



Technical note

Life-cycle economic analysis of distributed manufacturing with open-source 3-D printers



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ABSTRACT

The recent development of open-source 3-D printers makes scaling of distributed additive-based manufacturing of high-value objects technically feasible and offers the potential for widespread proliferation of mechatronics education and participation. These self-replicating rapid prototypers (RepRaps) can manufacture approximately half of their own parts from sequential fused deposition of polymer feedstocks. RepRaps have been demonstrated for conventional prototyping and engineering, customizing scientific equipment, and appropriate technology-related manufacturing for sustainable development. However, in order for this technology to proliferate like 2-D electronic printers have, it must be economically viable for a typical household. This study reports on the life-cycle economic analysis (LCEA) of RepRap technology for an average US household. A new low-cost RepRap is described and the costs of materials and time to construct it are quantified. The economic costs of a selection of 20 open-source printable designs (representing less than 0.02% of those available), are typical of products that a household might purchase, are quantified for print time, energy, and filament consumption and compared to low and high Internet market prices for similar products without shipping costs. The results show that even making the extremely conservative assumption that the household would only use the printer to make the selected 20 products a year the avoided purchase cost savings would range from about \$300 to \$2000/year. Assuming the 25 h of necessary printing for the selected products is evenly distributed throughout the year these savings provide a simple payback time for the RepRap in 4 months to 2 years and provide an ROI between >200% and >40%. As both upgrades and the components that are most likely to wear out in the RepRap can be printed and thus the lifetime of the distributing manufacturing can be substantially increased the unavoidable conclusion from this study is that the RepRap is an economically attractive investment for the average US household already. It appears clear that as RepRaps improve in reliability, continue to decline in cost and both the number and assumed utility of open-source designs continues growing exponentially, open-source 3-D printers will become a mass-market mechatronic device.

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1. Introduction

The technological development of additive manufacturing and 3-D printing has been substantial, fueling rapid growth in commercial rapid prototyping as it has proven useful for both design and small-batch production [1–8]. There has been speculation by the *Economist* that these technical advances could result in a ‘third industrial revolution’ governed by mass-customization and digital manufacturing following traditional business paradigms [9]. However, the recent development of open-source 3-D printers makes

the scaling of mass-distributed additive manufacturing of high-value objects technically feasible at the individual or household level [10–18]. These 3-D printers are self-replicating rapid prototypers (RepRaps), which manufacture approximately half of their own mechanical components (57% self replicating potential, excluding fasteners, bolts and nuts) from sequential fused deposition of a range of polymers and use common hardware [11,19,20]. The RepRap is a mechatronic device consisting of a combination of printed mechanical components, stepper motors for 3-D motion and extrusion, and a hot-end for melting and depositing sequential layers of polymers; all of which is controlled by an open-source micro-controller such as the Arduino [21,22]. The extruder intakes a filament of the working material (polyactic acid (PLA), acrylonitrile butadiene styrene (ABS), and high-density polyethylene

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(HDPE) among other materials [23,24]), melts it using resistive heating, and extrudes it through a nozzle. RepRaps have been proposed and demonstrated to be useful for standard prototyping and engineering [19], education [25], customizing scientific equipment [26], chemical reactionware [27], electronic sensors [28], wire embedding [29], tissue engineering [30] and appropriate technology-related product manufacturing for sustainable development [14]. Despite this wide array of applications, RepRaps are relatively simple mechatronic devices. Historically, mechatronics has been relatively isolated as specialist discipline, but now the advent of the RepRap with its inherent open-source nature offers the potential for widespread proliferation of mechatronics education and participation. However, in order for this technology to become as ubiquitous as are common 2-D electronic printers, the RepRap must be economically viable for the standard household.

This study reports on the life-cycle economic analysis (LCEA) of RepRap technology for an average US household. A new low-cost RepRap is described and the costs of materials and time to construct it are quantified. The costs for a selection of open-source printable designs that a typical family might purchase are quantified for print time, energy, and filament consumption and compared to low and high market prices for similar products. The results of this life-cycle economic analysis, the developmental trends including environmental impact, and comparison with commercial 3-D printers are discussed and conclusions are drawn about the future of distributed manufacturing.

2. Materials and methods

A new variant of the Prusa Mendel RepRap shown in Fig. 1 was used to print the physical parts for an LCEA analysis. The RepRap bill of materials (BOM) and printed parts list are shown in Appendix A and B, respectively. The capital cost (C_{RepRap}) of the RepRap was calculated by summing the individual costs of the BOM and the necessary printed components. The printers have an approximately cubic build envelope with sides 18 cm in length with a print rate of 60 mm/s (although the printers are capable of 120 mm/s). The RepRap used here had a 0.5 mm diameter nozzle, 0.1 mm positioning accuracy and used 0.2 or 0.25 mm layer thickness, depending on the detail necessary for the print.

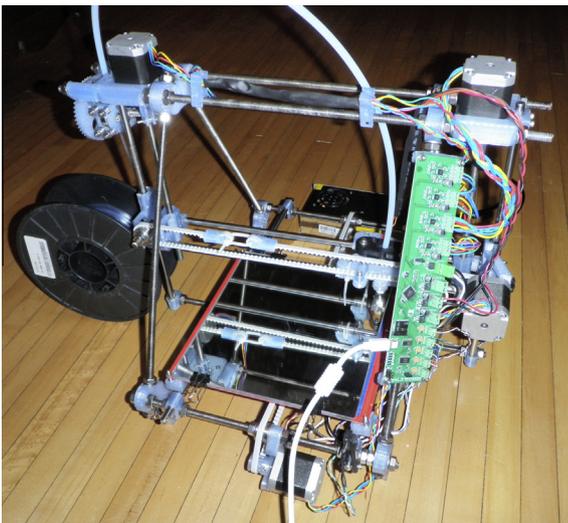


Fig. 1. A new variant of the Prusa Mendel RepRap and open-source 3-D printer capable of fabricating about half of its own parts. In the picture all the translucent blue parts were printed on an identical mechatronic machine.

The growth rate of open-source designs was determined by recording the date and posted item number on Thingiverse. Twenty open-source designs were selected from over 100,000 items in the Thingiverse repository [31], which met the following criteria: (1) printable in PLA with existing RepRap technology, (2) have a commercially available direct substitute, and (3) are likely to be purchased or owned by an average American household.

3. Calculations

The high and low commercial costs for each product were found using a Google Shopping search in February 2013 from conventional brick and mortar retailers, excluding shipping costs. It should be noted that shipping for low-value products often dominated total cost, but was nevertheless ignored to ensure conservative estimates of return. Operating costs for the RepRap-produced products (O_p) were calculated using energy and filament consumption as measured and described below, applying the US average electric rate of \$0.1174/kW h [32] and the average cost of PLA [33] as follows:

$$O_p = EC_e + 1000m_f C_f \text{ (US\$/part)} \quad (1)$$

where E is energy use in kW h, C_e is the average US electric rate in US\$, m_f is the filament mass consumed in grams (m_f also includes any support material that needed to be printed for a specific part), and C_f is the cost of the filament in US\$/kg. The total cost of a RepRap produced product is:

$$P_{\text{RepRap}} = \Sigma O_p + \Sigma A \text{ (US\$/product)} \quad (2)$$

where A represents the cost of individual non-printed components in \$US.

