Napier is no longer faced with the risk of significant debt, the need to gather investors resulting in the dilution of his ownership, and the overall delays with conventional production methodology and expense. His idea can now be potentially brought to market as a short run production for less than $3000, and in less than 4 months of research and development.

FIGURES

Figure 1: Original 1980's prototype

Figure 2: AM optimized CAD design

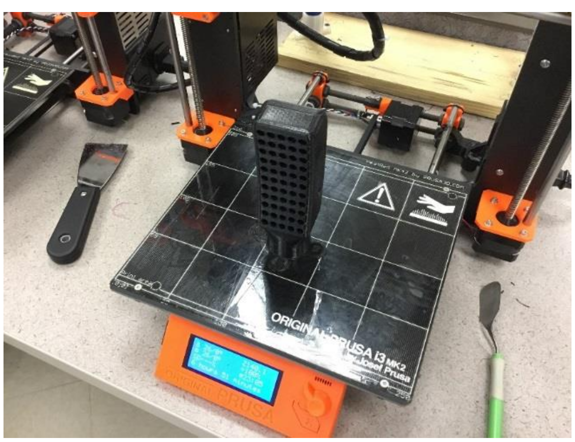


Figure 3: New design low cost AM fabricated

Figure 3: View of airflow holes

Figure 5: AM customization

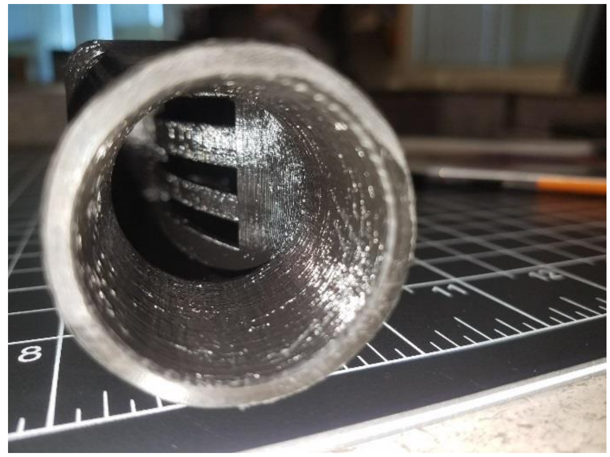


Figure 7: Interior view of baffles

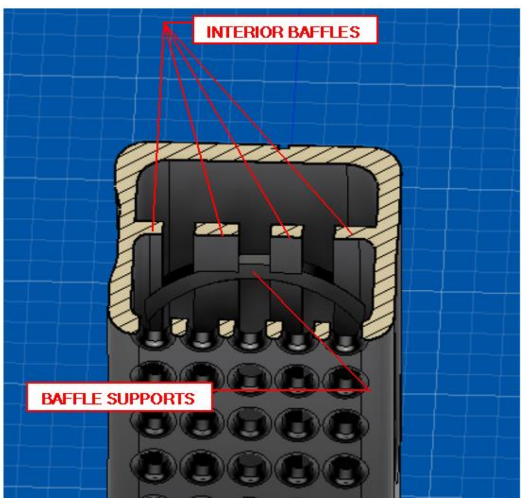


Figure 8: CAD model section view

Figure 9: Napier reviewing final design

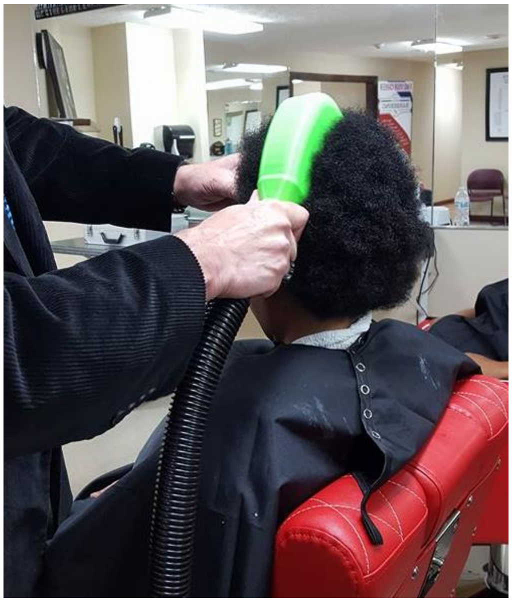


Figure 10: Testing on coarse hair

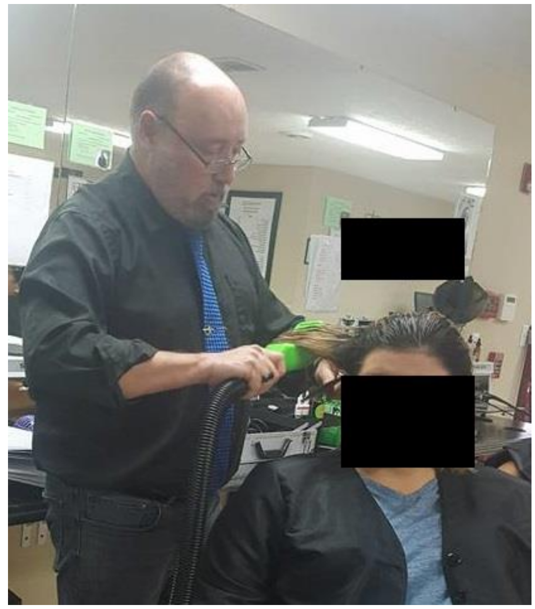


Figure 11: Testing on fine hair

CASE STUDY 2: THE FULTON'S ESSENTIAL OILS SHOWER ADAPTER

INTRODUCTION

The Fulton project represents the ideal scenario for a small business startup utilizing the benefits of low cost AM. A typical small family with no significant manufacturing experience or resources, simply has a good idea for a product in which they personally have interest. The product is one that falls within the current essential oils movement, a trend based on aromatherapy, massage, and nebulizing applications.

Regardless of the legitimate benefits of such applications or opinions, the fact is that the global essential oils market size was valued at $5.91B in 2016 (Lamb, 2017). Therefore, there are obviously products and profits to be made, and the Fultons had a product idea in which they wish to exploit.

The owner's concept was to infuse typical water flow from a modern residential shower with essential oils, allowing the user to essentially bathe in a small amount of essential oils. The design involved an adapter that could be connected between the shower head and its water supply pipe, using only threaded fittings. The user would unscrew their existing shower head, screw on the Fulton's product, and then screw their shower head back on to the other end of the Fulton's device. The adapter included a threaded wick that could be unscrewed, dipped, in the desired essential oils, screwed back into the adapter and would be ready for use. Shower water flow would enter the Fulton's adapter and a small stream would be diverted down into the wick mixing chamber and then flow back up into the main water channel to mix with the main flow and exit the adapter into the shower head and disperse as normal. The owner estimated that one dipping of the wick would last for 10 to 15 regular showers depending on the concentration and type of the essential oil desired.

CONVENTIONAL BARRIER

However, even though the Fulton's idea was novel and was apparently well received in early trade shows where the concept was presented, there are always barriers to introducing a new physical product. The most primary being the necessary capital to produce prototypes and first run versions for true market research and response. Then assuming success, even more of an investment to begin larger volume production.

Raising such capital is also involves an additional barrier, that of course being time. As this current market is considered a trend, there is a limited window of prime consumer spending. Therefore, spending the time necessary to just obtain the finances to begin prototyping and first run production, results in the risk of losing optimum consumer spending. With the additional risk of a competitor entering the market with a similar product and establishing name branding. As a comparison, an initial investment of $50,000 and 8 to 12 months of lead time would not be out of the ordinary for a small product of this nature to actually move from idea to consumer availability.

So to address this project from the perspective of conventional manufacturing, the Fultons were faced with several options to raise the necessary capital. One option was that they would have to develop a business plan and try to recruit investors or perhaps take out a business loan. Another would be to try to find partners with enough existing capital to cover the investment at the expense of the Fulton's ownership. Or they could sell their house, and risk their family's livelihood in the hopes that everything would work out in the end.

Additionally, the concept design itself also posed a conventional manufacturing barrier as the design required a specific internal fluid mixing process. Thus, conventional manufacturing would require multiple components to be produced and would drive up the production and assembly costs. This would impact the owner's desire for a sales price point of approximately $45, when overhead, marketing, and profit had to also be considered. The current prototype and sales model, manually produced by the owner involved multiple, common plumbing hardware parts and took a single individual roughly 1.5 hours to produce just one.

AM PROCESS & SOLUTION

Low cost AM prototyping and production offered an opportunity that could completely remove the barriers of cost and time, and greatly reduce the risk to the livelihood of their small family.

The technology could also remove the issues with multi-part assembly. By optimizing the concept design for AM processes, previously required multiple parts were no longer needed. The internal mixing components along with the desired exterior shapes, could be completely produced with low cost AM equipment. Likewise the exterior connection points were designed to receive typical plumbing hardware connectors such as PVC threaded adapters connected with common plumbing adhesive. Allowing for the owner to simply attach the desired plumbing adapters and then provide the desired external coating if necessary for marketing aesthetics. Although during preliminary reviews, the layering effect of low cost AM and the organic look were well received.

The target AM production method was to use several AM machines, such as the Prusa I3 MK2, approximately $800 in cost at the time of purchase, to produce the owner's adapter design in 24 to 28 hour cycles, that being two adapters per cycle, per machine, with 5 initial machines. Potentially producing nearly 275 units on average a month. Then scale up to more machines, over time as consumer demand increased, with the overall target of 900 units per month, requiring approximately 15 to 18 machines.

