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Green Fab Lab Applications of Large-Area Waste Polymer-based Additive Manufacturing

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Abstract

Fab labs, which offer small-scale distributed digital fabrication, are forming a *Green Fab Lab Network,* which embraces concepts of an open source symbiotic economy and circular economy patterns. With the use of industrial 3D printers capable of fused particle fabrication/ fused granular fabrication (FPF/FGF) printing directly from waste plastic streams, green fab labs could act as defacto recycling centers for converting waste plastics into valuable products for their communities. Clear financial drivers for this process have not been studied in the past. Thus, in this study the Gigabot X, an open source industrial 3D printer, which has been shown to be amenable to a wide array of recyclables for FPF/FGF 3D printing, is used to evaluate this economic potential. An economic life cycle analysis of the technology is completed comprised of three cases studies using FPF for large sporting equipment products. Sensitivities are run on the electricity costs for operation, materials costs from various feed stocks and the capacity factors of the 3D printers. The results showed that FPF/FGF 3D printing is capable of energy efficient production of a wide range of large high-value sporting goods products. In all cases, a substantial economic savings was observed when comparing the materials and energy related costs to commercial goods (even for customized goods). Using locally-sourced shredded plastic represented not only the best environmental option, but also the most economic. For the case study products analyzed even the lowest capacity factor (starting only one print per week) represented a profit when comparing to high-end value products. For some products the profit potential and return on investment was substantial (e.g. over 1000%) for high capacity use of a Gigabot X. The results clearly show that open source industrial FPF/FGF 3D printers have significant economic potential when used as a distributed recycling/manufacturing system using recyclable feed stocks in the green fab lab context.

Keywords: polymers; recycling; waste plastic; upcycle; circular economy

1. Introduction

A fab lab (or fabrication lab) is a small-scale workshop, which offers personal digital fabrication [1,2]. The lab itself functions as a technology prototyping platform for individuals to make their ideas a reality [3]. Fab labs are set up to foster learning, curiosity, creativity, experimentation, innovation, and invention [4]. These actions are encouraged through both hands-on making and open knowledge sharing [3,4]. Each fab lab provides a common set of tools, which include digital fabrication tools like laser cutters, CNC mills, and 3D printers. Fab labs train users to fabricate with these tools and provides access to make products for themselves. There are now more than 1,000 fab labs across the globe [5,6]. By empowering people to fabricate their ideas while being supported both locally (in the fab lab) and globally (the fab lab network and larger open source community), fab labs offer the potential for open source appropriate technology to flourish [7,8], particularly when coupled to additive manufacturing to drive sustainable development [9].

A *Green Fab Lab Network* is forming, which is a globally distributed design team [10]. The Green Fab Lab Network utilizes the concepts of open source symbiotic economies [11,12], biomimicry [13-15], regenerative design [16-19], and circular economy patterns [20-22]. For example, Fab Lab Barcelona has a Green Fab Lab project that aims to explore how digital fabrication can support a more sustainable lifestyle [23,24]. This is possible because digital distributed manufacturing with 3D printers has been shown to be less environmentally detrimental than conventional manufacturing [25-27] because of improved materials efficiency and reduced embodied energy of transportation [28,29]. Although the ecological benefits of distributed manufacturing with AM can be substantial, these can be improved further with the use of the most ecologically friendly materials. For example, distributed plastic recycling can be used to provide materials from local waste. This involves upcycling post-consumer polymer waste into 3D printing filament [30] with a recyclebot, which is an open source waste plastic extruder [31]. Environmental life cycle analysis (LCA) performed on the recyclebot production of filament showed the embodied energy of 3D printing filament could be reduced by 90% compared to manufacturing traditional filament [32-34]. By enabling true distributed recycling nearly all energy use from transportation as well as the pollution from transportation are eliminated, which tightens the loop of the circular economy making it more efficient [35]. Several types of recyclebot devices have been developed. This includes open source recyclebot variations from Filastruder, Lyman Plastic Bank, Perpetual Plastic and Precious Plastic. In addition, Felfil (OS), Filabot, Filastruder, Filafab, Filamaker (also has shredder), EWE, Extrusionbot, Noztek, and the Strooder provide fully commercialized versions of recyclebot technology [36]. In addition, following the RepRap (self replicating rapid prototyper) [37-39] method of making parts for a 3D printer using the machine, a “RepRapable Recyclebot” has been developed [40], where the majority of the recyclebot’s parts can themselves be 3D printed from waste plastic using RepRap-class 3D printers. Recyclebots have successfully recycled several thermoplastic filaments including poly lactic acid (PLA) [40-44], high density polyethylene (HDPE) [31,45,46], acrylonitrile butadiene styrene (ABS) [34,45,47], elastomers [48], and composites like both waste wood from furniture manufacturing [49] and carbon fiber reinforced polymers [50]).

