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Economic Impact of Home Manufacturing of Consumer Products with Low-cost 3D Printing of Free and Open-Source Designs

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Abstract

Centralized manufacturing of proprietary products has dominated the economy since the industrial revolution. Recently however, several studies have indicated potential of producing consumers (prosumers) digitally reproducing open source designs with 3-D printers to save money by offsetting the purchase of commercial products. With over 2 million desktop 3-D printers being purchased per year, the impact on conventional industry could be substantial, but is still unknown. The objective of this study is to begin to determine the economic impact created by proliferation of open-source digital designs for 3-D printed products. In order to do this, the top 100 most popular designs posted on the YouMagine 3-D printing repository are analyzed. The download substitution value is calculated based on Amazon prices of comparable products to estimate the potential savings those designs could generate for 3-D printer users. Case studies are provided on three types of open source designs: i) open source equivalent products, ii) non-commercial products of high value to the consumer, and iii) products for 3-D printing users. The savings available for prosumers was found to be highly dependent on the 3-D printing material. The means of percentage savings using commercial 3-D printing filament, commercial plastic pellets, recycled commercial pellets, and self-recycled consumer plastics are 82%, 94%, 97% and 98%, respectively. The potential for laterally-scaled wealth generation in a circular economy with widespread use of recyclebots, 3-D printing and sharing open designs is substantial. In the U.S., considering the use of household plastic waste over $359 billion/year could be used to offset filament purchases or over $7 trillion/year for products. If adoption of household-level DIY digital manufacturing of open source designs becomes widespread open business models are needed.

Keywords: additive manufacturing; distributed manufacturing; DIY; recycling; decentralized manufacturing; peer production

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1. Introduction

By the end of the 19th century, the production of large quantities of standardized products on assembly lines became widespread and dominant in economics (Hounshell, 1984). Due to a long list of benefits (Miltenburg, 2005; Mukherjeer, 2007) this trend continued toward large-scale manufacturing in low-labour-cost countries, especially for inexpensive plastic products (Kravis & Lipsey, 1982; Ruamsook et al, 2007). More than four decades ago Toffler (1980) predicted that the current centralized institutions and systems would be transformed into a more decentralized model. Yet, economies of scale favored the centralized phenomenon and Toffler's predictions seemed implausible. Recently, however, the technical development of additive manufacturing (AM) or 3-D printing technology, which was first used for rapid prototyping (Rayna & Striukova, 2016) has evolved to enable a viable path to a decentralized manufacturing-based economy (Richardson et al., 2013; Gwamuri, et al., 2014; Ben-Ner & Siemsen, 2017) particularly if coupled with decentralizd recycling (Hart et al., 2018; Büth, et al., 2020). Considering the technology barrier of operating 3-D printers (Ben & Siemsen, 2017; Steenhuis & Pretorius, 2016) and the amount of people that are scientifically illiterate (Duncan, 2007), the actual impact of AM on the existing industry is still to be determined. How widespread is this practice? How large of an economic impact is already being created by proliferation of open source digital designs for 3-D printed objects?

To begin to answer these questions this paper first reviews the literature and then analyzes the top 100 most popular designs posted on YouMagine.com. Download substitution value (Pearce, 2015) is used to estimate the potential savings those designs could generate for the public users. Commercial equivalent products are identified on major online shopping websites like Amazon.com. Case studies are provided on open source equivalent products, non-commercial products of high value to the consumer, and those meant only for 3-D printing users. The monetary savings using commercial filament, pellets, recycled pellets and recycled waste are quantified, and the potential implementation of 3-D printing and recycling units for individual household is theoretically scaled and the potential for laterally-scaled wealth generation by sharing is discussed. Conclusions about the impacts to the existing market of adoption of household-level DIY digital manufacturing of open source designs as well as the potential for mass-customization of products are drawn.

2. Literature Review

3-D printers are proliferating. Globally, 2.1 million 3-D printers were shipped in 2020, and the market is expected to reach 15.3 million 3-D printers by 2028 (Grand View Research, 2021). AM, can be viewed as a revolutionary technology in which decentralization evolves to the point that everyone could fabricate products for their own use in their own homes (Petersen & Pearce, 2017) and in the most radical formulation from their own waste referred to as distributed recycling and additive manufacturing (DRAM) (Sanchez et al., 2015; 2017; 2020; Byard et al., 2019; Reich et al., 2019; Dertinger et al., 2020). Traditional manufacturing (TM) methods like injection molding is capital intensive and takes a considerable amount of time to deliver a new mold to the manufacturer, while AM is to fabricate a completely new product within a few hours albeit at a much smaller rate per machine. The economic scale, which significantly affects the TM industries, is eliminated in the AM process as no mass-production is required to minimize the cost (Ben-Ner & Siemsen, 2017; Rayna & Striukova, 2016). AM produces little to no waste and can provide geometric freedom for the fabrication of complex structures (Canessa et al., 2013). Environmentally, AM requires less input with its additive nature while also accepting recycled materials as inputs (Despeisse, 2017), which makes DRAM environmentally superior to TM (Kreiger & Pearce, 2013a,b; Kreiger et al. 2013; 2014). In DRAM's most mature form it directly contributes to the circular economy by tightening the material flow cycle (Zhong & Pearce, 2018). Following the expiration of some major 3-D printing patents in the 2000s, and the open source release of the self-replicating rapid prototyper (RepRap) (Sells et al., 2010; Jones, et al., 2001; Boywer, 2014), a 3-D printer that can fabricate parts for itself, a proliferation of low-cost consumer-level 3-D printers (ranges from $1,000 to $2,000) became more affordable to the public and small businesses (Rayna et al., 2015). Along with the adoption of home-use 3-D printers, online open source communities started to appear like YouMagine, Thingiverse, and MyMiniFactory, which serve as online design repositories for people to upload and download 3-D models for free, so that they can modify and print those existing designs. Using download substitution value (Pearce, 2015), 26 random example digital products found on Yeggi.com (a free design file search engine) resulted in a value more than $4 million, and thus the return on investment (ROI) of owning the 3-D printer even if only used modestly is more than 100% within three years of ownership (Petersen & Pearce, 2017).

There are dozens of such online design repositories (RepRap, 2021a). which not only serve the role of saving digital files, they are also platforms for the hobbyists and professionals alike to communicate and exchange ideas. These repositories are compared to Web 2.0, as users of the websites are collaborating on improving existing designs or even creating new products (Yoo et al., 2016). Yoo et al. (2016) state in this democratized manufacturing era, prosumer (the combination of producer and consumer) and the activity of prosumption is tightly related to the ongoing trend in Web 2.0. Prosumption is the activities of the producing consumer. Prosumption, though criticized as an exploitation of consumers in the past (Ritzer & Jurgenson, 2010), is a net gain for the society as the co-creation activities happening in the 3-D printing related forums and repositories are constantly generating new ideas for existing designs or innovations and are available to everyone with no exploitation (Rayna et al., 2015). Prosumers can leverage 3-D printing technology to apply do it yourself (DIY) methods to digitally reproducible designs.