BARRIER REMOVAL & RESULTS

After finalizing design and witnessing a demonstration of the AM production, the owner began purchasing low cost AM equipment for short run production and market testing. As can be seen below, the overall equipment investment to the owner was less than $3000, and allowed them to explore their idea without risking their livelihood and home. The time from initial concept introduction to a design and successful AM production demonstration was less than 100 days.

Likewise with the nature of the available online marketplace environments, the intent is to use such sales platforms to get their idea on the market and gauge its response. However, at this time and due to the short term nature of this case study project, no further data has been collected in terms of market response.

It was determined that an interior coating of the AM produced part was necessary, due to layering issues of the low cost AM equipment and the water pressure of modern homes. This was addressed by pouring a 2-part resin coating called “Coat-It” through the part in post processing and allowing it to cure before connection PVC hardware attachment.

It was also determined that the owner may have selected equipment that was somewhat too “low cost.” Electing to purchase equipment that was inferior in performance to the equipment used for the actual AM production demonstration. This would likely account, but not rule out the layering issues that required internal coating.

Additionally, the original demonstration version of the product was produced in polylactic acid (PLA) thermoplastic and the owner began to attempt its production in acrylonitrile butadiene styrene (ABS) which is known for its 3D printing issues associated with residual thermal stresses. ABS is likely to curl and deform from such stresses if not fabricated in a well maintained, heated environment. An alternative material that should be considered as better production material should be polyethylene terephalate glycol (PETG) as it has better mechanical properties than PLA but with less fabrication issues than ABS.

FINAL COSTS

The owners purchased a single Prusa i3 MK2 3D printer for $700 at the time of purchase and 2 Anet A8 3D printers for $168.99 each to facilitate production.

The original concept model created by the owner cost $21 in conventional hardware parts plus the significant amount of time (1.5 hrs) to fabricate, assemble it, and finish it.

The owner established that the primary component, Figure 4, would cost $3.43 to produce via low cost AM using ABS, excluding energy costs, labor, and overhead. The wick component and typical PVC plumbing hardware adapters for insertion and connections resulted in an additional $5.50. The material cost for the Coat-It application was $2.14 per part for a total production cost of $20.43. Assembly time, which is estimated at 15 minutes per part for full assembly and packaging, excluding curing time of the Coat-It application, results in an estimated labor cost of $5 per part. The owner’s targeted retail price point is $45 per product plus shipping, allowing for an approximate 44% profit margin before overhead costs.

OUTCOMES AND CONCLUSIONS

As mentioned, little market response data is available at this time, however the project tentatively demonstrates the initial viability of low cost AM being an initial prototyping and production model for startup companies and entrepreneurs with little investment capital options.

It also brings to light a weakness in this start up and entrepreneurship model due to lack of technical expertise and marketing savvy. As AM production, even at the low cost equipment level, still requires significant design and technology expertise to facilitate production. This project as well as others have shown that conventional production mindsets are difficult to overcome even for those with little or no manufacturing experience, and AM optimization must be applied for production to be successful.

Therefore, a startup business desiring to use the benefits of AM will likely have to retain the services of an AM consultant or technician to gain traction, which will likely increase the initial investment costs by $1000 to $2000.

Another weakness regarding the potential success of this type of startup production model is the significant need for marketing work. This project has shown that a consumer product based startup company can be initialized with much less investment than conventional manufacturing would require by utilizing AM, but it does not address the issue of sales. Especially when considering the potential online marketplace opportunities available for startups. If such startups are not experienced or skilled in taking advantage of such marketing opportunities that these platforms offer, then the reduced time to market that AM offers will be negated. Low cost AM manufacturing models for new products likely need to incorporate online marketplace skills and manipulation to be successful.

Data is still being collected at this time, but thus far, the Fulton's design has been optimized for AM scaling production and is in testing for a total cost less than $3,000. It is also possible that owners may soon consider transitioning to using stereolithography (SLA) 3D printers versus FFF format as such printers are also now considered low cost, and result in a higher precision fabrication. The drawback is that SLA more expensive per unit, typically slower, and higher in material costs, but the speeds and expenses are improving, and likely to be a viable option very soon.

Ideally, this project represents what is truly possible with low cost AM production, that being the ability to remove the majority of the previous barriers that inhibited so many entrepreneurs from entering the market. However, it is clear that AM expertise and guidance is crucial to any type of success over a reasonable period of time. Simply stated, a small business startup based on new consumer products is not likely to succeed quickly with this production model without engaging the services of an experience AM technician.

FIGURES

Figure 1: Owner's conventional product, $21 of hardware and 1.5 hrs to manually fabricate and assemble

Figure 2: Owner's conventional product

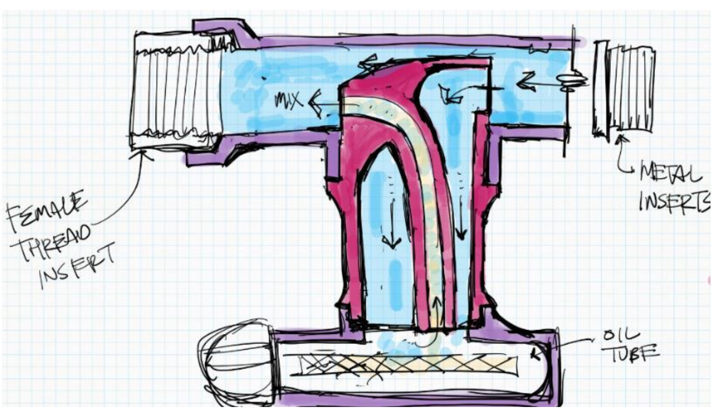


Figure 3: Conceptual sketch for single part production optimized for AM

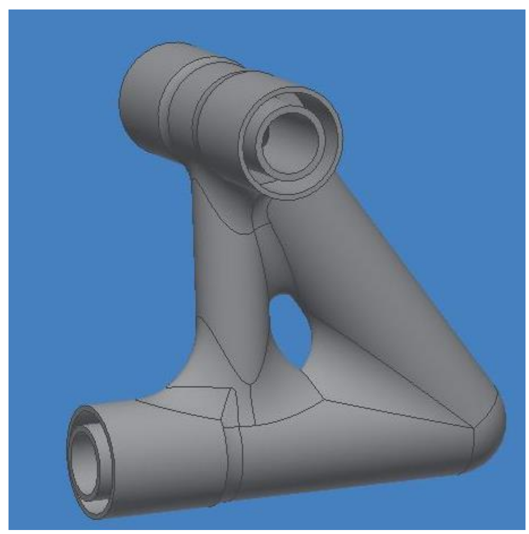


Figure 4: CAD model of new design

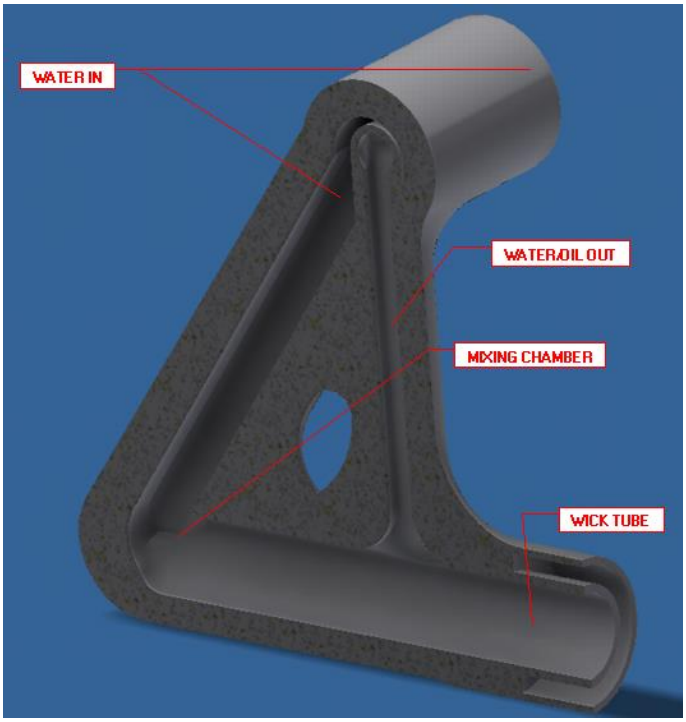


Figure 5: Section view of AM version showing internal features

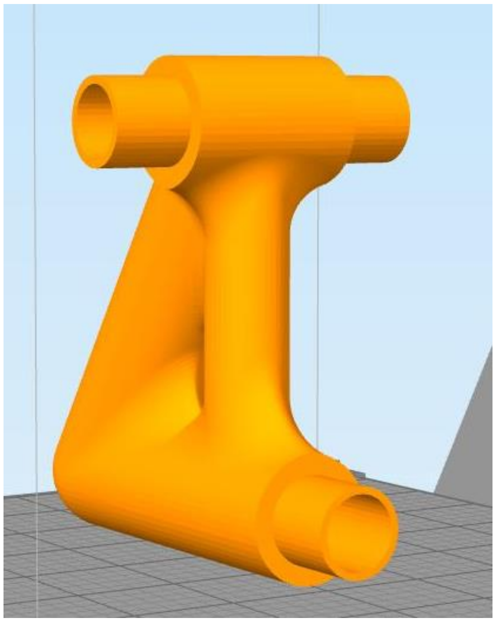


Figure 6: New design on AM production slicing software

Figure 7: Low cost AM machine used for demonstration production

Figure 8: AM produced final part, with silver finish coating

Figure 9: Example productions, half-versions were produced for visualization and marketing

Figure 10: Family inspection

Figure 11: Owner’s review of AM versions

CASE STUDY 3: MCE DIGITAL ARMORY, FULL AM PRODUCTION

INTRODUCTION

MCE Digital Armory (MCE) is a Colorado based company that specializes in the custom design and production of weapons accessories and other hardware. This company represents an existing business model that effectively uses low cost AM production over conventional manufacturing. MCE currently uses 10 low cost fused filament fabrication (FFF) machines as a 3D printer farm, a common term for an AM production platform, for their on-demand end use manufacturing of their products or components of their products. MCE also uses their printer farm to make consumer products unrelated to the weapons industry, such as seasonal lawn care products, and part components for some dental tools.