Although this process is effective the mechanical properties of the polymer are degraded with each melt/extrude cycle [41,42,51,52]. Thus, each cycle including the recyclebot process during conventional fused filament fabrication (FFF) (also referred to as fused deposition modeling (FDM) on proprietary Stratasys printers) 3D printing the material is slightly down-cycled. Without the introduction of reinforcement (e.g. carbon fibers) or virgin polymer, this process of recycling is limited to about five cycles as the mechanical properties weaken to the point of eliminating many applications [41,42]. To minimize the count of melt and extrude cycles of recycled plastic used for FFF-based 3D printing, the actual fabrication of filament can be replaced with printing directly from a number of sources such as pellets of plastic, flakes of plastic, regrind or shreds of recycled plastic (or polymer “particles” here). Several types of 3D printers already using fused particle fabrication (FPF) (or sometimes referred to as fused granular fabrication (FGF)), which have been developed to accomplish this in university labs [53-58], the RepRap/maker community [59-61], hacking industrial robots [62] and commercial systems [63-67].

Fab labs normally have a number of desktop 3D printers, so their users are already familiar with the concepts of additive manufacturing. In addition, as these 3D printers generate a noticeable amount of waste from failed projects from novice designers there is an opportunity to recycle failed prints [30]. Moving to a higher-end industrial printer capable of printing directly from waste plastic streams is within their technical competency. This would enable fab labs to act to reach some of their promise of sustainability centers [68-70] by becoming defacto recycling centers for all kinds of waste plastics for their communities. To reach this promise, however there must be clear financial drivers to enable sustainable operation. Thus, in this study the Gigabot X, an open source industrial 3D printer, which has been shown to be amenable to a wide array of recyclable feed stocks for FPF/FGF 3D printing [71], is used to evaluate the economic potential for large-area FPF/FGF AM in the green fab lab context. Specifically an economic life cycle analysis of the technology is completed comprised of three cases studies using FPF for large sporting equipment products. Sensitivities are run on the electricity costs for operation, materials costs from various feed stocks and the capacity factors of the 3D printers. The results are analyzed and discussed.

2. Materials and Methods

2.1 Recycled Materials

Acrylonitrile butadiene styrene (ABS) and polypropylene (PP) was used for printing of the consumer-grade products in this study. Overall pellet sizes successfully fed through the hopped ranged from a min of 0.006 mm^2 to a max of 18.20 mm^2 [71]. The recycled ABS was supplied by Northwest Polymers (Molalla, OR) and the PP tested was supplied by McDunnough, Inc. (Fenton, Michigan). Before printing ABS was dried in a vacuum oven at 70ºC for 8 hours and no preparation was made for PP.

2.2 AM Systems and Settings

A prototype Gigabot X [71] shown in Figure 1 with the extruder detailed in the cutaway rendering shown in Figure 2 was used to print the materials. The extruder is a drop-in conversion for the standard Gigabot large format 3D printer [67]. It uses a scaled down version of an industrial extrusion screw to promote more consistent extrusion and mixing of materials [71]. The machine uses large nozzles (1.75 mm in diameter) allowing for rapid deposition of materials for reduced print times for large parts. All designs for the machine are open source allowing for customization modification by the user to adapt the printer to allow for new materials and use cases [67]. 3D models were sliced with Slic3r [72] and the printer was controlled with Marlin Firmware [73]. Optimal printing parameters were determined by the methodology outlined in [71]. As the system has two heating zones non-uniform particles are melted in zone 1 before they are 3D printed in zone 2, which enables the system to be robust through a wide range of sizes and materials [71].