The DIY movement, first recognized during the 1950s due to shortage of human labor as the consequence of post-war (Atkinson, 2006), is thus now being highlighted once again as part of the maker movement (Dougherty, 2012; Hatch 2014; Martin, 2015) under the development of 3-D printing technologies (Richardson et al., 2013). One the one hand, this personalized fabrication enabled by 3-D printing technologies is allowing people to produce very specific objects they cannot obtain from the market (Mota, 2011). The possibility to customize objects fulfills emotional needs of prosumers – e.g. to make their products different from the trend and showcase their personalities (Campbell et al., 2013; Kudus, 2017; Kapetaniou et al., 2018). Users also often mash existing designs together to 3-D print, thereby creating other new products (Kudus, 2017; Mota, 2011). In addition, DIY household-scale manufacturing can save prosumers money directly, which indicates 3-D printers with open source designs available online pose a threat to existing traditional manufacturers (Peterson & Pearce, 2017; Pearce, 2021). This study will evaluate the extent this threat has already materialized and if it is contributing to a circular economy.

3. Methods

YouMagine, an online website hosts over 15,000 open source computer-aided design (CAD) files, is a community for 3-D printing hobbyists (YouMagine, 2021a). The data set used in this study consisted of 100 designs and the download statistics over their publication lifetime. The top 100 most popular designs in April, 2021 along with their download statistics and standard triangle language (STL) files, which describe the outer surface of the component to be used for 3-D printing, were obtained to do the analysis. Note this top 100 most popular designs changes based on download rates and this analysis should thus be considered a snap shot in time of part of the 3-D printing community's interest. Each design was loaded in to Cura LulzBot 3.6.20, a free software that slices the STL file into gcode to print the designs out physically (Cura LulzBot, 2015). Slicing software allows users to change the infill density, where 0% infill density means the object is printed will be hollow and 100% means it is completely solid. For this analysis, unless specified by the designer, 10% infill density is used for objects that are not considered a tool, such as toys and decorations; whereas 100% infill density is applied for the objects that are categorized as hardware tools to achieve the maximum strength, such as gear bearings and clamps. All other settings use the defaults in Cura for polylactic acid (PLA), which is the most popular and accessible 3-D printing polymer (Subramaniam, et al., 2019). Cura estimated masses were used and compared to those provided by YouMagine and the designer when available. The mass is used to calculate the price of filament require to print out each design assuming commercial filament with a cost of $23/kg (Amazon, 2021a). If the design requires 'vitamins' – i.e. any other components aside from filament (screws, stepper motors, electronics, etc.), the prices of those items are found. The cost to fabricate the product, C_f, is the total material costs, which include the filament and vitamin costs.

Next, the commercial equivalent of those designs are searched for on Amazon.com, the largest online retailer. For the few products not available on Amazon other online retailers were used. Designs with an equivalent were analyzed for costs (all measured in 2021 US$ and priced at the same time) and those that were not are discussed separately along with all designs that would only be useful to 3-D printer users. The difference in the total cost to 3-D print an object (with vitamins if necessary) and the cost to purchase the commercial equivalent online is found as the savings generated for consumers. This downloaded substitution value (V_D) at a specific time (t) of an open hardware design can thus be found by (Pearce, 2015):

$$V_D(t) = \left(C_p - C_f\right) * P * N_D(t) \qquad [\$] \qquad (1)$$

Where C_p is the cost to purchase a commercial product, C_f is the cost needed for the filament to print out the object including additional non-printable parts, N_D is the number of downloads recorded on the YouMagine website and P is the percentage of the downloads that result in a fabrication. For this study P is assumed to be 1. Although it is possible that each download does not result in fabrication, previous work with RepRap-class 3-D printer users indicates this is unlikely. Additionally, many of the downloads could result in multiple fabrications, so an estimate of P=1 will be considered conservative as the focus of this study is on a macroeconomic scale. The difference between C_p and C_f is the savings a prosumer realises for digitally reproducing the product for themselves. V_D is the total savings generated from the difference in cost between commercial product and the open source design. These average and sum of the savings found for the designs analyzed is calculated for the designs where an equivalent product is found. A percent saving is determined for each design from:

$$S = (C_p - C_f)/C_p \qquad [\%] \qquad (2)$$

These percentages are graphed in a histogram for which a mean and standard deviation are determined. Finally, to ascertain what type of designs are currently most manufactured by the 3-D printing community, each open hardware design is categorized into one of five categories: 1) hardware and gadgets, 2) toys, 3) 3-D printer parts and enhancements, 4) art, and 5) apparel.

To gauge the impact of distributed recycled and manufacturing (Dertinger, et al., 2020; Sanchez et al., 2020) to overcome barriers (Peeters et al., 2019) in the future, a sensitivity was run on the use of purchased recycled plastic pellets that cost ~$2.20/kg (McDunough, 2021) and recycled post-consumer waste plastic. Pellets were assumed to be used directly in a fused pellet 3-D printer (Alexandre, et al., 2020; Woern et al., 2018a; Whyman, et al., 2018) at a cost of $5.50/kg or turned into filament with a recyclebot (waste plastic extruder (Baechler, et al., 2013; Woern et al. 2018b; Zhong & Pearce, 2018)). The recyclebot can produce filament at 0.24 kWh/kg and an electricity cost of $0.139/kWh was assumed as the global average electricity price (GlobalPetrolPrices; 2021). This resulted in a cost of $5.53/kg. Finally, using the users own waste consumer plastic directly in the recyclebot was analyzed, which only had the electricity cost and resulted in $0.139/kg.

Finally, these results were extrapolated to the entire U.S, population. The potential value of filament that could be fabricated on a DIY basis is calculated from the waste plastic disposed of per person per year, which is estimated to be about 130 kg/year/person in year 2016 (Statista, 2021a).

The detailed inputs and outputs from the analysis along with all urls are available on the Open Source Framework (OSF, 2021).

4. Results

Following the methods outlined above, the vast majority of 3-D printed products downloaded had a commercial equivalent (89%) as shown in Figure 1.

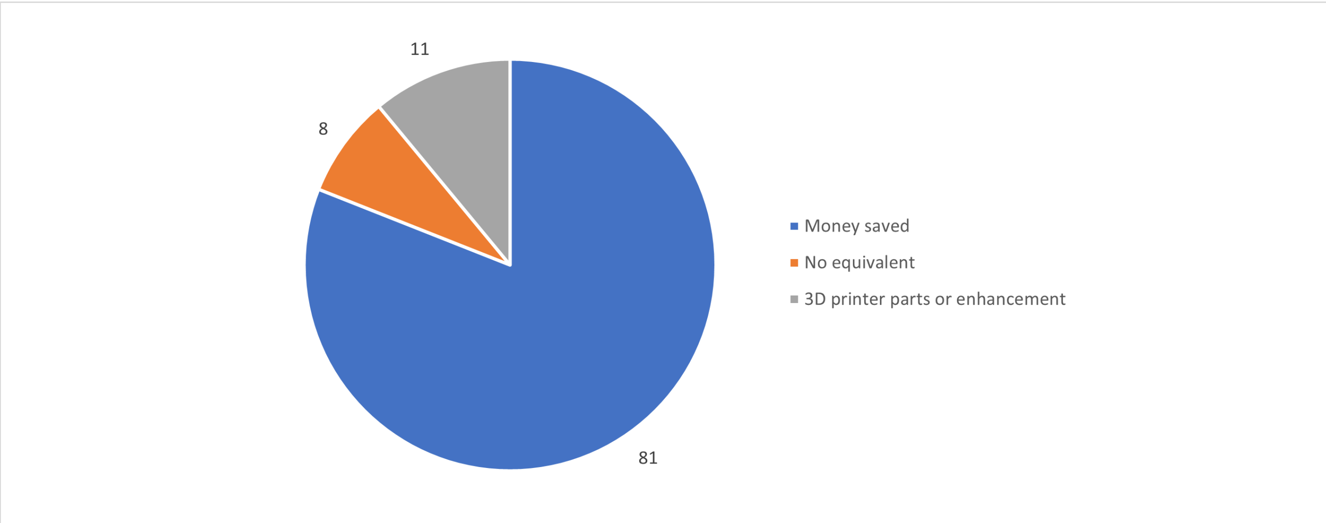


Figure (1): Main category for the 100 designs.