As a small production company, their primary sales platforms are Amazon.com, Ebay.com, and through their own webstores https://mce-digital-armory.myshopify.com/, providing them access to an international market. MCE states that 99% of their sales occurs outside of their own physical region in Colorado. And as a small company, their unique production methods gives them extreme flexibility and customization opportunities without the excessive overhead which is especially crucial to their success.

CONVENTIONAL BARRIER

Barriers for MCE in their startup included the significant cost of producing any products. Conventional tooling for any end use component is almost always a sunk cost of thousands of dollars minimum, and as a small company, the barrier of cost is always significant.

In MCE's case, the additional barrier of product replication by competitors using conventional manufacturing is an issue. If MCE could do it conventionally, so could any other competitor. Thus, unless MCE was willing to significantly invest in intellectual property (IP) protection and related legal services to enforce it, plus the costs of conventional manufacturing equipment, they were unlikely to enter the consumer market with their products.

AM PROCESS & SOLUTION

MCE initially began experimenting with several low cost additive machines, specifically several Makerbot Replicator 2 units, a common 3D printer that is optimized for a polylactide thermoplastic (PLA) fabrication. This provided an initial start for the company however, it was determined that general PLA was simply not going to function well as a product material. PLA does not have a very high resistance to thermal deformation and their initial products, often being black in color, would deform when left in vehicles in more southern climates.

However, this initial use of low cost AM equipment allowed MCE to model their business around a flexible manufacturing profile, in that equipment costs did not have to be isolated to simply one product. The equipment could instead be pivoted to produce a variety of products, with no down time or retooling, merely a change out of stock material when necessary, also referred to as filament for most FFF equipment.

MCE then progressed to purchasing another AM unit, that was slightly more expensive but was capable of utilizing more appropriate thermoplastics, and was known to have a quality track record, the Zortrax M200 (3Dhubs, 2018). MCE began testing the unit's capabilities with different filaments and their target products and became very satisfied with its performance and finish quality. MCE now uses 10 Zortrax M200 units, utilizing the device's capabilities of achieving 90 micron fabrication resolution with the manufacturer's proprietary acrylonitrile butadiene styrene (ABS) filaments, called Z-ABS, to produce their various product lines.

Many of MCE's AM produced parts do require some post processing work, and are not 100% additively produced. Conventional manufacturing processes are still employed. Final holes will be drilled out conventionally, as the low cost AM devices are typically not capable of producing circular holes within a high geometric tolerance. Instead the hole will typically be computer modeled to be slightly smaller allowing for easy post fabrication drilling. Additionally, some heat treating will occur to improve surface quality finish. Such work is typically provided by a common heat gun.

As previously mentioned, a primary risk for businesses when introducing new conventionally produced, products is that competitors may copy their product and try to flood the market with lower cost "knock-off" versions. Meaning that the original innovator will likely not recoup their initial investment to develop and produce their product within a reasonable amount of time, or at all. Generally to stop this from occurring, businesses will pay anywhere from $8,000 to $15,000 to file for a patent on their innovation. However, this approach is also risky not only due to significant sunk costs, but a patent is only viable if it is enforced, thus requiring the business to retain an attorney to prosecute the alleged infringer, which will also result in significant sunk costs. Likewise some innovations and products are simply not patentable, meaning that the innovator has virtually no protection from conventionally mass produced copies of their product. Therefore, the innovator is less likely to invest the time and resources to even introduce it.

However, AM technology and expertise offers a potential solution to these problems and risks. To address the barrier of IP protection, a unique solution that is made practical by AM, and employed by MCE on several of their products, is a form of IP protection by AM design optimization. In certain cases they will design their products such that AM production is the only method possible in which to cost effectively reproduce them, thus making conventional manufacturing replication of the product impossible or at least very difficult. Such as an internal feature or complex shape that is crucial to the functionality of the product. This helps protect their work from a variety of investment risks by adding an extra layer of property protection. Thus the ability for a competitor to easily take a new product and mass produce it by conventional manufacturing means is nearly eliminated, and the original innovator now has a layer of protection over their intellectual property.

Granted, competitors with AM expertise and capacity, could likely replicate the original innovator's product in its entirety, but this is currently much less likely. Additive equipment and production expertise is not as common place, and doesn't lend itself well to the conventional mass production model that the "knock-off" industry thrives on.

BARRIER REMOVAL & RESULTS

As the barriers of investment costs for production and IP protection were addressed by AM, MCE now operates on a very efficient business model. Balancing between marketing work, production, and research and development (R&D), MCE has found an excellent operating niche.

Inventory and supply chain management costs are fairly negligible, as the print-on-demand model eliminates the need for an inventory, and the supply chain is limited to only the very basic need for stock material and general hardware. MCE maintains a digital library of over 200 parts on each printer using SD cards and can switch parts on an as-needed basis from job to job. Noting that no essential retooling or downtime is necessary for transition from one product to the next using the exact same 3D printer. And MCE states that their low cost AM system is in operation for 24/7/365.

Their production cycles are obviously based on consumer demand, some of which are seasonal but MCE does employ a production cycle methodology. For example during normal business hours, the company will run printing production cycles of nearly 30 minutes to 7 hours. For unmanned, overnight cycles, MCE will generally run production at 9 to 14 hour cycles. Overall, MCE reports that they produce 25,000 to 40,000 parts or products per year using their 10 unit AM system, with part mass values ranging from 1.5 grams to 90 grams.

FINAL COSTS

Initially MCE purchased 3 Makerbot Replicator 2 units, for a total of approximately $6000, but has since discontinued their work with those devices because of their lack of material versatility and operational performance. Their expense for the 10 Zortrax units approximately totaled a one-time investment of $25,000. The general retail cost of filament for production of the majority of MCE's products is 5 cents per gram.

Although a privately owned and operated company, MCE reported that their current annual earnings exceed $100,000. Although operating costs and overhead are not addressed in this study, such revenue is pretty significant for a small business operation with only a $31,000 initial manufacturing equipment investment. Paying for itself many times over in just a short number of years.

OUTCOMES AND CONCLUSIONS

MCE's approach to weapons accessory manufacturing as well as other products is one that warrants significant consideration. Their ability to pivot their manufacturing model based on customer demand, seasonal markets, and new innovations, gives them a significant edge in terms of a small business. Additionally the low cost nature and scalability of their manufacturing system is ideal, allowing them to scale up production by simply ordering more 3D printers as market sales justifies it. Thus they would not incur much of a financial risk or overextend themselves in terms of credit.

MCE also employed a very impressive marketing strategy associated with their flexible AM production process. Although beyond the scope of this project, their innovative methods for achieving market impact and utilization of online marketplaces as well as Youtube.com reviewer popularity profiles, deserves further consideration.

FIGURES

Figure 1: Zortrax M200

Figure 2: MCE specialty product example

Figure 3: Seasonal lawn and garden bracket AM product

Figure 5: MCE AM product: ammunition holder for picatinny rail application

Figure 6: MCE AM product: custom belt shotgun shell holder

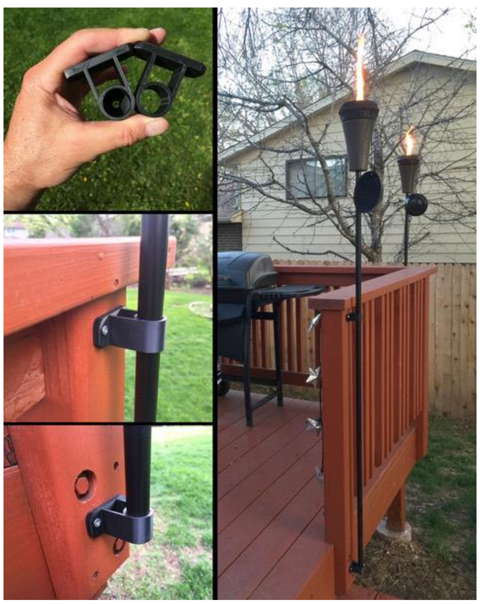


Figure 4: Seasonal lawn and garden bracket product, alternate application

Figure 7: Detail view of lawn and garden bracket product

Figure 9: Alternate tactical magazine low cost AM product, enlarged for review of finish quality