Figure 1. Gigabot X.

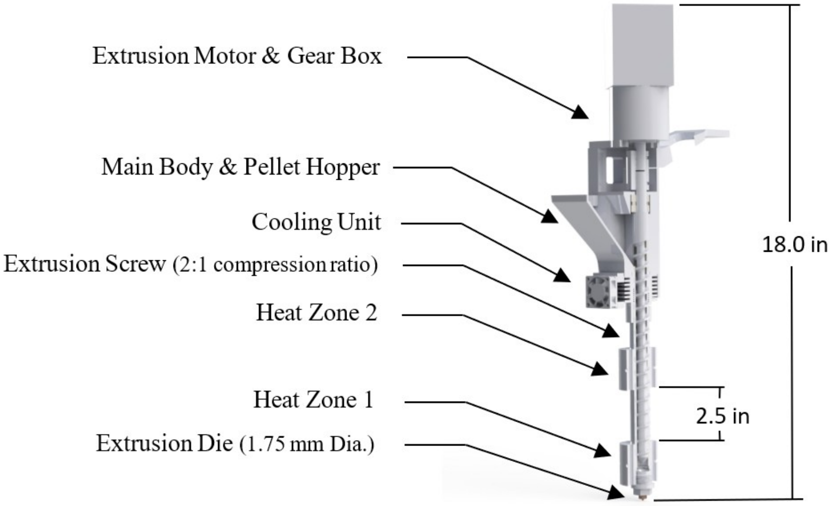
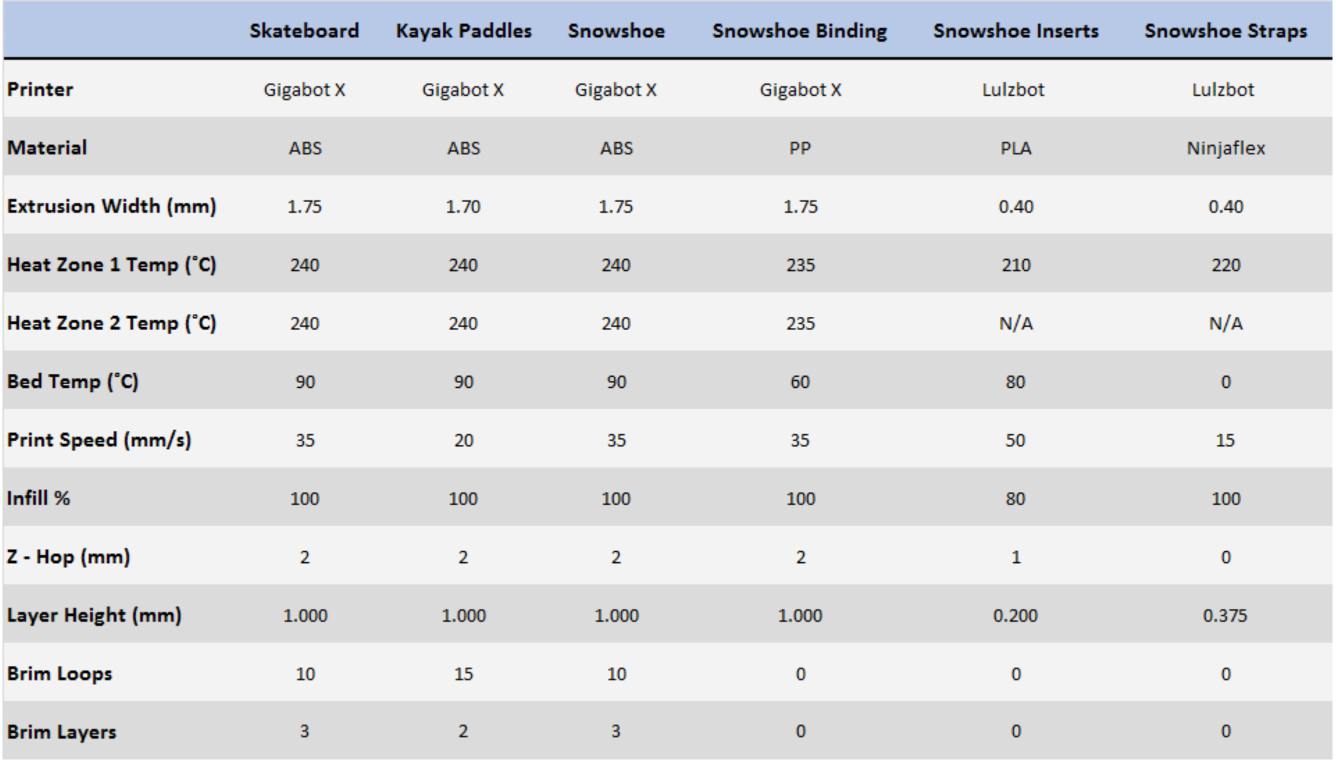


