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Emergence of Home Manufacturing in the Developed World: Return on Investment for Open-Source 3-D Printers

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Abstract: Through reduced 3-D printer cost, increased usability, and greater material selection, additive manufacturing has transitioned from business manufacturing to the average prosumer. This study serves as a representative model for the potential future of 3-D printing in the average American household by employing a printer operator who was relatively unfamiliar with 3-D printing and the 3-D design files of common items normally purchased by the average consumer. Twenty-six items were printed in thermoplastic and a cost analysis was performed through comparison to comparable, commercially available products at a low and high price range. When compared to the low-cost items, investment in a 3-D printer represented a return of investment of over 100% in five years. The simple payback time for the high-cost comparison was less than 6 months, and produced a 986% return. Thus, fully-assembled commercial open source 3-D printers can be highly profitable investments for American consumers. Finally, as a preliminary gauge of the effect that widespread prosumer use of 3-D printing might have on the economy, savings were calculated based on the items' download rates from open repositories. Results indicate that printing these selected items have already saved prosumers over $4 million by substituting for purchases.

Keywords: distributed manufacturing; additive manufacturing; 3-D printing; consumer; economics; open-source

1. Introduction

Private manufacturing, also referred to as household manufacturing, has a lengthy history in the United States which resulted in the emergence of domestic commerce [1,2]. With the development of interchangeable parts, however, came the assembly line, and manufacturing transitioned to standardized high-volume mass production [3,4]. Lower variable costs, greater flexibility, and higher average product performance contributed significantly to this transition [5]. Since then, a global trend toward large-scale, centralized manufacturing and global shipping, particularly for inexpensive plastic products, has arisen alongside growing world consumerism [6,7]. Economies of scale provided consumers with more convenient and lower-priced goods than what they could make themselves [8]. However, the rapid growth of the 3-D printing industry may change this trend.

Additive manufacturing (AM), or 3-D printing, promises to be an emerging 21st century innovation platform for promoting distributed manufacturing for many products [9–13]. The compound annual growth rate of worldwide additive manufacturing products and services over the past three years, from 2013 to 2015, was 31.5% [14]. Although a less centralized model of manufacturing than that currently practiced, the conventional 3-D printing industry is still focused on businesses manufacturing and selling products to consumers or other businesses [14]. However, with the rise of Internet sharing and open source hardware development [15], it may provide a more aggressive path to distributed production. Most notably, the self-replicating rapid prototyper (RepRap) 3-D printer [16–18] can fabricate more than half of its own parts. Already, RepRaps have significantly reduced distributed digital manufacturing costs for high-end products such as scientific equipment and have enabled economic non-business distributed manufacturing [19–21]. The savings for the distributed manufacturing of these high-end products [22] provide staggering value for the scientific community [23,24]. However, distributed manufacturing is not relegated to high-price specialty items.

Preliminary research has already shown that the number of free pre-designed 3-D products is growing rapidly, and low-cost do-it-yourself (DIY) 3-D printers such as the RepRap are already economically beneficial for the average American consumer [25]. This provides the opportunity for the most radical form of distributed manufacturing. At-home 3-D printing capitalizes on the elimination of product transport, establishing the technology within the realm of distributive manufacturing's three-tiered modes of operation [25] (tier 1: central manufacturing distributed to different locations, tier 2: decentralized further to local and agile production sites (e.g., localized manufacturing , fablabs, and makerspaces), and tier 3: at home manufacturing). Nonetheless, in order for this innovative form of localized and customized manufacturing to make a significant impact on the industry as a whole, ease of use and the economic advantage to the average consumer must be better understood [26]. In particular, the past study by Wittbrodt et al. [25] assumed that the consumer was technically savvy enough to build a 3-D printer from parts using freely available Internet plans. This may have been an overly optimistic assumption as less than a third of Americans are scientifically and technically literate [27,28]. Considering past work in the context of the technical sophistication of the American public, two questions arise: Will 3-D printing be relegated largely to replacing conventional manufacturing techniques and creating the potential for more distributed business-based manufacturing [29,30]? Alternatively, can 3-D printing be used to economically manufacture in the majority of American homes of technically illiterate people? In addition, it is worth acknowledging that financial savings provide just one contribution to a consumer's motivations, so economic analysis must be kept in context.