Prints were made with PLA using with a bed temperature of 65 °C and extruder temperature of 190 °C. Both the layer height and infill percentages are shown in Table 1 as they varied for the item being printed (e.g products such as the garlic press that require increased mechanical strength were printed with 100% fill, while lightly-loaded products like the spoon holder were printed with 10% fill). Energy use was measured during extrusion with a multimeter (± 0.005 kW h) for each part during printing. Energy required for pre-heating the stage was measured 10 times and averaged. Filament use is estimated by the open-source slicing software, Cura [34] and then verified by massing (± 0.05 g) on a digital scale. The avoided costs (C_a) for a product is the difference between the cost to print with the RepRap, which includes a factor for failed prints (determined from Appendix B by measuring the bad prints on a new RepRap with a user performing initial prints for parts for another RepRap). The percent change is given by:

$$(P_{\text{RepRap}} - P_c)/P_{\text{RepRap}} \times 100\% = C_a/P_{\text{RepRap}} \times 100\% \text{ (percent)} \quad (3)$$

for the low ($P_{c\text{-low}}$) and high ($P_{c\text{-high}}$) retail costs respectively. The simple payback time (t_{pb}) of the RepRap is given by:

$$t_{\text{pb}} = C_{\text{RepRap}}/\Sigma C_a = C_{\text{RepRap}}/\Sigma(P_{\text{RepRap}} - P_c) \text{ (years)} \quad (4)$$

where C_{RepRap} is the cost of the RepRap and the sum is taken over a collection of products avoided for purchasing by 3-D printing. The approximate return on investment (R) for a RepRap in percent following [35] can be given by:

$$t_{\text{pb}} = (1 - e^{RT})/R \text{ (years)} \quad (5)$$

where T is the lifetime of the RepRap in years and assumed to be at least 3 years

The durability of the machine has yet to be proven in longer-term real-world testing, however it is clear that a large portion of the machine can be printed, and therefore replaced when parts wear out. In the same way, the RepRap can be upgraded.

Table 1

Selected open-source designs that are printable on a RepRap with both Cura slicing simulations and experimentally measured values of energy, mass and print time.

Product	Thing	Meters	Mass (g)	Infill	Cura slicing simulation estimates			Experimentally measured values					
					Layer height (mm)	Nozzle diameter (mm)	Estimated print time	Actual print time	Time (min)	kW h	Mass (g)	kW h/ g	kW h/ h
iPhone 5 dock	33,338	5.87	53.2	0.5	0.25	0.5	1:35:00	2:04:30	124.50	0.28	46.2	0.0061	0.1349
iPhone 4 dock	6931	2.65	24.02	0.3	0.25	0.5	0:45:15	0:56:26	56.43	0.1	19.5	0.0051	0.1063
iPhone 5 case	43,279	1.05	9.51	1	0.2	0.5	0:23:00	0:33:27	33.45	0.04	7.5	0.0053	0.0717
Jewelry organizer	45,003	2.8	25.39	0.1	0.25	0.5	0:48:00	0:58:30	58.50	0.08	19.63	0.0041	0.0821
Garlic press	38,854	6.24	56.54	1	0.25	0.5	1:38:00	2:09:47	129.78	0.26	45.01	0.0058	0.1202
Caliper	48,413	0.92	8.38	0.25	0.2	0.5	0:17:00	0:22:22	22.37	0.05	6.37	0.0078	0.1341
Wall plate	47,956	2.16	19.59	0.2	0.2	0.5	0:41:00	0:46:15	46.25	0.07	15.7	0.0045	0.0908
Shower Curtain Ring xl2	42,667	4.72	42.68	0.1	0.25	0.5	1:28:00	1:44:36	104.60	0.24	33.6	0.0071	0.1377
Shower Head	40,903	10.01	90.72	0.5	0.25	0.5	2:16:00	2:48:04	168.07	0.27	71.32	0.0038	0.0964
Key hanger (3 hooks)	44,482	2.41	21.85	0.1	0.25	0.5	0:47:00	0:54:21	54.35	0.08	17.03	0.0047	0.0883
iPad stand	46,887	2.11	17.99	0.1	0.2	0.5	0:53:00	0:51:20	51.33	0.1	11.24	0.0089	0.1169
Orthotic	47,208	5.48	49.01	1	0.25	0.5	1:35:00	1:29:58	89.97	0.13	39.08	0.0033	0.0867
Safety razor	43,568	1.79	15.22	0.1	0.25	0.5	0:52:00	0:44:37	44.62	0.09	9.9	0.0091	0.1210
Pickup	38,220	5.31	45.28	0.3	0.25	0.5	1:39:00	1:59:21	119.35	0.19	39.31	0.0048	0.0955
Train track toy	47,528	1.75	14.94	0.1	0.25	0.5	0:44:00	0:27:22	27.37	0.06	11.27	0.0053	0.1315
Nano watchband (5 links)	44,761	1.37	12.47	0.1	0.2	0.5	0:20:00	0:32:49	32.82	0.05	9.15	0.0055	0.0914
iPhone tripod	47,944	1.82	16.47	0.1	0.25	0.5	0:36:00	0:44:44	44.73	0.08	12.88	0.0062	0.1073
Paper towel holder	44,068	9.47	85.84	0.25	0.25	0.5	2:48:00	3:24:05	204.08	0.31	63.44	0.0049	0.0911
Pierogi mold	17,545	2.63	23.86	0.15	0.25	0.5	0:39:00	0:50:00	50.00	0.07	18.9	0.0037	0.0840
Spoon holder	22,000	1.6	14.5	0.1	0.25	0.5	0:30:00	0:35:24	35.40	0.06	11.6	0.0052	0.1017
Totals		72.16	647.46				21:14:15	24:57:58	1497.96	2.61	508.63		
Averages												0.0056	0.1045

4. Results and discussion

4.1. Growth of open-source designs

The growth rate of open-source designs is shown in Fig. 2 as a function of time. It should be noted that this is the total number of designs and a high estimate for those listed on Thingiverse as this includes designs that were deleted by users or by Makerbot Industries, the host of the site, for any form of content restrictions (e.g. weapons, pornography, etc.). Thingiverse, however, is not the only repository of open-source designs as they are also stored on Google Sketchup 3-D Warehouse, 123D Content, 3Dvia, Shapeways 3-D parts database, Appropedia, Github and the GrabCAD library. Thus the data in Fig. 2 should be indicative of the growth rate not the total number of open-source designs. As can be seen from Fig. 2 the growth has been rapid and can be fit with an exponential growth function. As of June 6, 2013 there were over 101,150.

