3D Printing: On Its Historical Evolution and the Implications for Business

Elizabeth Matias, Bharat Rao
New York University Polytechnic School of Engineering, Technology Management and Innovation Department, New York, NY - USA

Abstract--**Additive manufacturing technologies have gained prominence in the recent past, and are increasingly entering the mainstream. Extant research on these technologies is typically focused on the mechanics, and user analysis is largely theoretical. Minimal applied research exists regarding why these technologies transform underlying business models, and how users (both business and consumer) approach them as they consider adoption. In this paper, we briefly describe the historical evolution of additive manufacturing technologies, highlight current 3D printing applications in both the consumer and business markets, and evaluate current skill sets of business users and potential consumers. We identify five factors that may affect users' understanding of 3D printing technologies, thereby influencing users' likelihood of adoption. The results from an exploratory study are then presented.**

I. INTRODUCTION

Background

In 1986, Charles "Chuck" Hull patented the stereolithography machine, one of the earliest 3D printers. Shortly thereafter, stereolithography, as well as several other key patents, became the core competencies of 3D Systems, founded by Hull [13]. A few years later in 1988, Scott Crump invented fused deposition modeling (FDM), another 3D printing technology. FDM became the foundation for the company he cofounded with his wife, Lisa Crump, a year later – Stratasys [8]. These two companies went on to become two of the most prominent companies in the field of 3D printing and rapid prototyping [9]. For roughly twenty years, 3D printing technology quietly evolved and developed, and was utilized mostly by designers and engineers in the business space.

However, this began to change in 2005 with the advent of the RepRap project. Dr. Gordon started the RepRap project, an open source community with the goal of making 3D printing technologies accessible to all. Three avid participants of the project then went on to start their own 3D printing company. Bre Pettis, Adam Mayer, and Zach "Hoeken" Smith decided to market the technology to consumers. They founded MakerBot in 2009, bringing to market one of the first full assembled, consumer 3D printers. Subsequently, awareness in the consumer market increased, and the "next big thing" was discussed amongst industry analysts, stock watchers, and mainstream media.

II. LITERATURE REVIEW

History

Quite simply, the term "additive manufacturing" refers to the process of building products by adding many very thin layers of material, layer on top of layer. Historically speaking, additive manufacturing can trace its roots back to the 19th century, particularly the fields of topography and photosculpture. However, in a "Brief History of Additive Manufacturing and the 2009 Roadmap…" by Beaman et al, they cite that in 1972 Ciraud released the first technology that truly represented today's definition of additive manufacturing [3]. Ciraud's process is described as taking meltable materials and using a beam of energy to melt the material, thereby building a product by melting layer on top of layer. Unfortunately, while there are drawings and sketches regarding Ciraud's invention, there is no proof that the technology was actually produced and executed.

In a final report published by the Japanese and World Technology Evaluation Centers in 1997, Beaman again is a contributor on the historical perspective of additive manufacturing. Here, he references Hideo Kodama as the first scientist known to have produced a functioning additive manufacturing system in 1981. Alan Herbert of 3M in 1982 then closely followed him. This time, there was proof that the technologies were developed and tested. Both Kodama and Herbert developed technologies where a prototype part was actually built, layer by layer [15].

After a few years, Chuck Hull invented the stereolithography machine (SLA) in 1986. This machine is considered to be the first 3D printer [10] [15]. The stereolithography machine slowly poured liquid plastic to build plastic outputs. Not surprisingly, this technology was very expensive and therefore only utilized by large research universities, large companies, and government research labs.

Flash forward to present day, there are three major additive manufacturing/3D printing methods: 1) Fused Deposition Modeling (FDM), 2) Laser Sintering Platform, 3) and the ZPrinter Platform. Hull makes an excellent analogy regarding FDM technology; he likens it to a very sophisticated glue gun. This is currently the most commonly used 3D printer. Laser Sintering Platforms can print other materials aside from plastic – metals, ceramics, etc. These printers are more sophisticated; however they are also more expensive. ZPrinters, the third major technology, are also more sophisticated and again more expensive. It utilizes a powder substance that solidifies with a sprayed binding chemical [10].