Figure 2. Gigabot X extruder with pellet/granules/particles and regrind feeder.

The printer settings are shown in Table 1 for the case study components detailed in section 2.3.

Table 1. 3D printer settings for all materials used in case studies.



	Skateboard	Kayak Paddles	Snowshoe	Snowshoe Binding	Snowshoe Inserts	Snowshoe Straps
Printer	Gigabot X	Gigabot X	Gigabot X	Gigabot X	Lulzbot	Lulzbot
Material	ABS	ABS	ABS	PP	PLA	Ninjaflex
Extrusion Width (mm)	1.75	1.70	1.75	1.75	0.40	0.40
Heat Zone 1 Temp (˚C)	240	240	240	235	210	220
Heat Zone 2 Temp (˚C)	240	240	240	235	N/A	N/A
Bed Temp (˚C)	90	90	90	60	80	0
Print Speed (mm/s)	35	20	35	35	50	15
Infill %	100	100	100	100	80	100
Z - Hop (mm)	2	2	2	2	1	0
Layer Height (mm)	1.000	1.000	1.000	1.000	0.200	0.375
Brim Loops	10	15	10	0	0	0
Brim Layers	3	2	3	0	0	0

Another FFF 3D printer, the Lulzbot Taz, was used for the detailed parts as it has a 0.5 mm nozzle. It uses 2.85 mm filament and the parts were printed in polylactic acid (PLA) with 80% infill or Ninjaflex at 0.2 mm layer height and at 100% infill. Fab Labs already have access to such small desktop FFF 3D printers to make small detailed parts.

2.3 Case studies

Three sports mobility products were chosen as case studies from a large initial list of consumer grade products that could be printed by the Gigabot X. These products were selected based on their use of the build volume of the Gigabot X (e.g. they are not appropriate for standard desktop 3D printers because they are too large), a wide market and thus interest from makers using a fab lab as well as the general public, a variety of sizes (e.g. print times), a large and variable economic value and the ability to provide higher value by customization.

A skateboard, kayak paddles and snow shoes (Figures 3, 4 and 5, respectively) were selected as the case study products that would provide greater mobility in the summer, on water and in the winter. Case study products were designed utilizing open source software (Blender [81] and FreeCAD [82]) to ensure universal accessibility and customizability of products by the open source community.

Visual renderings of the portions of the products designated for FPF were prepared and used to provide initial estimates of time and material required to produce the final product. Additional hardware not suitable for FPF was then either sourced commercially or printed with more traditional FFF 3D printing.