To probe this latter question of the economic viability of this scale of 3-D printing for home manufacturing in the developed world, this study reports on the life-cycle economic analysis (LCEA) of Lulzbot Mini technology for an average U.S. household. The Lulzbot Mini is a commercialized and fully assembled plug-and-play derivative of the RepRap, which can be used by a consumer with no training and modest technical familiarity [31]. A selection of twenty-six freely available open-source 3-D printable designs that a typical first-world household might purchase were selected to simulate use over half a year at the average rate of production of one "home-made" item per week. A selection of the parts was printed to determine energy use per mass of material. Printed products were quantified by print time and filament consumption by mass and the experimental masses and printing time were compared to slicer software estimates. The experimental values were converted to the cost to the user and were then compared to low and high market prices for comparable commercially available products. The results of this life-cycle economic analysis provide a return on investment (ROI) for the prosumer (producing consumer), which is compared to other potential investments. Finally, the downloaded substitution value of the selection of designs is quantified to draw conclusions about the future of manufacturing in developed-world economies.

2. Materials and Methods

For this analysis, it was critical that the methods of manufacturing and materials were relevant and accessible to the average consumer. A Lulzbot Mini [31] was selected due to the ease of use, high resolution capabilities, support of open-source hardware and software, and the ability to work with a variety of operating systems, as well as its relevance in the 3-D printing community following other similar products [32]. To be used by the Mini, 3-mm poly lactic acid (PLA) was selected as the filament because it is the most common household printing material. PLA has gained prominence, as not only does it demonstrate less warping during printing than other materials such as the second most common 3-D printing plastic (ABS), but the emissions during printing are less pungent [32,33]. Furthermore, PLA is made from corn-based resin, making it non-toxic, biodegradable, and able to be produced in environmentally friendly, renewable processes [34,35]. It should be noted that because the ABS filament costs are roughly equivalent to PLA and the melting temperature is not that much higher, the results from this study can be extrapolated to ABS.

Twenty-six items were selected from open source 3-D printable design repositories after searching for open source design files indexed on Yeggi.com, which is a 3-D design file search engine. The twenty-six items are summarized in the Supplementary Materials including the source of the design, and the low and high price URLs for roughly equivalent products. Items were selected to represent the average American consumer's use over the course of half a year of printing one product per week. Three criteria were used in the selection of products: (1) printable by a Lulzbot Mini in PLA (e.g., having an appropriate build volume, resolution, and material requirements); (2) widely considered to be a common product purchased (or class of product purchased) or owned by the average American consumer; and (3) has a commercially comparable alternative available for purchase online. The concluding analysis was mindful of the difficulty in quantifying the print quality, however the items included in this study met the authors' expectations for acceptable quality (e.g., z-level print lines are observable using the high-quality quick print settings, but not unacceptable for general consumer use).

One of the most challenging areas in 3-D printing technical knowledge for new users is optimizing the slicer settings that determine the tool path of the 3-D printer. To avoid this challenge, all parts were printed in PLA using the QuickPrint settings in the Lulzbot version of Cura [36] to demonstrate ease of use. Figure 1 shows the Lulzbot Mini mid-print using PLA and Cura Quick Print settings. The estimated and actual mass, filament length, and estimated and actual printing time were recorded. All parts were weighed on an electronic balance with an error of ±0.02 g.

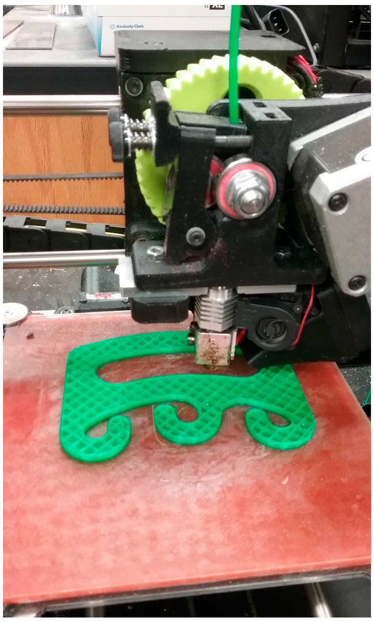

Figure 1. Lulzbot Mini mid-print using poly lactic acid and Cura Quick Print settings.

In order to apply a cost per hour for each printed item, the print time and energy consumption was recorded by a multimeter (±0.02 kWh) for complex, simple, and average geometric complexity.