4.2. Open-source 3-D printing fabrication times and energy use

Of these 100,000 designs the 20 designs were chosen (or less than 0.02% of those available only on one repository) for analysis and are listed along with their Thingiverse thing number in Table 1. The designs can be downloaded from [www.thingiverse.com/thing:\[thing number\]](http://www.thingiverse.com/thing:[thing number]). In addition Table 1 quantifies both the Cura sliced theoretical PLA filament length, mass, and estimated print time along with the experimentally verified mass, energy consumed in kW h and print times.

For both the simulation and the experimental results energy use per mass and energy use per time values are shown and graphed in Figs. 3 and 4 respectively. As can be seen in Figs. 3 and 4 there is a linear correlation with energy use and both mass printed and time to print with an R^2 of 0.85 and 0.9, respectively. Cura overestimated the mass due to a difference in measured density (1269 kg/m^3) with Cura's default setting of (1300 kg/m^3). In addition, the diameter of the filament used in Cura was 2.98 mm while the measured

diameter was about 2.8 mm. This difference existed because the Cura slicing diameter was used as a printing quality variable and altered to obtain high-quality prints and complete surface uniformity. As can be seen in Table 1 the actual printing time was about 12% longer than Cura estimated, due to retraction time and non-extrusion movement time of the printer. This was to ensure high-quality prints, but could be reduced for a highly-tuned printer. The total print time for the 20 products was just under 25 h and used about 500 g of filament. Energy use was minimal at 0.1 kW h per hour of printing and 0.01 kW h for the bed and extruder to be heated. The average deposition rate was 0.3 g/min and ranged from 0.2 to 0.4 g/min. This factor of two range existed because of the need for support, varying infill percentage, and geometric complexity of the print model.

4.3. Distributed production costs with open-source 3-D printing

The cost of HS RepRap, C_{RepRap} , is about US\$575 when purchasing parts in single printer quantities and the printed parts (shown in detail in Appendix A). This cost is low comparable with other in-home office equipment products, although it demands investment of approximately 24 h for one person with modest technical competence to assemble once the BOM has been procured (see Appendix B). Commercial versions of fully-assembled open-source 3-D printers are available ranging from US\$2199 from Trinity Labs [36], US\$1725 from Aleph Objects [37], US\$1400 from Type A Machines [38], and Printbot LC for US\$799 [39]. Many other open-source 3-D printers are now on the market [40]. It should also be noted there are less sophisticated RepRap-like commercial products like the Printbot Jr for US\$399 with a significantly smaller build volume (4 in.^3) [39]. These less expensive small 3-D printers can be used as 'RepStraps' to help manufacture the printed parts for a full scale RepRap. The RepRap parts can be printed in approximately 21 h, but a print failure rate of 20% could lead to longer print times as detailed in Appendix B. These values from Appendix B will be used as the inputs in the LCEA below.

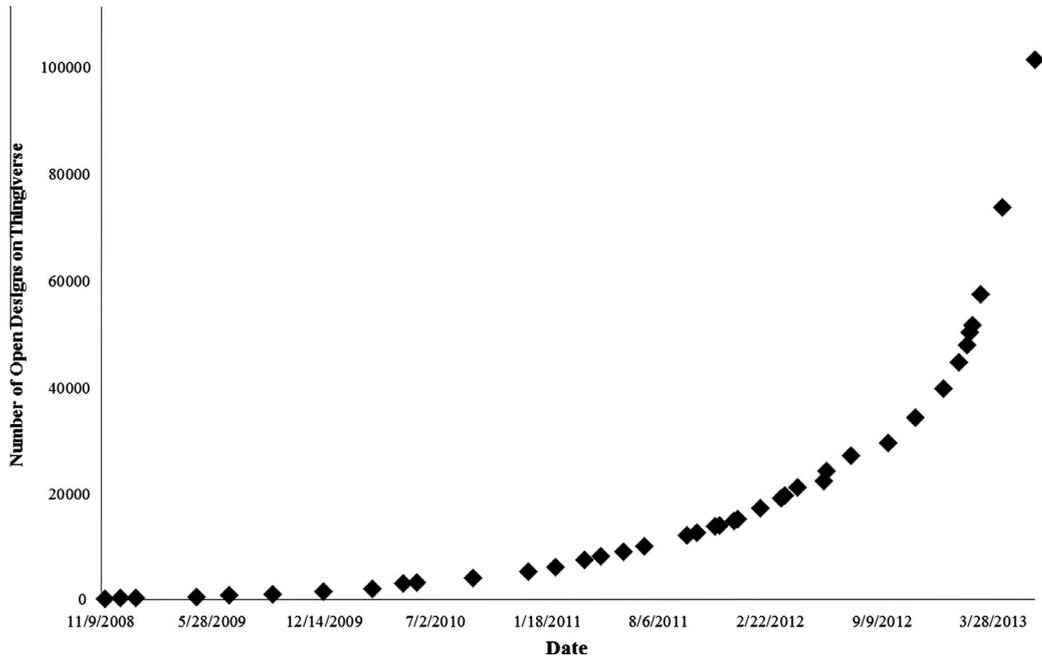


Fig. 2. The approximate number of open-source designs on Thingiverse, which can be printed on an open-source 3-D printer, as a function of date.

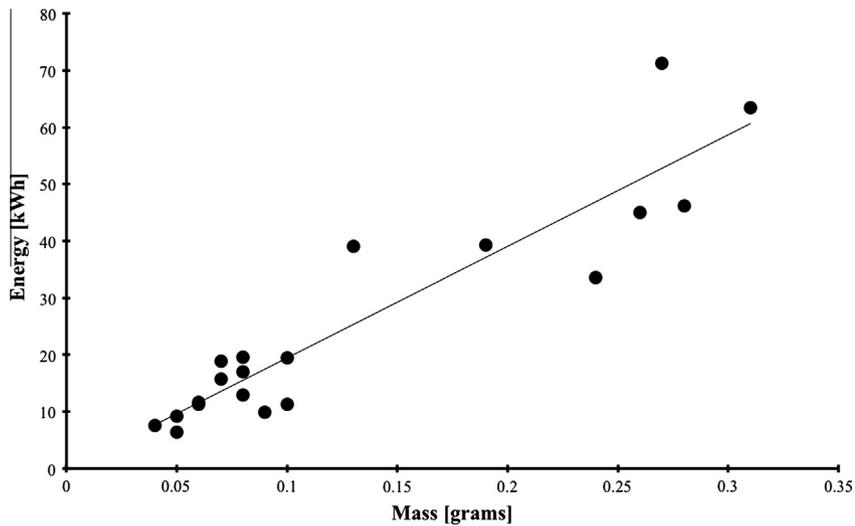


Fig. 3. Electrical energy consumption in kilowatt-hours as a function of mass in grams of filament deposited including support material.

