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Article

# Impact of DIY Home Manufacturing with 3D Printing on the Toy and Game Market

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**Abstract:** The 2020 toy and game market is projected to be US\$135 billion. To determine if 3D printing could affect these markets if consumers offset purchases by 3D printing free designs, this study investigates the 100 most popular downloaded designs at MyMiniFactory in a month. Savings are quantified for using a Lulzbot Mini 3D printer and three filament types: commercial filament, pellet-extruded filament, and post-consumer waste converted to filament with a recyclebot. Case studies probed the quality of: (1) six common complex toys; (2) Lego blocks; and (3) the customizability of open source board games. All filaments analyzed saved the user over 75% of the cost of commercially available true alternative toys and over 90% for recyclebot filament. Overall, these results indicate a single 3D printing repository among dozens is saving consumers well over \$60 million/year in offset purchases. The most common savings fell by 40%–90% in total savings, which came with the ability to make novel toys and games. The results of this study show consumers can generate higher value items for less money using the open source distributed manufacturing paradigm. It appears clear that consumer do-it-yourself (DIY) manufacturing is set to have a significant impact on the toy and game markets in the future.

**Keywords:** toy industry; additive manufacturing; 3D printing; consumer; economics; open-source

## 1. Introduction

After 20 years of legal intellectual monopoly, the fused filament fabrication (FFF) technology of additive manufacturing (AM), where a single layer of polymer is deposited after another, was unshackled by the open source release of the self-REplicating RAPid prototyper 3D printer (RepRap) [1–3]. This open source hardware approach [4] led to a rapid technical evolution, which resulted in aggressive cost declines and the desktop 3D printer market emerged [5], dominated by various RepRap derivative machines [6,7]. Early adopters of these 3D printers were largely used for prototyping and the maker community, but this has morphed into peer production [8]. Digital peer-production with RepRaps found an eager audience among scientists to develop experimental tools [9–12]. In addition, teachers adopted the technology looking for high-quality educational experiences for their students [13–17] as well as those looking for economic sustainable development with appropriate technologies [18,19]. Sales of desktop 3D printers, however, are now moving towards the mass consumer market [6].

A pair of recent studies indicate that 3D printing technology is lucrative to adopt for average consumers. In the first study, the purchase of US\$500 components of a RepRap were justified by printing a handful of consumer products [20]. However, not all consumers are technically sophisticated makers able to build such a complex mechatronic technology alone, so a second study [21] looked

at the use of an open source fully-assembled 3D printer (Lulzbot Mini, which retails for US\$1250). The costs of printing 26 free designs were compared with purchasing commercial equivalents and the study found that producing consumers would earn nearly a 1000% return on investment (ROI) from the purchase of a 3D printer over a printer lifetime of five years printing out only one product a week [21]. In addition, it appeared that consumers had already offset over \$4 million in purchases only from those random 26 products, which indicates that as 3D printer use in the home becomes more widespread, distributed manufacturing with open source designs could begin to have a significant macroeconomic impact [21]. There is significant skepticism of this potential [22] as the Foxconn CEO famously referred to 3D printers as “a gimmick” [23] and popular representations of 3D printers used only for toys in the home. However, the toy market is substantial and is not so easily dismissed, with the U.S. average spending per child on toys being \$371/year [24] resulting in a U.S. market of more than US\$10 billion/year [25] in 2013. In 2016, the NPD Group’s Retail Tracking Service noted that the U.S. toy market had grown to \$20.36 billion [26] and the global toys and games market is projected to reach US\$135 billion by 2020 [27]. What are the effects on these markets if consumers are offsetting purchases of products like toys with 3D printing and free designs now?

To probe the potential economic impact of home use of 3D printing technology, this study closely investigates consumer use of a popular free website (MyMiniFactory) for 3D printable products. An economic analysis is performed from the perspective of users producing toys for themselves in their own homes. Specifically, the economic savings of the top 100 most popular designs as indicated by downloads (not views) on MyMiniFactory are quantified for January 2017. These savings are quantified using the sliced mass of filament and electricity consumption of a Lulzbot Mini 3D printer, the U.S. average electricity rate and three prices of filament: (1) the most popular filament sold on Amazon; (2) the use of a plastic extruder to make filament from commercial plastic pellets; and (3) the use of a home recyclebot to convert waste post-consumer waste into filament. The type of product is also evaluated and, because of the preponderance of products that can be classified as toys and games, three detailed case studies are undertaken. First, six common toys with equivalent products are evaluated in detail for functionality and value. Next, as Lego currently dominates the toy market [28] an economic evaluation is run using 3D printers only as Lego-compatible block factories. Finally, the costs and customizability are evaluated for an open source board game. Overall, the results are discussed in the context of distributed manufacturing in consumer homes and economics of do-it-yourself (DIY) production.

## 2. Materials and Methods

### 2.1. Download Value Quantification

A selection of items comprised of the 100 most downloaded files in January 2017 from MyMiniFactory, a repository for free 3D printable objects, was selected for analysis. The design and number of downloads ( $N_d$ ) is shown in Table 1.

**Table 1.** Most popular designs downloaded on MyMiniFactory in January 2017.

Open Source 3D Printed Design	URL ( <a href="http://www.myminifactory.com/object">www.myminifactory.com/object</a> )	$N_d$
Pokemon Go aimer	pokeball-aimer-pokemon-go-23009	20583
Clash of Clans barbarian	barbarian-lv-1-clash-of-clans-858	8107
Voltron figure	voltron-defender-of-the-universe-22430	3881
Overwatch tracer gun	tracer-gun-overwatch-19011	3602
Overwatch reaper mask	reaper-mask-19004	3457
Overwatch McCree revolver	updated-mccree-revolver-by-jeff-lagant-not-me-19543	3303
Star Wars AT-AT	detailed-at-at-17606	3218
Last Word Destiny Hand Cannon	destiny-last-word-exotic-hand-cannon-6546	3140
Overwatch D.VA Light Gun	d-va-s-light-gun-18920	3135
Overwatch Reaper Shotgun	reaper-s-hellfire-shotguns-overwatch-19096	2943
Batman cowl	batman-cowl-20596	2926
Destiny Hawkmoon gun	destiny-hawkmoon-exotic-hand-cannon-6545	2885

Table 1. Cont.