Greater print complexity demonstrated a higher level of energy consumption primarily because of the operation time per unit mass. The average was found to be about 0.01 kWh/g, which is higher than that reported in the Wittbrodt et al. study [25] due to the additional energy consumed by the heated bed of the Mini. The average consumption of 0.01 kWh/g was applied for all prints included in the study.

High and low commercial prices for each product was found primarily on Walmart.com and supplemented using Google Shopping. Associated shipping costs were excluded from the analysis for both purchasing and distributed manufacturing (e.g., no shipping charges included for the plastic filament). The operating cost for the Lulzbot Mini (O_L) was calculated using the electricity and filament consumption during printing. The average electricity rate in 2015 in the United States is $0.1267 per kWh for the residential sector [37] and the cost of a 1 kg spool of 3-mm PLA was found to range between $23/kg and $25/kg [38,39], so $24/kg was used here. This operating cost was calculated as follows:

$$O_L = EC_E + \frac{C_F m_f}{1000} \text{ [USD]} \tag{1}$$

where E is the energy consumed in kWh, C_E is the average rate of electricity in the United States in USD/kWh, C_F is the average cost of the PLA filament in USD/kg, and m_f is the mass of the filament in grams consumed during printing. Thus, the total cost (C_T) to the average consumer using the selected printer an average of once per week is the following:

$$C_T = \sum_{0}^{T} O_L + C_L \text{ [USD]} \tag{2}$$

where the operating cost is summed over T years and C_L is the cost of the Lulzbot Mini itself. It should be noted here that the capital costs were not considered because it is assumed that the prosumer is not financing the cost of the capital equipment because the Lulzbot Mini cost is only $1250.00 [40]. It should be pointed out that if the 3-D printer were purchased on a credit card, which is the only feasible method of financing a consumer purchase such as this, this would need to be included in C_L. This would also be true if the prosumer purchased a large amount of inventory filament on credit. C_T was evaluated over a range of years from one to five. The marginal savings on each project, Cs, is given by:

$$C_S = C_C - O_L \text{ [USD]} \tag{3}$$

where C_C is the cost of the commercially available product (which is calculated for both low and high online prices), and the marginal percent change, P, between the cost to print a product and the commercially available product was calculated as follows:

$$P = \frac{C_C - O_L}{C_C} \times 100 \text{ [\%]} \tag{4}$$

where C_C is the cost for the commercial product at either the high or low price.

When the cost of the 3-D printer is taken into account the total savings, S, is given by:

$$S = \sum_{0}^{T} \sum_{0}^{A} C_C - C_T \text{ [USD]} \tag{5}$$

over T years and all, A, products.

The simple payback time of the printer (t_{pb}) was calculated by the following:

$$t_{pb} = \frac{C_L}{S} \text{ [years]} \tag{6}$$

An estimated return on investment (R) was calculated following [41,42] assuming a five-year lifetime for the 3-D printer.

$$\frac{C_L}{S} = \frac{1 - e^{-RT}}{R} \quad (7)$$

Finally, the value obtained from a free and open source 3-D printable design can be determined from the downloaded substitution valuation, $V_D(t)$ [23,24] at a specific time (t):

$$V_D(t) = (C_p - C_m) \times p \times N_d(t) \text{ [USD]} \quad (8)$$

This value is determined by the number of downloads (N_d) on 7 December 2016, where Cp is the retail cost of the traditionally manufactured product and C_m is the marginal cost to fabricate it with the Lulzbot mini. p is the percent of downloads resulting in a print. It should be noted that p is subject to error as downloading a design does not guarantee its manufacture. On the other more likely hand, a single download could be fabricated many times, traded via email, memory stick, or posted on P2P websites that are beyond conventional tracking. Here, to remain conservative, p is assumed to be 1 because downloading a design involves effort that is not repaid unless one does the printing. This is equivalent to assuming that if a consumer downloads an ebook that it is read at least once. It is thus reasonable to assume every download resulted in at least one print and the total savings for the random 26 objects can be conservatively determined by:

$$V_{DT}(t) = \sum_{i=0}^{26} V_D(t) \text{ [USD]} \quad (9)$$

All economic values are in U.S. dollars (USD), $.