These open hardware products also generally saved users money to fabricate the products themselves. An example is the toy/cosplay blaster model for Han Solo in the Star Wars movies; the 3-D printable version requires 387 grams of filament with 10% infill density, which costs $8.66 (rockets2, 2021), while a commercial version on Amazon costs $140 (Amazon, 2021b). The comparison of the open source version and the commercial version is shown in Figure 2.

Figure 2: Comparison of open source version (left) and the commercial version (right) of the blaster toy (rockets2, 2021; Amazon, 2021b).

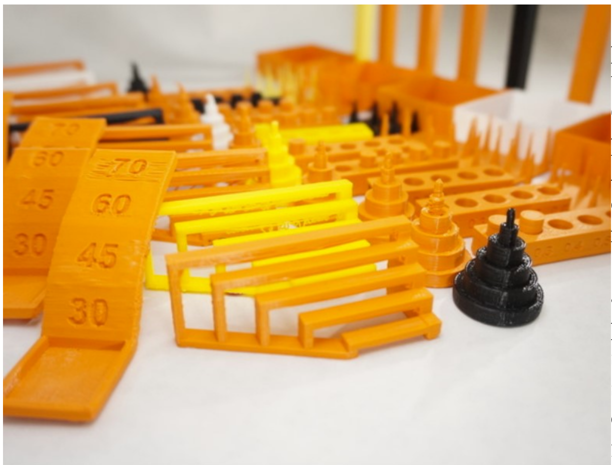
With a saving of $131 on each potential fabrication and 28,608 download times (YouMagine, 2021b), the total saving for the 3-D printing community is estimated to be about $3.8 million for this one design alone.

As shown in Figure 1, not all products are designed to save money or substitute an existing commercial product. These products did not have a commercial equivalent, but could still be popular among makers. For example, a trick "perpetual machine" (Figure 3), which was developed and shared by Greg Zumwalt, has been downloaded 2,770 times (Zumwalt, 2021). This design required vitamin components for its functionality. The basic idea is to include a hidden stepper motor to power a conceptual perpetual machine originally designed by Leonardo da Vinci (Zumwalt, 2021). An initial push is needed to start the cycle counter-clockwise, the ball bearings will tend to keep the motion going, but they will eventually come to a stop if no additional energy is provided because of the laws of physics. The battery-powered stepper motor is hidden inside the body of the machine to provide the additional energy needed to keep the motion going. Zumwalt recommended a 20% infill density, which requires 71 grams of filament ($1.54). Other components needed that are not printable detailed in the Appendix, increased the total material cost to $27. There were no comparable designs available commercially. All other such designs (8% of the total) were removed from the analysis.

Figure 3: Original perpetual motion sketch (da Vinci, c1600) on left and the automated 3-D printed sculpture called the

Perpetual Motion da Vinci Style II (right) (Zumwalt, 2021).

As shown in Figure 1, the remainder of the designs evaluated were 3-D printer parts and enhancements. These designs would not be useful in general to consumers that did not operate a RepRap-class or any other fused filament fabrication (FFF) or fused deposition model (FDM)-based 3-D printer. See for example the design of shootout test geometries (Make, 2021). This set of designs enables users to test the performance of their 3-D printers. This class of designs was also excluded from the analysis unless a commercial equivalent was identified.



Interestingly, in the open source spirit of development, the publisher *Make Magazine* of this design encourages the other users to upload their printing results with the specification used to print those (i.e. infill density, layer height), which allows users to peer check the performance and the recommended setting for different 3-D printers. *Make Magazine* publishes a 3-D printer design guide annually, where commercial 3-D printers of the prosumer class are evaluated and ranked.

Other designs that solely serve the 3-D printer user community are products like belt tensioners, which straighten the belt of 3-D printer if it is too long or too loose (Gijs, 2021); 3-D printer feet, which simply elevates a 3-D printer off the desk (SavageRodent, 2021) and so on. There are some 3-D printer parts and enhancements that have commercial equivalent products, they will be discussed in the following section.

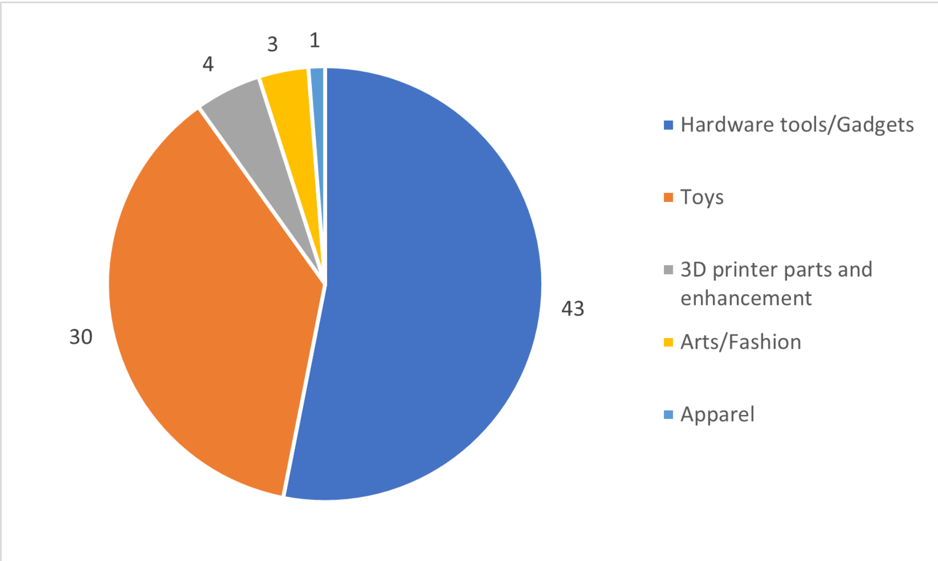


Figure 4: Subcategory for the money savers.

The designs that would save users money by personally fabricating them were further analyzed for class and the results are shown in Figure 4. As can be seen in Figure 4, more than 50% of the designs are hardware tools and gadgets. These range from low-cost products to high-cost products. For an example of the former, consider the humble banana slicer, an open source design uploaded on to YouMagine (Hüger LP, 2021), which has been downloaded 857 times. The comparison of the open-source design and the commercial equivalent is shown in Figure 5. As it is a hardware tool, the infill density is set to 100%, which requires 104 grams of filament. The cost to print this banana slicer is about $1, while the commercial equivalent costs $6 (Amazon, 2021c). Although the banana slicer saves prosumers more than 83% to fabricate them it only had a total saving for the 3-D printing community of $4,316 to date because of the relativity low value of the product.

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Figure 5: Comparison of open source version (left) and the commercial version (right) of the banana slicer (Hüger LP, 2021; Amazon, 2021c).