Open Source 3D Printed Design	URL ( <a href="http://www.myminifactory.com/object">www.myminifactory.com/object</a> )	N <sub>d</sub>
Destiny thorn gun	thorn-from-destiny-4494	2846
Star Wars VII Storm Trooper Helmet	star-wars-storm-trooper-vii-fully-wearable-helmet-12992	2588
Kylo Ren helmet	jj-industries-kylo-ren-helmet-14106	2451
Wall outlet shelf	wall-outlet-shelf-6382	2350
Kylo Ren lightsaber	kylo-ren-s-lightsaber-star-wars-6791	2347
Blade Runner blaster	deckards-blaster-blade-runner-5694	2337
Fallout 3 T45-d helmet	fallout-3-t45-d-power-armor-helmet-15253	2318
Venus de Milo figurine	venus-de-milo-at-louvre-paris-1657	2073
Warcraft Frostmourne sword	frostmourne-from-warcraft-4156	1999
3DR Iris+ quadcopter	3drobotics-iris-19615	1871
Pieta figurine	pieta-in-st-peter-s-basilica-vatican-3796	1862
P08 Luger gun	p08-luger-functional-assembly-5545	1798
Game of Thrones iron throne	game-of-thrones-iron-throne-1945	1786
The Thinker figurine	the-thinker-at-the-muse-rodin-france-2127	1755
Overwatch McCree Peacemaker gun	mccree-peacemaker-overwatch-19152	1723
Fallout 4 Pipboy 3000 MkIV	fallout-4-pipboy-3000-mkiv-16884	1705
Articulated lamp	articulated-lamp-6790	1704
Overwatch throwing star	genji-s-shuriken-18918	1695
Strong bolt	support-free-bolt-1281	1571
Mazinger Z Super Robot	mazinger-z-super-robot-24533	1570
Secret shelf	secret-shelf-3504	1564
Sombra pistol	sombra-s-machine-pistol-25186	1544
Han Solo blaster	han-solo-s-blaster-star-wars-1546	1520
Overwatch D.VA headset	d-va-headset-22077	1502
Overwatch Mercy staff	mercy-s-staff-22079	1484
Overwatch Mercy blaster	mercy-s-caduceus-blaster-18912	1481
Han Solo blaster	hans-solo-blaster-2488	1461
Gears of War Chainsaw gun	gears-of-war-lancer-chainsaw-gun-11478	1437
Destiny Duke MK.44 gun	duke-mk-44-hand-cannon-from-destiny-2140	1418
Fallout 4 Laser pistol	fallout-4-laser-pistol-18978	1417
Overwatch loot box	overwatch-loot-box-21670	1412
Cat at British Museum	gayer-anderson-cat-at-the-british-museum-london-4010	1364
Halo 5 assault rifle	halo-5-assault-rifle-11734	1334
Portal gun	portal-gun-18342	1328
Destiny hawkmoon gun	hawkmoon-from-destiny-full-scale-and-moving-6863	1327
Clash of Clans figurine	p-e-k-k-a-lv-1-clash-of-clans-857	1314
Harry Potter elder wand	dumbledore-s-elder-wand-2057	1299
Groot flower pot	baby-groot-flower-pot-gardens-of-the-galaxy-2-26442	1269
Melted Darth Vader mask	darth-vader-melted-mask-6685	1264
Fallout 4 10mm pistol	fallout-4-10mm-pistol-10475	1264
Starcraft Kerrigan statue	starcraft-kerrigan-statue-10432	1263
Destiny ghost	destiny-ghost-6038	1248
Lich king figurine	the-lich-king-6174	1212
Micro game bit	micro-bit-game-bit-13822	1199
Ant Man helmet	ant-man-mask-wearable-5322	1193
Game of Thrones House emblem	house-stark-game-of-thrones-1154	1182
Planetary gears	planetary-gears-1557	1163
Clash of Clans king figure	barbarian-king-clash-of-clans-871	1160
Tooth toothbrush holder	the-big-tooth-2-0-5759	1141
Halo 3 ODST helmet	halo-3-odst-helmet-wearable-cosplay-17614	1134
Fallout 4 procteron figure	fallout-4-procteron-action-figure-15585	1129
BFG Doom	bfg-21395	1122
Discobolus figurine	discobolus-at-the-british-museum-london-7896	1118
Anonymous mask	guy-fawkes-anonymous-mask-2582	1092
Guardian of the Galaxy Star Lord mask	guardians-of-the-galaxy-star-lord-s-mask-version-2-3045	1091
Pokeball	pokeball-high-detail-version-23506	1064
Witcher 3 wall plaque	the-witcher-3-wall-plaque-8882	1063
Overwatch widomaker rifle	overwatch-widomaker-sniper-rifle-21702	1029
Fallout 4 combat rifle and shotgun	fallout-4-combat-rifle-and-combat-shotgun-18428	1025
Michelangelo's David	micelangelo-s-david-in-florence-italy-2052	1023
Destiny ghost	ghost-destiny-2396	1022
Triceratops skull	triceratops-skull-in-colorado-usa-6225	1019
Skull ring	skull-ring-20782	1014
Star Wars NN-44 Rey's Blaster	star-wars-nl-44-reys-blaster-17422	1012
Joker mask	joker-mask-9743	1010
Fork/spoon support for disability	fork-and-spoon-support-for-person-with-disabilities-5480	1007
BFG Doom	bfg-parts-19092	1006
Gryffindor coat of arms	gryffindor-coat-of-arms-wall-desk-display-harry-potter-11834	994
Destiny Gjallahorn	gjallarhorn-2-0-destiny-19160	985
Pokemon figurines	low-poly-pokemon-collection-15905	983
Rubik's cube	3d-printable-rubik-s-cube-9734	980
Destiny bad juju pulse rifle	destiny-s-bad-juju-exotic-pulse-rifle-6618	977
Fallout 4 Kellogg's pistol	kellogg-s-pistol-fallout-4-21556	975
Dobby the Elf figurine	dobby-from-harry-potter-full-model-3294	970
Statue of Liberty figurine	statue-of-liberty-in-manhattan-new-york-2077	960
Nutcracker	nutcracker-v2-4361	946
Minions figurines	minion-movie-trio-10140	940
Destiny sleeper simulant	the-sleeper-simulant-from-destiny-14769	930

Table 1. Cont.

Open Source 3D Printed Design	URL ( <a href="http://www.myminifactory.com/object">www.myminifactory.com/object</a> )	N <sub>d</sub>
Frozen Elsa figurine	elsa-from-disney-s-frozen-6573	919
Star Wars storm trooper rifle	blaster-rifle-star-wars-storm-trooper-12097	914
Vitruvian Man sculpture	the-vetruvian-man-sculpture-at-belgrave-square-london-1669	908
Robocop ED209 figure	ed209-from-robocop-5090	904
Harry Potter wand	harry-potter-s-wand-10391	898
Cable guards	icableguards-21235	894
Game of Thrones dice cup	stark-dice-cup-1847	893
Overwatch McCree flashbang	mccree-flashbang-from-overwatch-21595	890
B2 bomber glider	b2-stealth-bomber-glider-improved-flight-powered-by-an-elastic-band-13337	886
Star Wars X Wing helmet	x-wing-pilot-helmet-starwars-episode-vii-the-force-awakens-9074	859

The items were uploaded into Cura 15.04.6 (Ultimaker, Geldermalsen, The Netherlands) [29] and the resulting data regarding estimated print time, item weight, and length of the filament used were recorded. In addition, a 3-mm poly lactic acid (PLA) was selected as the filament because it is the most common household consumer 3D printing material and is available from most 3D printing suppliers. PLA has gained prominence, as not only does it demonstrate less warping during printing than other materials such as the second most common 3D printing plastic (ABS, acrylonitrile butadiene styrene), but the emissions during printing are less pungent [30,31]. Furthermore, PLA is made from corn-based resin, making it non-toxic, biodegradable, and able to be produced in environmentally friendly, renewable processes [32]. The items were then categorized into three groups using commercial PLA: (1) those that saved the consumer money when compared to a commercially available alternative product; (2) those that lost money because a less expensive product was available; and (3) those for which there was no alternative product. Items ranged from action figures and masks to non-toy items and cosplay paraphernalia as seen in Table 1.

A commercial price 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 plastic filament). Following [21], the operating cost (O) for the Lulzbot Mini [33] was calculated using electricity and filament consumption during printing with 15% infill. The average electric rate in the United States was found to be \$0.1267 per kWh for the residential sector [34]. A sensitivity was run on the cost of the filament ( $C_{F(\text{source})}$ ) using:

(1) the most popular filament sold on Amazon.com,  $C_{F(\text{filament})}$  is US\$23/kg [35];

(2) the use of a plastic extruder such as a commercial systems (e.g., Filastruder, FilaFab, Noztek, Filabot, EWE, Extrusionbot, Filamaker, Strooder, Felfil, ExtrusionBot) to make filament from commercial PLA pellets (source)  $C_{F(\text{pellets})}$  is US\$5.50/kg [36];

(3) the use of a home recyclebot (waste plastic extruder) to convert waste post-consumer waste plastic into filament [37]  $C_{F(\text{waste})}$  (which can be as low as a few cents per kg in horizontal recyclebots) for ABS in vertical recyclebot in another study it was found to be US\$2.16/kg [38] and will be used here to be conservative.

The operating cost, O, of a 3D printer was calculated as follows:

$$O = EC_E + \frac{C_F m_f}{1000} [\text{USD}], \quad (1)$$

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 cost of a given filament in USD/kg, and  $m_f$  is the mass of the filament in grams consumed during printing. The marginal savings on each project,  $C_s$ , is given by:

$$C_s = C_c - O \quad [\text{USD}], \quad (2)$$

where  $C_C$  is the cost of the commercially available product and the marginal percent change,  $P$ , between the cost to print a product and the commercially available product was calculated as follows:

$$P = \frac{C_S}{C_C} \times 100[\%], \quad (3)$$

where  $C_C$  is the cost for the commercial product at either the high or low price. Finally, the value obtained from a free and open source 3D printable design can be determined from the [39,40] at a specific time ( $t$ ):

$$V_D(t) = C_S \times P \times N_d(t)[\text{USD}], \quad (4)$$

This value is determined by the number of downloads ( $N_d$ ) during January 2017 and  $P$  where is the percent of downloads resulting in a print. It should be pointed out that  $P$  is subject to error as downloading a design does not guarantee manufacturing. 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 and the total savings found over MyMiniFactory in 1 month on the top 100 downloaded items is determined by:

$$V_{DT}(t) = \sum_{i=0}^{100} V_D(t)[\text{USD}]. \quad (5)$$

Three case studies are then presented to probe the economics of individual types of toys and games.