An economic evaluation is shown in Table 2 for all 20 products, including printing costs, high and low retail costs, and the percent change in the high and low cases. As can be seen in Table 2, there are substantial cost savings for distributed manufacturing over purchasing from online retailers. The total cost for printing the 20 selected products was about \$20 including energy and feedstock costs. On average the products cost less than one dollar a piece to print. In comparison, online retail costs ranged from of \$300 to \$1900; averaging between \$15 and about \$100 per product. The average change yields savings over 2500% when considering the low retail price and over 10,000% with the high retail choices. The largest savings (e.g. over 10,000%) were seen with individually customized products, such as the orthotic, while the smallest savings were observed with simple mass-produced items like shower curtain rings. However, even in the case of the shower curtain rings, where there was no option for a high-cost alternative, the savings remained at over 100% for distributed manufac-

turing. It should be pointed out here that for most products the higher-cost retail estimate is a more appropriate comparison for the RepRap printed product as those tend to have customized or intricate designs. There is also some evidence of a 'maker premium' where consumers assign a higher value to products that as they took part in fabricating [41]. The actual perceived value varies widely, however, as it is dependent on the individual consumer.

4.3.1. Electrical energy costs

As RepRaps have been shown to be more efficient than conventional manufacturing of polymer products [42], the energy consumption for the selected products was expected to be small as demonstrated in Table 1. As seen in Table 2, the total electrical cost for printing all 20 products was only 31 US cents; it is inconsequential on a per-print basis. This holds true even in areas where energy prices are well above average (e.g. in the upper peninsula of Michigan, where electricity is roughly double the US average).

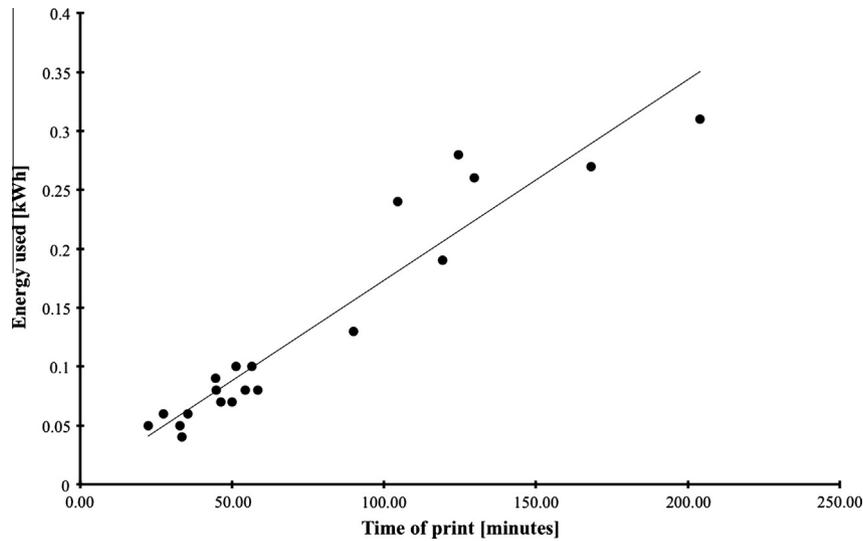


Fig. 4. Electrical energy consumption in kilowatt-hours as a function of printing time in minutes.

It can be assumed any energy price escalation observed over the life cycle of the RepRap would favor distributed manufacturing because of the reduced embodied energy of transportation.

This would not be the case with off-grid applications or in rural areas of developing countries. Energy in these contexts can be the largest component of the operating cost and research on reducing specific energy of parts produced is still needed. As the machine is completely DC powered at low voltage (12–24 V) it is a good candidate for powering with solar photovoltaic technology. While the machines used in this study require a host PC to operate, other low cost, open-source solutions exist for making them stand-alone. The introduction of the Raspberry Pi [43] and a new generation of ARM micro-controllers [44,45] makes completely stand-alone web-enabled printers possible requiring less energy to operate while simultaneously expanding their feature set. This may expand the market interest beyond the US into the developed world [14].

4.3.2. Polymer filament costs

Filament made up the bulk of operating costs at \$17.80 for the 20 products. It should be pointed out here that relatively common costs for filament were used (\$35/kg). Currently there is filament on the market for \$20–175/kg. There have been several efforts to create open-source RecycleBots [24,46], which are plastic extrusion systems for fabricating RepRap feedstock. RecycleBots allow RepRap users to recycle bad prints and convert waste plastic into filament. There are versions for both the DIY enthusiasts (e.g. Lyman [47]) as well as the successful Filabot KickStarter project [48], which foreshadows eventual open market competition following the example of the RepRap itself, versions of which are sold by dozens of companies on the Internet. This RecycleBot technology essentially eliminates the plastic cost associated with failed prints and has the potential to significantly reduce filament cost by allowing for the substitution of waste containers (e.g. milk jugs

Table 2

Components and total economic costs for selected open-source designs that are printable on a RepRap compared to high and low retail costs.

Product	Thing	Mass (g)	kW h	Cost of plastic	Cost of electricity	Total RepRap cost	Total retail cost low	Total retail cost high	Percent change low	Percent change high
iPhone 5 dock	33,338	46.2	0.28	\$1.62	\$0.03	\$1.65	3.56	\$29.99	-116	-1718
iPhone 4 dock	6931	19.5	0.1	\$0.68	\$0.01	\$0.69	\$16.99	\$39.99	-2347	-5660
iPhone 5 case (custom)	43,279	7.5	0.04	\$0.26	\$0.00	\$0.27	\$20.00	\$56.00	-7385	-20,858
Jewelry organizer	45,003	19.63	0.08	\$0.69	\$0.01	\$0.70	\$9.00	\$104.48	-1192	-14,902
Garlic press	38,854	45.01	0.26	\$1.58	\$0.03	\$1.61	\$5.22	\$10.25	-225	-538
Caliper	48,413	6.37	0.05	\$0.22	\$0.01	\$0.23	\$6.08	\$7.88	-2557	-3344
Wall plate	47,956	15.7	0.07	\$0.55	\$0.01	\$0.56	\$2.30	\$22.07	-312	-3857
Shower curtain ring x12	42,667	33.6	0.24	\$1.18	\$0.03	\$1.20	\$2.99	2.99	-148	-148
Shower head	40,903	71.32	0.27	\$2.50	\$0.03	\$2.53	\$7.87	\$437.22	-211	-17,196
Key hanger (3 hooks)	44,482	17.03	0.08	\$0.60	\$0.01	\$0.61	\$6.98	\$49.10	-1053	-8010
iPad stand	46,887	11.24	0.1	\$0.39	\$0.01	\$0.41	\$16.99	\$49.00	-4094	-11,995
Orthotic	47,208	39.08	0.13	\$1.37	\$0.02	\$1.38	\$99.00	\$800.00	-7058	-57,743
Safety razor	43,568	9.9	0.09	\$0.35	\$0.01	\$0.36	\$17.00	\$78.00	-4661	-21,745
Pickup	38,220	39.31	0.19	\$1.38	\$0.02	\$1.40	\$9.99	\$22.99	-615	-1544
Train track toy	47,528	11.27	0.06	\$0.39	\$0.01	\$0.40	\$39.48	\$58.98	-9733	-14,590
Nano watchband (5 links)	44,761	9.15	0.05	\$0.32	\$0.01	\$0.33	\$16.98	\$79.95	-5107	-24,416
iPhone tripod	47,944	12.88	0.08	\$0.45	\$0.01	\$0.46	\$8.50	\$29.95	-1747	-6408
Paper towel holder	44,068	63.44	0.31	\$2.22	\$0.04	\$2.26	\$11.20	\$25.00	-396	-1008
Pierogi mold	17,545	18.9	0.07	\$0.66	\$0.01	\$0.67	\$6.95	\$24.99	-938	-3631
Spoon holder	22,000	11.6	0.06	\$0.41	\$0.01	\$0.41	\$4.95	\$15.00	-1098	-3532
Totals		508.63	2.61	\$17.80	\$0.31	\$18.11	\$312.03	\$1,943.83		
Average						\$0.91	\$15.60	\$97.19	-2550	-11,142

or shampoo bottles) as feedstock. As this technology matures and begins to be deployed more widely there will be downward pressure on filament prices [24]. Both of these trends will be ignored in the analysis below in order to provide a conservative economic return on investment for distributed manufacturing.

