Int J Adv Manuf Technol (2016) 85:633–642
DOI 10.1007/s00170-015-7970-9

ORIGINAL ARTICLE

Open-source, self-replicating 3-D printer factory for small-business manufacturing

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Received: 15 June 2015 / Accepted: 12 October 2015 / Published online: 21 October 2015

Abstract Additive manufacturing with 3-D printers may be a key technology enabler for entrepreneurs seeking to use disruptive innovations such as business models utilizing distributed manufacturing. Unlike centralized manufacturing, distributed manufacturing makes the parts and products (the prints) at (or closer to) the source of the demand, cutting out much of the traditional supply chain. Although many expect 3-D printing to take off at the household level and previous work has shown significant returns for those choosing to do so, there are still significant barriers to entry for typical consumers. Our analysis demonstrates that for an individual to make an abnormally high return on their investments in 3-D printers, they must serve others to achieve high utilization rates. The impetus to do so is created by a service that can undercut traditionally manufactured products due to affordability and customizability. Low-cost, open-source 3-D printers are now priced within range of individual entrepreneurs who can take advantage of the long tail of consumers with highly varied interests. The margin advantage, net present value, and return on investment (ROI) analysis provided herein could form the basis of thousands of new small-business ventures in the coming years.

Keywords 3-D printing · RepRap · Entrepreneurship · Disruptive innovation · Distributed manufacturing · Business model

Electronic supplementary material The online version of this article (doi:10.1007/s00170-015-7970-9) contains supplementary material, which is available to authorized users.

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1 Introduction

Recent developments in additive manufacturing technology, known popularly as 3-D printing, have gripped the attention of the popular press with publications such as the *Economist* and the *Guardian* calling it a second "industrial revolution" [1–3]. Conventional analysis of the sector focuses on the ability of 3-D printing to increase the efficiency of centralized industrial manufacturing such as improving rapid prototyping [4] and specialty manufacturing (e.g., making injection molds for conventional manufacturing) [1, 5]. Although dwarfed by the near-term projected economic impact of industrial 3-D printing, sales figures indicate that personalized or desktop manufacturing with 3-D printers is a growing trend [1, 5, 6]. This trend is in large part driven by improved accessibility as historically proprietary 3-D printers cost over US$20,000, and now, low-cost, open-source printers run under US$500 for unassembled components. When 3-D printing was made open-source with self-replicating rapid prototypers (or RepRaps), resultant competition and innovation pushed prices down of the printers to within reach of consumers [7, 8]. RepRaps can manufacture over 50 % of their own components (excluding fasteners) creating a low-cost, easily repairable, and upgradeable 3-D printer that can be used for fabrication of complex parts and products at costs that are a fraction of commercially available alternatives [7, 8].

The potential for distributed manufacturing of high-value, complex 3-D products for household use has become both technically and economically viable, enabling individuals to fabricate consumer products [8–10]. These products include everything from toys (thingiverse.com, 2013) to tools for sustainable development [10], engineering prototypes [11], customized scientific [12–16] and medical [17, 18] equipment, teaching aids [19, 20], electronic sensors [21, 22], and co-creative product realization [23]. This wide range of printable products is growing at an exponential rate [8, 24]. Nonetheless, as we will demonstrate herein, before mass adoption takes place in the household, there will exist a gap between what would-be users might want, and what can be provided by others owning the machines. Those who own the machines become de facto entrepreneurs as they use their machines to make things for others. Most of these entrepreneurs will find the business tedious, charge too little, and fail to develop sustainable businesses. As we will demonstrate, the main problem on the supply side is throughput.

RepRap 3-D printers deposit sequential 100–400-μm-thick layers of polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), high-density polyethylene (HDPE), and a wide range of other feedstock materials to fabricate products or components [25]. RepRaps capable of printing metal are just now emerging [26, 27]. Despite the enormous potential of the technology, existing 3-D polymer-based printers are less mature and user friendly than most consumer devices (e.g., their 2-D counterparts, inkjet, or laser printers) requiring greater technical competence on the part of consumers. To fill this gap, online 3-D printer services have developed [23, 28, 29]. These services operate under the same paradigms and suffer from the same delivery challenges as conventional businesses. Currently, their prices are an order of magnitude above the cost of raw materials. There is, therefore, a business opportunity: localized 3-D print shops capable of printing customized objects on demand. There is currently no study available looking at the technical and economic viability of such a business opportunity making this study necessary. During the stage of fermentation leading to a dominant design, it is normal to have many competing designs. Therefore, we take the RepRap and some of its variants as a set of prototypical examples.