## 2.2. Case Studies

### 2.2.1. Six Toy Product Comparisons

As is clear from Table 1, the most popular types of 3D printable design are niche-community toys (e.g., gamers, cosplay, etc.). Six more common toy products with existing free designs on MyMiniFactory were selected for more detailed comparisons attractive to a wider audience. Printing costs for these toys were estimated using \$24/kg filament and the closest commercial equivalent was found online. The toys are compared visually and the savings percent is calculated by Equation (3), where it is conservatively assumed to be zero (e.g., the electricity cost was ignored).

### 2.2.2. Lego Case Study

Lego is one of the top five leading toy industry manufacturers with 5% of the market [41]. Lego's signature toy is manufactured to exacting specifications from ABS, a common consumer polymer. In a past study, on average, a single Lego piece costs \$0.104 USD, and the average cost of a Lego set without pieces, thereby the cost of the box and printed instructions, is \$7.34 [42]. It should be pointed out that, in consideration of their larger size intended for small children, Duplo blocks and thus Duplo sets are more expensive at \$0.63 per brick. When grouped into themes, it was found that Lego city-themed and architecture-themed sets had the lowest base cost while Marvel-themed sets had a base cost of \$3.61 per piece [42].

The study by Allain is expanded here to look at the cost per block in the 10 most popular Lego kits at Wal-Mart. The cost to print a  $3 \times 2$  block is then determined. The 3D printed blocks are then tested and compared to Lego blocks and generic Lego-compatible commercial blocks on a quality and price basis.

### 2.2.3. Board Game Comparison

The hobby games market is more than US\$1.2 billion, with the hobby game board market having grown 56% from \$160 million in 2014 to \$250 million in 2015 [43]. ICv2 CEO Milton Griep has claimed that there is often a transition from digital games to tabletop games when users are more interested in

face-to-face interaction [44]. The global board games market is expected to experience a 29% growth over the period from 2017 to 2021, largely due to increased popularity amongst the adult consumer demographic [45]. Three market trends—the growth of organized retail, increase in projects funded through crowdsourcing, and game evolution with time—have been cited as driving forces behind this projected growth. Here again, 3D printing can be used to manufacture board games at home. Technavio points out that 3D printing have been shown to boost the sales of board games [45]. To demonstrate the feasibility and compare the costs to a traditional board game, an open source game, ‘Save the planet’ board game hosted on Appropedia [46] has been selected. The costs to commercially print out the board and the cards is quantified from a professional print shop and compared to 2D printing on paper by a home printer. Then, the costs for the dice and four player pieces are determined by printing and weighing on a digital scale ( $\pm 0.1$  g) and assuming filament costs from above. These costs are compared to the top ten board games by sales on Amazon [47].

### 3. Results and Discussion

#### 3.1. Downloaded Value

##### 3.1.1. Microeconomic Advantages of Home Manufacturing

When the cost was calculated for each designed item printed with each of the filaments as described in the Methods section, the recyclebot-produced filament proved to demonstrate the greatest savings for the user. By using an at-home recyclebot or extruder-produced pellets, printing costs can be significantly reduced, and even using more expensive filament found on Amazon demonstrates savings when compared to equivalent, commercially available products. Table 2 shows the cost of each design printed in each of the three filaments as well as the cost of the commercially available product equivalent. On average, printing the items in Amazon filament cost \$9.28 while printing in pellets and recyclebot filament cost on average \$2.59 and \$1.31, respectively. Table 2 shows a clear financial advantage to the consumer in printing items as opposed to purchasing them as shown by the printing cost with recyclebot filament costing on average a mere 3.09% of the cost to purchase. Even when compared to the more expensive Amazon filament, printing costs, on average, only 22% of the cost to purchase. It should also be noted here (and is shown in Section 3.3) that for applications such as toys there is not a noticeable tradeoff between quality and cost of filament. A tuned recyclebot can produce filament with equivalent visual quality to commercial filament.

**Table 2.** Cost of producing toys and benchmark purchase price (US \$).

Design	Mass (g)	Cost: Commercial Filament	Cost: Pellet	Cost: Recyclebot	Commercially Available Alternative (USD)
Pokemon Go aimer	27	\$0.66	\$0.18	\$0.09	\$4.99
Clash of Clans barbarian	21	\$0.51	\$0.14	\$0.07	\$19.00
Voltron figure	1247	\$30.26	\$8.44	\$4.27	\$9.99
Overwatch tracer gun	190	\$4.61	\$1.29	\$0.65	\$26.59
Overwatch reaper mask	333	\$8.08	\$2.25	\$1.14	\$25.00
Star Wars AT-AT	683	\$16.57	\$4.62	\$2.34	\$7.50
Last Word Destiny Hand Cannon	367	\$8.91	\$2.48	\$1.26	\$100.00
Overwatch D.VA Light Gun	261	\$6.33	\$1.77	\$0.89	\$55.00
Overwatch Reaper Shotgun	269	\$6.53	\$1.82	\$0.92	\$40.38
Batman cowl	147	\$3.57	\$0.99	\$0.50	\$6.76
Destiny Hawkmoon gun	473	\$11.48	\$3.20	\$1.62	\$99.99
Destiny thorn gun	425	\$10.31	\$2.88	\$1.46	\$17.99
Star Wars VII Storm Trooper Helmet	948	\$23.01	\$6.42	\$3.25	\$20.20
Kylo Ren helmet	550	\$13.35	\$3.72	\$1.88	\$4.08
Wall outlet shelf	69	\$1.67	\$0.47	\$0.24	\$10.00
Kylo Ren lightsaber	319	\$7.74	\$2.16	\$1.09	\$20.00
Blade Runner blaster	249	\$6.04	\$1.68	\$0.85	\$12.99
Fallout 3 T45-d helmet	1586	\$38.49	\$10.73	\$5.44	\$185.91
Venus de Milo figurine	28	\$0.68	\$0.19	\$0.10	\$9.00

Table 2. Cont.