Figure 10: Magnetic tool holder, low cost AM produced internal component


Figure 8: Tactical magazine low cost AM product

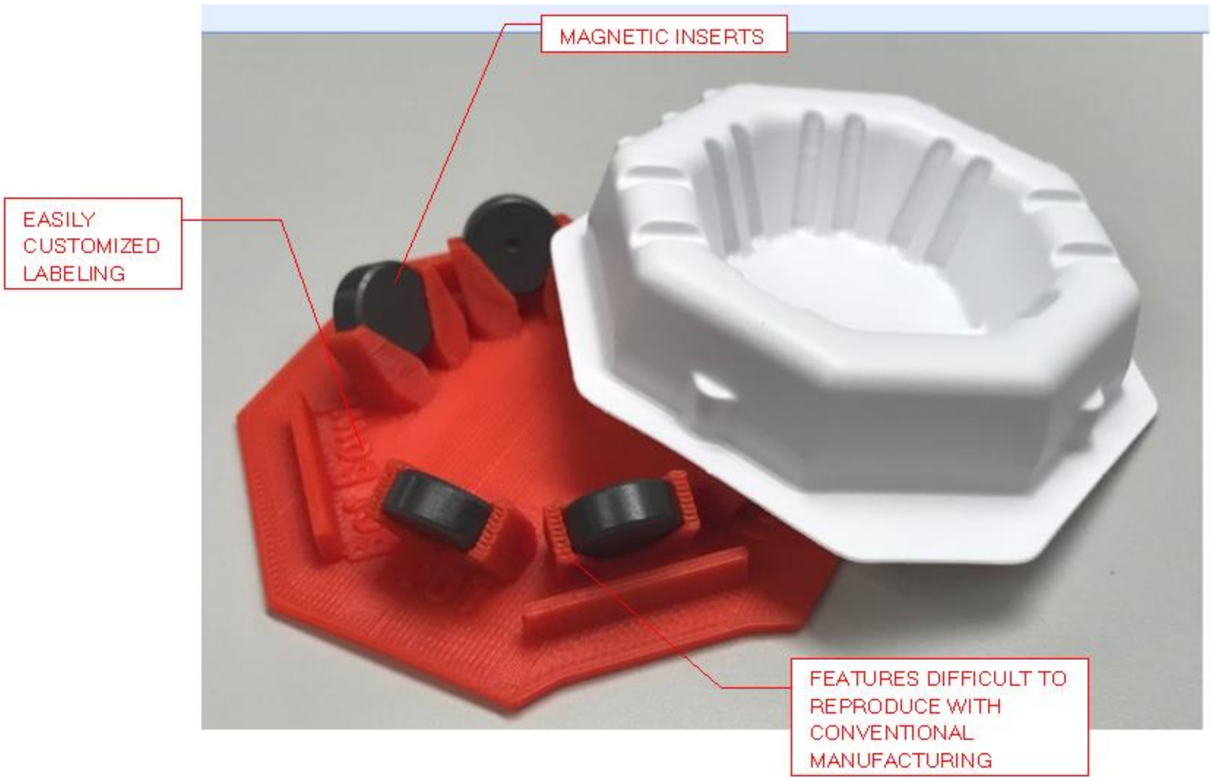


Figure 11: Assembly of product from Figure 10, enlarged view of low cost AM component. Utilizing feature design to protect against ease of conventional manufacturing reproduction, and allowing for ease of part labeling

CASE STUDY 4: AMERICAN WOODMARK CORP. AM INTEGRATION

INTRODUCTION

American Woodmark Corporation (AWC) specializes in a variety of mass production wood cabinetry and furnishings worldwide and maintains 9 manufacturing facilities nationwide. Over the past 4 years, AWC's revenue sales have grown significantly, and posted over one billion in sales in 2017 (Amigobulls.com, 2017). And although markets and accent style trends will always change, AWC is at heart a manufacturer and thereby highly focused on optimization of their manufacturing process and always on the lookout for new ideas.

One idea specifically involved a unique stage of their manufacturing process involving cabinet doors, at the AWC plant located in Monticello, KY. The process involved the application of a specific adhesive to several components for assembly. The adhesive process consisted of the manual use of an adhesive bottle being squeezed, a bead of adhesive applied, and then brushed by hand for coverage. As the process was rudimentary in nature, and continually had varying results requiring addition post processing work and cleanup, it was seen as an ideal opportunity for improvement.

Therefore, a preliminary concept was introduced utilizing a design for a unique adapter plus a mechanical process that would remove the need for the manual squeezing. Potentially reducing excess adhesive being applied, reduce application time, reduce post processing work and cleanup, and reduce worker fatigue.

Although the new adapter design and mechanical process are proprietary and thus will not be specifically detailed or shown in this document, the overall application was an ideal example for low cost AM integration.

CONVENTIONAL BARRIER

Although the mechanical process was fairly straight forward, the required new adapter design had to be internally complex to perform correctly. However, what was soon determined was that the adapter design simply could not be produced using conventional manufacturing methods, such as CNC or even plastic injection molding due to that internal complexity. Alternatives that could actually be produced using conventional manufacturing were considered, however, such alternatives were not close enough to the needed design to be effective, including internal design issues and physical external profile shapes. Additionally, the conventional alternatives came with an expense of $1000 per adapter. Therefore, the project remained at a standstill due to the costs and limitations of conventional manufacturing.

AM PROCESS & SOLUTION

After some time, the idea of using low cost, desktop AM equipment to potentially produce the adapter was introduced. Since AM technology is ideal for internally complex designs, the adapter design was a perfect candidate for consideration. Therefore, AWC began purchasing and utilizing low cost AM equipment as well as experimenting with the variety of materials that such equipment can employ. The adapter design was slightly modified both internally and externally for best AM and overall functionality performance.

BARRIER REMOVAL & RESULTS

By using low cost AM, AWC was able to produce 27 different prototype adapter designs for testing within 30 days. The relative production cost per AM adapter was $4 per adapter.

FINAL COSTS

Although several AM units were purchased, the final one used for adapter production was a Lulzbot Taz6, with a purchase expense of approximately $2500. Another unit that was purchased was a Prusa i3 MK2, for approximately $800 at the time of purchase, but was only used in the testing phase, and is being used for other AM applications within the AWC site, such as the production of jigs and fixtures. The AM stock material was PETG, and currently costs less than $30 per kg, with shipping included.

AWC estimates that a total of $480 has been spent in material and machine time to produce both the prototypes and all the final working adapters now used in production.

Comparatively, assuming some form of a conventional manufacturing produced adapter been possible, AWC estimates that the expense would have been over $120,000 to reach the same operational state. With an additional $500 per replacement adapter as needed, which would also involve shipping costs and be subject to lead times. The AM versions, which are digitally inventoried within AWC's system, and printed on demand, can be produced in under 6 hours, and for less than $5, with no labor or post processing required.

OUTCOMES AND CONCLUSIONS

The new process involving the low cost AM produced adapter and the mechanical process, referred to as "The Glue Cat," has reduced the cycle time of this specific adhesive process down from 13 seconds to 2 seconds in time studies.

The employee moral as part of this process work has also greatly improved as The Glue Cat system has removed the significant forearm fatigue that such workers were experiencing. One supervisor commented on how much better their subordinates feel at the end of a shift, due to not being exhausted by having to maintain "Popeye the Sailor-like forearms" for their station tasks of squeezing adhesive bottles.

Additionally, because The Glue CAT system reduces excess waste, and normalizes the size and application of the adhesive. The post processing/repair primarily performed by sanding, has been reduced by 1100 occurrences per month, or a reduction of 52 occurrences per day.

Overall, AWC estimates that because of this system, made possible by low cost AM equipment integration, AWC Monticello, is saving at least $160,000 per year. A very impressive accomplishment, considering that the total one-time AM equipment investment was less $5000.

The project was deemed a very significant success by AWC leadership, and the Monticello plant has been sharing their results and expertise with their sister plants throughout the AWC system for not only duplication but also for expansion into other opportunities. Currently, 4 of the 9 AWC plants now have some form of low cost AM equipment available. As positive data such as this is shared, and the return on investments are realized, that ratio is likely to grow quite quickly.

An additional outcome of this project, and as previously mentioned, AWC Monticello uses their AM equipment for other projects. Including a replacement for a conventional part for a sanding machine that continually wore out at average rate of 30-40 units per year, costing roughly $200 per part to replace. The cylindrical part replacement was not only printed using the same AM equipment, but also the design was optimized for better performance within the sanding equipment prior to 3D printing. As a result, what was previously a costly unit to replace, could then be 3D printed for $11.50. Additionally, the material used in the 3D printing process resulted in not having to need any further replacements following the first installation. Overall resulting in an additional $6000 savings per year by low cost AM integration. Images of the sanding part, AM replacement version can be seen below.

Both projects clearly demonstrate the impact and incredible return on investment potential for low cost AM integration even when just considering maintenance and operations improvements. Although AWC is not likely to begin using AM for production of its actual consumer products, such as wood cabinetry and doors in the near future. It is likely that they will be looking for additional applications for additive and will be watching to see what they might be able to one day produce for consumers using the technology.