This paper provides a techno-economic analysis of the use of four types of 3-D print shops with: (1) a single MOST Prusa RepRap 3-D printer [13], (2) a single MOST delta RepRap, (3) a single MOST quad-delta RepRap, and (4) a small farm of five MOST quad-delta RepRaps [30]. For instance, the main costs involved in 3-D printing other than capital costs (to buy the machine), are electricity use and filament (plastic) consumption. We measured these with metrics developed for determining production costs for all four cases. These values are then compared to traditional brick-and-mortar retailers. We made our assumptions using disruptive innovation theory [31]. The results are analyzed and discussed and conclusions are drawn about the economic viability of distributed manufacturing.

2 Method

We pit the traditional retail model against several variations of the 3-D print shop business model using data obtained by testing and experimentation using the specific models described in the following section. Manufacturing costs for four cases each having different capital costs were determined and evaluated. The first case employs only a single RepRap Prusa 3-D printer as shown in Fig. 1 [13]. This variant is relatively mature and has a build envelope of 200 mm × 200 mm × 180 mm (x, y, z) with a layer resolution and positioning accuracy of 100 μm. Following convention, the MOST Prusa has a heated bed used to prevent warping during printing. The heated bed is not needed to print PLA, which is increasingly popular in the desktop 3-D printing industry (the remaining three printer options did not utilize a heated bed). Second, a single MOST delta RepRap (Fig. 2) with a cylindrical build volume 270 mm in diameter and 250 mm high and overall dimensions of 375 mm diameter and 620 mm high. Third, a quad delta, essentially comprising four MOST delta RepRaps stacked vertically as seen in Fig. 3a. The quad delta is 375 mm in diameter and 1840 mm high with four build envelopes each about 270 mm in diameter and 150 mm high. This is an experimental system capable of printing four identical parts simultaneously and employs a new type of open-source extruder drive as shown in Fig. 3b [32]. This drive uses only a single stepper motor to push filament to multiple platforms simultaneously. Finally, a small farm of five quad delta RepRaps is evaluated using the data collected during operation of the single quad delta as a basis. It should be noted that this farm

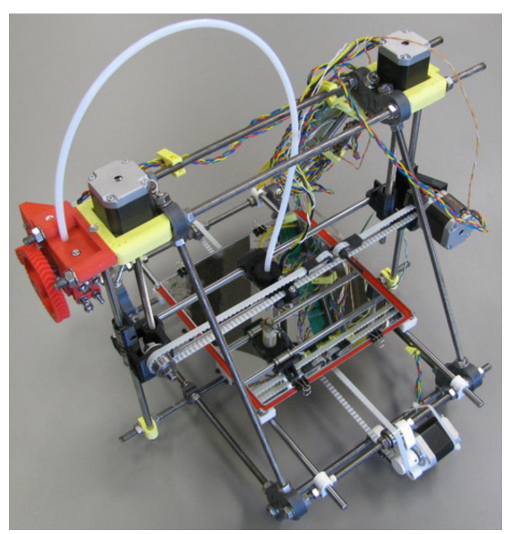

Fig. 1 MOST Prusa RepRap

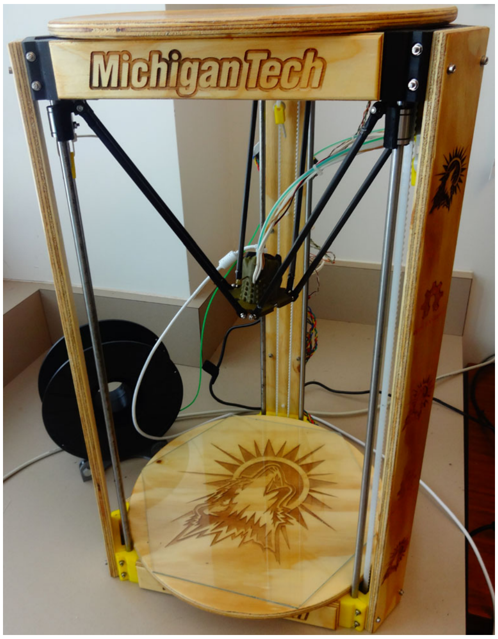

Fig. 2 MOST delta RepRap

could be run by a single computer so each quad delta can be printing different components simultaneously.

Direct operating costs consist of the cost of energy (electricity) to warm up the printer and then print the part as well as the cost of the print media consumed. Indirect costs include the cost to operate a host computer, which may also serve to locate and download models to print or be used as a design platform for custom part development. Only direct operating costs were considered for this analysis. This is justified subsequently by explaining that from experiencing training students to operate 3-D printers for long periods of time, it is reasonably easy for a single individual to operate five or six machines at a time—mainly due to the long run times needed to print many dense and large items.