3. Results

Printing twenty-six items to model use over the course of 6 months resulted in a total of 104.18 m of filament consumption with a mass of 737.8 g. An estimated total of 100.18 h, and 7.26 kWh were expended on 3-D printing. This translates to $17.71 worth of material and $0.92 in electricity based on average U.S. electric rates, for a total operational cost of $18.63 over half a year. Thus, at a printing rate of one object per week, operating the 3-D printer costs less than $40 per year. Table 1 shows the projected cumulative cost of owning and using a Lulzbot Mini as a function of years.

Table 1. The projected cumulative cost for owning a Lulzbot Mini increased from year 1 to 5. The cost includes the price of the printer itself, the cost of the filament, and the energy consumption to print an average product per week.

Year	Cumulative Cost of Ownership (USD)
1	1287
2	1325
3	1362
4	1399
5	1436

Retail costs for the products totaled $278.57 and $1376.03 for low- and high-priced items, respectively, as seen in Table 2.

Table 2. 3-D printable object, length of filament, print time, energy consumption, low and high retail price, operating cost, marginal savings, and percent savings for 26 freely available designs.

Object	Length (m)	Weight (g)	Total Print Time (min)	Energy Consumption (kWh)	Price: Low (USD)	Price: High (USD)	Operating Cost (USD)	Marginal Savings: Low (USD)	Marginal Savings: High (USD)	Marginal Percent Change: Low	Marginal Percent Change: High
Spoon holder	1.55	10.69	139	0.11	7.75	29.00	0.2701	7.48	28.73	96.51	99.07
Arduino nano enclosure	2.84	20.44	168	0.20	8.82	9.95	0.5165	8.30	9.43	94.41	94.81
Carpet corner	0.15	0.84	8	0.01	9.99	10.30	0.0212	9.97	10.28	99.79	99.79
Bathroom wine glass holder	5.75	41.01	359	0.41	8.70	44.96	1.0362	7.66	43.92	88.09	97.70
Tool holder	1.65	11.75	106	0.12	4.70	21.10	0.2969	4.40	20.80	93.68	98.59
Soap holder	7.60	54.57	482	0.55	4.86	12.99	1.3789	3.48	11.61	71.63	89.39
Snowboard bind plate	4.51	30.54	265	0.31	11.95	12.96	0.7716	11.18	12.19	93.54	94.05
Dremel cutting table	10.06	67.13	619	0.67	26.00	43.99	1.6961	24.30	42.29	93.48	96.14
Rotary tool attachment	2.12	14.16	152	0.14	12.98	49.99	0.3578	12.62	49.63	97.24	99.28
Solder stand	4.24	29.31	276	0.29	13.65	28.95	0.7406	12.91	28.21	94.57	97.44
Nikon lens cap holder	2.04	14.26	118	0.14	5.15	7.05	0.3673	4.79	6.69	93.00	94.89
Speaker grill	2.84	18.73	173	0.19	9.70	50.95	0.4733	9.23	50.48	95.12	99.07
Espresso tamper	5.48	36.77	334	0.37	17.86	40.99	0.9291	16.93	40.06	94.80	97.73
Sewing machine presser foot	0.24	1.48	21	0.01	5.99	20.49	0.0374	5.95	20.45	99.38	99.82
Coin holder	8.30	58.23	540	0.58	9.88	64.87	1.4713	8.41	63.40	85.11	97.73
Shower head	10.49	68.11	183	0.68	5.18	110.61	1.7209	3.46	108.89	66.78	98.44
Seatbelt guide	0.79	4.82	53	0.05	15.00	27.99	0.1218	14.88	27.87	99.19	99.56
Trumpet mute	3.93	26.53	379	0.27	11.95	99.99	0.6703	11.28	99.32	94.39	99.33
Ski pole GoPro mount	1.08	7.39	74	0.07	7.96	99.99	0.1867	7.77	19.80	97.65	99.07
Canon lens hood	1.61	9.25	116	0.09	5.99	52.99	0.2337	5.76	52.76	96.10	99.56
Insulin belt clip	0.69	3.85	51	0.04	15.99	22.41	0.0908	15.89	22.31	99.39	99.57
Torque wrench nozzle	2.59	21.02	165	0.24	4.20	419.58	0.5349	3.67	419.05	87.26	99.87
Rodin figurine	6.98	54.9	380	0.53	22.32	46.99	1.3847	20.94	45.61	93.80	97.05
iPhone6 case	2.37	19.10	100	0.13	0.99	59.99	0.4749	0.52	59.52	52.03	99.91
Deathstar model	4.77	38.02	285	0.45	25.98	35.00	0.9695	25.01	34.03	96.27	97.23
Pokemon planter	9.51	74.90	465	0.61	5.03	31.95	1.8749	3.16	30.08	62.73	94.13
Total	104.18	737.80	6011	7.26	278.57	1376.03	18.63	259.94	1357.40	**Average** 93.31	**Average** 98.65