4.4. Print quality and time investment

The two primary concerns about the viability of wide-scale use of low-cost 3-D printing are (1) print quality and thus the suitability for market applications and (2) the ease of use, which encompasses time investment in learning the software and hardware associated with a RepRap.

The RepRap print quality can be seen for the spoon rest in Fig. 5. This kitchen item was printed in PLA with 0.2 mm step height, which is the current standard, although many open-source 3-D printers can already print with 0.1 mm step heights. The steps are visible and thus some printed products may not be perceived of as high-enough quality for some consumers. This perception is highly dependent on specific consumer preferences. Obviously for many parts and products that are not visible and meet the mechanical requirements of the application this is not an issue. For products where a specific aesthetic quality must be met there are several options of post processing 3-D prints. 3-D printed objects can be sanded and polished and painted to meet many consumer preferences. In addition, post-print chemical treatments have been developed. ABS prints can be smoothed with acetone (nail polish remover) either by direct brush application or via a vapor treatment. PLA, however, is the primary printing material of choice. PLA can be smoothed with a dip treatment in dichloromethane (CH_2Cl_2 , DCM). The results of such a treatment are shown in Fig. 6, where the handle of the razor holder was dipped into DCM



Fig. 5. Example of RepRap print quality – close-up photograph of the spoon rest.

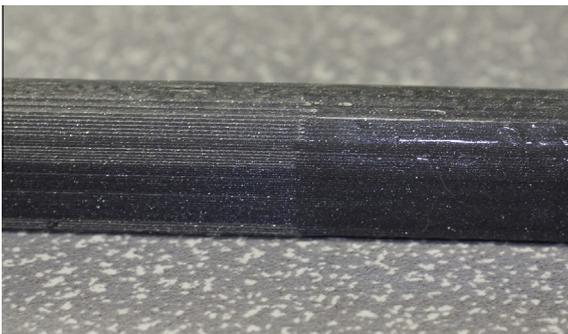


Fig. 6. The results of post-print processing using dip smoothing of PLA with dichloromethane (right) compared to unprocessed print showing 0.2 mm step heights (left).

for 45 s and rinsed with water. It is clear from Fig. 6, that the DCM smooths the surface and creates a coat to seal it as seen on the right against the unprocessed print on the left. Future work is needed to investigate the acceptability of 3-D printed products for the average consumer, particularly in light of the cost savings discussed in the next section. The second common concern is the ease of use, which involves the barrier to adoption created by the need for users to invest their time to learn CAD and the operation of a RepRap. First, it should be pointed out that all of the products printed for this study were pre-designed and available on Thingiverse for free and thus involved no CAD skills to print. In addition, on-line applications are now available that enable users to customize designs without knowing CAD. Thus, there is no real investment necessary. However, it is anticipated, as will be discussed in Section 4.6.4, that 3-D printer users will want to make that investment to create products for themselves that have not been designed by others. Similarly for the commercialized open-source 3-D printers the learning curve for printer maintenance and use is relatively shallow and actually less complicated than setting up a networked office color laser printer. The time investment in building a 3-D printer from parts, trouble shooting it, and working to develop it is substantial and will not be of interest to all consumers. However, for many individuals the RepRap can provide an access point into the innovative area of mechatronics. This can be viewed as a benefit rather than a cost as it is clear that having a greater percentage of the population knowledgeable about CAD and mechatronics and sharing their designs and experiences would benefit the mechatronics community as a whole by providing more knowledgeable students and employees. The cost in the time to make the 3-D prints themselves is small as users can do other activities (e.g. read, watch tv, exercise, etc.) while products are manufactured.

4.5. Avoided costs, payback times, and ROI of distributed manufacturing

As can be seen in Table 2 the total avoided costs for the low and high retail estimates are about \$290 and \$1920 (including a 20% failed print rate) and inputting these values into Eq. (3) gives simple payback times of less than 2 years to about 4 months. These payback times are based on the extremely conservative premise that only 20 items are printed per year and that printing is evenly distributed throughout the year despite the fact it could be accomplished in little over 1 day. Again using Eq. (3) the simple payback times assuming only 20 products printed per year for even the most expensive commercial open-source 3-D printers are less than 1 year or 6 years for the low and high retail prices, respectively. The payback times for the RepRap can then be inserted into Eq. (5), to provide ROIs, but demand an estimated lifetime. This is less straight forward than with most capital manufacturing equipment as the components that are most likely to wear out in the RepRap are easily replaced by the self-replicating nature of the 3-D printer. In addition, the RepRap design continues to improve and evolve usually through the refinement of printed parts – so it is similar to an upgradeable computer in that lifetime can be extended. Although, this self-upgrade-ability and maintenance could indicate an infinite lifetime, if 3 year and 5 year lifetimes are chosen as illustrations, the ROI for the RepRap shown in Fig. 1 compared to low retail costs is over 20% and 40% respectively. For the high retail costs the RepRap ROI > 200%. These RepRap ROIs are clearly extremely conservative as they assume that the users do not print out more than 20 products (as listed in Table 2) per year. As these products can be printed in under less than 25 h, any owner could print them in less than a week even if printing was restricted to after working hours. The products analyzed here represent less than 0.02% of an exponentially expanding catalog, so it is safe to

assume the typical household would print far more than 20 fabricated products per year. These RepRap ROIs compare extremely favorably to after tax income from other investments (e.g. savings accounts $\sim 0\%$, $\sim 2\%$ certificate of deposit, or $\sim 4\%$ on the stock market, adjusted for inflation) [35]. RepRaps and distributed manufacturing thus offers a much better investment opportunity than standard manufacturing practices as the inflation adjusted before tax internal rate of return for companies is about 10%, after corporate income taxes 7%, and after investors pay capital gains taxes, about 4% [49]. The RepRap can be regarded as an extremely conservative investment opportunity that has significantly higher returns than most investment opportunities with similar risks. This investment is limited, however, to only the relatively modest cost of a single RepRap for a US household.