FIGURES

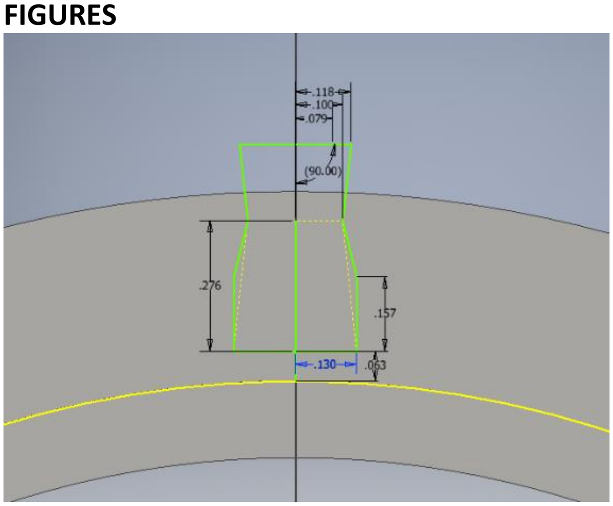


Figure 1: Profile of CAD model extrusion of sanding machine replacement part

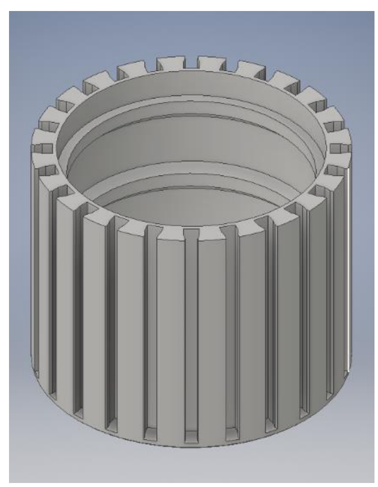
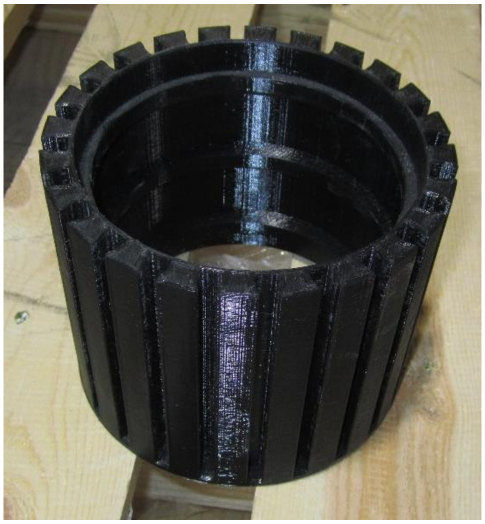


Figure 2: CAD isometric view of sanding machine replacement part



Figures 3 and 4: Final low cost AM produced sanding machine replacement part

CASE STUDY 5: PRUSA RESEARCH, VOLUME LOW COST AM PRODUCTION

INTRODUCTION

Prusa Research S.R.O. is a manufacturing company located in the Czech Republic that produces low cost desktop 3D printers and sells them internationally via their webstore. They do not use resellers and do not sell their products through online marketplaces such as Amazon.com. Their products however are one of the most internationally popular desktop printers on the market. In 2016 their 3D printer was the most used printer in the world (Jackson, 2018) and has won multiple awards from publishers related to additive manufacturing several years in a row (Prusa, 2018). Also when researching publications for this project, it was noted how often the Prusa I3 MK2 was identified in research publications as being used for some experiment or demonstration, further confirming its popularity.

The company is known for their innovations and rapid response to the customer feedback in terms of product performance and modifications. The company also facilitates 24/7 customer support, live chat, forums, and user groups. The printers currently range from $599 to $749 in kit form, and $899 to $999 for fully assembled units.

Essentially the company is popular, the products are popular, and their 3D printer kits function well. But, this company is included within this project for a very specific reason. That being the fact that Prusa produces a large percentage of the end use product parts by 3D printing them with their own 3D printer kits. Parts that would be considered critical to the performance of the overall product itself, such as the forward interface housing, the extruder mounts, the motor mounts, the z-axis rod mounts, etc. Not simply parts that might conceal a wire or cover a screw, but the parts that control the inherent success of a device that is likely the most popular product within its market worldwide. Essentially meaning that 3D printers are being used to replicate some of their own critical parts. And during its high demand times, this company ships over 3000 printers a month either in kit form or fully assembled form. Considering there are over 25 AM produced parts included in each printer that is a production volume of 75,000 end use parts per month, being produced by very low cost AM equipment.

Also of considerable significance is that the owner Josef Prusa began his product production initially using his own creations. Meaning that he continually scaled up his production platform of 3D printers as the consumer demand grew. In a recent article Prusa stated that they were again scaling from using 300 printers to 500 printers to increase their manufacturing capability.

CONVENTIONAL BARRIER & ADDITIVE SOLUTION

When considering the volume of parts being produced, the question was raised as to why the owner does not switch to conventional manufacturing techniques such as plastic injection molding. The owner responded with several reasons as to why he avoids using such a conventional method. One was that AM offers more part complexity than conventional can provide. Another reason was because of optimized workflow. Meaning that no retooling is necessary for a part change, improvement, or modification (3dprintingmedia.network, 2018).

Only the digital version of the file must be changed, thus allowing one 3D printer to serve as a versatile production platform for old, new, or existing parts with no retooling required.

This type of manufacturing flexibility at respectable volume is simply impossible with conventional equipment. Only additive offers an opportunity to easily pivot the equipment to produce a batch of one part group one cycle and then a batch of completely different parts the next cycle.

This capability also has an unqiue customer experience as well. As the company maintains a close relationshiop with its customer base through its online presence and mentality, customer feedback offers a great method for R&D. For example the customers will often make suggestions and post the digital files for printer component improvements for both the company and other customers to use for replication and upgrading of the printers. The company can also rapidly implement these improvements, even overnight if it is desired. It is doubtful that the company does actually respond that quickly as they would likely need to test these improvements first, but after such testing could immediately update everything. And since the production system is essentially the same as what the customers have in their possession, existing customers can replicate the same physical update as well for their own equipment. This is one of the reasons that the company has such a strong and supportive customer base, as the company and customer can continually work together, almost in a symbiotic relationship.

This also allows for a concept referred to as operating in "Constant Beta." Beta Testing is the term often associated with software development, describing the phase of product evaluation by a limited number of customers or testers. Such testers will provide feedback and the producer will iterate their product until the producer believes the product is ready for full market production/release. At that time, speaking in terms of conventional manufacturing, the product becomes fixed as tooling and equipment for production is finalized. The product is then mass produced and the company begins moving toward the next iteration of its product and the cycle repeats. However, with additive, a producer can existing in a constant Beta Testing mode, where every consumer is a Beta Tester and as issues or improvements are made the entire line of products can be updated immediately. No inventory loss, no need to provide a fire sale to move previous versions of a product, and no sunk costs associated with transitions. A company producing in Constant Beta phase is always improving their product and not waiting on the next iteration for a big marketing push and release, it is always getting better. Giving that company a severe advantage over their competitors as they could be iterating their product in periods of months, possibly even weeks, instead of periods of years. Continually giving the customer the best version of a product, and being able to outpace bad reviews and experiences. Allowing the company to establish more than just name branding effect of new type of product, but establishing a new type of branding recognition. One that is more associated with the continual innovation and benefits to the customer from a specific product that is always evolving while in production.

It is important to note that Prusa Research products are only partially produced by AM, and also rely on conventional manufacturing and a conventional supply chain. The 3D printers they produce still have conventional stepper motors, electronics, power supplies, threaded rods, shafts, etc. They also use a laser cut support frame as central mount and support point for the majority of the system. So they are still limited in the amount of improvements they can make to their product “on the fly” so to speak. They can only potentially improve what is made with their AM system in a rapid fashion. With the exception of the laser cut frame as that could be moderately adjusted fairly easily while maintaining production. The company also noted that final holes in AM produced parts were conventionally drilled out. This is fairly common practice as low cost AM equipment does not always give the best results in terms of holes depending on part orientation. Therefore the hole will be designed slightly smaller and allow the drilling process to provide the final size and finish.

Prusa also supports it customer base by providing the digital files to reproduce the same parts that it produces for the kit. So that their customers can fabricate replacement parts as needed. Using these files, it was estimated that it would take approximately 36 total hours to fabricate all of the same AM parts for the kit. However, due to size and batch arrangement, this would not be a continuous run, rather to produce the parts it would require 3 separate runs for a total of 36 hour runtime. Or 3 printers running simultaneously for a combined run time of 36 hours. The combined parts would require 420 grams of material total to be produced, roughly equating to around $12 dollars at current market pricing for PETG filament, though it is likely that Prusa pays much less for its stock filament material than the average consumer does.

It is also important to note that Prusa Research is not the only company using AM for product mass production. A competitor, although in a higher price market range, Lulzbot which is owned by Aleph Objects, Inc. also uses its own printers to produce its end use product parts on a volume scale. Stating that they now produce over 500,000 parts per year using 140 low cost AM machines operating 100 hours per week (Lulzbot, 2018).

Also, Adidas, a much larger and recognizable company, is currently integrating, testing, and scaling to begin AM production of a new line of midsoles and shoes. Stating that they will be producing over a 100,000 AM fabricated midsoles in 2018 (Booton, 2018).

And there are others, but many are not as aggressive in this approach. In fact in a recent survey many companies acknowledged their interest and preparation for AM, but 67% responded that they wished to be ready but will wait and see what their competitors do (Dulchinos, 2018). Demonstrating that over half of respondents wish to be first followers. And as more results and publications become mainstream it is very likely that there will be a very fast transition towards this type of business production model, and allowing for a Constant Beta approach to many other products.