Design	Mass (g)	Cost: Commercial Filament	Cost: Pellet	Cost: Recyclebot	Commercially Available Alternative (USD)
Warcraft Frostmourne sword	1233	\$29.92	\$8.34	\$4.23	\$133.00
3DR Iris+ quadcopter	255	\$6.19	\$1.73	\$0.87	\$13.89
Pieta figurine	164	\$3.98	\$1.11	\$0.56	\$16.88
P08 Luger gun	138	\$3.35	\$0.93	\$0.47	\$79.00
Game of Thrones iron throne	124	\$3.01	\$0.84	\$0.42	\$15.25
The Thinker figurine	92	\$2.23	\$0.62	\$0.32	\$22.32
Overwatch McCree Peacemaker gun	301	\$7.30	\$2.04	\$1.03	\$69.99
Fallout 4 Pipboy 3000 MkIV	884	\$21.45	\$5.98	\$3.03	\$74.99
Articulated lamp	180	\$4.37	\$1.22	\$0.62	\$7.97
Overwatch throwing star	13	\$0.32	\$0.09	\$0.04	\$6.99
Strong bolt	9	\$0.22	\$0.06	\$0.03	\$19.14
Mazinger Z Super Robot	117	\$2.84	\$0.79	\$0.40	\$9.99
Sombra pistol	495	\$12.01	\$3.35	\$1.70	\$85.00
Han Solo blaster	216	\$5.24	\$1.46	\$0.74	\$10.12
Overwatch D.VA headset	65	\$1.58	\$0.44	\$0.22	\$18.99
Overwatch Mercy staff	1768	\$42.90	\$11.96	\$6.06	\$165.89
Overwatch Mercy blaster	411	\$9.97	\$2.78	\$1.41	\$19.49
Gears of War Chainsaw gun	1556	\$37.76	\$10.53	\$5.33	\$199.99
Destiny Duke MK.44 gun	325	\$7.89	\$2.20	\$1.11	\$125.00
Fallout 4 Laser pistol	1322	\$32.08	\$8.95	\$4.53	\$89.99
Overwatch loot box	124	\$3.01	\$0.84	\$0.42	\$8.98
Cat at British Museum	62	\$1.50	\$0.42	\$0.21	\$75.99
Halo 5 assault rifle	2295	\$55.69	\$15.53	\$7.86	\$50.00
Portal gun	1528	\$37.08	\$10.34	\$5.24	\$279.99
Clash of Clans figurine	2	\$0.05	\$0.01	\$0.01	\$29.99
Harry Potter elder wand	17	\$0.41	\$0.12	\$0.06	\$4.79
Groot flower pot	57	\$1.38	\$0.39	\$0.20	\$8.99
Meltd Darth Vader mask	172	\$4.17	\$1.16	\$0.59	\$8.00
Fallout 4 10mm pistol	793	\$19.24	\$5.37	\$2.72	\$24.99
Starcraft Kerrigan statue	112	\$2.72	\$0.76	\$0.38	\$55.79
Destiny ghost	116	\$2.81	\$0.78	\$0.40	\$7.00
Lich king figurine	487	\$11.82	\$3.30	\$1.67	\$15.00
Ant Man helmet	367	\$8.91	\$2.48	\$1.26	\$44.59
Game of Thrones House emblem	34	\$0.83	\$0.23	\$0.12	\$9.95
Clash of Clans king figure	24	\$0.58	\$0.16	\$0.08	\$19.00
Tooth toothbrush holder	120	\$2.91	\$0.81	\$0.41	\$2.00
Halo 3 ODST helmet	1118	\$27.13	\$7.57	\$3.83	\$9.99
Fallout 4 protectron figure	98	\$2.38	\$0.66	\$0.34	\$24.99
Discobolus figurine	35	\$0.85	\$0.24	\$0.12	\$7.25
Anonymous mask	383	\$9.29	\$2.59	\$1.31	\$4.95
Guardian of the Galaxy Star Lord mask	351	\$8.52	\$2.38	\$1.20	\$5.99
Pokeball	221	\$5.36	\$1.50	\$0.76	\$1.00
Witcher 3 wall plaque	100	\$2.43	\$0.68	\$0.34	\$45.00
Overwatch widowmaker rifle	1364	\$33.10	\$9.23	\$4.67	\$145.89
Fallout 4 combat rifle and shotgun	351	\$8.52	\$2.38	\$1.20	\$85.00
Michelangelo's David	75	\$1.82	\$0.51	\$0.26	\$29.93
Triceratops skull	66	\$1.60	\$0.45	\$0.23	\$40.00
Skull ring	5	\$0.12	\$0.03	\$0.02	\$9.95
Star Wars NN-44 Rey's Blaster	141	\$3.42	\$0.95	\$0.48	\$45.00
Joker mask	751	\$18.22	\$5.08	\$2.57	\$11.56
Fork/spoon support for disability	17	\$0.41	\$0.12	\$0.06	\$11.00
Gryffindor coat of arms	48	\$1.16	\$0.32	\$0.16	\$8.00
Pokemon figurines	63	\$1.53	\$0.43	\$0.22	\$30.00
Rubik's cube	12	\$0.29	\$0.08	\$0.04	\$4.99
Fallout 4 Kellogg's pistol	152	\$3.69	\$1.03	\$0.52	\$100.00
Dobby the Elf figurine	365	\$8.86	\$2.47	\$1.25	\$31.36
Statue of Liberty figurine	85	\$2.06	\$0.58	\$0.29	\$6.44
Nutcracker	61	\$1.48	\$0.41	\$0.21	\$4.99
Minions figurines	121	\$2.94	\$0.82	\$0.41	\$26.80
Destiny sleeper simulat	1274	\$30.92	\$8.62	\$4.37	\$211.66
Frozen Elsa figurine	33	\$0.80	\$0.22	\$0.11	\$7.99
Star Wars storm trooper rifle	486	\$11.79	\$3.29	\$1.67	\$170.00
Vitruvian Man sculpture	12	\$0.29	\$0.08	\$0.04	\$31.49
Robocop ED209 figure	736	\$17.86	\$4.98	\$2.52	\$21.99
Harry Potter wand	8	\$0.19	\$0.05	\$0.03	\$13.55
Cable guards	7	\$0.17	\$0.05	\$0.02	\$1.25
Game of Thrones dice cup	59	\$1.43	\$0.40	\$0.20	\$8.32
B2 bomber glider	20	\$0.49	\$0.14	\$0.07	\$10.57
Star Wars X Wing helmet	949	\$23.03	\$6.42	\$3.25	\$41.40
Hawkmoon #2	621	\$15.07	\$4.20	\$2.13	\$99.99
Destiny ghost #2	48	\$1.16	\$0.32	\$0.16	\$7.00
Average	382.29	\$9.28	\$2.59	\$1.31	\$42.44
Total	34,406	\$834.93	\$232.83	\$117.91	\$3819.59



Table 3 shows the cost and percent savings calculated for each design in each of the three filament types when compared to their respective commercially available alternative products. As expected based on the results in Table 2, printed items using recyclebot-made filament saved the user significantly more money than printed items using commercial or pellet filament; however, each of the three filament types on average saved the user over 50% of the cost of commercially available alternative toys. When items that cost more to print than purchase were removed, the average cost and percent savings were nearly 75% when using commercial filament and over 90% for pellet-extruded filament and recyclebot filament.

**Table 3.** Cost savings for individual toys (US\$) and percent (%) savings.

Design	Cost Savings (USD)			Percent Savings (%)		
	Commercial Filament	Pellets	Recyclebot	Commercial Filament	Pellets	Recyclebot
Pokemon Go aimer	\$4.33	\$4.81	\$4.90	87%	96%	98%
Clash of Clans barbarian	\$18.49	\$18.86	\$18.93	97%	99%	100%
Voltron figure	\$(20.27)	\$1.55	\$5.72	−203%	16%	57%
Overwatch tracer gun	\$21.98	\$25.30	\$25.94	83%	95%	98%
Overwatch reaper mask	\$16.92	\$22.75	\$23.86	68%	91%	95%
Star Wars AT-AT	\$(9.07)	\$2.88	\$5.16	−121%	38%	69%
Last Word Destiny Hand Cannon	\$91.09	\$97.52	\$98.74	91%	98%	99%
Overwatch D.VA Light Gun	\$48.67	\$53.23	\$54.11	88%	97%	98%
Overwatch Reaper Shotgun	\$33.85	\$38.56	\$39.46	84%	95%	98%
Batman cowl	\$3.19	\$5.77	\$6.26	47%	85%	93%
Destiny Hawkmoon gun	\$88.51	\$96.79	\$98.37	89%	97%	98%
Destiny thorn gun	\$7.68	\$15.11	\$16.53	43%	84%	92%
Star Wars VII Storm Trooper Helmet	\$(2.81)	\$13.78	\$16.95	−14%	68%	84%
Kylo Ren helmet	\$(9.27)	\$0.36	\$2.20	−227%	9%	54%
Wall outlet shelf	\$8.33	\$9.53	\$9.76	83%	95%	98%
Kylo Ren lightsaber	\$12.26	\$17.84	\$18.91	61%	89%	95%
Blade Runner blaster	\$6.95	\$11.31	\$12.14	53%	87%	93%
Fallout 3 T45-d helmet	\$147.42	\$175.18	\$180.47	79%	94%	97%
Venus de Milo figurine	\$8.32	\$8.81	\$8.90	92%	98%	99%
Warcraft Frostmourne sword	\$103.08	\$124.66	\$128.77	78%	94%	97%
3DR Iris+ quadcopter	\$7.70	\$12.16	\$13.02	55%	88%	94%
Pieta figurine	\$12.90	\$15.77	\$16.32	76%	93%	97%
P08 Luger gun	\$75.65	\$78.07	\$78.53	96%	99%	99%
Game of Thrones iron throne	\$12.24	\$14.41	\$14.83	80%	94%	97%
The Thinker figurine	\$20.09	\$21.70	\$22.00	90%	97%	99%
Overwatch McCree Peacemaker gun	\$62.69	\$67.95	\$68.96	90%	97%	99%
Fallout 4 Pipboy 3000 MkIV	\$53.54	\$69.01	\$71.96	71%	92%	96%
Articulated lamp	\$3.60	\$6.75	\$7.35	45%	85%	92%
Overwatch throwing star	\$6.67	\$6.90	\$6.95	95%	99%	99%
Strong bolt	\$18.92	\$19.08	\$19.11	99%	100%	100%
Mazinger Z Super Robot	\$7.15	\$9.20	\$9.59	72%	92%	96%
Sombra pistol	\$72.99	\$81.65	\$83.30	86%	96%	98%
Han Solo blaster	\$4.88	\$8.66	\$9.38	48%	86%	93%
Overwatch D.VA headset	\$17.41	\$18.55	\$18.77	92%	98%	99%
Overwatch Mercy staff	\$122.99	\$153.93	\$159.83	74%	93%	96%
Overwatch Mercy blaster	\$9.52	\$16.71	\$18.08	49%	86%	93%
Gears of War Chainsaw gun	\$162.23	\$189.46	\$194.66	81%	95%	97%
Destiny Duke MK.44 gun	\$117.11	\$122.80	\$123.89	94%	98%	99%
Fallout 4 Laser pistol	\$57.91	\$81.04	\$85.46	64%	90%	95%
Overwatch loot box	\$5.97	\$8.14	\$8.56	66%	91%	95%
Cat at British Museum	\$74.49	\$75.57	\$75.78	98%	99%	100%
Halo 5 assault rifle	\$(5.69)	\$34.47	\$42.14	−11%	69%	84%
Portal gun	\$242.91	\$269.65	\$274.75	87%	96%	98%
Clash of Clans figurine	\$29.94	\$29.98	\$29.98	100%	100%	100%
Harry Potter elder wand	\$4.38	\$4.67	\$4.73	91%	98%	99%
Groot flower pot	\$7.61	\$8.60	\$8.79	85%	96%	98%
Melted Darth Vader mask	\$3.83	\$6.84	\$7.41	48%	85%	93%
Fallout 4 10mm pistol	\$5.75	\$19.62	\$22.27	23%	79%	89%
Starcraft Kerrigan statue	\$53.07	\$55.03	\$55.41	95%	99%	99%
Destiny ghost	\$4.19	\$6.22	\$6.60	60%	89%	94%
Lich king figurine	\$3.18	\$11.70	\$13.33	21%	78%	89%
Ant Man helmet	\$35.68	\$42.11	\$43.33	80%	94%	97%
Game of Thrones House emblem	\$9.12	\$9.72	\$9.83	92%	98%	99%