This results in a substantial prosumer savings for each individual product with an average marginal cost reduction of 93.3% and 98.7% when compared against the low and high retail costs, respectively. This results in total savings of $259.94 and $1357.40 for the low and high cost estimates, respectively. Table 3 shows the projected prosumer profit per year assuming one product fabrication per week using the average of the 26 objects chosen here when compared to low-cost commercially available products and high-priced commercially available products. As shown, profit is realized after the second year of ownership when only low-cost commercially available products are considered in the analysis. When compared to high-cost products, however, profit is realized within the first year of ownership. It should be noted that as many of the objects allow some form of customization, the latter values are a better estimate for comparison.

Table 3. The profit to the user was projected when printed items, produced at a rate of one per week, were compared to low and high cost comparable, commercially available products.

Year	Low-Cost Projected Profit (USD)	High-Cost Projected Profit (USD)
1	−730.11	1464.81
2	−210.23	4179.61
3	309.66	6894.42
4	829.55	9609.23
5	1349.43	12,324.03

Comparing the printed objects to the lowest-priced equivalent product, there was a payback time of 2.4 years. In comparison to high-priced items, payback time was only 0.46 years. The return on investment was 25% in year 3 and 108% by year 5 when low-range cost values were considered. Comparing printing costs to high-end commercial prices resulted in a 552% ROI in year 3 and 986% in year 5.

The number of downloads for each item file was used to estimate the total savings for the global 3-D printing community when compared to marginal savings using the high and low commercial prices. These values are shown in Table 4. When compared to the low-end prices, the 26 printed items saved $803,945.70. Compared to the high-end prices, the savings were $4,033,657.89. The URLs for the designs and the low/high equivalent products are found in Supplementary Material. Prior research has provided economic justification for quantifying these projected values [23].

Table 4. The downloaded substitution value for the 26 free design example files.

Object	Number of Downloads	Low Marginal Savings of Downloads (USD)	High Marginal Savings of Downloads (USD)
Spoon holder	3113	23,248.92	89,436.17
Arduino nano enclosure	157	1303.66	1481.07
Carpet corner support	382	3808.07	3926.49
Bathroom wine glass holder	847	6491.24	37,203.46
Tool holder	534	2356.60	11,108.86
Soap holder	492	1712.74	5712.70
Snowboard bind plate	154	1801.80	1957.34
Dremel cutting table	7027	170,782.99	297,198.72
Rotary tool attachment	6080	76,743.09	301,763.89
Solder stand	1765	22,785.15	49,789.63
Nikon lens cap holder	1312	6284.08	8776.88
Speaker grill	233	2149.83	77,761.08
Espresso tamper	1195	20,232.46	47,872.81
Sewing machine presser foot	235	1398.86	4806.36
Coin holder	183	1538.79	11,601.96
Shower head	3921	42,691.94	369,272.03
Seatbelt guide	119	1708.50	3254.31

Table 4. *Cont.*

Object	Number of Downloads	Low Marginal Savings of Downloads (USD)	High Marginal Savings of Downloads (USD)
Trumpet mute	561	6585.59	55,976.03
Ski pole GoPro mount	121	873.34	2328.97
Canon lens hood	3421	20,135.60	180,922.60
Insulin belt clip	383	6044.91	8503.77
Torque wrench nozzle	3797	13,918.25	1,591,116.11
Rodin figurine	8129	170,163.13	370,705.56
iPhone6 case	1175	608.10	69,933.10
Deathstar model	6829	170,800.02	232,397.60
Pokemon planter	8807	37,742.05	264,850.38
Totals		**803,945.70**	**4,033,657.89**

4. Discussion

The impact of introducing additive manufacturing to the average American home demonstrates both microeconomic and macroeconomic advantages.