Finally, a comparison of print quality from parts made using the quad delta RepRap is made with a single delta RepRap using the printed motor ends (rendering shown in Fig. 4) needed to construct both printers themselves. The wings were measured on experimental sets of three prints using calipers ±0.05 mm and mass for the printed parts was quantified on a digital scale ±0.01 g. The error for the external dimensions and mass for the four prints of the quad delta were determined.

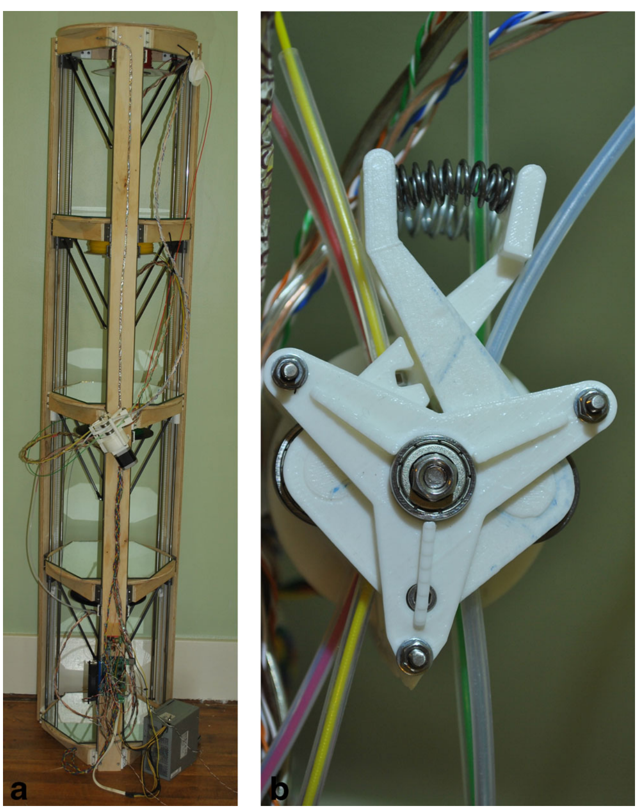

Fig. 3 **a** MOST quad delta is made up of 4 single MOST delta RepRaps stacked vertically. **b** MOST quad delta extruder

2.1 Details of the costs

Following energy measurement protocols in [8], electricity consumption was measured with a multimeter having precision of ±0.01 kWh. Filament consumption was determined by weighing the completed 3-D printed parts with a digital scale and recording to the nearest gram. Parts were printed starting with a room temperature printer so that total energy consumption required to produce a part was measured. Different designs of varying complexity were printed as print speed is a key cost driver and print speed is affected by part complexity. Energy consumption per weight was determined by plotting energy against the mass of the part printed and fitting a line to the data yielding values for both printer warmup (intercept) and specific energy consumption (slope). Both of these values remain relatively constant for a given printer, print speed, and

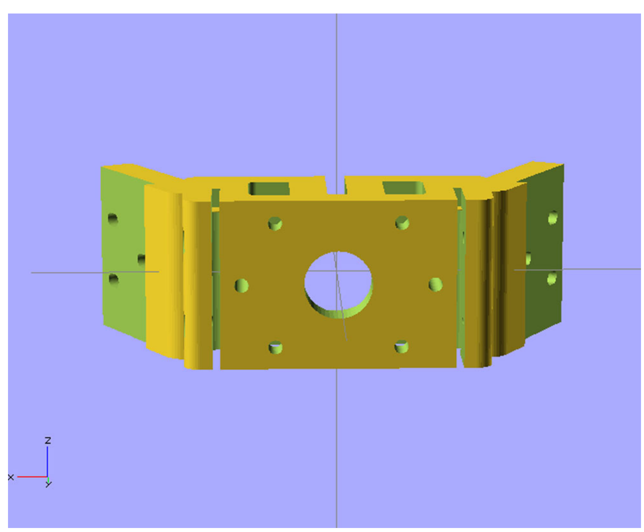

Fig. 4 Rendering of printed motor ends of MOST delta

print media combination. An example plot generated for the MOST Prusa RepRap 3-D printer is shown in Fig. 5. The generalized equation for energy consumption describing the least squares fit to the data is shown in Eq. 1.

$$E = E_s m_p + E_w \quad (1)$$

where

E Total energy consumption (kWh)
E_s Specific energy consumption (kWh/kg)
m_p Mass of the printed part (kg)
E_w Energy consumption for warming the printer (kWh)

Overall energy cost for the print is then the product of the energy consumption (E) and the unit energy cost as shown in Eq. 2.

$$C_E = EC_u \quad (2)$$

where

C_E Cost of energy (US$)
C_u Unit energy cost (US$/kWh)

Finally, the cost of filament consumed is simply the product of the weight of the print and the unit cost of the filament:

$$C_C = m_p C_f \quad (3)$$

Where:

C_C Cost of filament consumed (US$)
C_f Unit cost of filament (US$/kg)