On the other end of the product cost spectrum consider the 3-D printable glidecam uploaded by Thomas Sanladerer (2021), which has been downloaded 15,355 times. 40% infill density is recommended that results in approximately 500 grams of filament needed because the support required to print some of the components. Costs of additional materials like bolts, screws, aluminum tubes, etc. were added, which results in a total material cost of around $40 (AliExpress, 2021; Amazon, 2021d; 2021e). The cost of a commercial equivalent product is $224 (Amazon, 2021f). Each prosumer that fabricated this saved over 80% from purchasing the commercial product and thus this open hardware design alone generated a savings in the prosuming community of more than $2.9 million. The comparison of the open source version and the commercial equivalent is shown in Figure 6.

Figure 6: Comparison of open source version (left, camera is not included) and the commercial version (right) of the camera stabilizer (Sanladerer, 2021; Amazon, 2021f).

Around 37% of the items fall in the category of toys, the rest of the items (less than 1%) are in the categories of 3-D printer parts and enhancement, art, and apparel. The consumer savings available for 3-D printing toys is well documented by Peteresen et al. (2017), which found when a commercially available toy was available for comparison from the most popular open source designs on the MyMiniFactory, printing with commercial filament saved prosumers more than 75% of the cost and the recyclebot filament saved more than 90 %. In total—and just using the data from 100 toys (less than one percent of MyMiniFactory's repository)—people offset $60 million dollars per year in toy purchases (Petersen et al., 2017). The results here are consistent with that study. For example, an R2D2 replica toy has a duplicate design uploaded on YouMagine with download statistics of 21,187 times (Somerwil, 2021). As a toy, 10% infill density is used, so 1,303 grams of filament is needed for the print. This results in $28 for the total cost of the material. Additionally, users have to glue the parts together and color it if wanted or print in colored filament. The cost of commercial equivalent is identified on Amazon to be $50 (Amazon, 2021g). The total savings generated for the maker community from this item is $0.46 million.

Savings were also found with art products. For example, a life size open source art design of Neferneferuaten Nefertiti (c. 1370 – c. 1330 BC) was a queen of the 18th Dynasty of Ancient Egypt, has been downloaded 4,177 times (Horne, 2021). In the economic analysis of the design, 10% infill density is assumed and resulted in the large print requiring 1,816 grams of filament, which cost $39. The cost of an equivalent commercial product is $150 (Amazon, 2021h) shown in Figure 7. This item generates an estimate savings for the prosumer community of $0.46 million. It should be noted that colored 3-D prints either demand a multi-color 3-D printer or coloring (e.g. painting) in post processing. The former involves no additional operational cost, but an increased capital cost of the printer and the latter was not factored into the economic analysis here.

Figure 7: Comparison of open source version (left) and the commercial version (right) of the Nefertiti life size model (Horne, 2021; Amazon, 2021h).

As shown in Figure 8, out of 81 identified money savers from the top 100 designs, 36 (more than 40%) of them result in a percentage saving of more than 90%. More than 90% of the mover savers have a percentage saving of more than 40%.

Users of 3-D printers or with a recyclebot could further save from producing filament from commercial or recycled pellets and house waste plastic. The recyclebot is able to produce filament at 0.24kWh/kg (Woern, 2018b), taking the electricity price into consideration, the production of filament from commercial pellets costs $5.53/kg. If the users make filament from their own waste consumer plastics, the cost for a kg spool of filament is only $0.139/kg, which is just the cost of the electricity. More than 70% of the items that have a percentage savings were higher than 80. The mean savings was found to be 82% for filament, and the standard deviation was 19%.

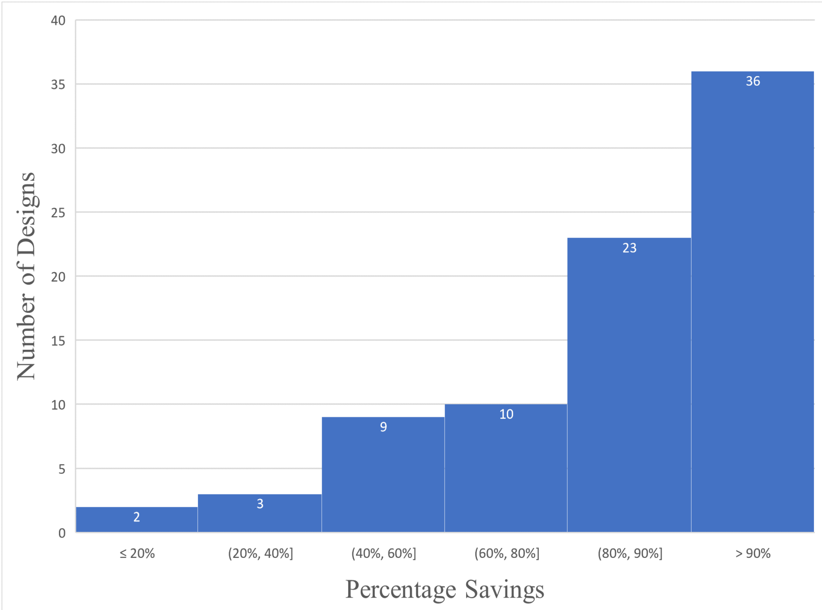

Figure 8: Percentage savings for the designs that saved prosumers money for self fabrication for commercial filament.

The mean and the standard deviation for the percent money saved for the projects that saved users money for self fabrication using each of the material types: 1) commercial filament, 2) commercial pellets, 3) recycled commercial pellets and 4) self-consumer plastic is shown in Figure 9.