B. Common Applications

1. Rapid Prototyping

"Rapid Prototyping" is perhaps the most mature application of additive manufacturing/3D printing technologies in the business space. In fact in some research, rapid prototyping refers to the different additive

manufacturing/3D printing methods patented by the key players in the field – Stratasys, 3D Systems, Objet, Z Corp, and Solidscape [17] [8]. However, throughout this paper, rapid prototyping will refer to the process of designing a 3D model with computer aided design software (CAD), and producing a prototype, typically out of plastic, via 3D printing technology. This prototype then becomes the basis for the design of the final product [14].

Rapid prototyping reduces manufacturing costs by enabling the multiple iterations of the design process. This means engineers and designers can design a more precise model in 3D and review a scaled, physical object. Users are then able to evaluate a concept and provide several rounds of design feedback or modifications [8]. This is quite different than former prototyping methods in 2D. In 2D, designers and engineers would sketch, with measurements, a prototype from many different perspectives on paper or in 2D software. With 3D design and rapid prototyping, companies are less likely to send incorrect measurements or faulty specifications into full-fledged production.

2. Tinkering

> "A big part of the American tinkering spirit is about finding inspiration in the creative pocket that exists between the metronomic beats of business as usual" [6].

"Tinkering" is the most discussed consumer application of 3D printing technologies. It is the process of casually playing with or futzing with a product design in hopes of improving or repairing the product. Much of current 3D printing literature discusses consumers engaged in "tinkering," known as Tinkerers. A Tinkerer is anyone with an idea and time to explore it [6]. This collective group of experimenters are also known as "Makers" [1]. Tinkerers and Makers who purchase 3D printers, such as MakerBot, learn the technology and then make their own products, designs, and/or outputs at home. These products are sometimes for home use and sometimes just to experiment. In many cases, tinkerers and makers can also be sophisticated 'consumers' who are trying to fashion solutions to their own particular problems, in the absence of marketplace choices - also referred to as Lead Users by Von Hippel [19].

Those who follow and participate in the RepRap project are perhaps the earliest tinkerers/makers in the 3D printing space. The RepRap project is an open source community, founded in 2005 by Dr Adrian Bower, a mechanical engineer. With the help of the RepRap project, users built their own 3D printers, and then self-replicate or self-manufacture their existing 3D printers with user enhancements and improvements. For example, MakerBot got its start this way – the founders were early users of 3D printers via RepRap [4]. Another set of researchers used information from the RepRap project to determine the effect open source communities have on the development 3D printing by building a 3D printer out of Legos [11]. RepRap continues to be a model for the open source community.

3. Personal Manufacturing

Personal Manufacturing takes the idea of "tinkering" one step further. *In Custom Nation: Why Customization is the Future of Business and How to Profit From It*, the authors, much like Anderson [1], imagine an economy where consumers have 3D printers in their homes. When a consumer identifies or creates a product that can better fit their requirements, the consumer designs a prototype with CAD software (or scans a prototype with a 3D scanner). Then, the consumer prints it on their 3D printer at home, or sends it to a 3D printing service for production [5]. This idea, where consumers are creating their own products, rather than waiting for companies to customize product offerings, is known as "Personal Manufacturing." With Personal Manufacturing, consumers are filling a market need on their own, thereby executing their own product development cycle. They do not need to wait for a company to prototype, manufacture, assemble, distribute, warehouse, or retail the new product.

In fact, in some instances consumers do not have to design a unique prototype with CAD software. They can search torrent sites like Pirate Bay for "Physibles," which are CAD files or blueprints of various products that can be downloaded, much like an MP3 or video file. From there, consumers can send the file to their 3D printer. Of course, much like the controversies of Napster and LimeWire, these files may become the subject of piracy and intellectual property concerns in the future.

4. Small Batch Production

> "Think ten thousand units, not ten million (mass) or one (mass customization). Products no longer have to sell in big numbers to reach global markets and find their audience" [1].