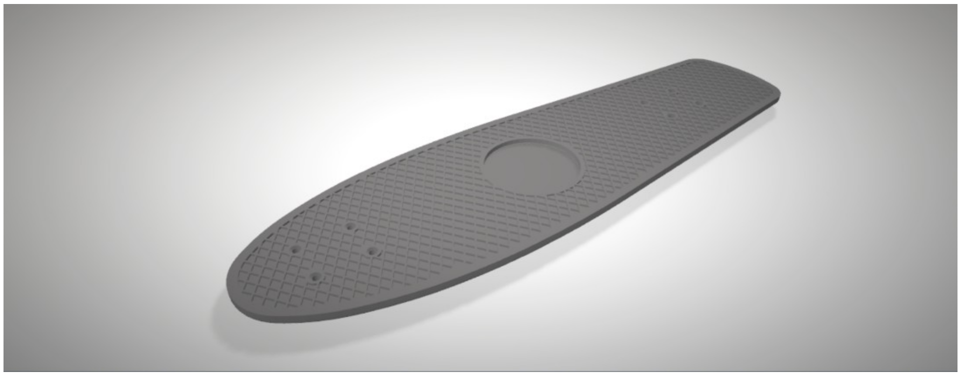


Figure 3. Skateboard CAD file prepared for print

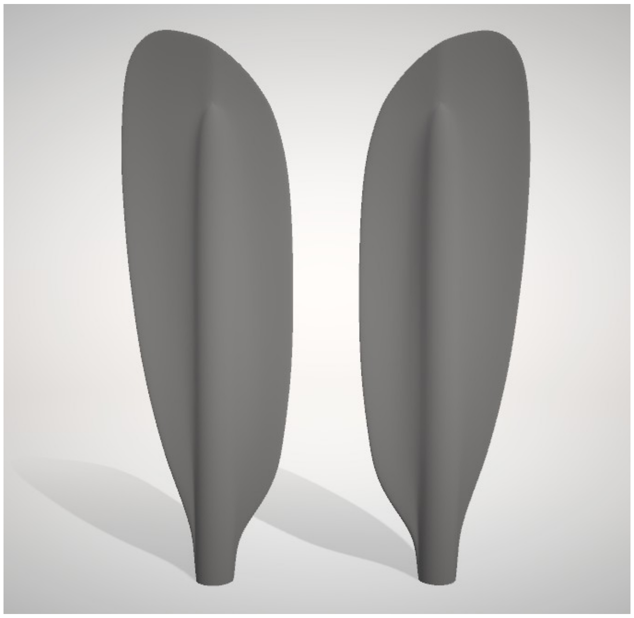


Figure 4. Kayak paddle CAD file prepared for print

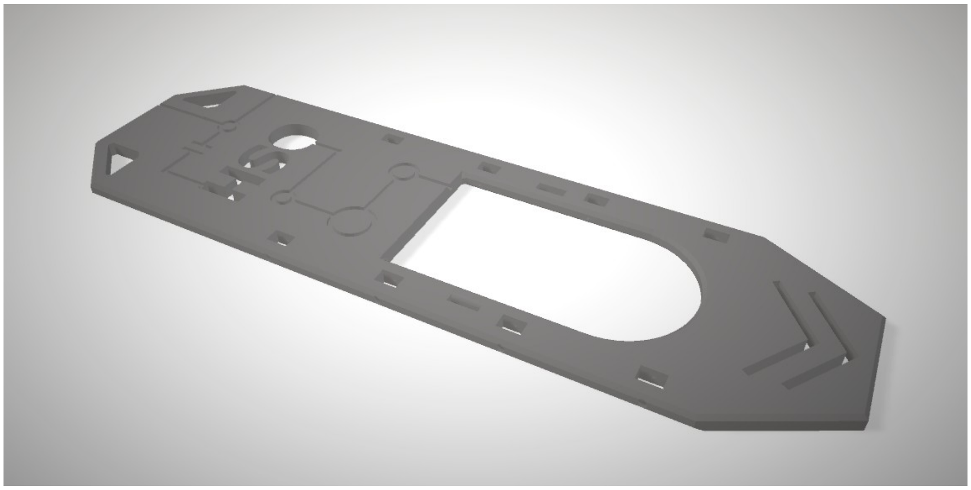


Figure 5. Snowshoe CAD file prepared for print

The skateboard shown in Figure 3 was designed in FreeCAD and printed as shown, using the Gigabot X system. The circular indentation located in the middle of the board was created to allow for the placement of high detail, multi-colored and fully customizable inserts, intended for print on an FFF system. The trucks and remaining hardware were sourced from commercially available options. They were not included in the economic analysis – only a direct comparison between commercial skateboard decks and the customizable 3D printable deck is used here.

Kayak paddles shown in Figure 4 were designed in Blender, with the intention of heat forming them onto an aluminum handle. Due to the use case of the kayak paddles, a smooth surface finish is required for optimal performance. This was to be achieved through sanding and an acetone painting process. Both child- and adult-sized versions of the kayak paddles were created, to better demonstrate the customizability of the process.