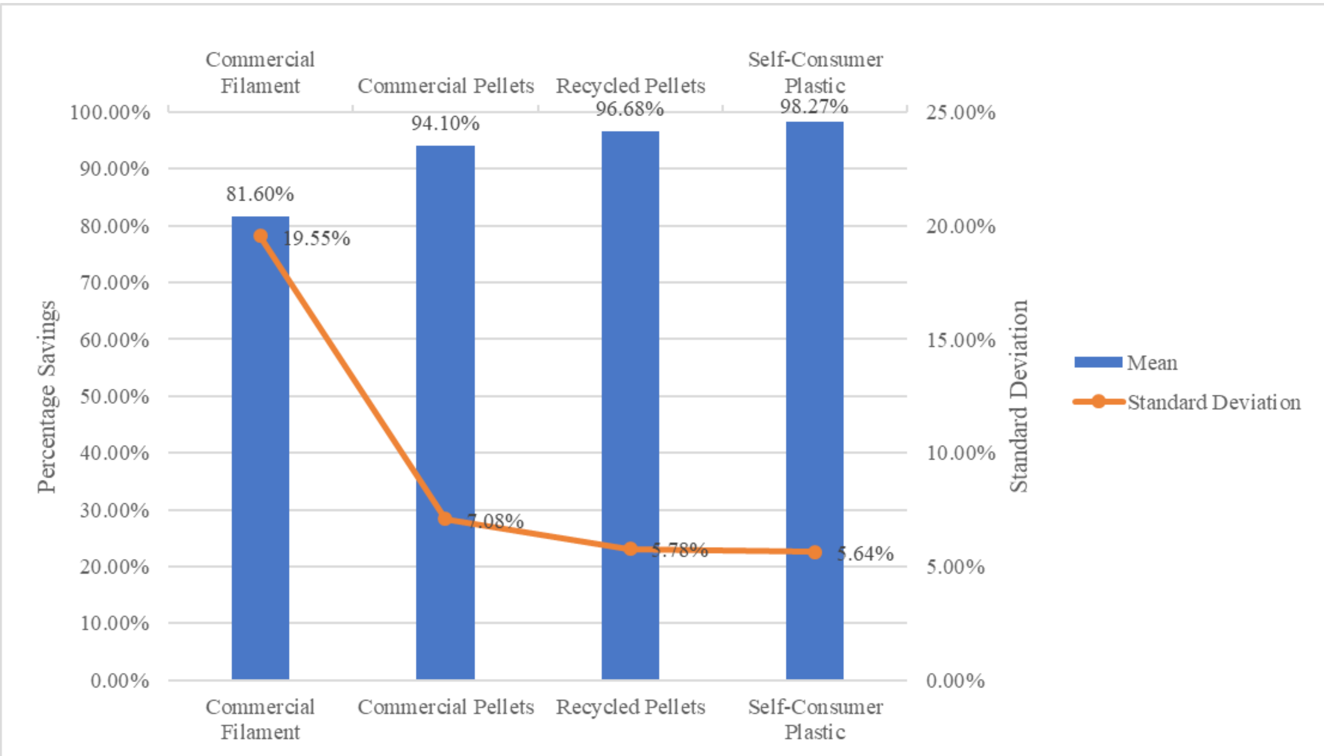

Figure 9: The mean of percentage savings for four types of AM materials used.

Overall, for the 81% of open source designs that provided economic savings the total savings for the 3-D printing community is more than $35 million. For context, this is close to the profit of GameStop ($34 million) in 2018 (Fortune, 2021). If the community had used full DIY recycling their savings would have been close to $40 million.

The means of percentage savings when using commercial filament, commercial pellets, recycled pellets, and self-consumer plastics are 81.60%, 94.10%, 96.68% and 98.28% respectively as shown in Figure 9. Their standard deviations decrease from 19.55% for commercial filament to 5.64% for the cheapest self-consumer plastic.

5. Discussion

The economic benefits of individuals adopting DIY manufacturing with a 3-D printer are proven here to not only be positive, but also to be significant on a macroeconomic scale already. The advantages of an open source approach to distributed manufacturing with 3-D printing are not limited to financial benefits. The emergence of Web 2.0, provides a path to understanding this impact as it could be seen as a milestone for prosumption (Ritzer & Jurgenson, 2010). Prosumption has occurred in stages, as initially occurring in fast food restaurants, where consumers take their food with themselves from the counter and clean their own tables, using ATMs or pumping gasoline to eliminate labor costs. While these action were criticized by Ritzer & Juegenson (2010), the prosumption activities in Web 2.0 based environment are seen as beneficial to the consumers too. 3-D printing arguably takes the prosumption to another level as it eliminates the need for external payments for products entirely. It integrates the user interaction in Web 2.0 communities and the ability of a 3-D printer to generate something physical as a final product. Customization is made possible as anyone is welcome to modify the content posted on those open source 3-D communities. In fact, this is perhaps the open source model's greatest strength. In general, 3-D printing files are licensed under an open source license that not only enables prosumers to fabricate the products for themselves, but it also encourages further mixing, changing and enhancing the design with the requirement that the change is reshared. During the pandemic companies in cooperation with individual makers have been organized into local manufacturing and distribution hubs to reduce transportation time and accelerate the supply of required equipment at local hospitals until the conventional production lines managed to catch up with demand (Stavropoulos, et al., 2020). Recycling is already a large part of obtaining circularity in this context (Costanza, 2020). Thus, for example, a 3-D printable protective face shield in the list is quite popular due to the ongoing pandemic with a download statistic of 74,546 times (Cederberg, 2021). Aside from its popularity, several community members expand from this very own design with their ideas, on YouMagine, this item has 26 recorded derivatives; details are shown in Appendix A (YouMagine, 2021b).

The derivatives are also not limited to face shields (Appendix A Figures A1, A2, A3). Some configured the original design so several identical face shields could be printed at one go; one derivative was a breaker for breaking the face shields apart as some support filament is connecting the printed face shields, others just changed the design to match their community's preferences. It is also possible users would just modify the CAD file upon printing without uploading it as a derivative, so the actual phenomena of this peer creation or peer production may be considerably underestimated what is occurring based on data from the repositories.

Instead of simply letting users choose from existing options such as different colours and sizes, which are possible with conventional retail/online retail centralized manufacturing models, open source approaches to DIY fabrication literally enable users to put their faces on anything (All3DP, 2019). Users can actually make major modifications based on the design they obtain to fulfil their specific preferences. Some of the designs are purposefully coded to be parametric to make this particularly easy for prosumers. For example, the Customizable U-Hook uploaded by Serge Payen (2021) is a parametric design developed in OpenSCAD (OpenSCAD, 2021) that allows users to simply change parameters to achieve the desired shape they want specifically for their U-Hook. The user also added the link to his website for more detailed instructions about how to load the parametric CAD file and customize it in an open source CAD software that is available to everyone (Payen, 2016). Figure 10 shows some of the options users could change with their matching U-Hook designs. Users non-familiar with OpenSCAD can have easier access with an open source customizer (Nilsiam & Pearce, 2017).

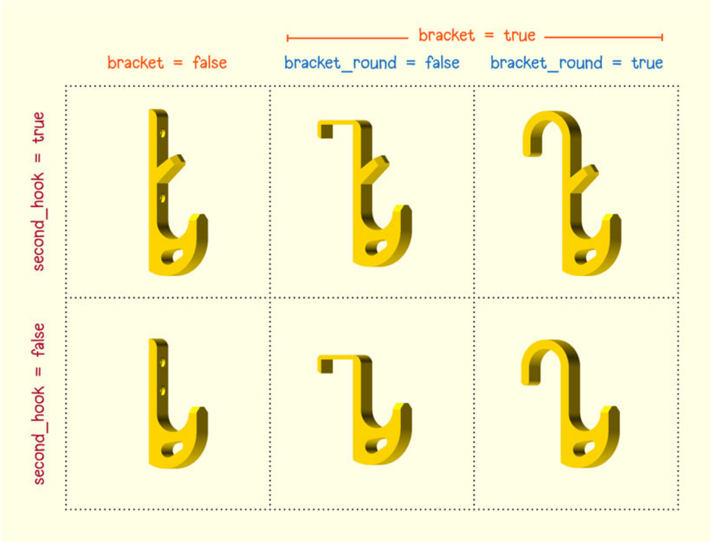

Figure 10: Different U-Hook designs with matching parameters (Payen, 2016).

In a heterogeneous market, it is found that some consumers are unsatisfied by the existing commercial products (De Jong & De Bruijn, 2013), while companies may not be willing to create a new production line just to satisfy a (small) portion of the costumers due to the economics of scale. The use of 3-D printing is particularly advantageous in those cases, users could modify based on an existing design or even create something entirely new. If companies see the value and need to do so, they could even absorb those new ideas from the open source platforms and commercialize it so they could upgrade their existing products and expand their target customers. With that being said, the idea of prosumption certainly do not only benefits the consumers, it could also help the companies to find what is missing in their existing designs and learn from the users' suggestions.

Though historically served for industry uses, 3-D printers are now extremely affordable. Some personal 3-D printers' prices fall under $2,000 (Rayna et al., 2015), while one can also purchase a RepRap kit under $500, which requires the user to build it by themselves (Reprap, 2021a). The price of 3-D printers as well as the filament will likely decrease in the future with more companies entering the market, which will make owning a 3-D printer more feasible. Financially, the ROI for owning a low-end 3-D printer has already reached more than 500% in three years and close to 1000% in five years (Peterson & Pearce, 2017) based on use.