"Small Batch Production" is a manufacturing process whereby an entrepreneur or business determines a low volume of a particular product is economically viable. Historically speaking, small batch production has not been as cost effective as assembly line manufacturing. Production is typically most profitable when economies of scale are achieved, meaning the price to produce each subsequent unit decreases as more units are produced [16].

3D printing and additive manufacturing may facilitate small production volumes to small global markets [1]. With small batch production, small companies and startups commit to the development of a product with a very small, niche market [12]. Crowd funding sites like Kickstarter and shared working spaces like the Wix Lounge are contributing to the feasibility of this business model. For larger companies, highly customized 3D printed products may soon show significant profitability potential [5]. One such industry is the apparel industry, where companies can utilize 3D scanners, supplied by companies like Styku, to scan customers' exact measurements to produce truly customized clothing.

5. On Demand Manufacturing

As labor costs continue to rise in markets like China, the cost advantage of outsourcing jobs overseas begins to dissipate. Hence, a recent article by McKinsey has coined the term "Next Shoring." Next Shoring is the idea that manufacturing jobs will return to the United States because now there is a competitive advantage to setting up facilities near the markets served [7]. Arguably, this is partially credited to 3D printing. "Think local, act global approach" [11]. When specifications or drawings of products are sent directly to a local manufacturing facility, the logistical costs associated with transporting an item from the facility to the end user are reduced, as well as the costs of inventory management. Theoretically, setting up smaller local facilities for each respective market could make the product cheaper and faster.

This is suggested by another article published by CSC – "3D Printing and the Future of Manufacturing" [2]. With 3D printing, a simpler supply chain is possible, resulting from shorter shipping times and reduced inventory levels. When an item is ordered online, the customer first designs the item and then proceeds to checkout. Once the order is placed, a local manufacturing facility builds the item, and then ships it to the local customer. Since products would be shipped shorter distances, shipping costs are less.

6. Some Observations

Despite the advent of the first 3D printer about thirty years ago; consumers and small to mid-sized businesses have only begun to utilize the technology in the last five or six years. Small to mid-sized companies are utilizing the technology to design prototypes and reengineer discontinued parts. Additionally, service like Sculpteo and Shapeways are satisfying needs of new entrepreneurs interested in producing low volumes of their product designs. Leading researchers, Lipson and Tibbits, are presenting real life applications for 3D printers to be used by construction and manufacturing industries [13] [18].

However, current research does not address potential factors affecting the technological adoption of 3D printing, not from a consumer perspective (tinkering and personal manufacturing) nor from a business perspective (rapid prototyping, small batch production, and on demand manufacturing). This exploratory research study identifies and evaluates five factors affecting users', both consumers and businesses, current understanding of 3D printing/additive manufacturing.

III. RESEARCH PLAN

As mentioned above, this exploratory research study is organized based on two user groups – consumers and businesses. These user groups were evaluated based on five factors to evaluate knowledge profiles: 1) hardware familiarity, 2) software familiarity, 3) hardware specifications, 4) cost, and 5) interest in customization. These factors were determined based on observations from the research and case studies discussed in the literature review. They are briefly described below. Additionally, in the business space, users' knowledge levels were also evaluated based on current and past experiences with the technology.

A. Hardware Familiarity

Hardware familiarity refers to the user's understanding of a 3D printer's capabilities and product outputs. Additionally, hardware familiarity also addresses the user's understanding of 3D printing materials – plastics, metals, ceramics, food, and human cells.

B. Software Familiarity

Software familiarity refers to the user's understanding of computer aided design software (CAD), as well as 3D scanners or digitizers. CAD software is a critical skill in the 3D design process. Do users recognize that proficiency in products like SketchUp, Autodesk, and Inventor are prerequisites for the 3D printing process?

C. Hardware Specifications

Key 3D printer hardware specifications include filament material (plastic, metal, ceramics, etc.), durability, size of build, peripheral technologies, and ease of use. Do users understand the design considerations required to address any or all of these hardware specs?

D. Cost

Consumer 3D printers price points currently range from $400 to $3000. In the business space, most 3D printers range from $500 –$80,000, and the 3D printers are often procured to facilitate the research and development process. How much are users willing to pay for these technologies?