Total direct operating cost for a printed part (C_O) is then calculated as follows:

$$C_O = C_E + C_C [\text{US\$/part}] \quad (4)$$

Capital and operating costs for the three cases are summarized in Table 1. These values are based upon the US average

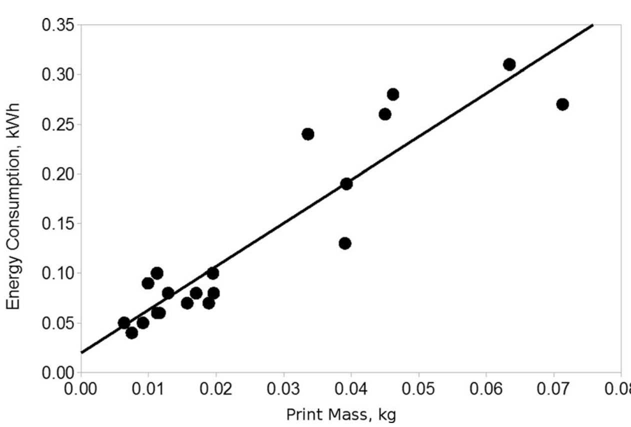

Fig. 5 Plot of energy consumption against printed part mass for the MOST Prusa RepRap 3-D printer

electric rate of US$0.1174/kWh [33] and print media (filament) costs of US$35/kg [34]. The value of 20 % failed prints is based upon experience with novice 3-D printer operators, is therefore conservative and should take into account any kind of complex geometry needed for products that may result in higher than average failure rates. The capital cost for the quad-delta is less than four times that of the single delta because it uses essentially the same high-cost components (e.g., it uses the same motors and electronics, which are the most expensive components of the printer).

3 Analyses

Wittbrodt et al. [8] analyzed a sample of 20 typical household items printed using a new MOST Prusa RepRap printer (case 1), which costs US$575. Drawing on this data, the average cost per item was under US$2 (including electricity, material, and waste due to misprints). By contrast, the low-end retail price of traditionally made substitutes was US$15 and the high-end retail price of traditionally made substitutes was US$100. Marketwatch [35] estimated the markups of several retailers as follows: Costco 10 %, Wal-Mart 32 %, Target 46 %, Staples 41 %, Macy's 80 %, Nordstrom 67 %, Nieman Marcus 65 %, Amazon 15 %, and Bed, Bath & Beyond 81 %. We use the Costco (10 %) and Macy's (80 %) markups in the analysis because they represent large mainstream retailers at the low and high ends of the market.

Utilizing this data two types of analysis were performed: First, the revenue per year required to generate US$100,000 gross profit is determined by comparing the low end and high end of traditionally manufactured goods to the four case studies of 3-D print shops. This value is chosen as a point of comparison and explained in the following section. It is assumed that a 3-D print shop could divert sales from traditional retailers by providing low-cost products that may be esthetically inferior to those that are traditionally manufactured (i.e., at a 33 % discount over the low-end retail price of traditionally made products). Although it should be noted that with additional post processing, nearly the same esthetic quality can be obtained [8], this would entail additional labor costs and was not analyzed. Second, we present a net present value (NPV) analysis and return on investment (ROI) incorporating cost and revenue assumptions.

4 Results and discussion

Combining the data from Table 1 [8, 35], Table 2 is generated comparing 3-D print shop business models using a farm of quad deltas with that of retailers of traditionally made products. It should be noted that the fifth column in Table 2 is the cost of goods sold, which does not include overhead costs. Goods

Table 1 Capital costs and printing costs per kilogram of material for the four case studies assuming a 20 % failure rate

Open-source 3-D Printer	Capital cost (US$)	Unit energy cost (US$/kg)	Unit media cost (US$/kg)	Total unit cost (US$/kg)	Source
MOST Prusa RepRap	575	0.62	42.00	42.62	Wittbrodt et al., 2013
MOST Delta RepRap	400	0.33	42.00	42.33	Appendix 1*
Quad Delta RepRap	1000	0.20	42.00	42.20	Appendix 2*
Farm of Quad Delta	4500	0.20	42.00	42.20	5 x Appendix 2**

*Note: Following Appendix 1 and 2 material costs with shipping estimate

**Capital estimate based upon actual material costs of US$850 per machine as per Appendix 2

initially are focused on non-metallic products (e.g., plastic and rubber), replacement parts for equipment and machinery, normal household items, and custom low-volume products.