More than 0.2 million of non-metal 3-D printers were shipped in year 2015, and it is projected that the 3-D printer market will reach more than 2 million units in 2022 (Statista, 2021b) and more than 8 million units by 2027 (Statista, 2021c). Aside from the growing number of AM unit sales, among the 100 service providers surveyed by Wohlers Associates, approximately half of them are already printing parts including metal (Wohlers Associates, 2017). Printable material selection will likely expand along with the increase of sales of AM units.

The cost of running a 3-D printer could be further reduced choosing alternatives for the printing material, particularly if using DRAM with a recyclebot or direct waste 3-D printer. The results here showed that moving to recycled commercial pellets or recycling DIY waste resulted in savings of 96% and 98%, respectively. This is consistent with a study done by Peterson et al. (2017), using pellet extruded filament or recycled waste filament that showed users could save more than 90% of the cost of commercial products if an open source 3-D printable version of the product exists. Although the quality of the recycled thermoplastic does decrease every time it is recycled (Sanchez et al., 2017), they could still be sufficient if the result object does not need a high-level strength and a fraction of virgin materials or additives can enable full strength.

Assuming all of the 128.45 million households (Statista, 2021d) could own a recyclebot to produce filament with their own average of 130 kg/year of household plastic waste, they could collectively save over $359 billion per year if all household plastic waste are to be recycled into 3-D printing filament. Assuming the yearly estimated household plastic waste (around 130 kg) is to be recycled through recyclebot, 3-D printer owner could potentially save around $2,795 per year instead of purchasing commercial filament (which would cover the cost of a low-end 3-D printer and a recyclebot already) compared to purchasing commercial filament if all waste is to be recycled to filament by recyclebot. This savings is substantial but the real savings comes from converting the feed stock filament into substitute products. For the 81 money saver designs in this case study, the amount of filament to print all of them is obtained to be about 18kg, which costs $389 using Amazon basic filament (Amazon, 2021a), while it only costs $2.50 if all filament is produced by a recyclebot with household plastic waste. Each kilogram of plastic filament and on average $12 of vitamins would create an average of $188 value if converted into open source products.

The amount of waste generated would enable consumers to print these 81 items 20 times and save more than $60,000 per year if they indeed wanted that number of plastic products using the average savings. Although it is unlikely that the average household needs that many products. All together the 128.45 million households have the potential to generate $7.7 trillion/year from their own waste plastic. Clearly, the potential for wealth generation by sharing open source designs is substantial. Unlike wealth generation from centralized manufacturing, in this case mass manufacturing is laterally scaled among many producers making their own products. This is achieved by peer sharing of designs and production of products for oneself, family or community.

Although it is clear distributed manufacturing by prosumers is already well underway and will expand in the foreseeable future as more end-products can be produced by 3-D printers (Laplume et al., 2016; Kapetaniou et al., 2018), the majority of the products still involve many components that are not printable (Sandström, 2016). While it is possible that the adoption of 3-D printing would be a threat to existing firms if many commercial products can be manufactured at home (Kapetaniou et al., 2018), many argue the availability of 3-D printing technologies are in fact an attractive avenue for established firms and entrepreneurs (Sandström, 2016; Beltagui et al., 2021; Rayna & Striukova, 2021). In addition, adoption of 3-D printing, which decreases the lead time for manufactures to deliver the product, is a complementary for the firms as part of the technologies are still not adaptable for independent users (Bogers et al., 2016; Sandström, 2016). It is also likely firms simply take advantage of the ability to rapid prototype, but still mass produce the end products in TM (Kapetaniou et al., 2018). AM also encourages startups and entrepreneurs as the required capital inputs are less compared to TM (Rayna & Striukova, 2021). As AM allows production after demand, it is possible for entrepreneurs to have a positive cash flow before delivering the products in contrast to stocking products ahead to minimize the cost per item (Rayna & Striukova, 2021).

Taking a step back, adopting AM might have significant benefit existing firms. Aiming the heterogeneous markets or even the conventional ones, using AM faces little risk in over stocking the product as the production could be made after the order or the money is received (Berman, 2012), so theoretically there will be no unsold items in the inventory. Concerns towards dislocations of the economy is mentioned by Ben-Ner and Siemsen (2017), however, since AM only requires certain material input and its production is based on specific order instead of the economic scale (volume production) to lower its cost, it requires way less investment to operate and maintain compared to a TM-based institution. The idea of local 3-D printing shop is brought up by many (Ben-Ner & Siemsen, 2017; Rayna & Striukova, 2016; Wittbrodt et al., 2013), people without 3-D printer but have the intention to obtain 3-D printed objects could utilized those facilities to do so. This mode could be seen as the internet café, in contract to a TM-based company, local 3-D printing shops or firms adopting AM are considered to be more flexible to the changes in the market as they are able to produce various types of products with the same material required (Ben-Ner & Siemsen, 2017). A similar idea, the makerspace, was combined with 3-D printing technologies to serve people with disabilities (Bosse & Pelka, 2020). Medical devices to disabled person are commonly quite costly due to the fact they cannot be mass produced with the customization needed for different patients. Gallup et al., have shown that distributed 3-D printing adaptive aids for arthritis patients had financial savings of more than 94% compared to commercially-available products and that printing a tiny subset of the adaptive aids needed by a single patient would recover the full capital and operational costs of a low-cost open source 3-D printer (Gallup et al., 2018). Bosse and Pelka's (2020) study involves the peer-production of people with disabilities as well as people who are interested in technology, they identified the connection presented in the community that allows knowledge sharing and exchange.

On the other hand, there is a historical pressure against an open source business methodology. MakerBot, a one-time leading open source desktop 3-D printer provider, shifted to a proprietary structure and provides perhaps a cautionary tale for other firms considering that route. At the time of Makerbot's purchase in 2013 for $403 million by a conventional AM company Stratasys, it was the largest and most successful prosumer 3-D printing company. They also housed the largest repository of free and open source 3-D printable designs: Thingiverse. The abandonment of the open source ethos jeopardized the support from the community, particularly the open source RepRap community that helped build its success (Pearce, 2017). Makerbot still kept control of Thingiverse to complement the proprietary sector (West & Kuk, 2016). It is seen as an advantage for an established firm to participate or even create a platform to connect to their customers and other interested individuals in an open-source way to capture the value created by the interaction between firms and consumers (Bogers et al., 2016; West & Kuk, 2016). Previous supporters and customers, however, were outraged by the sudden change in licensing of their files on Thingiverse, as the company attempted to patent designs which were freely uploaded, deleting previously supported documentation, and only releasing new printers and software as proprietary technology (Pearce, 2017). MakerBot's initial proprietary designs were an engineering failure (Benchoff, 2016) as their "Smart Extruder" was so poor that it resulted in a class action suit against Stratasys (United States District Court of Minnesota, 2015). As previous highly-skilled employees that started under the open source era fled, the resulting compounding failures have largely destroyed the company as their 3-D printer sales have dropped. In addition, previous to its past pride in making 3-D printers in the U.S., MakerBot announced it was laying off its entire manufacturing workforce in the U.S. and outsourcing it all to China (Benchcroff, 2016). Nardi (2020) points out that "after being bought out by Stratasys and abandoning their open source roots, the company is all but completely absent in the market they helped to create."