E. Interest in Customization

Outputs from 3D printers are highly customized. In the consumer space, users' interest in personalized gifts or products may affect their likelihood to adopt the technology. Particularly, if users frequent complementing services like Zazzle, Etsy, and Bonanza. In the business space, the need for unique parts or components, tailored to a specific business need, may affect and increase in adoption levels.

Expected Observations

These two user groups (consumer and business) were expected to have different levels of understanding regarding the potential resolvable problems and/or challenges that 3D printing technologies facilitate, as well as different agendas or goals for using the technology. We expected that consumers would understand 3D printers as a technology to print spare toy pieces or knick knacks, whereas business would understand 3D printers as a technology for rapid prototyping, on demand manufacturing, and small batch manufacturing.

We anticipated that roughly half of all consumers understand basic concepts of 3D printing technology, and roughly a tenth of them have used the technology. We further

hypothesized that the majority of consumers (>60%) would not be willing to spend more than $299 on a 3D printer. On the other hand, all of the business users sampled had experience with 3D printers and designing products utilizing CAD software. We expected our research to show that business users continue to utilize 3D printers predominantly for rapid prototyping, while beginning to explore other applications of the technology such as small batch production and on demand manufacturing.

IV. RESEARCH METHODOLOGY

A. Mixed Methods Approach

To investigate our research hypotheses described above, we employed a mixed methods research approach. This included 1) a survey of consumers and 2) interviews of business users with 3D printing experience. Data was collected with the use of two methods (consumer survey and business interviews), and data was analyzed from two predominant user groups (consumers and businesses). The consumer survey facilitated responses from more consumers than interviews would have provided, thus a more substantive sample set. Conversely, the interviews were a purposive, targeted sample with the goal of understanding business users who had been utilizing the technology for years. Hence, a survey was not possible, as it is difficult to gain access to a representative sample set of experienced business users.

B. Consumer Segment

The Consumer User Base Survey, administered through SurveyMonkey, included nineteen questions split across five web pages to increase likelihood of response. One question included yes/no logic; only those that answered yes to Question 5 were prompted to respond to Question 6. Therefore, some people answered eighteen questions, not nineteen. Based on an average response rate of 10%-15% for most online surveys, the targeted sample population was 300, with 45-50 responses. The survey was communicated in a phased approach via Facebook, LinkedIn, and email. Ultimately, due to a very high response rate of 61% after one week, the sample population was reduced to 115.

C. Business Segment

Five interviews were conducted to evaluate the business users. The sample set was a purposive sample of individuals identified through our business networks. Each of the five interviewees' positions and companies are listed below:

TABLE 1: BUSINESS INTERVIEWEES

Interviewee	Position	Company
No. 1	Design Specialist	NRI
No. 2	Frame Design Engineer	Cycling Sports Group
No. 3	Quality Team Lead	Shapeways
No. 4	Engineering Manager	Richards Manufacturing Co
No. 5	Designer	Con Edison

Note: See Appendix for Company Descriptions

The interviews took place over two months from May 2014 to end of June 2014. In addition to evaluating each interviewee based on the five factors identified in Section 3 – Research Plan, key interview questions were also determined. They are bulleted here:

- How is the technology used?
- What model?
- What kind of software?
- Are any of the outputs the final product?
- What are the current challenges of the technology?
- In 5-10 years, will the average consumer own a 3D printer?

V. RESEARCH FINDINGS

In total, 66 out of 115 users responded to the Consumer 3D Printing Survey, or 57%. This response rate was 42-47% higher than the anticipated response rate of 10-15%, based on average online survey response rates, according to SurveyMonkey. The five business interviews provided qualitative data, and are grouped into two segments. Not surprisingly, business users were much more knowledgeable than consumers. As mentioned earlier, all business users interviewed had experience operating and designing with a 3D printer. In summary, some predictions were validated and some predictions were challenged.