Note as shown in Figure 5, the snowshoes were printed entirely flat and a hot water bath was used post printing to bend up the front of the snow shoe. The part of the print needing reforming is placed in boiling water for 10 minutes and then bent between two pieces of wood. The process can be repeated until the required shape is met. The snowshoes were designed using FreeCAD and were meant to be assembled using a variety of smaller 3D printable components designated for FFF printing. A full assembly of components can be seen in Figure 6.

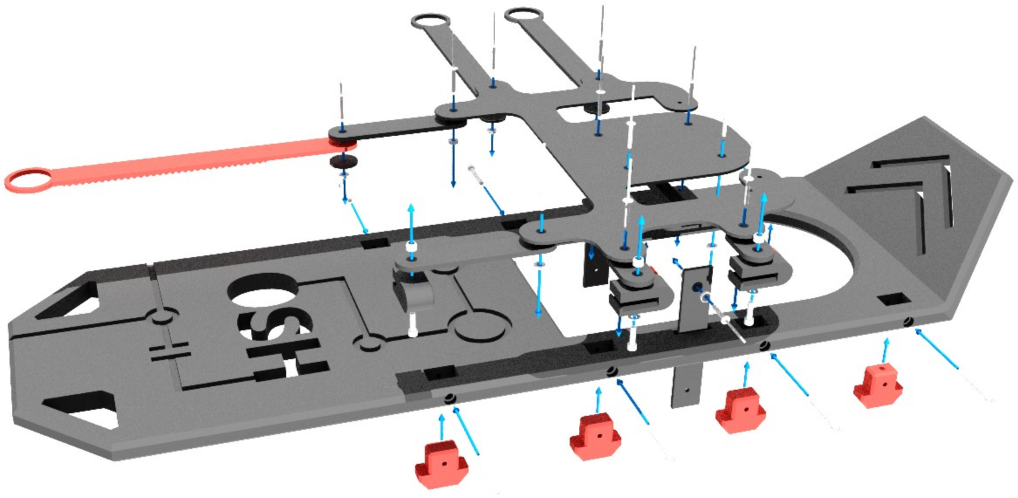


Figure 6. Snowshoe assembly exploded view

2.4 Post Processing

For post processing the large ABS parts, acetone smoothing was used to provide an improved surface finish. For parts like the Kayak paddle where surface finish would impact the functionality of the part, acetone was used to melt the layers together by chemically breaking down the outer surface of the plastic and blending together the peaks and valleys of each layer. A regular paintbrush was used to brush onto the part, and several applications were needed to get an adequate finish. An appropriate solvent should be used for each 3D printed plastic following [74]. This process should also be conducted in a well-ventilated area or fume hood.

2.5 Economics

2.5.1 Capital Costs

The Gigabot X (Fig. 1) will retail for 17,500.00 USD, the extruder shown in Fig. 2, will retail for 4,500 USD. Although some accountants may use a capital equipment depreciation of 3 to 5 years, the expected physical lifetime of the Gigabot is longer at 15 years, given the relatively high set aside for maintenance. Thus, 15 years will be used as the life cycle time for this study.

2.5.2 Operational Costs

The FPF 3D printer has an estimated maintenance costs of 500 USD/year assuming a capacity factor of 85% associated with replacement of small components such as heater cartridges, thermocouples, and cooling fans. The primary costs associated with operating the AM device are associated with the materials and electric costs. To obtain material costs as a function of time, multiple standard use case parts were run at optimum speed and flow rate slicer settings. Print times were recorded and parts were massed on a digital scale (±1 g). Using this method, averaged material flow rate at optimized slicer settings was found to be 0.125 kg/hr. Electricity (electrical energy) use was monitored during extrusion printing with a multimeter (±0.005 kW h) for each part during printing. Energy required for pre-heating the system was measured 10 times and averaged. Measurements were taken at room temperatures ranging from 23 to 24 °C, bed temperatures between 60 and 90 °C and with temperature zones 1 and 2 ranging from 230 to 250 °C. A sensitivity on the electricity costs ranged from \$0.0953/kWh to \$0.3203/kWh corresponding to low costs in Louisiana and high costs in Hawaii [75]. For comparison the U.S. average electricity cost is \$0.1325/kWh.

A range of materials costs were considered summarized in Table 2. Labor costs were not considered and will be discussed in detail below.