Options 3, 4, and 5 cannot achieve annual production rates sufficient to produce US$100,000 profit. Option 6, a farm of five quad deltas, with a maximum annual capacity of 33,280 units can produce targeted profit of US$100,000 while running at only 37.6 % utilization. At 100 % utilization, gross profits of US$266,240 could be expected. Retailers of RepRap prints would have a gross profit advantage over retailers of traditionally manufactured products at the low end of the market. To put this difference in perspective, a print shop targeting US$100,000 gross profit (profit before deducting fixed costs) for the year would need only US$125,000 in sales compared with US$1,100,000 for a low-end traditional retailer. The print shop would also need about half the revenue of a high-end retailer. The potential market for high-end retail is smaller because fewer consumers can afford expensive items.

Note the above discussion of gross profit ignores differences in fixed costs. A 3-D print shop would require a machine operator, who may also double as a cashier, whereas a traditional retailer must deal with procurement of products and maintenance of inventory and therefore, more labor. Low-cost business models require the retailer to sell higher volumes and are therefore more likely to need additional cashiers (electronic or human) to handle higher transaction volumes and more workers to keep shelves stocked. In comparison, the 3-D print shop needs to sell only about one sixth of the volume and so would be less burdened.

The customizability of 3-D printed products allows 3-D print shops to make unique products that can differentiate buyers from others who purchase mass-produced goods. For instance, Zara dominates profits in women's clothing retail by producing high variety, not by having the highest or lowest prices or quality. Probably, a more important comparison is at the low end, where the bulk of customers reside. Although very large markets (big cities) may support several specialized 3-D print shops catering to customization, most smaller or more spread-out markets (including economically disadvantaged areas) would more likely be able to support low-cost, high-variety, low customization 3-D print shops. High-end 3-D print shops may thrive online (e.g., Shape Ways).

Table 2 The retail price, retail mark up, costs of goods sold, gross profit per item sold, volume per year for a US$100,000 gross profit, and revenue per year for US$100,000 gross profit for the low and high-end of traditionally manufactured products and the four case studies of 3-D print shops

Type of business	Case	Retail price (US$)	Retail markup (%)	Cost of goods sold (US$)	Gross profit per items sold (US$)	Maximum volume	Volume per year for a US$100,000 gross profit	Revenue per year or US$100,000 gross profit
Traditionally manufactured	1. High-end (Macy's)	100	80	55.50	44.5	N/A	2247	224,700
Traditionally manufactured	2. Low-end (Costco)	15	10	13.63	1.37	N/A	72,992	1,100,000
3-D printed	3. MOST Prusa RepRap	10	500	2.00	8.00	1664	Unattainable	Unattainable
Unattainable 3-D printed	4. MOST Delta RepRap	10	500	2.00	8.00	1664	Unattainable	Unattainable
Unattainable 3-D Printed	5. Quad Delta RepRap	$10	500	$2.00	$8.00	6656	Unattainable	Unattainable
US$125,000 3-D Printed	6. Farm of Quad Delta	10	500	2.00	8.00	33,280	12,500	125,000

A single operator can run five machines at a time. Each print takes 1.25 h to complete, on average. A single machine can produce seven prints a day during normal business hours

While there is no meaningful difference in unit cost operating a quad delta, production rate increases almost fourfold with a machine having the same footprint as the single head delta printer. With a capital cost 62.5 % of that required for four deltas and only 43.5 % of four Prusa printers, it may be particularly well suited for cottage industry. It may also fill a niche need, producing small quantity production runs of bespoke parts. In the future, such consumers may have their own printers; but currently, the market for custom parts is fulfilled by companies like Shapeways.

The quality of the prints from the quad delta can be observed in Fig. 6, which shows a representative quad-delta print of four motor ends using the design from Fig. 4. As can be seen in Fig. 6, the prints are not quite identical. The wing width (9.00 mm) showed a slight over extrusion with a mean width of 9.08 mm (or just under a 1 % error). The worst error on the external dimensions of all prints was 2 %. The masses of the 60.2 g part also ranged up to 5 %, but followed a pattern where the levels one and three were within 2.2 % and levels two and four were within 2.5 % of each other. Levels one and three are driven off the same drive gear, levels two and four off of another. There is likely a slight difference in the diameter of the hobbed portions of each drive gear that results in these larger errors. The smaller error between the coupled layers is likely due to variations in the filament itself. Overall, these errors are acceptable for many 3-D printed products including RepRap components themselves, but they are not acceptable for prints with exacting tolerances.

Competition for the would-be 3-D print shop operator is expected from the anticipated rapid rise of a home printing culture and peer production. Competition does not affect the cost side of the business, but it can be expected to reduce demand, making it harder to achieve projected revenues. Competition also brings price pressure, reducing what the prints can be sold for. The difference is that on-demand production alters the supply demand landscape since demand, even of bespoke objects, can be filled almost instantly by savvy 3-D printer operators. There is no inventory to dump or maintain and personalize/one-off productions occurring with virtually zero tooling costs. This is the primary opportunity for this type of cottage industry. Competition from home-based printers is a future threat, but may be slow to start up until the machines become easier to use, repair, and upgrade. Knowledge and specialized skills acquired through repeated use, repair, and upgrading of machines may constitute a key capability of 3-D print shops that would be difficult to replicate in the home by novice users. Eventually, we might expect the machines to reach a well-evolved design that is sufficiently easy to use; so a 10-year projection of sales would be expected to follow an inverted u-shaped curve.