A. Consumers

As predicted, only a small fraction (roughly 10%) of consumers have used 3D printers. Overall, most consumers have some sense of 3D printing's technological capabilities. We anticipated that the majority (>60%) would not be willing to spend more than $299. However, roughly 15% of consumers were willing to pay a higher price for a 3D printer than predicted. 45% of consumers were not willing to pay more than $299 for the technology. Three consumers were quite savvy in terms of their overall understanding of the technology. They detailed creative uses of the technology, including 3D models of base camps, small batch production, and personal manufacturing.

B. Businesses

The companies interviewed during the research process can be separated into two groups – 1) 3D printing service companies and 2) R&D driven companies. These two groups are both key players in the 3D printing space, but their roles are different. The 3D printing service companies, NRI and Shapeways, are heavily focused on user education, whereas R&D driven companies are focused on utilizing 3D printing technologies to drive efficiencies in the research and development process. This section will compare and contrast these two groups.

The difference in 3D printing service companies versus R&D focused companies is a result of the 3D printed outputs. For Shapeways and NRI, the 3D printed output is considered

the final product. It is sold to the consumer as a model, a piece of jewelry, electronic accessory, art, etc. Con Edison, Cycling Sports Group, and Richards Manufacturing's outputs are not the final product. These 3D printed outputs are for the purposes of R&D only. The outputs are used to test the fit of to an existing product, view a model of re-engineered product, or test the dimensions of a design before sending to a CNC or water jet machine. The 3D printing services have many different models of 3D printers, and are concerned with the quality and material of the final output. The R&D companies had one or two 3D printers, and they are nominally concerned about the quality or material of the final output.

Shapeways is focused on educating consumers and entrepreneurs, whereas NRI is focused on educating their clients. NRI positions itself as a trusted consultant/advisor for clients' design and prototyping needs. Shapeways has positioned itself differently; they aim to be a one-stop shop for all things 3D printed. The R&D driven companies, depending on complexity of design and 3D printing knowledge, could hire either Shapeways or NRI as a 3D printing service. If the R&D company has the final file and it is structurally adequate, they can send the file to Shapeways for production. A company may need to print the object with a specific material that their in house printer does not use, or supplement production due to time constraints. Additionally, if the R&D company needs help designing and visualizing the output, NRI could be consulted.

This could be a decision point for any of the three R&D driven companies interviewed for this research– 1) Cycling Sports Group 2) Richards Manufacturing or 3) Con Edison. Perhaps Richards is the most likely candidate for farming out a job to either Shapeways or NRI, as they have the simplest printer model. On the other hand, Cycling Sports Group has sufficient skills, knowledge, and experience to design and print prototypes in house. Finally, Con Edison may take the middle road by utilizing existing CAD files from suppliers or a 3D scanner to design 3D models. Although these three firms use the technology mainly for rapid prototyping, the 3D printing strategies differ amongst the companies.

However, these three R&D driven firms, as well as the two 3D printing services, do have some important similarities. They are all key players in educating both businesses and consumers. R&D firms are educating their employees on the rapid prototyping process, as are the 3D printing firms. Additionally, the lead users in each group are all transferring knowledge on CAD software and 3D scanners to their peers. Table 2 is a summary based on the key interview responses.

To sum it up, these users are the savviest, most sophisticated users in the 3D printing space. They are important innovation drivers to 3D hardware, 3D software, and 3D scanner developments. Further, they are key proponents of innovation in their respective business lines – client services, bicycles and components, utility components, and energy distribution.

VI. RECOMMENDATIONS AND FUTURE DIRECTIONS

This section discusses the recommended future directions for the 3D printing industry. Based on the consumer survey and business interview research findings, these research recommendations are focused on three segments of the 3D printing industry: 1) consumer 3D printing companies 2) 3D software companies and 3) 3D printing services.