Table 2. Materials Costs

Materials	**Low cost (USD/Kg)**	**High cost (USD/Kg)**	**Sources**
Filament (for comparison to conventional FFF/FDM)	15.00	35.00	[76,77]
Virgin Pellets	2.84	9.34	[78]
Recycled Pellets	1.10	2.20	[79,80]
Shredded Plastic[1]	0.013	0.044	[35]

1. Shredded plastic costs assumed the shredding was occurring in the fab lab for zero labor costs using free waste materials. The only cost was thus the cost for electricity to run a shredder similar to [35], which found the energy consumption for shredding 1 kg of ABS is 0.138 kWh and shredding rate is 4.358 kg/h. The low and high costs are calculated from the low and high electricity costs of 0.0953 and 0.3203 (\$/kWh) [75], respectively. This is the case where the recyclables were already relatively clean– e.g. PP vials and bottles or ABS toys – collected for the purpose of recycling. If the waste stream was single source mixed then cleaning and sorting would need to be added to the costs.

For the capacity factor a number of scenarios are evaluated including 1) continuous printing (e.g. after each print a new one is started regardless of time of day or night), 2) one new print start per day, 2) two print starts per day (e.g. staring one at beginning of day and one at closing to print overnight), 3) maximum number of new print starts per 8 hour working day, and 4) one new print start weekly. The capacity factor will also thus depend on what object is being printed and over what length of time. To examine this three case studies are selected of products making use of the build volume of the Gigabot X.

3. Calculations

The cost calculations for distributed manufacturing followed [83]. The high and low commercial costs for each product were found using an Amazon search in July 2018 from conventional brick and mortar retailers, excluding shipping costs. The costs of the FPF-produced products (C_p) were calculated using energy and material consumption as measured and described above, and the pro-rated operation and maintenance cost of the Gigabot X as follows:

$$C_p = E\,C_e + m\,C_m + \left(\frac{t}{T_h}\right) C_o \left(\frac{US\$}{product}\right) \qquad (1)$$

where E is energy use in kW h (this includes both pre-heating and printing electricity consumption), C_e is the electric rate in US$/kWh used for a particular sensitivity run, m is the polymer mass consumed in kg for a given product, and C_m is the cost of the materials in US$/kg, t is the time in hours to produce the printed product, T_h is the lifetime of the Gigabot X in hours, and C_o is the operation and maintenance cost of the Gigabot X over its lifetime in USD.

The number of new products (P_y) of each case study type are calculated per year based on the four capacity factor scenarios to produce a total number of products (T_p) in the Gigabot lifetime measured in years:

$$T_p = T_y \times P_y \quad \text{(products)} \qquad (2)$$

The avoided costs (C_a) for a product is the difference between the cost to manufacture with FPF (C_p) and purchase conventionally. The total a=voided cost for each case study product is given by

$$T_{ac} = T_p \times C_a = T_p \times \left(P_c - C_p\right) \quad \text{(US\$)} \qquad (3)$$

The percent change is given by:

$$\frac{\left(P_{Gigabot} - P_c\right)}{P_{Gigabot}} \times 100\,\% = \frac{C_a}{P_{Gigabot}} \times 100\,\% \quad \text{(percent)} \qquad (4)$$

for the purchased retail costs (P_c) for the low estimate ($P_{c\text{−low}}$) and high estimate ($P_{c\text{−high}}$), respectively. The simple payback time (t_{pb}) of the Gigabot X is given by:

$$t_{pb} = \frac{C_{Gigabot} \times t}{\sum C_a} = \frac{C_{Gigabot}}{\sum \left(P_{Gigabot} - P_c\right)} \quad \text{(years)} \qquad (5)$$

where $C_{Gigabot}$ is the cost of the Gigabot X and the sum is taken over a collection of products avoided for purchasing by 3D printing. The approximate return on investment (R) for a RepRap in percent following [84] can be given by:

$$t_{pb} = \frac{\left(1 - e^{RT}\right)}{R} \quad \text{(years)} \qquad (6)$$

where T is the lifetime of the Gigabot in years and assumed to be at least 15 years.

4. Results

The Gigabot X successfully produced three commercial grade sporting goods products from recycled waste as shown in Figures 7, 8, and 9 for skateboard, kayak paddles, and snow shoes, respectively.