Table 3. Cont.

Design	Cost Savings (USD)			Percent Savings (%)		
	Commercial Filament	Pellets	Recyclebot	Commercial Filament	Pellets	Recyclebot
Clash of Clans king figure	\$18.42	\$18.84	\$18.92	97%	99%	100%
Tooth toothbrush holder	\$(0.91)	\$1.19	\$1.59	−46%	59%	79%
Halo 3 ODST helmet	\$(17.14)	\$2.42	\$6.16	−172%	24%	62%
Fallout 4 protectron figure	\$22.61	\$24.33	\$24.65	90%	97%	99%
Discobolus figurine	\$6.40	\$7.01	\$7.13	88%	97%	98%
Anonymous mask	\$(4.34)	\$2.36	\$3.64	−88%	48%	73%
Guardian of the Galaxy Star Lord mask	\$(2.53)	\$3.61	\$4.79	−42%	60%	80%
Pokeball	\$(4.36)	\$(0.50)	\$0.24	−436%	−50%	24%
Witcher 3 wall plaque	\$42.57	\$44.32	\$44.66	95%	98%	99%
Overwatch widowmaker rifle	\$112.79	\$136.66	\$141.22	77%	94%	97%
Fallout 4 combat rifle and shotgun	\$76.48	\$82.62	\$83.80	90%	97%	99%
Michelangelo's David	\$28.11	\$29.42	\$29.67	94%	98%	99%
Triceratops skull	\$38.40	\$39.55	\$39.77	96%	99%	99%
Skull ring	\$9.83	\$9.92	\$9.93	99%	100%	100%
Star Wars NN-44 Rey's Blaster	\$41.58	\$44.05	\$44.52	92%	98%	99%
Joker mask	\$(6.66)	\$6.48	\$8.99	−58%	56%	78%
Fork/spoon support for disability	\$10.59	\$10.88	\$10.94	96%	99%	99%
Gryffindor coat of arms	\$6.84	\$7.68	\$7.84	85%	96%	98%
Pokemon figurines	\$28.47	\$29.57	\$29.78	95%	99%	99%
Rubik's cube	\$4.70	\$4.91	\$4.95	94%	98%	99%
Fallout 4 Kellogg's pistol	\$96.31	\$98.97	\$99.48	96%	99%	99%
Dobby the Elf figurine	\$22.50	\$28.89	\$30.11	72%	92%	96%
Statue of Liberty figurine	\$4.38	\$5.86	\$6.15	68%	91%	95%
Nutcracker	\$3.51	\$4.58	\$4.78	70%	92%	96%
Minions figurines	\$23.86	\$25.98	\$26.39	89%	97%	98%
Destiny sleeper simulant	\$180.74	\$203.04	\$207.29	85%	96%	98%
Frozen Elsa figurine	\$7.19	\$7.77	\$7.88	90%	97%	99%
Star Wars storm trooper rifle	\$158.21	\$166.71	\$168.33	93%	98%	99%
Vitruvian Man sculpture	\$31.20	\$31.41	\$31.45	99%	100%	100%
Robocop ED209 figure	\$4.13	\$17.01	\$19.47	19%	77%	89%
Harry Potter wand	\$13.36	\$13.50	\$13.52	99%	100%	100%
Cable guards	\$1.08	\$1.20	\$1.23	86%	96%	98%
Game of Thrones dice cup	\$6.89	\$7.92	\$8.12	83%	95%	98%
B2 bomber glider	\$10.08	\$10.43	\$10.50	95%	99%	99%
Star Wars X Wing helmet	\$18.37	\$34.98	\$38.15	44%	84%	92%
Hawkmoon #2	\$84.92	\$95.79	\$97.86	85%	96%	98%
Destiny ghost #2	\$5.84	\$6.68	\$6.84	83%	95%	98%

Upon review, the items that cost more to print than to purchase (e.g., potentially lost the user money) when compared to commercially available and comparable products were often of noticeably higher value. For example, in Figure 1, the Game of Thrones inspired dice cup shown rendered in Cura is not commercially available but was compared to simple dice cups.

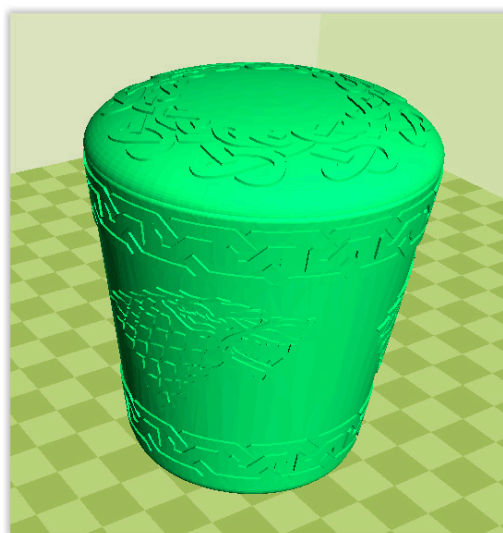


Figure 1. Cura rendering of details of freely available design of a Game of Thrones dice cup.

The majority of the items that cost more to print than to purchase were specialized cosplay items. The term “cosplay” was added to the Oxford English Dictionary in 2008 as “the practice of dressing up as a character from a film, book, or video game, especially one from the Japanese genres of manga or anime” [48]. The appeal of cosplay is largely the expression of individualism within a shared community [49]. Not only does at-home additive manufacturing grant individual users the power to design and build completely customized items, but repositories such as MyMiniFactory provide an outlet for users to share designs and inspire one another in their creativity. Items in this study that did not save the user money when printed in all filaments such as the Voltron figure had dozens of specially designed parts that together made up a customized product of arguably significantly higher quality than the simple commercial alternative.

In addition, 6% of designs had no commercially available alternative either on Walmart.com nor offered by individual makers. Many of these were highly detailed cosplay items that came from specific games. While a cost saving could not be calculated, these items only highlight 3D printing’s ability to allow users unlimited creativity in their work, and MyMiniFactory’s data for these designs’ downloads prove that these items are highly desired by the 3D printing and cosplaying community. Figure 2 shows the average percent savings of the cumulative designs with commercially available alternative elements based on the filaments used to print the items. Items printed with recyclebot-made filament demonstrated the greatest percent savings at 93% when all items were considered and 97% when only items that saved the user money were considered. It is clear that using recycled waste plastic would save consumers more than 90% of the costs of the conventionally-manufactured cost regardless of the circumstances. As 3D printing continues to become a more widely spread at-home activity and investment, filament technology may progress such that many users will utilize waste plastic as opposed to commercially available filament. Given the multi-billion status that is the toy industry, consumers may begin printing toys, games and specialty items in mass, saving substantial amounts of money in comparison to commercially available products.