TABLE 2: QUICK SNAPSHOT OF BUSINESS INTERVIEWS

	NRI	**Cycling Sports Group**	**Shapeways**	**Richards**	**Con Edison**
Hardware Application	service for clients	prototypes, decal testing	service for customers - businesses and consumers	prototypes	prototypes
Software	n/a*	PTC Creo	user selected - TinkerCad, Sculptris, SketchUp	MakerBot "MakerWare"	Inventor, Autodesk
Printer Model	various	Dimension SST 1200es (Stratsys)	various	MakerBot Replicator 2	Fortus 250mc (Stratasys)
Cost of Printer	various	$35,000	various	$2,000	$70,000
Final Products Outputs	all - models, protoypes	none	all - includes jewelry, home goods, toys, electronic accessories	very small washers	wrench holder
Challenges	user education - lack CAD experience, post processing	post processing, printing with metals	user education, post processing	3D modeling software, weather effects on output	time - planning/batching jobs
Consumer Market Prediction (5-10 years)	no, will not be adopted by mass market	no, will not be adopted by mass market	yes, consumers will utilize 3D printing services	no, will not be adopted by mass market	n/a*

***question was not answered during interview**

A. Consumer 3D Printing Companies

The consumer survey found that 46.77% of respondents indicated that they would only spend $0-$299 dollars on a 3D printer. Given the discussed capabilities of 3D printing technologies, this suggests that consumers have not been convinced of the technology's value. Why would a consumer purchase a 3D printer currently? A majority of respondents still see 3D printing as mostly a business application, not a solution for tinkering or personal manufacturing. As the price of 3D printers decrease over time, more consumers and entrepreneurs may not necessarily consider purchasing a 3D printer. Consumers need to be convinced that the technology is valuable, particularly since 90% of consumers have not used a 3D printer.

Consumer 3D printer companies like MakerBot should consider expanding their marketing and education efforts. According the consumer survey responses, designers and engineers are currently the lead users of consumer 3D printers. These individuals have used the technology during school or at work. Therefore, they are able to transfer potential ideas or applications from work to home. For all other consumers, again based on survey responses, they need to be educated on the 3D design process – having an idea, designing a 3D model in CAD, converting the design file it to the appropriate file type, and then printing the model. This recommendation, increased marketing and education by consumer 3D printing companies, is necessary for consumer 3D printing companies to accelerate the consumer adoption rates of the technology.

Spivey, the business user interviewed from NRI, also had a recommendation for consumer 3D printing companies – a 3D printing repair shop. From his perspective, one of the challenges in the 3D design process is also hardware maintenance. If something goes wrong with a consumer 3D printer, many users are not sure where to take it for repair. MakerBot only has a few walk in store fronts, and retail/repair shops like Best Buy and TekServe do not have the skill set as of yet to diagnose and repair the hardware.

B. 3D Software Companies

Contrary to Anderson's belief [1], we are not all designers; average consumers still have relatively high barriers to entry. 3D software is still difficult to use and is a key competency required to print 3D outputs designed by consumers. As Spivey explained, consumers that do purchase 3D printers are not educated on the 3D design process. In one instance, an individual purchased a MakerBot and thought that Adobe Illustrator could be used to create the design. This is not 3D modeling software, and Illustrator will not produce the type of 3D model needed to send to a MakerBot for printing.

This example demonstrates a knowledge gap. However, it also demonstrates an opportunity for 3D software companies – design a user-friendly package, and then educate consumers. There are a few that have come to market recently – Sculptris and Tinkercad. The consumer survey showed that even though these products exist, 76% of consumers have not used CAD software. Perhaps if consumers were aware of these easier to use, easy to learn products, they would be more likely to tinker or dabble in personal manufacturing. This recommendation, additional, easy to use 3D design software applications in the consumer market place, would lessen the current learning curve required to competently engage in the 3D design process.

C. 3D Printing Services

Based on the interview with Boyle, Shapeways may be one the most interesting companies in the 3D printing industry. Particularly since 46.77% of consumers are not willing to spend more than $299 on the technology, and currently most consumer 3D printers cost about $2000. Perhaps this is why Shapeways is taking steps to educate consumers with programs like #madewithcode, partnerships with companies like Hasbro, and outreach sessions at coworking spaces like the Wix. Until consumer 3D printers are at price that more users are willing to pay, and the software is easier to use, they can utilize a 3D printing service. This is a much more cost-effective option, and users do not have to bother with post processing or calibrating the 3D printer.