4.1. Microeconomic Advantages of Home Manufacturing

With projected savings to a single owner per year of $519.89 and $2,714.81 when compared to low and high range commercially available items respectively, the Lulzbot Mini could serve as a significant means by which the average consumer can reduce personal expenses. The items selected for the study represent those frequently found in the home such as tool mounts, shower heads, seat belt guides, figurines, and espresso tampers. From the perception of the consumer, they can begin to substitute free designs and 3-D printed objects for high-end consumer purchases such that printing only a single product a week recovers the cost of the printer in under a year. Some prosumers will use their 3-D printers considerably more than that and will be able to recover their initial investment more rapidly by printing out the same types of items at a greater rate or in a few expensive substitutional prints (e.g., custom orthotics) [25].

It is instructive to consider the purchase of a consumer-friendly printer as an investment and compare it to more traditional investments available to the average consumer. For example, five-year CD rates have 1.85%–2.10% APY [43] and savings account rates on investments less than $5000 and even those over $100,000 (jumbo) only go up to 1.05% [44]. In the volatile stock market, the historic corporate earnings have gone up an average of 7% per year. Thus by comparison, the return on investment demonstrated here with distributed manufacturing in the home of common products is an extremely positive outlook for the average consumer. When compared to low-range commercial prices, the return on investment was over 100% within five years of ownership. In comparison to high-priced items, the return was a staggering 117% by the end of the first year. Within three years, the return grew to 552%. It should again be pointed out that all estimates for the purpose of this study remained conservative, but a consumer's willingness to accept the perceived risk of such an investment is based largely on their discount rate, not a comparison to their other available investment options.

Discount rate, a frequent point of contention in the literature, has been confirmed to vary among consumers depending on factors including income, race, and education [45]. For instance, with increasing consumer education the discount rates used for decision-making decreases [45]. High, triple-digit discount rates have been used as some studies have attempted to determine "implicit consumer discount rates" [45–49]. The lack of information and consumer illiteracy regarding alternative investments (e.g., energy consumption information) has contributed to the greater trend of the un-educated and poorly educated making unfavorable economic decisions, thus lending to higher observed discount rates [49]. Previous studies such as [46] and modern studies have erroneously argued for the application of implicit discount rates (e.g., 27% to 102%) to low and median-income households, reserving low discount rates for the efficiency standards for high-income households [50].

The unattainability of three-digit returns on low-risk investment opportunities to the lower and middle class highlight the implausibility of such policy recommendations, and if adopted would advance the ignorant dialogue of economic errors commonly observed in the American lower and middle class. By quantifying the time value for money and risk associated with future cash flow, it is possible to establish a model of discount rates. In the closest investment analog, the U.S. Department of Energy (DOE) has looked at consumers treating home energy conservation measures as investments. The DOE has established a set of energy efficiency standards for common household appliances, and in order to economically justify investment in reducing electrical consumption, a sensitivity analysis was performed. The discount rate in the study was conservative, varying from 3% to 7% [51]. A 3% "social rate of time preference" was approximated to mirror the average saving rate using the real rate of return on long-term government debt [52]. In this way, a model can be established for how American consumers value current and future consumption. The 7% limit was set as the marginal rate of return on an average stock market investment prior to taxes [51]. Thus, in general 1% to 7% should be used in the sensitivity analysis by determining the amount of printing a prosumer would need to do at the average savings per print found in this study to reach a 1% and 7% return to break even. As can be seen by the results, the ROI from distributed manufacturing with 3-D printers surpasses these rates by orders of magnitude and are even competitive with the implicit consumer discount rates. This indicates that sales of prosumer 3-D printers will continue to climb as discussed in the next section.

It should also be pointed out that the return on a 3-D printer investment by a consumer is all tax free as they represent a reduction in consumer spending. In addition, consumers would reduce their personal taxes in a second way as they would only pay taxes on the investment of the 3-D printer and the filament. Thus they would avoid the sales taxes on all substituted products. These savings along with the savings on shipping were not included here, but would only assist in driving the ROIs for the purchase of a 3-D printer higher for an individual consumer.