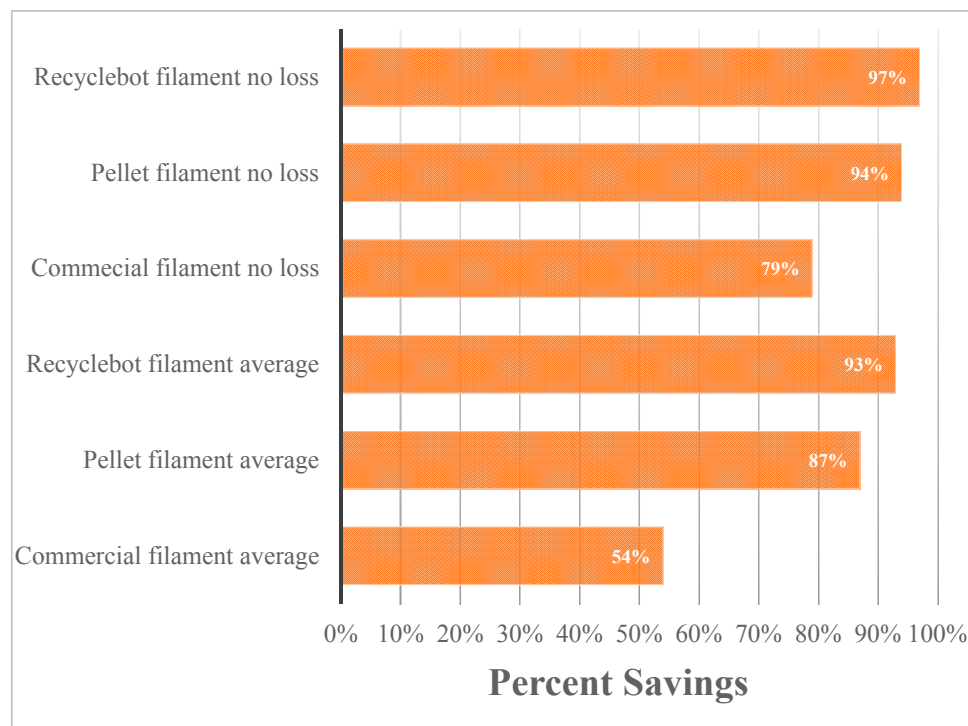


Figure 2. Bar chart showing the percent savings of printing designs with various filament types.

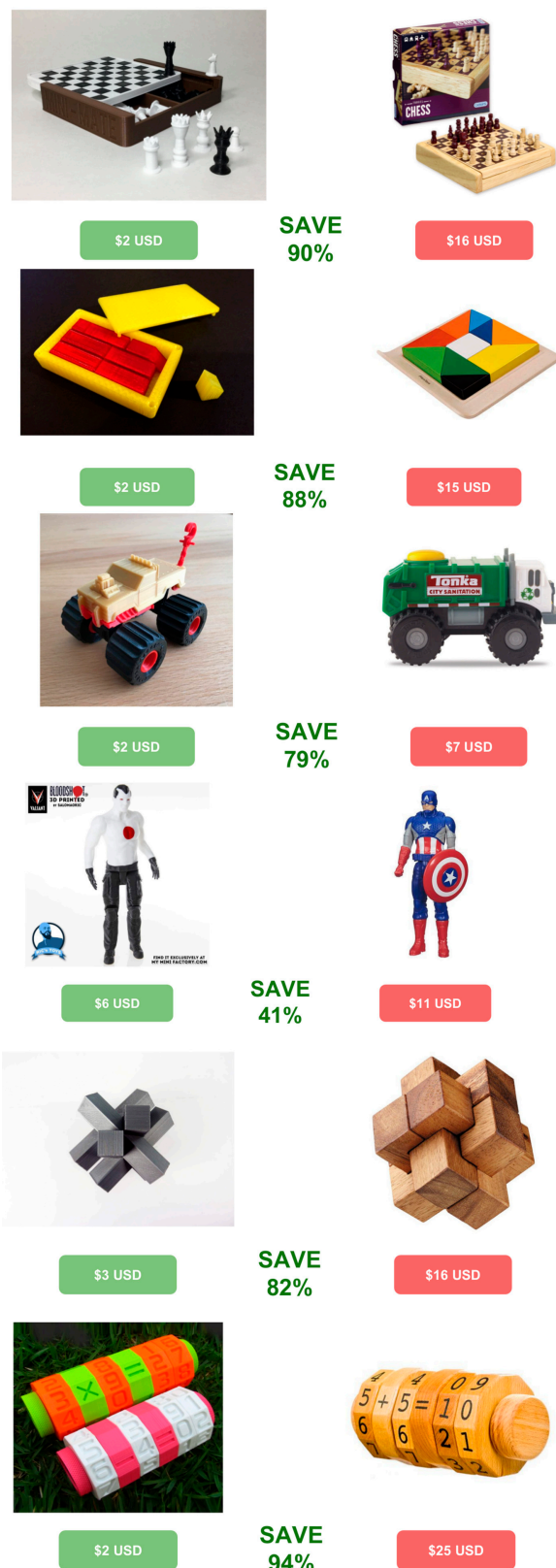
### 3.1.2. Macroeconomic Impact of Home Manufacturing

The total results from Table 3 are the most striking. Over a single month period, MyMiniFactory saved its users more than \$5 million in avoided consumer purchases for only the top 100 downloaded designs. This assumes filament costs \$20/kg or less, which is a reasonable assumption as the most popular filament is \$23/kg and there are many commercial suppliers (even available on Amazon) that are selling filament for less than \$20/kg as well as the much lower costs observed with pellet extruded filament or recyclebot manufactured filament. Extrapolated over a year, these results indicate that MyMiniFactory, just a single 3D printing repository among dozens, is saving consumers over \$60 million a year in offset purchases. Again, this value is conservative as many of the designs discarded from the analysis here would be more (not less) expensive to acquire commercially. In addition, this only considers 100 designs. MyMiniFactory currently has 26,355 published designs as of 30 April 2017 so this study only looked at 0.38%. In addition, this represents, but a small fraction of the overall freely available designs, which is at least several million [21].

It can be safely concluded that the open source 3D printing community is already having more than \$100 million/year on the toy and game market. As the microeconomic savings are significant for individual consumers and the number of desktop 3D printer users continues to climb, this impact can be expected to grow.

### 3.2. Six Example Printable Toys

Although the toys can be made for less than purchased commercially, they may not be of the same value. Figure 3 shows the visual results of six common household toys to probe this effect. The free design 3D printable version is shown on the left and the commercial version is shown on the right. First, the mini travel chess set available from the largest online retailer, Amazon, results in a 90% savings if 3D printed. The color difference actually provides a visual advantage to 3D printing. Although it should be pointed out that identical (or different) color schemes could be enabled simply by using different colors of plastic filament for the different components of a toy. For those that find the wood more aesthetically appealing, there is already a wide range of wood filaments on the market and other biocomposites [50], and recent work indicates that even wood waste can be converted to 3D printer filament [51]. Home manufacturing of toys is also more economic when compared to a dedicated toy seller like ToysRUs. The shape puzzle available from ToysRUs results in a 88% savings and the toy truck 79% savings. In both cases, the commercial versions have a higher degree of color variance than shown, but this could be overcome by using more colors of filament and/or changing filaments during a single print. For more complex toys, like the action figures, 3D printing still results in a savings, although lower (e.g., 41%) values. In addition to mass manufactured toys, wood toys made available on sites like Etsy can also be replaced with distributed manufacturing using 3D printing with substantial cost savings. For example, the wood puzzle star available on Etsy can be 3D printed for 82% savings as can the math spinner toy for 90% savings. It should be noted here that the relative cost savings can be heavily influenced not only by the filament selection but also the infill percentage. For example, when comparing 3D printed toys to wood based objects, the environmental impact can be lower when low infill settings are used, and, in general for non-solid plastic products, 3D printed ones have a lower impact than conventionally manufactured ones [52,53].



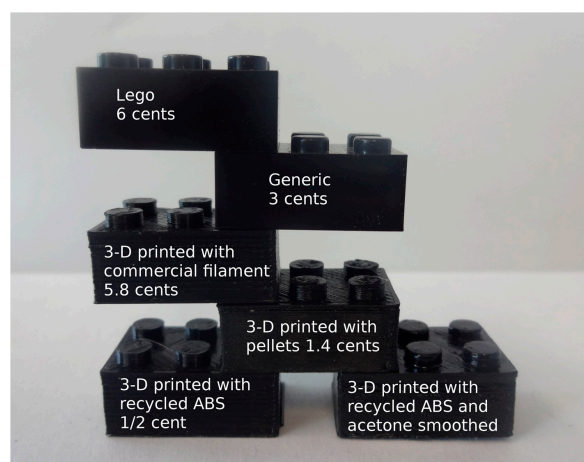
**Figure 3.** Visual comparison of open source 3D printed toys and their commercial mass manufactured equivalents. Costs and percent savings are shown for each toy.