Since 3D printing services are the most cost effective, Shapeways, as well as other 3D printing services, have the potential to facilitate multiple 3D printing applications, including tinkering, personal manufacturing, on demand manufacturing, and small batch production. Other 3D printing services should use Shapeways as a model. Potentially, even companies like MakerBot could benefit from utilizing Shapeways as a case study. Once the market is educated and the technology gets better, maybe then the consumer mass market will adopt the technology.

VII. CONCLUSION

This was an exploratory research study, which utilized both a consumer survey and interviews in the business segment to gather quantitative and qualitative research. The study had three major limitations. Firstly, as mentioned in Section 4 – Research Methodology, the consumer survey was a convenience sample. Survey respondents were determined based on our personal and professional networks. Secondly, the study had time constraints, as it was our goal to survey the state of the art in a reasonable timeframe. Thirdly, the technology is very new in the consumer space. Consequently, most academic research on the consumer user base is rather hypothetical and very recent– within the past five years.

Overall, 3D printing is most valuable for intricate, complex designs. Jewelry is a good example. A simple wedding band can be easily made with traditional methods. However, an extremely intricate wedding band with fine details and cut outs might turn out better if manufactured with a 3D printer. Other intricate designs include the 3D models of architecture and engineering projects, as discussed by Spivey

and Con Edison. Although 3D printing has great potential for on demand manufacturing and small batch production, these intricate designs are still mainly created as prototypes. This was confirmed in the interviews with Richards Manufacturing, Cycling Sports Group, and Con Edison.

In the consumer space, most consumers have not utilized 3D printing technologies. Section 6 – Research Recommendations, discussed three segments in the 3D printing industry that have the opportunity to positively affect the consumer user base. Again, these segments are consumer 3D printing companies, 3D software companies, and 3D printing services. Those consumers that have used 3D printers are using the technology mostly for tinkering. The consumer research survey did not find any instances of consumers utilizing the technology for personal manufacturing.

This exploratory study identified one major area for additional user base research – the technological adoption rate of 3D printing and additive manufacturing. The potential research might attempt to calculate the current projected rate of consumer adoption as the industry currently stands. Then, the research could hypothesize a revised projected rate of consumer adoption, which would likely occur if consumer 3D printing companies, 3D software companies, and 3D printing services implemented the recommendations discussed in Section 6 – Research Recommendations.

In closing, engineers and designers in the business space have been utilizing 3D printing technologies for several years. As a result, these users are the savviest and will continue to impact the future applications and developments of this technology, particularly as it evolves from the current, predominant utility in business – rapid prototyping. However, consumer users are just starting to figure out how to use the technology and its potential applications. Many researchers, discussed in Section 2 – Literature Review, are very optimistic regarding the future applications of consumer 3D printing. Despite the optimism, there remain several barriers to entry that need to be removed before the consumer adoption rate can exponentially increase. In addition to considering these barriers to entry, the industry would benefit greatly from additional academic research on current and potential users and applications of this technology.

REFERENCES

[1] Anderson, C. (2012). *Makers: The new Industrial Revolution.* New York, NY: Crown Publishing Group.

[2] Bassan, J., & V. Srinivasan. (2012). 3D Printing and the Future of Manufacturing. *CSC Leading Edge Forum.*

[3] Beaman, J. J., M. C. Leu, D. A. Rosen, D. Bourrell, & D. L. Bourrell. (2009). A Brief History of Additive Manufacturing and the 2009 Roadmap for Additive Manufacturing: Looking Back and Looking Ahead. *RapidTech 2009: US-TURKEY Workshop on Rapid Technologies.*

[4] de Jong, J. P., & E. de Bruijn. (2013, Winter). Innovative Lessons in 3D Printing. *MIT Sloan Management Review.*

[5] Flynn, A., & E. F. Vencat. (2012). *Custom Nation: Why customization is the future of business and how to profit from it.* BenBella Books.

[6] Foege, A. (2013). *The Tinkerers: The amateurs, DIYers, and inventors who make America great.* New York, NY: Basic Books.

[7] George, K., S. Ramaswamy, L. Rassey. (2014, January). Next Shoring: A CEO's guide. McKinsey & Co.