AM PRODUCTION EVALUATION

As the goal of this project was to evaluate such an AM production model, it was necessary to physically evaluate the products. Therefore, a total of 5 sample 3D printers were purchased from Prusa Research, specifically the Prusa I3 MK2 models. Of the group, 4 were in kit form and one was preassembled. The goal was to evaluate how well the kits went together and also to evaluate specific parts for dimensional, repetitive accuracy.

KIT ASSEMBLY

The kit assembly evaluation involved 3 of the original 4 kit purchases. The purchasing of 2 of the kits were separated by a 60 day time span to establish a variation of time regarding production. All three kits were assembled separately at different times, but in the same environment and by the same technician.

While assembling the kits it was found that all of the printed parts used to assemble these machines fit perfectly. Implying that AM produced parts had high enough accuracy and dimensional stability to ensure the intended production purpose. Making for a well-built machine with increased reliability. The connection points and mating interactions were very tight when assembling the kits, which was a positive feature.

The assembly steps for these machines was exactly the same with no difference in any process. It took approximately 4 hours to assemble each machine and each came together without fault. However, it is to be noted that the technician that performed the assembly was experienced in such kit assembly, so it is likely that a novice would not have a 4 hour turnaround on assembly.

Each printed part appeared to be produced in typical FFF thermoplastic. Possibly acrylonitrile butadiene styrene (ABS) or it has been noted that Prusa Research may have switched to using polyethylene terepthalate glycol (PETG) for their AM production parts. PETG has very desirable low cost AM production qualities over ABS and has dropped significantly in costs over the last 12 months. But both ABS and PETG are used in conventional thermoplastic production and have acceptable thermal resistance and durability characteristics for the application of these parts. PETG typically has less actual AM fabrication issues associated with residual thermal stress.

Also, the manual and provided access to video assembly tutorials made the process quite streamlined and smooth. And after the assembly, the kits were activated and run successfully on the first calibration run.

Overall the assembly evaluation was a positive success, as was the 4th kit, but it was assembled at a different time and not a part of the evaluation process. The evaluation demonstrated that not only does Prusa Research produce a good, well-conceived product, but the fact that so many of the components are low cost AM produced, added to the significance of their manufacturing approach.

PART EVALUATION

The parts tested within this study were from the original kit orders as previously mentioned all produced by the company's low cost AM system.

The parts were visually inspected for significant flaws of which none were noted. Specific parts and measurements were selected for evaluation based on their significance to the functionality of the device, such as the Z-axis motor mounts. The concept was that if these critical parts varied much in repetitive dimensional stability, the assembled 3D printer kit would print parts that were not as smooth, or worse not function at all. This would of course greatly affect their consumer response and popularity based on Prusa's AM production system. Also included were parts associated with the extruder and cooling fan mounting system and the mounts used to hold the z-axis vertical screw and alignment shaft. These mounts in particular would create significant functionality issues of the device if dimensional part-to-part stability was not maintained. The main instrument used measurement testing was a digital caliper with the SI system used for measurement.

The following figures visually demonstrate a measurement example, identify the parts selected for evaluation, the actual measurements taken relative to the parts, the collected measurements, and calculations.


Figure 1


Figure 2


Figure 3

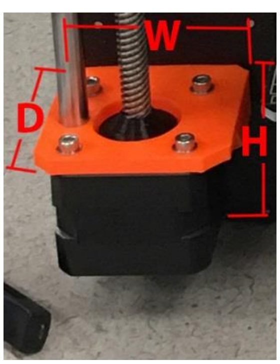


Figure 4: Part A

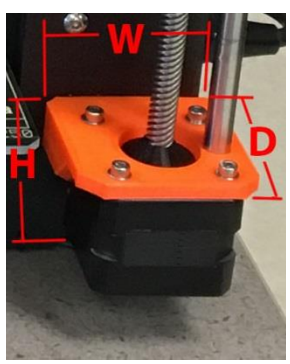


Figure 5: Part B

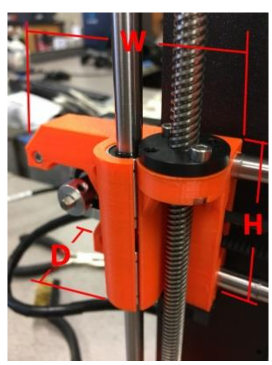


Figure 6: Part C

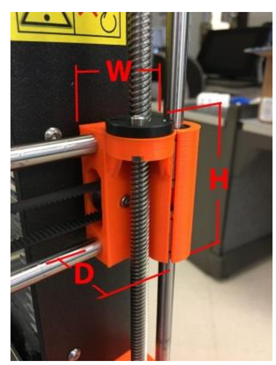


Figure 7: Part D

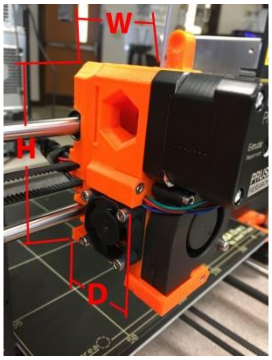


Figure 8: Part E

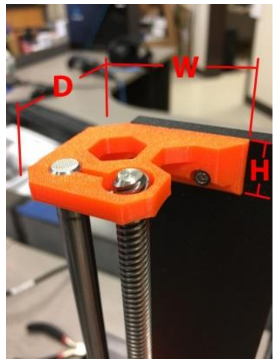


Figure 9: Part F

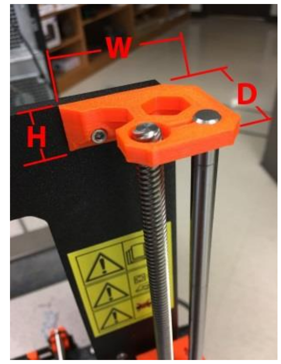


Figure 10: Part G

Results	Machine Number 1			Machine Number 2			Machine Number 3			Range			Max. Range
Part Number	H	W	D	H	W	D	H	W	D	H	W	D	H,W,D
Part A	38.01	52.33	50.06	37.97	52.30	50.12	37.99	52.35	50.11	0.04	0.05	0.06	0.06
Part B	37.92	52.15	50.09	38.04	52.11	50.03	38.10	52.20	50.00	0.18	0.09	0.09	0.18
Part C	58.01	81.25	34.16	57.98	81.21	34.19	58.08	81.26	34.09	0.10	0.05	0.10	0.10
Part D	58.03	38.97	33.97	57.96	39.05	33.96	57.97	38.99	33.99	0.07	0.08	0.03	0.08
Part E	88.59	51.78	41.97	88.60	51.96	41.96	88.65	51.97	42.01	0.06	0.19	0.05	0.19
Part F	16.27	45.14	38.14	16.25	45.24	38.08	16.19	45.22	38.16	0.08	0.10	0.08	0.10
Part G	16.23	45.15	38.00	16.20	45.19	38.09	16.23	45.20	38.10	0.03	0.05	0.10	0.10

All measurements are mm	Average for all 3 machines			MINIMUM - MAXIMUM dimensions for all 3 machines			Standard Deviation		
	H	W	D	H	W	D	H	W	D
Part A	37.99	52.33	50.10	37.97	52.30	50.06	0.020	0.025	0.032
				38.01	52.35	50.12			
Part B	38.02	52.15	50.04	37.92	52.11	50.00	0.092	0.045	0.046
				38.10	52.20	50.09			
Part C	58.02	81.24	34.15	57.98	81.21	34.09	0.051	0.026	0.051
				58.08	81.26	34.19			
Part D	57.99	39.00	33.97	57.96	38.97	33.96	0.038	0.042	0.015
				58.03	39.05	33.99			
Part E	88.61	51.90	41.98	88.59	51.78	41.96	0.032	0.107	0.026
				88.65	51.97	42.01			
Part F	16.24	45.20	38.13	16.19	45.14	38.08	0.042	0.053	0.042
				16.27	45.24	38.16			
Part G	16.22	45.18	38.06	16.20	45.15	38.00	0.017	0.026	0.055
				16.23	45.20	38.10			

Figure 11: Measurement results

As can be seen by the results, the sequential AM produced parts faired very well in terms of dimensional stability from one kit to the next. For example, the height (H) value range for Part A across three samples was 0.04mm or 40 microns. The width (W) of Part F was 50 microns. However in the case of width for Part E the range was 190 microns, a significant variation and also the highest standard deviation value, but that particular part is actually an assembly of AM produced parts, not a single part, therefore that value is somewhat misleading. Part B though was a single printed part and did have a range of 180 microns, well above all the other single printed parts, which did not exceed over 100 microns in range.

For all the parts other than E, the standard deviation still falls below 0.095 a very impressive result again when considering these parts are all produced on a low cost AM machine. In fact, although it is unknown what Prusa's actual profit margins are, assuming total production cost of a kit is 60% of the retail sales value, that equates to a machine that costs Prusa $360 to build and installed as production equipment.

Hole locations on specific parts were also evaluated. Below are the z-axis motor mounts that require fairly high accuracy and repetitive production stability regarding the screw holes that attached the motor to the printer. If these measurements deviated significantly, it would impact the functionality of the machine. The following figures identify the parts, holes, and measurements evaluated.