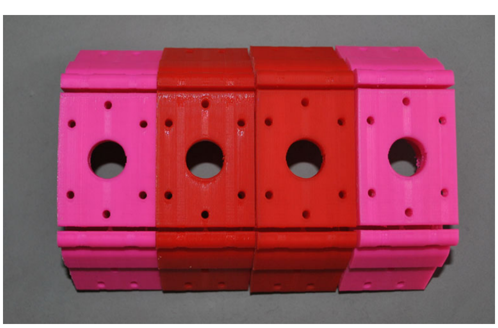

Fig. 6 Representative quad-delta print of motor end from Fig. 4

Print shop operators have another distinct advantage over the conventional retail store since they have the ability to partially self-replicate. All four case studies, because they used open-source 3-D printers based on the RepRap concept, can print a large fraction of their own parts. As the RepRap open design community continues to improve the quality, reliability, and design of RepRaps, the 3-D printer company owner would be in a position to capitalize on these improvements and implement production upgrades with no expenses for research and development. This is a distinct advantage to using open-source 3-D printers rather than simply purchasing proprietary "black box" desktop printers on the market to start a print shop business.

The use of the open-source paradigm also decreases operational costs. The ability to print replacement parts for the components that are most likely to fail after extended use radically reduces the cost to repair the machines. Using these methods, the repair costs can be conservatively estimated to be under US$100/year. There are routine problems with the machines such as clogging and the need for realignment and belt tensioning, but these costs are factored into the very conservative 20 % failure rate. Startup of the business would demand the use of a computer (US$1000) and Internet connection (US$30–60/month). The computer can be any type of desktop or laptop if it is loaded with an efficient open-source operating system like Debian Linux, which is free. The firmware and software to operate RepRap 3-D printers are also free.

Although some 3-D design repositories are charging for models, there are a large number of open-source design repositories that house hundreds of thousands of free models. The costs of purchasing models was not factored in as the consumer would either provide their own, or, in most cases, a free model can be obtained online. In order to design new models, CAD software is needed. Proprietary CAD packages can run thousands of dollars, but there are a large assortment of free and open-source CAD programs like OpenSCAD (http://www.openscad.org/) and FreeCAD (http://www.freecadweb.org/), both of which are parametric, the former being script based while the latter is a conventional visual CAD package. In addition, excellent 3-D models can be made with Blender (http://www.blender.org/), which is also free and open-source 3-D creation software originally designed for animation. While it would not be necessary for a 3-D printer shop operator to make new designs, those who do could charge on an hourly basis and, depending upon obligations, could incorporate it into their catalog of parts.

Table 3 presents an NPV and ROI analysis with optimistic and pessimistic scenarios. The NPV is positive, even in the pessimistic scenario with a conservative 20 % discount rate. The NPV for the more optimistic scenario is well over US$100,000 and provides an ROI of 1008 %. The ROI for even the pessimistic case of 55 % compares extremely favorably to after tax income from other investments (e.g., ~0 % savings accounts, ~2 % certificate of deposit, or ~4 % on the stock market, adjusted for inflation) [36], or small conventional retailers, which often lose money [37]. In our example, an investment of just a few thousand dollars (e.g., US$4600 for a Farm of five Quad Deltas) and as small retail space with minimal advertising can potentially make hundreds of thousands of dollars per year (i.e., see year 5 in Table 3). In short, these analyses suggest that 3-D print shops offer a much better investment opportunities than those found in retailing products that are traditionally manufactured. For instance, 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 % [38]. ROI ranges by industry and within industries. For instance, Costco has an ROI of about 12 % per year.

RepRaps have been shown to be more efficient than conventional manufacturing of polymer products [39, 40]. Energy consumption for printing products is relatively trivial as shown in the small variance around a total cost of US$42/kg shown in Table 1. This holds true for any expected energy price escalations (including for solar photovoltaic converted electricity) in the vast majority of populated areas [41]. It can be assumed that any energy price escalation observed over the life cycle of the investment in an open-source 3-D printer (even if printable upgrades extend it to decades) would favor distributed manufacturing because of the reduced embodied energy of production, transportation and packaging.