[8] Gibson , I., D. W. Rosen, & B. Stucker. (2010). Additive Manufacturing Technologies - Rapid Prototyping. New York, NY, 10013: Springer Science+Business Media.

[9] GridLogics Technologies Pvt Ltd. (2014). *3D Printing Technology Insight Report: An analysis of patenting activities from 1990-current.* GridLogics Technologies Pvt Ltd.

[10] Hatch, M. (2014). *The Maker Movement Manifesto: Rules for innovation in the new world of crafters, hackers, and tinkerers.* New York: McGraw Hill Education.

[11] Kostakis, V., & M. Papachristou. (2013, October). Commons-based Peer Production and Digital Fabrication: The case of a RepRap-based, Lego-built 3D printing-milling machine q. *Telematics and Informatics.* Elsevier.

[12] Leckart, S. (2013, March 27). *Popular Mechanics.* Retrieved July 1, 2014, from New American Success Stories: http://www.popularmechanics.com

[13] Lipson, H., & M. Kurman. (2013). *Fabricated: The New World of 3D Printing - The promise and peril of a machine that can make (almost) anything.* Indianapolis, IN: John Wiley & Sons Inc.

[14] Pham, D., & R. Gault. (1998). A Comparison of Rapid Prototyping Technologies. *International Journal of Machine Tools & Manufacture Design, Research, and Application* . Cardiff, United Kingdom.

[15] Prinz , F. B., C. L. Atwood, R. F. Aubin, J. J. Beaman, R. L. Brown, P. S. Fussell, et al. (1997). *Rapid Prototyping in Europe and Japan.* JTEC/WTEC Panel. Japanese and World Technology Evaluation Centers.

[16] Rosenberg, N. (1982). *Inside the Black Box: technology and economics.* New York, NY: Cambridge University Press.

[17] Sells, E. A. (2009, January). Towards a Self-Manufacturing Rapid Prototyping Machine. Bath, United Kingdom: University of Bath.

[18] Tibbits, S. (2013, February). *Skyler Tibbits: The Emergence of 4D Printing.* Retrieved March 20, 2014, from TED: http://www.ted.com/talks/skylar_tibbits_the_emergence_of_4d_printing

[19] Von Hippel, E. (2005). *Democratizing Innovation.* Cambridge , MA: The MIT Press.

APPENDIX – COMPANY DESCRIPTIONS
(business interviews)

NRI

NRI provides 3D printing, creative visuals, and reprographic services to businesses and some consumers. The interviewee Arthur Young-Spivey, digital fabrication specialist at NRI for over 10 years, has been using and teaching the technology for many years. Clients include architecture firms, engineering firms, urban planners, fashion designers, and car companies.

Cycling Sports Group

Cycling Sports Group (CSG) is a division of Dorel Industries, a Canadian conglomerate. CSG designs and manufacturers Cannondale, GT, Schwinn, and Mongoose bicycles, as well as bicycle parts and accessories. The interviewed lead engineer, Jeremy Mikesell, has been utilizing 3D printing technology for over 10 years.

Shapeways

Shapeways is a privately owned 3D printing service, offering consumers and businesses (both small and large) the opportunity to print or manufacture a product with one of their many 3D printers - Stratasys, 3D Systems, Voxeljet, etc. Matthew Boyle, Quality Team Lead at Shapeways, used their partnership with Google, #madeincode, to describe the 3D printing process at Shapeways.

Richards Manufacturing

Richard Manufacturing custom designs and manufactures network protectors, meters, connectors and other components for energy utilities. Jeff Madden, Engineering Manager at Richards Manufacturing uses two 3D printers; but has been using the company's MakerBot Replicator for a few years.

Con Edison

Con Edison is a publicly traded energy utility. The company transmits and distributes gas, electricity, and steam to New York City, Orange county, Rockland county, and parts of Pennsylvania. Additionally the company has three subsidiaries for retail energy supply, wholesale energy, and alternate energy projects. The Diamond Team, interviewed for this research, has been utilizing 3D printing technology for about two years.