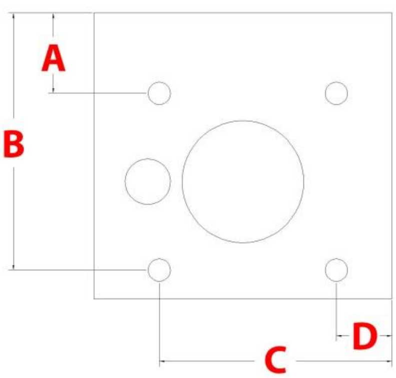


Figure 12: Left Part #A - Top View

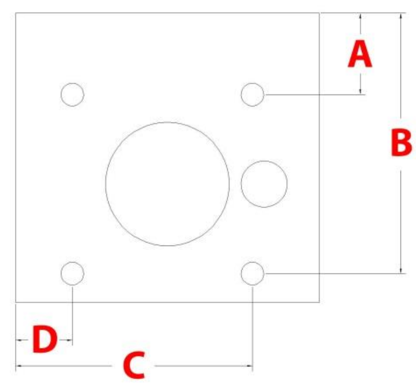


Figure 13:Right Part #B - Top View

mm	Machine Number 1				Machine Number 2				Machine Number 3				Range			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Part A	14.00	44.98	40.79	9.74	13.89	45.07	40.79	9.71	14.12	45.01	40.77	9.70	0.23	0.09	0.02	0.04
Part B	13.95	45.30	40.87	9.69	14.00	45.20	40.77	9.77	14.12	45.10	40.86	9.77	0.17	0.20	0.10	0.08
	Average Dimensions				MINIMUM - MAXIMUM Dimensions				Standard Deviation				Avg. Range			
Part A	14.00	45.02	40.78	9.72	13.89	44.98	40.77	9.70	0.115	0.046	0.012	0.021	0.095			
					14.12	45.07	40.79	9.74								
Part B	14.02	45.20	40.83	9.74	13.95	45.10	40.77	9.69	0.087	0.100	0.055	0.046	0.137			
					14.12	45.30	40.87	9.77								

Figure 14: Measurements and results from hole locations

As can be seen by the results shown in Figure 14, hole location variation had a higher range of variation, up to 230 microns, but had respectable, if not impressive standard deviation values and average ranges given the equipment. It should also be noted again that these measurements were manually obtained using a digital caliper and these are fairly small holes, therefore it is to be assumed that the measurement process had some inaccuracies.

OUTCOMES AND CONCLUSIONS

This study was especially of significant for the project for a multitude of reasons. First, the effectiveness of low cost AM for production volume and its scalability. Going from an extremely low risk investment of a few 3D printers for initial manufacturing, to several hundred printers operating 24/7 with only 15 person staff producing at least 70,000 parts a month, demonstrated an extremely impressive production model. Then considering the company's current plans to scale up another 200 printers, demonstrated how effective a well-planned AM production model could operate, and the potential return on investment (3dprintingmedia.network, 2018). Assuming again that the true cost to build one printer was $360 per unit, then another 200 units would result in a minimum investment $72k. But also assuming that the company makes at the very least $10 profit from each printer. And at the reported high sales rate of 3000 printers per month, that would equate to only 2.5 months or 75 days to pay for the equipment investment. Yet by the estimates of this study, 200 more printers could produce enough parts for over 4000 more kits a month. These types of numbers, which albeit are estimates based on reported information, are incredibly significant.

The customer R&D feedback loop resulting from the flexible manufacturing model was also a surprising result from this study, and is something to consider not only from a technical perspective but also from a business standpoint. As such a company existing in such a Constant Beta state could use this as a powerful marketing and name branding tool, which this company clearly does already. This model allows for all the desired attributes of any physical product based company, low cost R&D, a competitive edge, continual innovation, etc. And it is likely that this company's story will soon make its way into publications more associated with business and economics because of this manufacturing model.

The repetitive dimensional accuracy of the parts and just how well the kit goes together was also very surprising considering the low cost AM production model. It is planned to purchase another 2 kits in the near future to create a larger sample of data, but for now, the measurements speak very favorably towards the success of their manufacturing model. But with the worldwide popularity of the product and the company in general, it is quite likely that the results of the next 2 kits and parts will be the same.

It is important to note that certain significant facts were not obtained in this study. No information was able to be determined regarding the company's failure rate of their low cost AM production system. Important factors that are unknown at this time are how often a complete batch of parts is lost due to machine error, or how many individual parts get rejected on a daily basis. Or their overall quality assurance processes in general. All information that would have been very useful for evaluation, but the company did not provide during the correspondence of this project.

ADDITIONAL FIGURES

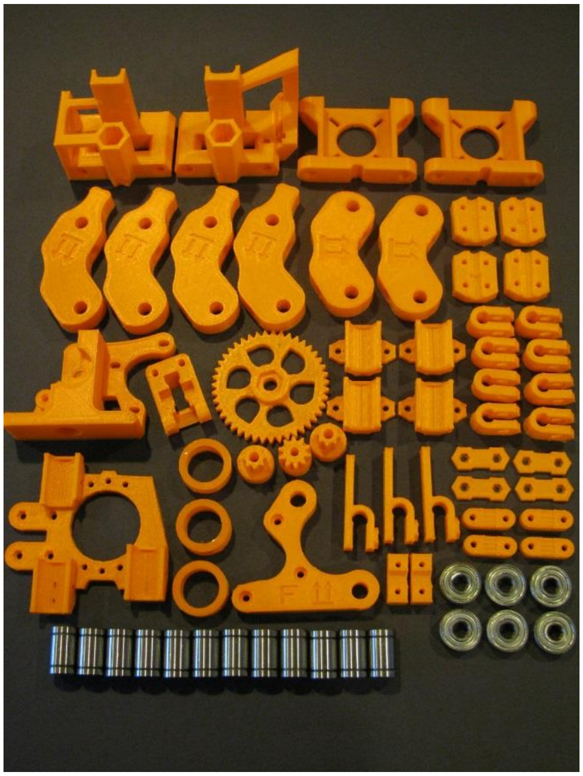


Figure 15: Prusa low cost AM produced parts (orange parts) used in product kits

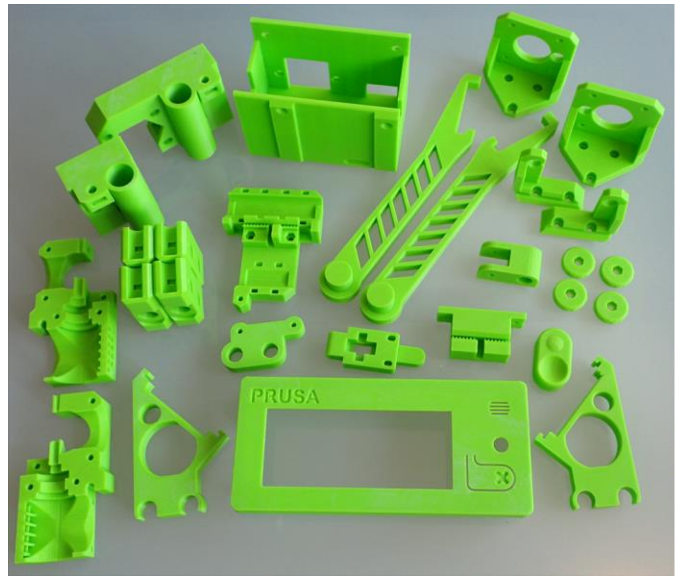


Figure 16: Other examples Prusa low cost AM produced parts used in product kits

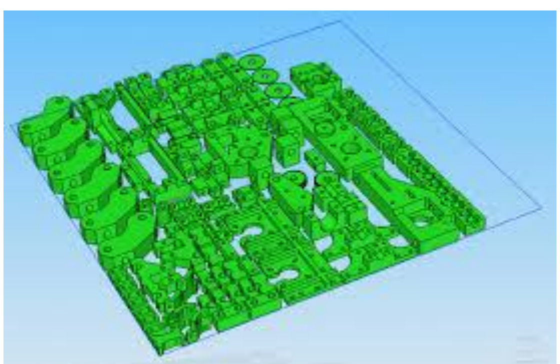


Figure 17: Concept batch arrangement of Prusa low cost AM produced parts on one 3D printer bed

Figure 18: Owner Josef Prusa, in low cost AM manufacturing “closet” in 2016


Figure 19: Prusa’s new low cost AM production facility in 2018

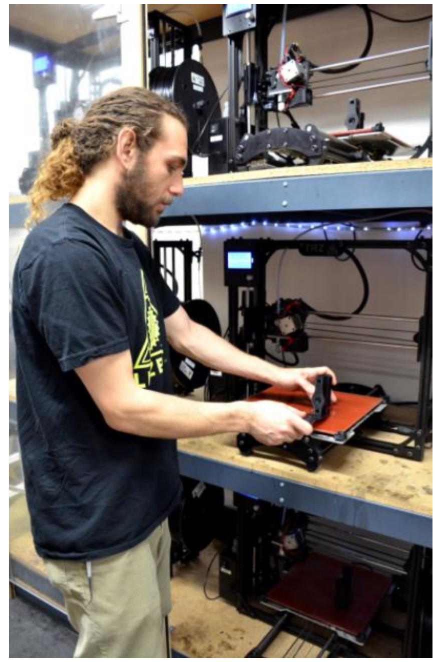


Figure 20: Lulzbot’s low cost AM production system, “The Cluster”