Making a more careful comparison of some of the example toys shown in Figure 3, it is clear that these toys both appear and are actually different than the commercial counterparts (e.g., design, shape,

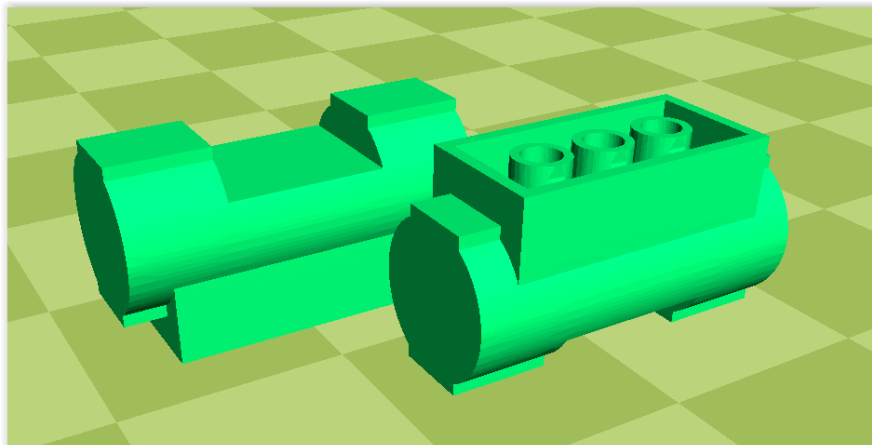
and color) although the functionality (e.g., play) is similar or identical. The difference is perhaps most stark with the action figure (e.g., Captain America vs. BloodShot). There is currently no equivalent quality BloodShot action figure and the intellectual property surrounding the example is owned by Valliant Comics. The play with either action figure is identical (or nearly identical as super powers for both comic book characters arose from former soldiers being injected with super soldier formula and nanites, respectively). However, a specific branded toy has a value to the consumer. This value can be acquired by the consumer by customizing the toy to fit their need (e.g., add minor changes to the existing action figure and/or repaint it) as well as print accessories such as a Captain America shield, which is already available on MyMiniFactory. The intellectual property concerns of home manufacturers doing such modifications are left for future work.

### 3.3. Lego Analysis

Lego is well known in the open source maker community (e.g., commons based peer production using a Lego-built 3D printing/Milling machine [54]). There are already hundreds of Lego designs available and customized OpenSCAD code generators for various Lego-compatible blocks. As can be seen in Figure 4, it is possible to fabricate Lego compatible bricks for less money than purchasing them with any type of ABS filament. It should be noted that the fit of the Lego blocks are superior to the generic compatible block and all of the 3D printed blocks on their first run. The fit of the 3D printed blocks, however, can be adjusted by the individual consumer to make blocks easier to disassemble (e.g., for weaker hands) or tighter (e.g., to make more permanent structures). The quality of the 3D printed parts can also be a key determinant in demand. Care must be taken by home toy manufacturers to ensure both the polymer used as well as the infill is appropriate for the toy being fabricated. In addition, there are some inherent limitations on the visual quality of FFF 3D printed parts. As can be seen in Figure 4, for the three unsmoothed 3D printed blocks lines can be observed on the z-axis. However, if this is important to the home user, ABS can be smoothed (bottom right block in Figure 4) with acetone, rendering a block very close to the visual quality of the generic block and removing print lines. In addition, 3D printed blocks can be made that are not available from Lego as shown as the example of the Lego to Lincoln Logs adapter blocks rendered by Cura [55] in Figure 5. It should be noted that several runs may be needed by the home manufacturer of Lego compatible blocks to obtain an ideal fit for the users, which would contribute to higher costs, although to a small degree. For example, it might take five tries to get the perfect fit, but then the settings could be used to print out a standard set of 1000 blocks so the trials needed would represent a minor loss and cost (e.g., 0.5%). For many other toys, such careful tolerances are not necessary.

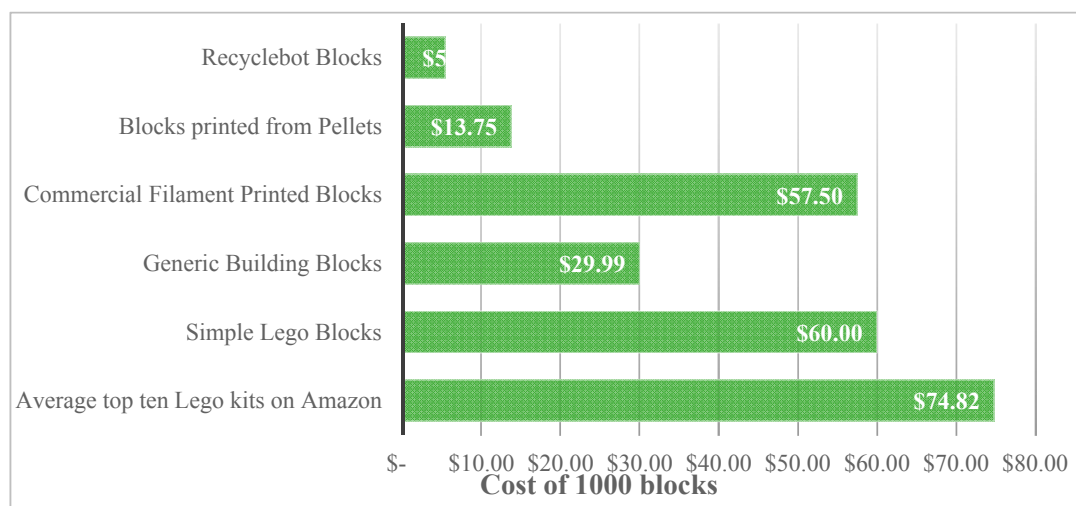


**Figure 4.** Photograph of 2 × 3 toy bricks: Lego brick, Lego-compatible generic brick, 3D printed commercial ABS and 3D printed recycled acrylonitrile butadiene styrene (ABS) both natural and acetone smoothed with costs.



**Figure 5.** Adapterz LLC free design of a Lego to Lincoln Log adapter [55] shown in Cura.

$2 \times 3$  3D printed Lego compatible blocks have a mass of 2.5 g. To provide a fair comparison to a commercially available Lego-compatible generic brick set [56], the costs of fabricating 1000  $2 \times 3$  Lego compatible bricks is shown with the various sources shown in Figure 6. In reviewing the top 10 most popular Lego sets on Walmart.com, it was found that the average cost per piece was \$0.075. The average cost for these kits on Amazon.com was \$74.82 with simple Lego blocks costing \$60.00. Generic building blocks cost less at \$29.99 [56]. When estimating the cost using 3D printed blocks, a comparable kit printed with commercial filament would cost \$57.50. A kit printed from pellets would cost \$13.75 and one printed from recyclebot-made filament would cost only \$5.40. In consideration of *Wired's* cost estimate of a single Lego brick [42], a 1000-piece kit would cost \$104, nearly double that of the kit printed with the more expensive commercial filament. Interestingly, with the cost of RepRap 3D printer kits now breaking the \$100 cost barrier (the Startt 3D printer from iMakr (London, England) is currently selling for \$99.99) [57], only roughly two sets of Legos need to be printed with pellet-made filament to recover the cost of the 3D printer. However, it should be noted that such kits still require substantial technical competence from the consumer.



**Figure 6.** The costs of fabricating 1000  $2 \times 3$  Lego compatible bricks or purchasing.

### 3.4. Board Game

*Save the Planet Board Game* is a free and open-source DIY cooperative board game [46] shown in Figure 7. In the game, players work together to save the planet to win the game while learning

how to save the planet in real life. Users must 2D print out the game board and card decks for the beginner and advanced options, respectively. This can be done on 8 × 11 inch office paper (4 × 11 cents/page is 44 cents) and laminated to be glued to cereal boxes or printed directly on cardstock (1 × 69 cents) so the total 2D printing cost is \$1.13. The beginner option has game pieces for simple acts of environmental benefit and is appropriate for children 4 and up and the advanced option is for teens and adults interested in more scalable impact. This game is open-source so like the RepRap, users are encouraged to build on it—make it better, add more “good deeds”, make a local deed list and make more advanced derivatives.



**Figure 7.** Open-source fully 2D and 3D printable do-it-yourself (DIY) cooperative *Save the Planet Board Game* in mid-play.