A 3-D print shop also has the advantage of a new inventory paradigm: the carrying cost for maintaining high-value inventory is potentially eliminated (although it should be noted for customers unfamiliar with 3-D printing some demonstration products may need to be showcased). As demonstrated by this analysis, the technology places one-off items (note with the quad Delta 1, 2, 3, or 4 identical items can be printed at a time) that

Table 3 Net present value and ROI for 3-D print shop using a farm of quad deltas

	Year 1	Year 2	Year 3	Year 4	Year 5
Printers and maintenance	4600	100	100	100	100
Computer and software	1000	–	–	–	–
Retail space and utilities	20,000	20,000	20,000	20,000	20,000
Labor and management	60,000	60,000	60,000	60,000	60,000
Marketing, accounting, and insurance expenses	15,000	15,000	15,000	15,000	15,000
Working capital	5000	–	–	–	–
Total costs	105,600	95,100	95,100	95,100	95,100
Volume (optimistic)	12,500	15,000	18,000	21,600	25,920
Total revenues (optimistic)	100,000	120,000	144,000	172,800	207,360
Volume (pessimistic)	12,500	12,500	12,500	12,500	12,500
Total revenues (pessimistic)	100,000	100,000	100,000	100,000	100,000
Profit/loss (optimistic)	(5600)	24,900	48,900	77,700	112,260
Profit/loss (pessimistic)	(5600)	4900	4900	4900	4900
Discount rate	20 %				
NPV (optimistic)	US$123,509		NPV (pessimistic)	US$5904	
ROI (optimistic)	1008 %		ROI (pessimistic)	55 %	

Assumptions:

1) In the optimistic scenario, the volume of sales will grow at 20 % per year, whereas in the pessimistic scenario, the volute does not grow.

2) Volume of 12,500 can be achieved in year 1.

3) Revenues assume a gross margin per item of US$8.

4) A single operator can manage five quads and generate a volume of up to 33,280 units per year.

5) Analysis ignores terminal values (i.e., post 5 years), making it more conservative.

6) Profit/loss is before interest, taxes, depreciation, and amortization (i.e., EBITDA).

7) ROI excludes labor/management and retail space from the cost side.

8) Discount rate set at 20 %, which is conservative given Costco's ROI is about 13 %. http://www.bloomberg.com/news/2013-08-30/wal-mart-vs-costco-iii-why-my-critics-are-wrong.html

historically carry high prices well within reach of the small-business owner. 3-D print shops need only inventory low-value, low-cost printer feedstock (e.g., filament). Instead of insuring and protecting expensive inventory, 3-D print shop operators produce on a per-order basis and can offer a variety of products heretofore unheard of. This also represents an opportunity to produce premium value, highly personalized products for end users. In the case of the quad delta, relatively high productivity can be delivered in a very small footprint; the necessary area for manufacturing can be approximated by a closet. Since the machine prints many of its own parts, scaling requires procurement of only non-printed parts. Cloned printers can be arranged neatly in rows.

The open-source 3-D print shop business also has unprecedented mobility for a manufacturing business. All of the RepRaps in the four case studies can be run off of either a car 12 V battery or AC mains, making it possible to power them in any building with grid electricity or anywhere a vehicle can transport them (e.g., even the 6-foot-tall quad delta can be transported in a van, while the single RepRaps comfortably fit in a car seat of a normal automobile). There has also been recent work to power RepRaps with solar photovoltaic electricity [42], which would enable a 3-D print shop to be operated in most regions of the world in a sustainable fashion [43]. Work has already shown how open-source 3-D printers, such as the RepRap, enable the use of designs in the public domain to assist in sustainable development [10]. This is accomplished by fabricating open-source appropriate technologies (OSAT) [44], which are easily and economically made from readily available resources by local communities to meet their needs. This method of small-business creation appears to be particularly well suited for low-income countries to “print themselves out of poverty” [45] using ethical filament [46].

This business model does not come without risks, however, which include: (I) technical obsolescence, (II) surge in homeownership of 3-D printers, (III) conventional retail stores integrating 3-D technology, (IV) reduced costs of online retailers (e.g., Amazon + Shapeways), (V) regulation and safety, and (VI) the power of design repositories.

First, the RepRap technology is developing quickly and even comparing the devices in Figs. 1 and 2, the costs dropped by almost 20 % in a year as a radically innovative design was produced. It is very likely with the nature of open-source development that the 3-D printers purchased will quickly be technically obsolete. The ability to print upgrades is useful and may provide some insurance for 3-D printer operators.

Second, as shown in Wittbrodt, et al. [8] it is economically viable for homeowners to purchase and operate a RepRap to provide for their own needs. Currently, the technology is too immature and not user friendly enough for many consumers, but again with the aforementioned rapid evolution of the designs, there is risk that RepRaps will be ubiquitous products and that the need for specialized 3-D print shops will diminish.