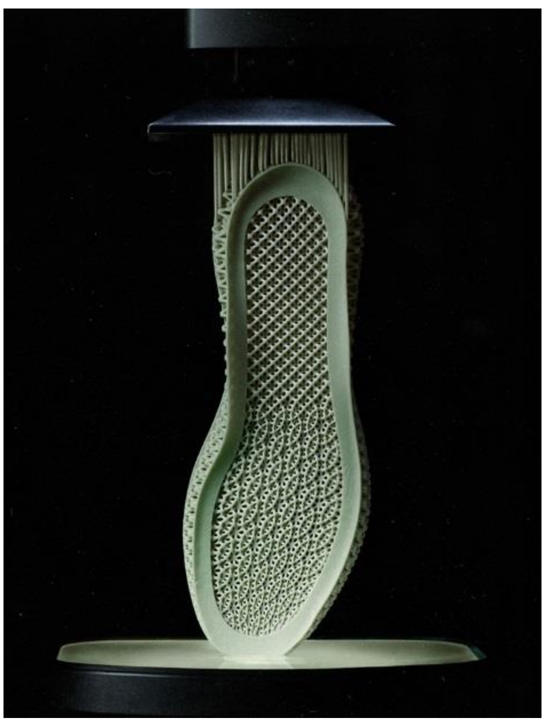


Figure 21: Adidas demonstration image of AM production of midsoles


Figure 22: Adidas marketing imagery for new 3D printed shoes

OVERALL PROJECT CONCLUSIONS

This project has demonstrated that low cost AM equipment and technology holds a significant opportunity in the manufacturing realms that many do not realize or have disregarded due to the nature of the equipment. This could the result of bias towards a particular business or comfortable skillset, or simple lack of knowledge. Regardless of the reasoning, low cost AM offers a variety of opportunities that need to be considered.

It provides a cost and risk barrier removal for startup companies and entrepreneurs. It can easily reduce lead times down to days or weeks instead of months or years If utilized correctly it can also provide a form of intellectual property protection for such companies or individuals, providing the freedom to try a product that previously could have easily been copied by conventional manufacturing techniques. It offers a surprising level of repetitive dimensional accuracy even at the scale of tens of thousands of parts on a monthly basis. The technology offers a new form of production flexibility, allowing a user to pivot from one product production line to another on a daily or even hourly basis without retasking, retooling, or rearranging their workflow.

It also provides low risk production scalability. Starting with a few low cost AM machines for production results with less initial investment, and users can quickly scale on demand. With most equipment supplier lead times of less than 3 weeks, a user could easily add 1, 4, or 8 machines to their existing line at a fraction of the cost of conventional equipment as the customer demand increased. As opposed to large higher risk equipment investments of typically hundreds of thousands of dollars. Such high risk investments often over stretch financial resources of small businesses, and dispose of funds that would likely be better spent towards marketing and sales impact.

Additionally low cost AM production gives the user the advantage of less supply chain risk and cost. By producing more of the parts internally, and not outsourcing, users can benefit in a variety of ways. They can increase their profit or provide a more competitive retail price by not having to pay a subcontracting vendor within their chain. They can also reduce their overall risk by not having to rely on a vendor to deliver on time and to specifications. And they can reduce their overall operating overhead costs by not having to manage vendors within their supply chain. One of the primary arguments for outsourcing production is cost, and with a conventional manufacturing profile that is a strong argument. However with low cost AM production, that argument may no longer be valid. Several companies, although focused on much higher cost AM applications, have already demonstrated the significance of such a business move. Paramount Group, a South African defense company, has plans to produce 2 small, manned aircraft a month from a single facility utilizing advanced manufacturing techniques including additive. What is very unique in this situation is their plans to manufacture everything under one roof with “very little outsourcing to other suppliers … without being burdened by a lagging supply chain.” (3dprint, 2018). General Electric with its LEAP fuel nozzle project as well as other GE projects, also demonstrated a significant reduction in overhead costs by using additive to remove a conventional supply chain (Mook, 2017).

The technology offers a new form of a business model allowing for a better customer experience with a constant feedback R&D loop, referred to the Constant Beta approach. By being able to continuously update the digital files during live production, it allows for constant evolution of the product without the conventional time or investment cost limitations. Being able to be branded as a company that is always able to respond to the consumer in a reasonable fashion and being known for staying at the top of their competitive game.

Low cost AM, although quite effective in the production of tools, jigs, and fixtures, as demonstrated in this project, can be much more than that. It can be much more than just a useful prototyping tool as well. It can be a powerful and flexible production platform, but requires a diligent production mentality on the front end of design to be effective.

Additive technology as a whole offers a variety of benefits, but the most significant is likely the ability to create ultra-complex structures and parts. Allowing designers and engineers to develop new products that were previously impossible or not cost effective, such as those demonstrated in this project. However, high cost high, high precision AM applications receive the majority of the world's attention, such as metal AM applications or extremely fast UV curable resin printers such as those made by Carbon. But, low cost AM offers much of the same options for design complexity, but not necessarily the extreme precision or speeds. Likewise, its current precision capabilities are quite adequate for many products and applications. And its cost accessibility means that users can afford to purchase more equipment to manufacture at the desired volume flow. Therefore, more businesses might well benefit from a low cost AM way of thinking and its advantages. And the best time to capitalize on those advantages is now while their competitors continue to ignore what the technology is already accomplishing.

OVERALL CONSIDERATIONS FOR THE FUTURE

It became very apparent during this project that there were multiple opportunities for continued research and growth of the technology. The first being directions or best practices on how to replicate the low cost AM production or integration models for businesses or individuals. Although the technology is quite cost accessible, there is a need for general knowledge on how best to proceed. Guidance regarding the best equipment, materials, software, safety procedures, and the like is very much needed to be successful but is not readily available at this time. As most AM companies and educational programs utilizing training provided by such companies are heavily biased towards the eventual sales of proprietary equipment and consumables, which are generally not considered low cost. Likewise, they are also likely not to be focused on end use production methodology. Therefore, there is an excellent opportunity to capitalize on this lack of knowledge and training.

An obvious need is for better low cost AM user training in marketing and online marketplace utilization. It was seen on multiple occasions during this project that users simply lacked good marketing skills and did not have the experience in proper manipulation of worldwide market made available to them through online tools. A misconception that was realized early is that most users tended to consider a webpage or a Facebook account being all that they needed for online sales. And this could not be further from the truth in terms of missing the market. The online sales market looks very different than it did 10 years ago and low cost AM production users need to more aware of modern best practices.

Another need is enhanced AM design training for technicians, engineers, and designers. Many AM users, even brand new ones with no conventional manufacturing background, still operate with conventional design mindsets and it is very counterproductive. They do not typically understand the impact of AM layering and fabrication direction, and optimization benefits of complex design. One theory is that most CAD skills are still taught by designing conventional looking parts. Plates and cylinders with holes and fillets are still the norm in CAD classes. And since AM relies heavily on CAD skills for production, the users will design and orient their parts that look conventional and are placed squarely on the build plate. Because that is what their CAD training exposed them to and they practiced with, therefore their visualization of an ideal design will mimic that conventional approach. The other problem is that complex parts now produced easily by AM are still difficult and complex to design in CAD. Therefore many AM users simply avoid the complex potential of AM because they cannot figure out how to make it work in CAD. Plus, from experience, instructors will avoid very complex CAD problems for homework and testing because of the time consumption and the difficulties for them to troubleshoot, score, and guide students in generating. So for AM to be truly effective both in low and high cost applications, there must be an overhaul of the CAD educational approach.

The material options for low cost AM have exploded over the last 12 months. Such equipment is now capable of utilizing fiber reinforced composite polymers, flexible polymers, quasi-metal polymers, various grades of nylon, fire retardant polymers meeting UL 94 ratings, etc. New materials are being added monthly to the list of available mediums because so many upper level material producers, such as Owens Corning and BASF, are investing their resources into new AM product lines (Jackson, 2018) (Böhme, 2017). This is creating a wealth of opportunities and needs for study in both optimized design and practical usage, so that low cost AM producers are aware of these opportunities and can be trained in best practices.

This project focused on low cost AM equipment that was typically FFF or fused deposition modeling (FDM) in application. However, many SLA and digital light processing (DLP) additive devices are now available under the $5000 threshold of this project. And many new material resins for these processes are becoming available as well, though they are still at a much higher cost per unit value than most FFF materials. Therefore as both the equipment and material competitors enter the market, their purchasing costs will continue to drop, and likely result in similar production models as demonstrated in this project. Therefore, there will soon be a need to review these production models and develop resources to help effectively facilitate more of them.

It is to also be noted that this project incorporated several other case studies but were not mentioned due to the practical size of this project, and limited data collection at the time of its drafting. Therefore, to facilitate additional learning opportunities the following webpage has been provided where users can access these additional case studies as they become available, as well as a video presentation of this project. Simply follow the link, then click on the large colored button labeled Research and Grant Materials. This button will take users to a cloud storage drive where additional research, individual case studies, video lectures, and other useful materials are available for review and download.

https://somerset.kctcs.edu/academics/programs_of_study/digital_printing_tech.aspx

This webpage can also be found using a Google.com search: SCC 3D printing

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