The following needs to be printed (summarized in Table 4): a card holder, dice and four mini-figures. The mini-figurines are completely up to the interests of the user and, with thousands of designs to choose from, enable some creativity of the user. There is also some flexibility in the size of the figures that will affect the cost and found items (e.g., a small stone) could reduce the cost of the figures to zero but is of lower value. Here, in order to demonstrate the range of options a fox, The Thinker at the Musée Rodin France, a figurine from another open board game, and a superman bust are used.

**Table 4.** 3D and 2D printed components, source and cost of *Save the Planet Board Game* assuming commercial filament and cardstock.

Item	Source (myminifactory.com/object/)	Mass/Sheets	Cost [USD]
Card holder	card-holder-for-save-the-planet-board-game-35620	39.15	0.90
Dice	the-magnificent-dice-27043	1.68	0.04
The Thinker	the-thinker-at-the-muse-rodin-france-2127	13.86	0.32
Fox	fox-support-free-5865	8.04	0.18
Open board game figurine	open-board-game-figurine-6013	7.50	0.17
Superman bust	superman-bust-3518	6.46	0.15
Game Boards	2D printing costs	5 sheets	1.13
Total			2.89



The top 10 best-selling board games on Amazon as of 3 May 2017 averaged in price at \$18.18 with a range of \$23.22, where the most expensive game was \$31.99 and the least expensive was \$8.77 [47]. The 3D and 2D printed components, source and cost of *Save the Planet Board Game* costs less than \$3 as shown in Table 4, representing a 67%–91% savings. However, in this case, it is not an apple to apple comparison for identical games, which would come with a risk of intellectual property infringement. Instead, this analysis was for comparing a custom board game (with potentially greater value) to a generic board game. The closest analog of the example game is *A Beautiful Place* that costs \$16.49 on Amazon and is significantly less sophisticated, although similar in game play.

Already, many custom games are available in the open source community that have identical game play to conventionally manufactured and sold games, but are superior in some way. For example, many conventionally-manufactured *BattleShip* games are available on the market in the general price range of the most popular board games. All of them have relatively simple injection molded ships. A 3D printable game has been developed (*battlefleet-star-wars-vs-star-trek-33840*), which has identical game play but uses fan art mockups of *Star Wars* and *Star Trek* ships. The printed game also comes in 3D printable carrying cases for easy mobile play and is potentially of greater value than the *Battleship* games on the market for *Star Wars/Star Trek* fans.

### 3.5. Discussion

As the use of 3D printing has shifted from rapid prototyping in industry to production [58], research has shown DIY in-home manufacturing could easily justify the capital costs of a 3D printer with consumer items [21], and this study shows that even when a home printer is focused on making only games and toys, it is clear consumers can generate higher value items for less money than is currently available commercially. It should be pointed out here that these conclusions are in general conservative as this study focused only on relatively simple toys and games that required minimal assembly. Coupling open-source electronics to 3D printed toys (e.g., Arduino-driven 3D printable quad copters and VR headsets) enables far more sophisticated toys with higher values to be produced in the home. One area where this study was not conservative was in the estimation of failed print waste. Here, it was assumed to be zero as in the vast majority of cases printing a known 3D printable part (e.g., guaranteed 3D printable by MyMiniFactory) on an auto-calibrating/bed-leveling 3D printer (e.g., Lulzbot Taz or Mini) nearly always results in a successful print. This is not always the case, as a previous study using a home-built RepRap 3D printer estimated a 20% failure rate [20]. It should be noted, however, that this is only the case on the first prints from an inexperienced user on a much less sophisticated RepRap than are currently available to build, purchase assembled or buy in kit form. Future work could provide a more robust estimate of print failure rates by studying a large group of home 3D printer users.

3D printing gives consumers the unique ability to relatively easily fabricate products only for themselves, which may disrupt manufacturing in a wide array of markets [59–61]. Rifkin argues distributed manufacturing with 3D printers can lead to a zero marginal cost society [62]. It is unclear if the inconvenience of 3D printing yourself will not overcome the convenience of producing exceptionally low cost but high value bespoke products in one's own home; however, it is clear that it will have an impact on global value chains [63,64]. There have been a number of studies concluding that 3D printing will continue to have an increased impact on society [65,66] both in the developed and developing world [67,68]. It is clear that 3D printing will play a major role in the rapidly emerging business models based on open source hardware [69] and open innovation [70]. In addition, even the humble toys here can have added value in the context of medicine when used as therapeutic aides (e.g., magnetic resonance imaging (MRI) visual demonstration tool [71]). Future open-source toy designs can also begin to take advantage of printing [72] or home milling electronic components [73], multimaterials [73,74] and 4D printing smart materials [75] to increase the toy complexity and playability. As the complexity increases, methods will be needed to ensure that such home manufactured toys meet known standards. Work in this area has already commenced [76]. In

addition, there has been significant efforts targeting quality control for low-cost FFF 3D printers both informally [77–79] and formally [80–82] to enable real-time control, which when widespread will only enhance the conclusions in this study.

Future work is needed in both the technical areas to continue to reduce costs and improve reliability of open source 3D printers as well as to expand the economic analysis presented in this study. Future work can probe the time needed to design toys using open source software to determine ROIs for designers. In addition, more granular values can be obtained by doing sensitivity analysis on 3D printer user time for setting up a print and on routine maintenance (as well as associated costs). Future work is also needed to quantify the value to the prosumer of making his or her own toys. In this study, the value of the assembly time was considered to be zero as most of the toys were relatively simple to assemble. However, for more complex toys, there would be a time investment. Normal manufacturing considers this assembly time a cost, while, in this case, the assembly may be treated as part of the value of the toy itself in the same way that assembling a Lego kit is part of the game play. Finally, further work is needed to address the quality of recycling plastic for filament. This study showed that the largest savings could be found for distributed home manufacturing for products using recycled waste plastic filament. However, each time a thermoplastic is recycled, the mechanical properties are degraded. Cruz et al. have begun to investigate this phenomena's impact on open source 3D printing [83], but considerably more work is needed in the area over the complete array of polymers used in FFF.

With both the continued decrease in the cost of open source 3D printers and 3D printing filament along with the increase in the number and quality of free designs, it appears clear that consumer DIY manufacturing in the home [84] is set to have a significant impact on the toy and game markets in the future.

#### 4. Conclusions

This study quantified the savings for consumers that utilize free and open source designs with a desktop fused filament 3D printer to fabricate their own toys and games. The cost of the filament was the largest variable controlling savings per product; however, each of the three filament types analyzed here on average saved the user over 75% of the cost of commercially available true alternative toys and over 90% for pellet-extruded filament and recyclebot-made filament. The reduced visual quality (e.g., 3D printer lines) was offset when compared to commercially available and comparable products because the 3D printable version could contain customization and increased complexity that created noticeably higher value for consumers. Over a single month period, MyMiniFactory saved its users more than \$5 million in avoided consumer purchases for only the top 100 downloaded designs. These results indicate that MyMiniFactory, just a single 3D printing repository among dozens, is saving consumers well over \$60 million a year in offset purchases. The specific case studies found that most common toy savings fell: 40%–90% in cost savings when using the most expensive filament. These cost savings came with ability to make never before seen toys. For example, although the cost of Lego blocks could be cut from 6 cents/block to about 0.5 cents per block using recycled filament, the real strength of 3D printing blocks is to make exactly what the consumer wants Lego compatible. Professional looking games fostering more creativity, customization and in-depth thought of the consumer can also be manufactured at home for a small fraction of purchasing them directly. The results of this study make it clear that consumers can generate higher value items for less money using an open source distributed manufacturing paradigm. With both the continued decrease in the cost of open source 3D printers and 3D printing filament along with the increase in the number and quality of free and open source designs, it appears clear that consumer DIY manufacturing is set to have a significant impact on the toy and game markets in the future.

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### Acronyms and Symbols

ABS	acrylonitrile butadiene styrene
AM	additive manufacturing
$C_C$	cost of the commercially available product USD
$C_E$	average rate of electricity in the United States in USD/kWh
$C_F$	cost of a given filament in USD/kg
$C_s$	marginal savings on each project USD
E	energy consumed in kWh
FFF	fused filament fabrication
$m_f$	mass of the filament in grams
$N_d$	number of downloads
$O_L$	operating cost
P	marginal percent change between the cost to print a product and the commercially available product
PLA	poly lactic acid
RepRap	self-REplicating RAPid prototyper 3D printer
$V_D(t)$	downloaded substitution valuation USD

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