Third, there is already some evidence that conventional retail stores may be interested in 3-D printing custom products for their customers. For instance, McDonalds is flirting with using 3-D printers to make the toys they sell with Happy Meals. The company is, by number of units, the largest toy retailer in the world, and has also been plagued by more than its fair share of product recalls for defective and dangerous products. If other retailers followed a similar path the potential market for print shop owners would shrink. For example, UPS already offers 3-D printing services in some stores.

Fourth, Amazon already has a 3-D printing section and could begin offering 3-D printing services. This suggests that print shops should also aim to become Amazon sellers similar to what currently occurs on E-bay.

Fifth, 3-D printed products have yet-to-be understood product liability implications [47] and there could be issues related to 3-D shops obtaining insurance coverage. Suits usually target retailers and manufacturers of defective products, but 3-D printing makes it harder to distinguish the target of litigation (e.g., the printer operator, the designer of the product, or manufacturer of the printer itself … none are good targets). A 3-D print shop could be liable for selling defective or dangerous products just as retailers are today. Most consumer products do not undergo “regulation” prior to hitting the market, but agencies like the Consumer Product Safety Commission (CPSC) can inspect products in stores and warehouses and force a recall if they are deemed to be hazardous. In addition, some products like toys are regulated [48].

Many of the suppliers of 3-D print designs currently give them away for free as they are self-funded in the maker movement or funded on grants, donations, or ads, but they may later begin charging for them. However, it would seem that unless intellectual property rights were strengthened to cover 3-D print designs, it would be difficult to prevent the continuous reappearance of new free repositories. Extending patents and even copyrights so that they cover 3-D designs will make it possible for infringement lawsuits to target downloaders and extract licenses. This is likely to occur when large incumbents start to feel threatened by the new industry. In the meantime, IP laws may currently be impotent to deal with 3-D printing technology (see Bradshaw et al. [49] and Pearce [50]).

4.1 Limitations and future research

This study has some limitations due to the assumptions used in the analysis. First, the results are limited to the open-source 3-D printers evaluated in this study as other open-source printers could have higher or lower throughput. Next, the assumption that, for instance, a 33 % discount would attract demand away from traditional low-cost retailers. This assumption is grounded in theory [31], but it has yet to be empirically test in the specific case of 3-D print shops.

Although cost numbers rely on experimental values and high probability assumptions (e.g., the cost of Internet connections and electricity), there can be considerable variance in other costs, and most of all, in demand for printed products. The analysis assumed the current cost of 3-D printer filament would remain steady. This is unlikely because of the development of a technology called the Recyclebot [25], which allows waste plastic from post-consumer beverage containers to be turned into 3-D printer filament. The energy costs to produce this filament are approximately US$0.10/kg compared to commercial filament that currently retails for US$35–50/kg [25]. The technology is not as advanced as 3-D printing itself, but the Ethical Filament Foundation has already been created to help waste pickers commercialize filament production in developing countries to improve their standard of living. The Recyclebot is open source and there have already been several DIY variants created and successful Kickstarter campaigns. Filament technologies are in substantial flux, particularly in regard to recycled materials [51], and although not all of the materials used in commercial products are available yet for 3-D printing, the number of materials available for RepRap printers is expanding rapidly. For example, the latest edition of Cura for Lulzbot Taz printers as of Sept. 2015 comes with pre-sets for 20 materials as compared to last year's edition that had only three (PLA, ABS, and HIPS). The widespread deployment of this technology would further increase material selection, reduce operating costs, increase margin, or allow them to reduce prices of items to drive more sales. Counter to this, both the demand for 3-D printed goods in a given community and the growth rate of the demand are not known with confidence. We have addressed this with a sensitivity study (i.e., providing optimistic and pessimistic scenarios).

Future research is needed following the business practices of the growing number of local 3-D print shops, but also micro-entrepreneurs using their home 3-D printers to sell printing services on the web such as MakeXYZ represents a significant business threat. On the technical side, more high-quality, open-source model designs, advancements in printer reliability, cost, speed, resolution, and a greater variety of print media able to be fabricated with Recyclebots will all help improve the viability of this distributed manufacturing business model.

4.2 Conclusions

This study has shown that the 3-D printing business model is viable, even at a small scale, with current open-source 3-D printers. As described, the 3-D printing business model can offer products at a substantial discount as compared to low-cost brick-and-mortar and online retailers. In addition, 3-D print shops can provide highly customized items for only slightly more than the cost of materials while still maintaining healthy margins. Low-cost, open-source 3-D printers are now within investment range of individual entrepreneurs and their open-source nature ensures that they can continue to be upgraded as the technology improves. The margin advantage, net present value, and ROI analysis provided herein could form the basis of many new small-business ventures in the coming years. For example, the ROI ranged from 55 % in the pessimistic scenarios to over 1000 % for optimistic scenarios.

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