4.2. Macroeconomic Advantages of Home Manufacturing

Despite the relatively low 0.7% growth of the United States economy in the final quarter of 2015, consumer spending remained steady due to a steady gain in jobs and rising wages [53,54]. Consumers remained cautious in 2015 as personal saving rates reached at or near their highest levels since 2012, laying the groundwork for economically beneficially and innovative technology to penetrate the at-home consumer market [55]. This trend contributed to projected consumer trends in 2016 including the automated creation of ideas and designs, resource sharing, and personalization [56,57]. Accessible additive manufacturing with new lower-cost 3-D printers, such as the Lulzbot Mini used as an example in this study, fit into this trend, providing the average consumer with an economic alternative to commercial purchasing and a platform through which to innovate and collaborate with other users. The high return on investment values calculated from this study show a clear advantage to the average consumer, even when compared to low-priced commercial alternatives.

Furthermore, the transition of additive manufacturing from industry to the consumer market has followed the growing trend of conscious consumerism [58]. By providing a means by which to make products, consumers develop a heightened level of responsibility and become more selective in their consumerism [59]. In addition, it is clear that distributed AM represents an environmental benefit because of reduced material use, transportation, and the elimination of packaging [60–62], and a growing contingent of responsible consumers are considering environmental concerns into their purchase decisions [63–67]. This has encouraged a more vibrant do-it-yourself (DIY) community, one that is driven not only by saving money but also by the enjoyment of the experience [68]. DIY production implies a negative impact on government tax income, which needs to be investigated in more detail in the future. In addition, there could be an impact on employment/unemployment rates through its substitution within industrial production/increase in at-home businesses, which needs to be further investigated. Early analysis [69] saw at-home additive manufacturing's niche use for customizable, small, high-value items. However, 3-D printing can be used for far more than such a limited range of products as shown in this study. Low-cost 3-D printers have enabled emerging additive manufacturing technology to transition from industry and academia to the average consumer, resulting in a market that has exploded from 66 purchased printing units in 2007 to 23,265 units in 2011 [70]. Improvements have made this technology both technically accessible and economically advantageous to the consumer market [25].

Significant savings at the macroscopic level appears to already be occurring for early-adopting prosumers. The savings of just the 26 printed items used as examples in this study have already saved consumers over $4 million when the number of downloads recorded on Thingiverse.com and Youmagine.com are combined and compared to high priced retail goods. As many designers post their files on other depository sites in addition to free and open access pages, these estimates are again conservative values. It is noteworthy that these two websites have over 2 million free and open source designs, while dozens of other repositories exist [71]. The values found in this paper indicate that distributed manufacturing by prosumers could have a substantial economic impact in the near future as the number of 3-D printer users and free designs continue to climb. Furthermore, the items selected for the purpose of this study were not placed in the greater context of item popularity which would further increase the download rate and thus the projected savings. Finally, it should be noted that the items were all freely accessible having been created by a global network of makers and shared under open licenses. In the analysis, the operation cost per minute (filament plus electricity) was calculated to total $0.08/min for all 26 items. This did not include personnel costs as would normally be calculated for a business manufacturing an item. The user time is truly limited as operation requires a "time investment" equivalent to approximately the cost of time for online shopping thanks to pre-made designs (e.g., instead of inputting credit card information, prosumers download the stl and click print). Thus, here it was ignored because when using the quick print settings, as soon as the stl is loaded, the user clicks print and can then walk away and has no active participation in the manufacturing. In general it takes less than 1 minute to load an stl, have it slice in Cura, and click print (it should noted, that large complex designs take longer to slice). Thus for this study, it can be assumed that roughly half an hour of user time was invested and thus the prosumer's hourly rate for making their own products was over $500/h to over $2,600/h based on low and high value product estimations, respectively. In some cases, (e.g., the last two designs) it appears to be the 3-D equivalent of 'fan art'. The reality of the ease with which this is done challenges both the premise of patent law [72] as well as the viability of current intellectual property laws covering trademarks and copyright. Significant future work is needed to determine how to optimize the use of the concepts of intellectual property to maximize the public benefit.

4.3. Limitations and Future Work

There are several areas of technical study that would improve the viability of distributed manufacturing with 3-D printers including: (1) materials selection; (2) reliability; and (3) first costs.