4.6. Implications of results

The potential implications of these results are (i) expected rapid growth of distributed manufacturing using open-source 3-D printing, (ii) large-scale adoption and shifts to life-cycle thinking in consumption, (iii) growth of localized cottage industries, and (iv) a revitalization of hands-on engineering based education.

4.6.1. Rapid growth

It is clear from these results that the economic benefit and the open-source nature of the RepRap project is driving rapid growth. This is verified by the rapid growth of open-source 3-D designs shown in Fig. 2, which can be assumed to be due to more 3-D printer users making designs for themselves and sharing them following the open-source paradigm. This trend is likely to continue as the majority of the Thingiverse community up until this time has been using OpenSCAD [50]. OpenSCAD is an open-source, script-based computer aided design application, which allows users to describe the geometric specifications of the required object by using three primitive shapes (cylinder, sphere and cube) and complex polygons using polygon, polyline and the 2D-3D extrusion commands. OpenSCAD allows for parametric designs; the ability to alter a design by changing parameters of the describing geometry. This allows changes to be made to the design easily and quickly by simply adjusting the value of user-defined variables. Although extremely powerful, CAD scripting in OpenSCAD is clearly beyond the technical comfort level of the average US consumer and as of this writing the vast majority of the designs on Thingiverse are from hackers/makers with considerably higher-comfort levels with technology than average consumers. Thingiverse, however, has recently introduced a Customizer App that acts as a front end for OpenSCAD code to enable inexperienced users to customize designs interactively (e.g. with the use of sliders on parametric variables). This development makes customizing open-source CAD designs accessible to the average consumer. This significantly expands the number of participating designers. There is already some evidence of this effect seen in Fig. 2, in the sudden rise in the number of designs putting the total back on the exponential growth curve. It should be noted that the newly instituted default customizer saves any customization as a new design and thus the method of design counting used in this article will lose some utility in the future. As this App opens up design to more people, the number of open-source designers is assumed to increase along with those who begin using 3-D printers. This will provide even more designs of steadily increasing complexity and value, as users make designs relevant to their lives expands. This will create a positive feedback loop, increasing the value of owning a 3-D printer beyond the threshold of the purchase price. For many consumers the existing catalog of open-source designs already has crossed this threshold as the market for 3-D printers is expanding rapidly [51].

For many consumers the ROI of a RepRap will steadily increase as more designs are made as indicated by the results. Similar to the situation in scientific labs, which can justify the cost of a RepRap by customizing and printing a single piece of scientific equipment [26,52], for some US households with high-value custom needs the printer pays for itself within a day of printing. For example, although custom orthotics can be purchased on the Internet for about \$100, those provided by a professional are normally \$500–\$800 and presumably of higher quality and value to the consumer. These high costs are normally prohibitive for those wishing more than one pair of orthotics, but with the design for thing: 46,922, which uses the Thingiverse customizer, it is possible to print as many as you like for less than 1% of the cost. In addition, open-source [53,54] or free [55–57] image processing and 3-D scanning tools make possible replication of a professionally customized orthotic by direct creation of a 3-D mesh that is then suitable for printing as many as desired. This enables consumers to print \$500–800 quality orthotics for $\sim \$2$ as long as they have one existing pair. Such opportunities for consumers would also be expected to increase the growth rate.

4.6.2. Mainstream adoption and shifts in consumption

If distributed manufacturing with open-source 3-D printing becomes common, there will be a steadily increasing number of products printed by consumers that would otherwise have been retail purchases. This will create a slow shift to hyper-localized manufacturing, at least for some classes of product. However, it may also create a fundamental and more subtle shift in the nature of consumption in the overall economy.

For some time now the trend in consumer goods has been towards lower cost, often disposable over the more expensive durable consumer goods [58]. Consider the case of shaving. Most American men who shave buy disposable razors or disposable razor cartridges that fit into reusable handles because the initial cost is much lower than more robust product options (e.g. a safety razor, for example, costs US\$20–80 online). This initial startup cost prevents consumers from using the more economical (over the life cycle) choice. Now that there is an open-source safety razor design available for free download (thing: 43,568), which costs about 36 US cents to print, the barrier to entry has been eliminated for everyone with a 3-D printer. A 10 pack of double edge safety-razor blades cost about US\$5 (28 cents per blade) on Amazon. If it is assumed that an average user consumes one double blade every 2 weeks the blade costs for open-source safety razor shaving is about US\$7/year. To put this in perspective, the cost of shaving using drugstore blades or cartridges is between US\$100 and US\$300/year [59,60]. Assuming the average man shaves for about 65 years, using the printed razor and only replacing the metal blades would result in a net savings of between US\$6500 and US\$19,000 over a lifetime. Similar opportunities exist for a large number of currently disposable products, whose designs may not have yet been put in the public domain, but can be expected in the near future. By shifting to distributed manufacturing in this way, consumer spending could be reduced significantly.

4.6.3. Open-source cottage industry

It is not clear that every consumer will need or want a 3-D printer when there is the option to print custom products at competitive or lower prices. Already several Internet-based 3-D print shops [61–63] produce items as-ordered and can print a number of different materials including metal, ceramic and plastic. 3-D print shops could also be more localized similar to local bakeries. The open-source RepRap printer is well suited for cottage industry, potentially filling local niche markets [41].

A completely new inventory paradigm is introduced to micro-scale manufacturers who utilize this technology: the carrying cost for maintaining high value inventory is eliminated. As demonstrated

by this analysis, the technology places one-off items that historically carry high prices well within reach of the average citizen. Micro-scale manufacturers need only inventory low-value, low-cost printer feedstock, reducing both direct and operating costs. Instead of insuring and protecting expensive inventory, micro-manufacturers produce on a per-order basis and can offer a variety of products heretofore unheard of.

4.6.4. Education

The widespread use of distributed manufacturing with RepRaps may also have a positive educational benefit and is in line with current pedagogical trends [64]. The educational value of building and then using a RepRap type 3-D printer can be considerable, encompassing, for example, CAD/CAM, mechanical engineering, electronics, and materials science. Most obviously widespread use of RepRaps will be an enormous benefit for pre-training students in mechatronics. Students can work to develop their fundamental mechatronics skills while servicing their RepRaps. In addition, students can create their own designs, print them and share them as open-source models on Thingiverse. The open-source 3-D printer compliments the Next Generation Science Standards (NGSS) [65], which are currently in the final revision phase and scheduled to be completed in early summer 2013. These new standards are slated for adoption in many states throughout the US and have a primary focus on process rather than content and contain significant emphasis on science and engineering practices. The open-source 3-D printers can provide an opportunity to engage in these practices with a “hands on” and “minds on” approach. For example, the NGSS calls for students to learn about three phases of solving problems in the realm of Engineering Design, all of which can be accomplished *physically* with a RepRap: (1) defining the problem, (2) designing solutions, and (3) optimizing design solutions. In addition, schools can simply reduce costs by fabricating learning aids in house such as chemistry models, physics bench equipment, or mechanical devices for classroom demonstrations. Already a printable collection of open-source optics components has been created, which can save schools money by printing in house [66]. More complex creations such as open-source colorimeters, automated filter wheels, and other analysis equipment have been designed and are available as open source hardware [52]. By working in teams to create these things, students will play an unprecedented role in their own education as well the education of others.