On the other hand, by harnessing appropriate open source business models (Pearce, 2017) combined with those that support the circular economy (Piontek, et al. 2021), the existence of the 3-D printing communities might in fact benefit the traditional industries (De Jong & De Bruijn, 2013). De Jong & De Bruijn pointed out that existing companies can identify the profitable products from the user generated ones, further improve and commercialize them. Without known demand, it is hard for companies to prepare products for the heterogeneous segment of the market (Rayna & Striukova, 2016), while the Web 2.0 phenomenon in the 3-D printing communities helps to identify the needs of the customers that do not get fulfilled by existing commercial products. Commercial companies can also identify and hire those individuals in the 3-D printing communities with desired skills (De Jong & De Bruijn, 2013). Learning how to work with communities that have already started some form of distributed production to recover in the post-COVID era is important (ur Rehman et al., 2020).

6. Limitations

There are several limitations to this study. First, additional post production costs were not considered. Some designs need users to glue the parts and color it to match the commercial product, which are not included as the cost of production. Additionally, no failed printing is considered, while previous studies found that printing errors on a self-built RepRap by an inexperienced user could be as high as 20% (Wittbrodt et al., 2013). Although, even this level of print failures would not change the fundamental conclusions of this study that DIY production is now economic, it should be noted that failures are now much less likely with self-bed leveling and even modest experience. In addition, there has been considerable academic efforts to use open source machine vision and artificial intelligence to reduce printing errors (Hu, 2016; Nuchitprasitchai, et al., 2017a,b; Wei et al., 2019; Petsiuk & Pearce, 2020). As a widespread first step thousands of 3-D printer owners utilize the open-source software called Spaghetti Detective (Jiang, 2021), which attempts to detect and cease printing during catastrophic 3-D printing failures. Finally, it should be pointed out that 3-D printing communities are likely to provide recommended settings with the published designs, which also minimize print failures.

The second major limitation of this study is that choosing the commercial equivalent of an open source design, can never be fully objective as it is unlikely the open source version will perfectly match with a commercially available product. Here the best possible attempt was made to reach an apples-to-apples comparison for each product, but is should be clear that the price range even for apples-to-apples commercial equivalents to one another vary widely. In addition, prices from online retailers are also subject to change. In the case studies shown here only one commercial equivalent is identified, while different providers will likely have a different price for even the same product and this price will vary over time (e.g. sales). The exact values, however, are less important than the trend and averages for predicting savings for prosumers.

7. Future Work

YouMagine is only one of the many existing 3-D printing design repositories (RepRap, 2021b) freely available to everyone, with more than 15,000 open source designs saved on this website (YouMagine, 2021a), the 100 items analyzed here are not able to capture the actual impact this community is contributing to the 3-D printer users as well as the industries that are seeking what could they improve on the products they are already providing. Future work could consider running a larger data set across many of the various similar 3-D printable design websites to avoid any bias observed in a single repository. Potential algorithm could be developed and match the open source design to a commercially available product for the users to compare while browsing so the users would know how much they could be saving by 3-D print the object instead theoretically.

Future research could analyze the influence of the 3-D printing technology (individuals or firms adopting AM units) to existing business in a short and a long run. Whether the shift of TM to AM will be feasible for the firms and the current structure of the market. And if disruptive, would it reverse and turn to be beneficial to the society as a whole at some point? The extent of prosumerism could also be analyzed, how much it is progressing the field of 3-D printing and whether or not this is still an exploitation of the customers or net gain for both consumers and producers.

Repositories could ask for users' inputs upon uploading a design. Whether they came up with the idea to replace an existing commercial product or it is a pure creation. And if it was to replace an existing commercial product, is it due to financial reasons, or there is something they are not satisfied with of the commercial design. These questions could go down deeper and deeper if the user is willing to contribute their time for a better data collection for the website. Which could help further research to better study the behaviors of those freelance designers. Repositories could also ask the categories of the users' design, whether the idea comes from an existing design available on any online repositories, etc. Finally, additional work is needed to probe the social impact of a shift towards global sharing of open source designs and local distributed manufacturing. For example, this methodology may provide more resilience to future societal shocks like the COVID pandemic (Stavropoulos, et al., 2020).

8. Conclusions

It could be posited the significant economic benefits of individuals adopting AM units. While further study is needed to analyze the potentially disruptive impact that individuals adopting AM units could have on the existing industries, industries themselves could also take advantage of using AM units to manufacture. Less waste will be produced, less cost is needed on storage as volume production does not necessarily minimize the cost per item. Decentralized manufacturing could also lead to local sourcing which provides more job opportunities locally. With the expected growth in sales of AM units and the expanding variety of printable materials, 3-D printers will likely to be more popular not only to firms that see the potential in them but also with individuals who are willing to learn and customize existing products.

Furthermore, the Web 2.0-orientated open source 3-D printable designs create an ideal environment for users to communicate with each other and refine their designs. The phenomena of prosumption is pushed to another level, and firms would not only receive a textual suggestions from the users, but also the designs of physical prototypes that the users upload on the online repositories. All these could be seen as a positive gain for society.

Acknowledgements

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Appendix A.

The evolution of open source face shield designs on YouMagine.