First, the range of materials would expand the potential list of products that can be substituted with 3-D printing. Material selection has contributed to the freedom that 3-D printing presents to the average user, but it is far from complete. Not only does a variety of materials available to the average consumer exist, but the environmentally-friendly nature of a filament such as PLA is in line with the transition of consumer markets to green consumerism [73]. This trend could be further supported by adopting new polymer recycling codes to further expand the materials selection while reducing costs without introducing otherwise negative environmental impacts [74]. Furthermore, the lifetime of 3-D printed products is a topic of future work, as negative perceptions of low-lifetime prints could inhibit adoption within the greater manufacturing community.

The reliability of prosumer 3-D printers can be lower than experiences consumers are accustomed to with more mature products. The most common failure mode in fused filament fabrication (FFF) 3-D printing is nozzle clogging during printing due to one or a combination of the following mechanisms: particulate contamination from the printing environment, contamination on the exterior or the interior of the filament, and non-uniform properties of the material within the extruder. In addition, older filament can be brittle and break before entering the extruder, ruining the print. These errors represent catastrophic failures during a print, some of which can be after several hours of printing. Wittbrodt et al. estimated that such errors represented 20% of all prints for new users with a self-built RepRap 3-D printer [25]. Such errors are significantly reduced for systems like the Lulzbot Mini; however, they still exist. To correct that error here, a systematic approach toward troubleshooting was adopted and can be used by inexperienced consumers. First, the filament was removed on heating to extract contaminants from the head and the extrusion head was cleaned. The filament end was cut so that a clean edge was used upon re-insertion. This level of maintenance is possible for most prosumers, but the uptake among consumers can be expected to increase if such tasks are automated/eliminated in the future. As long as well-designed 3-D printable parts are chosen, the error rate is ~0%; however, novice printer users are likely to choose some designs that are not conducive to perfect FFF style printing and then these higher errors should be taken into account. Future work could involve a detailed study of many novice printer users for actual behavior and printable part selection.

In this study it was assumed that the prosumer simply purchased the relatively low-cost printer and filament with cash. As noted in the methods these values would change if purchased on credit. It is not anticipated that the average consumer would utilize credit card financing in order to purchase a printer; however, considering the average purchase interest rate is 12.51% on all accounts and 13.76% on interest-bearing accounts [75], these interest rates are dwarfed by the ROI of 3-D printing products at home as found in the results (e.g., 25% in year 3 and 108% by year 5 when low-range cost values were considered and 552% ROI in year 3 and 986% in year 5).

Finally, although prosumer 3-D printers can easily pay for themselves by printing a modest number of consumer products, prices for most prosumer 3-D printers are still greater than $1000. This price makes them more expensive than the average laptop computer, which limits their market. In addition, there are other motivations to current consumption patterns (e.g., some consumers have been trained by marketers to consider shopping a leisure activity, conspicuous consumption provides positive peer feedback in some demographic groups, and fitting into U.S. consumer culture), which may impact their willingness to adopt distributed manufacturing despite overwhelming economic benefits.

Future work is needed to quantify the downloaded substitution value on all of the currently available free 3-D printable designs along with the possible savings for new types of commercially available materials such as flexible polymers. These studies could be better supported with surveys of users to develop a more refined value of p and a more accurate knowledge of how prosumers utilize their 3-D printers (e.g., rate of use, printing available designs vs. making their own, etc.). In addition, future work could analyze consumers' willingness to purchase a 3-D printer by comparing rational economic savings as was done here to large iconic personal prints for cultural status.

5. Conclusions

This study shows a clear financial advantage to owning and using prosumer-friendly printers. Additive manufacturing has demonstrated a clear advantage in reducing the cost of research equipment, however penetration into consumer markets has proven to be more difficult due to printer usability and print qualities. By employing a printer operator who was relatively unfamiliar to 3-D printing and printing files considered common items used by the average American consumer, this study serves as a representative model for the potential future of 3-D printing in the home. With a calculated return on investment of over 100% within three and one year of ownership when compared to low and high price ranges respectively, this study has shown that 3-D printers are an economically advantageous purchase for the average consumer. In addition, based on the downloaded substitution value of the 26 example products used here already being over $4 million, there is an indication of significant macroeconomic impact in the future as more consumers purchase 3-D printers and use them to fabricate freely available digital designs to offset conventional product purchases.

Supplementary Materials: The following are available online at www.mdpi.com/2227-7080/5/1/7/s1, Table S1: Sources of design files and low and high retail prices.

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