4.7. Limitations and future work

This study had several limitations including a limited number of products analyzed; 20. Although this study did not take into account detailed financial variables such as (i) energy cost escalation rates, (ii) inflation, (iii) discount factors, (iv) loan rates/capital costs, or (v) opportunity costs, the nature of the investment analyzed and the method of US consumer decision making enables the use of the simple

payback and simple ROI. For many individuals the effort needed to make their own products may not be worth the time involved even if only a fraction of print time is active user time. Although this study quantified the time it was not used in the LCEA as there is extreme variability due to individual perception of opportunity costs across the US population. In addition, rarely do individuals make this calculation with 2-D printing as it is actually more effort and time consuming to employ commercial printers to print a document.

In this study only a single printing material (PLA) was used. The cost of using other printing materials such as ABS and waste/recycled plastic can also be investigated in future work. There are already a number of RepRap compatible designs that vastly expand the materials catalog of print media, including versions of paste extruders [67], which can be used with many viscous materials [68], a spoolhead extruder to print metal wire onto plastic, which in the future can be used to print circuit boards [29], and a granule extruder including a method to create the granules [69,70]. The classic RepRap design is also attractive for repurposing for uses beyond additive manufacturing. Lightweight CNC milling of printed circuit boards (PCB) using a RepRap fitted with a light duty cutter has been demonstrated [71] and others have fit RepRaps with pens and solid state lasers for PCB making. A full LCEA is needed for each of these material possibilities and alternative designs as one of them may further expand the economic utility of open-source 3-D printing for the consumer.

5. Conclusions

The results of this LCEA study of the open-source RepRap 3-D printer show that even making extremely conservative assumptions, the average US household would save hundreds to thousands of dollars per year in avoided purchases by printing commercial products in their own homes. Only about 1 day of printing is necessary to fabricate the group of 20 open-source printable designs selected for this study, which represent less than 0.02% of those currently available on a single design repository. If it is assumed this printing is evenly distributed throughout the year these savings provide a simple payback time for the RepRap of 4 months to 2 years and provide an ROI between >20% and >200% when compared to high and low retail costs, respectively. The results show that the RepRap is already an economically attractive investment for the average US household. It appears clear that as RepRaps improve in reliability, continue to drop in cost and the number and assumed utility of open-source designs continue growing exponentially, open-source 3-D printers will become a mass-market mechatronic device.

Acknowledgements

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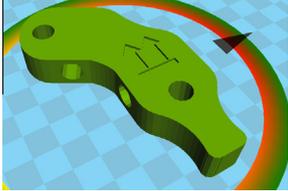
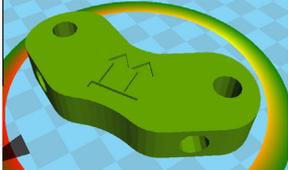
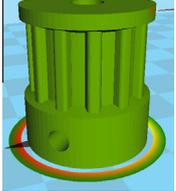
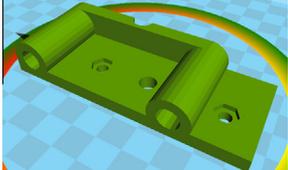
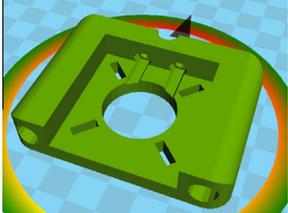
Appendix A. Printer bill of materials (BOM)

	Part number/sku	Source	Units	Unit cost	Total
1	Controller	1284P	http://matterfy.com/products/melzi-ardentissimo-1284p	1	\$120.00 \$120.00
2	6T5 Timing belt	B6T5-MPS	http://shop.polybelt.com/6T5-Open-End-Belt-Roll-Polyurethane-with-Steel-Cords-B6T5-MPS.htm	7	\$1.09 \$7.63
3	608 Bearings	608zz	http://www.amazon.com/VXB-Skateboard-Bearings-Double-Shielded/dp/B002BBGTK6/ref=sr_1_3?ie=UTF8&qid=1351727094&sr=8-3&keywords=608zz	2	9.47 \$18.94

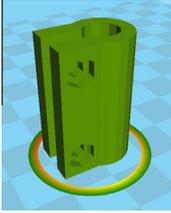
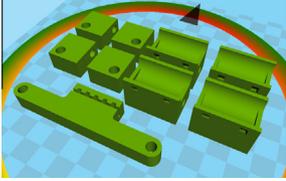
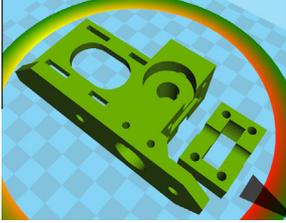
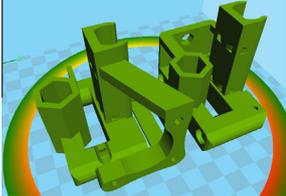
Appendix A. (continued)