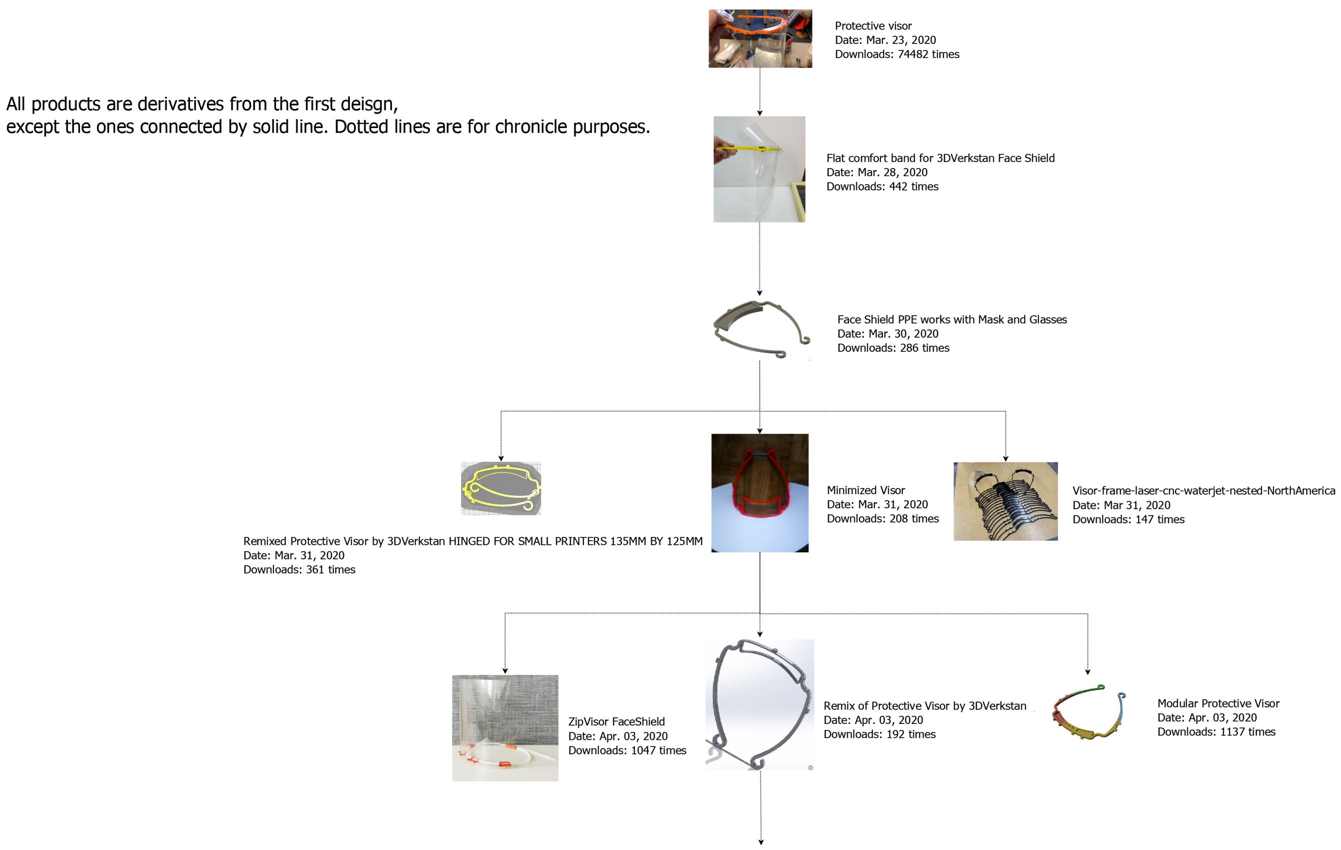

Figure A1: Derivatives of Cederberg's face shield design on YouMagine part 1.

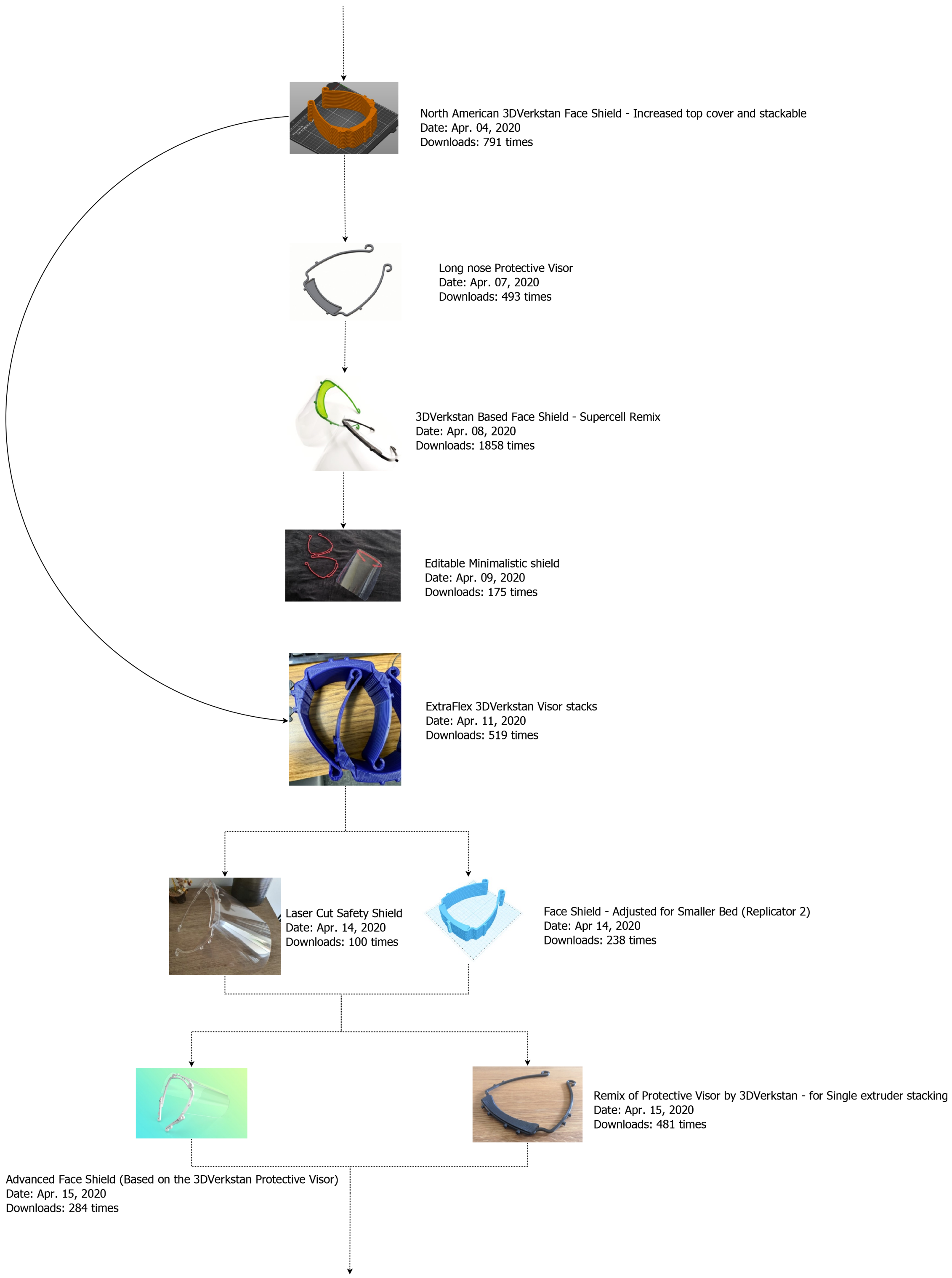

Figure A2: Derivatives of Cederberg's face shield design on YouMagine part 2.

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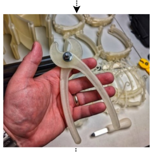
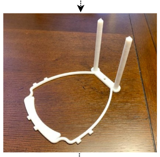
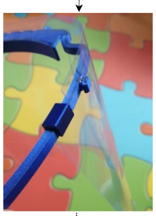


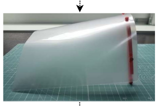
Stack Breaker for 3DVerkstan Visor
Date: Apr. 17, 2020
Downloads: 236 times



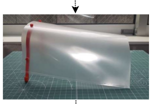
Protective Visor Stacker
Date: Apr. 26, 2020
Downloads: 123 times



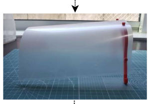
Modified "Protective Visor by 3DVerkstan"
Date: May 14, 2020
Downloads: 120 times



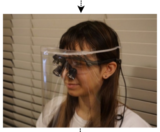
Face Shield for Small 3D Printers
Date: May 27, 2020
Downloads: 168 times



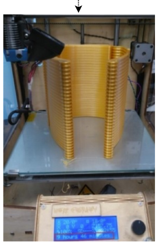
Face Shield for Small 3D Printers - ver2
Date: May 28, 2020
Downloads: 199 times



Face Shield for Small 3D Printers - ver3
Date: May 29, 2020
Downloads: 179 times



Extended Face Shield For Loupes With Light
Date: Jun. 08, 2020
Downloads: 70 times



Visor Frame (faster printing)
Date: Nov. 11, 2020
Downloads: 498 times

Figure A3: Derivatives of Cederberg's face shield design on YouMagine part 3.

Appendix B

Abbreviations

AM: additive manufacturing
CAD: computer aided design
C_f : the cost needed for the filament to print out the object including additional non-printable parts
C_p : the cost to purchase commercial product
DIY: do it yourself
DRAM: distributed recycling and additive manufacturing
FDM: fused deposition model
FFF: fused filament fabrication
PLA: poly lactic acid
ROI: return on investment
S: percent savings
STL: standard triangle language
TM: Traditional manufacturing
V_D: downloaded substitution value

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