4	Limit switch	SW767-ND	http://www.digikey.com/product-detail/en/SS-3GLPT/SW767-ND/664728	3	\$1.11	\$3.33
5	Thermistor for heated bed	495-2157-ND	http://www.digikey.com/product-detail/en/B57891M0103J000/495-2157-ND/739907	1	\$0.83	\$0.83
6	Heated build platform	817752010412	http://www.lulzbot.com/en/14-heated-print-bed.html	1	\$33.00	\$33.00
7	Hot End	817752010047	http://www.lulzbot.com/en/166-budaschnozzle-11.html	1	\$95.00	\$95.00
8	Hobbed Bolt	817752012416	http://www.lulzbot.com/en/7-hobbed-bolts.html	1	\$7.00	\$7.00
9	M8 Metric Drill Rod	88625K67	http://www.mcmaster.com/#drill-rods/=jyro7o	3	\$5.59	\$16.77
10	M8 Metric DIN 125 18-8 SS Flat Washer	93475A270	http://www.mcmaster.com/#metric-flat-washers/=jyovoj	1	\$7.90	\$7.90
11	M6 Metric 18-8 Stainless Steel Hex Nut	91828A251	http://www.mcmaster.com/#metric-hex-nuts/=krvyhs	1	\$8.73	\$8.73
12	M3 Metric DIN 125 18-8 SS Flat Washer	93475A210	http://www.mcmaster.com/#metric-flat-washers/=jyp0sb	1	\$1.62	\$1.62
13	M4 Washers	93475A230	http://www.mcmaster.com/#metric-flat-washers/=jys2cq	0.08	1.86	\$0.15
14	M8 Metric 18-8 Stainless Steel Hex Nut	91828A410	http://www.mcmaster.com/#metric-hex-nuts/=jyov6p	2	\$9.98	\$19.96
15	M3 Metric DIN 125 18-8 SS Nut	91828A211	http://www.mcmaster.com/#metric-hex-nuts/=jyp186	1	\$5.55	\$5.55
16	M4 Metric Din 934 18-8 SS Nut	91828A231	http://www.mcmaster.com/#metric-hex-nuts/=jys1i0	0.04	6.45	\$0.26
17	M3x8 Metric 18-8 SS Cup Point Set Screw	92015A105	http://www.mcmaster.com/#metric-set-screws/=jypdj2	0.04	\$6.56	\$0.26
18	M3x20 Metric 18-8 SS Socket Head Cap Screw	91292A123	http://www.mcmaster.com/#metric-socket-head-cap-screws/=jyoylf	1	\$5.74	\$5.74
19	M3x10 Metric 18-8 SS Socket Head Cap Screw	91292A113	http://www.mcmaster.com/#metric-socket-head-cap-screws/=jyoylf	0.06	\$5.85	\$0.35
20	Metric 18-8 SS Nylon-Insert Hex Locknut	93625A300	http://www.mcmaster.com/#nylock-nuts/=jyrz5m	0.02	9.98	\$0.20
21	Hex Cap M4x50	91287A057	http://www.mcmaster.com/#standard-cap-screws/=jys0xf	0.16	5.78	\$0.92
22	M8 Metric 18-8 Stainless Steel Threaded Rod	90024A080	http://www.mcmaster.com/#standard-threaded-rods/=jyoeuu	6	\$8.31	\$49.86
23	Springs	9657K272	http://www.mcmaster.com/#compression-springs/=krvzrx	1	\$9.58	\$9.58
24	1/8 × 1/4 PTFE tubing	5033K31	http://www.mcmaster.com/#standard-ptfe-tubing/=krvxad	2	\$3.73	\$7.46
25	LM8UU linear bearings	14003979	http://www.suntekstore.com/goods-14003979-6pcs_lm8uu_8mm_linear_ball_bearing_bush_bushing.html	2	\$7.13	\$14.26
26	Stepper motor	UMN17MTR	http://ultimachine.com/content/kysan-1124090-nema-17-stepper-motor	5	\$16.50	\$82.50
27	Carbon fiber kite rod	20961	http://www.goodwinds.com/merch/list.shtml?cat=carbon.pultrudedcarbon	1	7.79	\$7.79
28	Glass		Local		0.99	\$0.00
29	Power supply, 12 v/20 A	9SIA0U008P5040	http://www.newegg.com/Product/Product.aspx?Item=9SIA0U008P5040&nm_mc=KNC-GoogleMKP&cm_mmc=KNC-GoogleMKP-_-pla_-NA_-NA	1	27.99	\$27.99
					Total	\$553.58
	Single purchase					
	Heat shrink tubing	344	https://www.adafruit.com/products/344		\$4.95	
	Solder	734	https://www.adafruit.com/products/734		\$24.95	
	Flux	779008835661	http://www.amazon.com/dp/B0080X79HG/ref=biss_dp_t_asn		\$8.95	
	Wire ties	GB 50098	http://www.amazon.com/GB-50098-Electrical-Assorted-500-Pack/dp/B00004WLJ9/ref=sr_1_5?ie=UTF8&qid=1351724946&sr=8-5&keywords=wire+ties		\$9.55	
	Lubricants	Local				
	Filament	Various	http://ultimachine.com		varies	

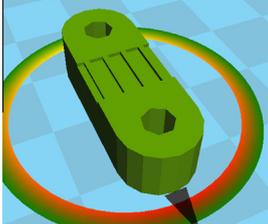
Appendix B. RepRap parts printing times

RepRap printed parts Part name	Print time elapsed (min)	Total time good parts (min)	Total time (min)	Part images	Days printing
Frame vertex foot1 – estimated time = 52	45	45			Day 1 – three good prints and two failed prints – printing time 122/152 = 80% efficiency
Frame vertex foot2	23	45	68		
Frame vertex foot3	7	45	75		
Frame vertex foot3	37	82	112		
Frame vertex foot4	40	122	152		
Frame vertex 1 – estimated time = 47	43	165	195		Day 2 – six good prints and three failed prints – printing time 211/256 = 82% efficiency
Frame vertex 2	52	217	247		
Hearingbone gears – estimated time 1:42	58	275	305		
12 Tooth T5 gear1 – estimated time 31-	16	291	321		
12 Tooth T5 gear2	16	307	337		
Buda mount	26	333	363		
Prusa extruder mount	10	333	373		
Prusa extruder mount	44	333	417		
z Motor mount	1	333	418		
z Motor mount	55	388	473		

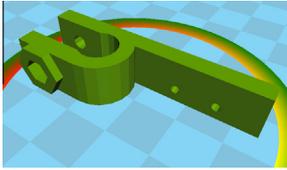
Appendix B. (continued)

RepRap printed parts Part name	Print time elapsed (min)	Total time good parts (min)	Total time (min)	Part images	Days printing
Bar clamp × 8	55	388	528		Day 3 – fifteen good prints and one failed prints – 455/ 510 = 89% efficiency
2 × Melzie mount	25	413	553		
Parametric coupling 1	23	436	576		
Bar clamp 1	14	450	590		
Bar clamp 2	12	462	602		
Bar clamp 3	12	474	614		
Bar clamp 4	13	487	627		
Bar clamp 5	12	499	639		
Bar clamp 6	14	513	653		
Bar clamp 7	12	525	665		
Bar clamp 8	14	539	679		
Parametric coupling 2	20	559	699		
C_rod_Y_axis	49	608	748		
Wades Plate	159	767	907		
C_rod_holder	21	788	928		
X_end_plate	195	983	1123		Day 4 – ten good prints and one failed prints – 354/ 414 = 86% efficiency (continued on next page)

Appendix B. (continued)

RepRap printed parts Part name	Print time elapsed (min)	Total time good parts (min)	Total time (min)	Part images	Days printing
Frame vertex foot 2 y Motor bracket	44 32	1027 1059	1167 1199		
Belt clamp	5	1064	1204		
Belt terminator1	11	1075	1215		
Belt terminator2	9	1084	1224		
Belt terminator3	11	1095	1235		
Belt terminator4	10	1105	1245		
Exdrivespacerdirect Prusa extruder mount	25 12	1130 1142	1270 1282		
z Mounter mount2	60	1142	1342		
z Mounter mount2	62	1142	1404		Day 5 – two good prints and one failed prints 20/82 = 24% efficiency
wireholder1	10	1152	1414		
wireholder2	10	1162	1424		

Appendix B. (continued)

RepRap printed parts Part name	Print time elapsed (min)	Total time good parts (min)	Total time (min)	Part images	Days printing
Shim	10	1172	1434		Day 6 – five good prints and zero failed prints – efficiency of 151/151 = 100%
spacer_w_insert	25	1197	1459		
z-motor mount part	60	1257	1519		
Buddha Mount	26	1283	1545		
3 × end stop holder	30	1313	1575		
Totals		21 h and 52 min for printing good prints	26 h and 15 min total time spent printing	Forty-one good prints and eight failed prints	Overall = 1313/1575 = 83% efficiency

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