Figure 7. Finished skateboard

Figure 8 (a) Finished kayak paddles (children’s version) and (b) Finished kayak paddles (Adult version)

Figure 9. Finished snowshoes

The printing time for the case study products took 11 hours and 54 minutes for the skateboard, 3 hours 53 minutes (7 hours 45 minutes per set) for the kayak paddles, and 9 hours and 8 minutes (18 hours and 16 minutes per set) for the snow shows to print respectively. This corresponds to 0.127 kg/hr, 0.067 kg/hr and 0.123 kg/hr of printing speed for the various geometries (the paddles were printed vertically, which explains the roughly 1/2x rate of deposition). The minimum energy required to preheat the system was found to be 0.23 kWh, the max was 0.36 kWh, with the averaged energy to preheat the system at 0.31 kWh. Once the Gigabot X is at temperature is uses 0.85 kwh/hr to operate. The cost to produce the products is shown in Figures 10, 11, and 12 as a function of the cost of electricity.

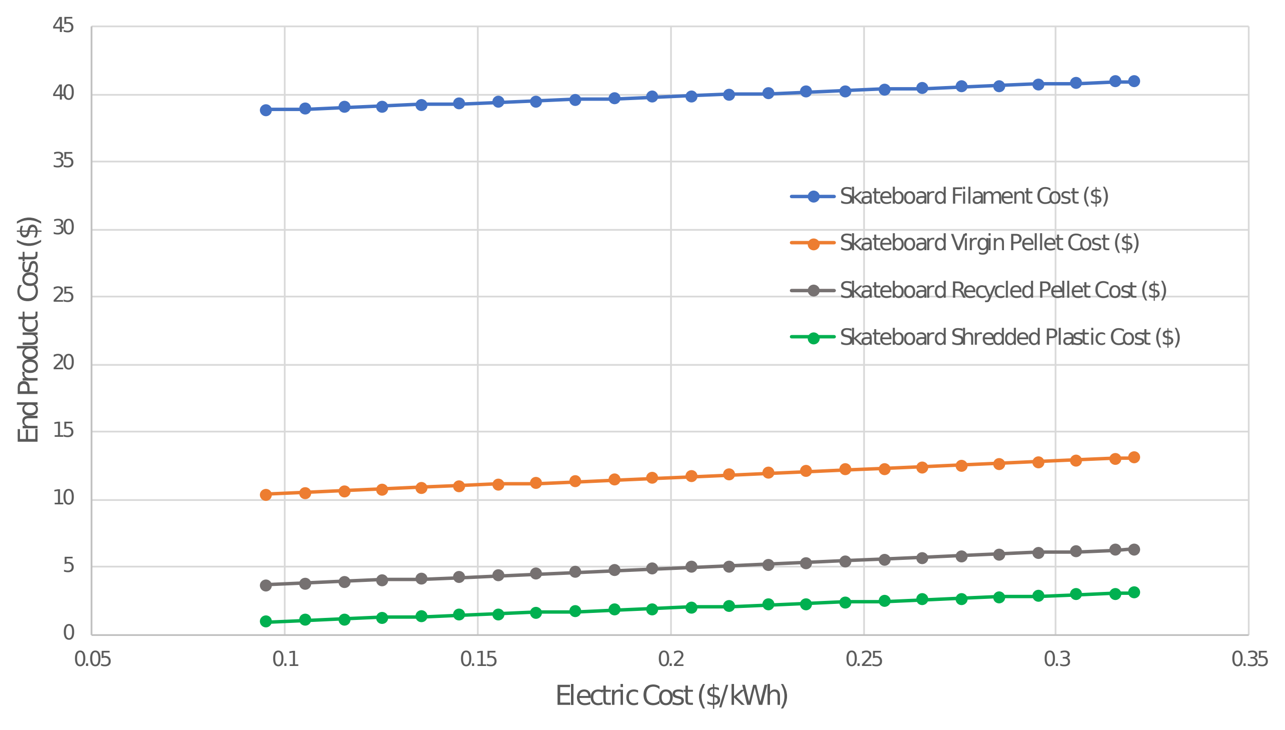


Figure 10. Economic cost to produce a skateboard as a function of the cost of electricity

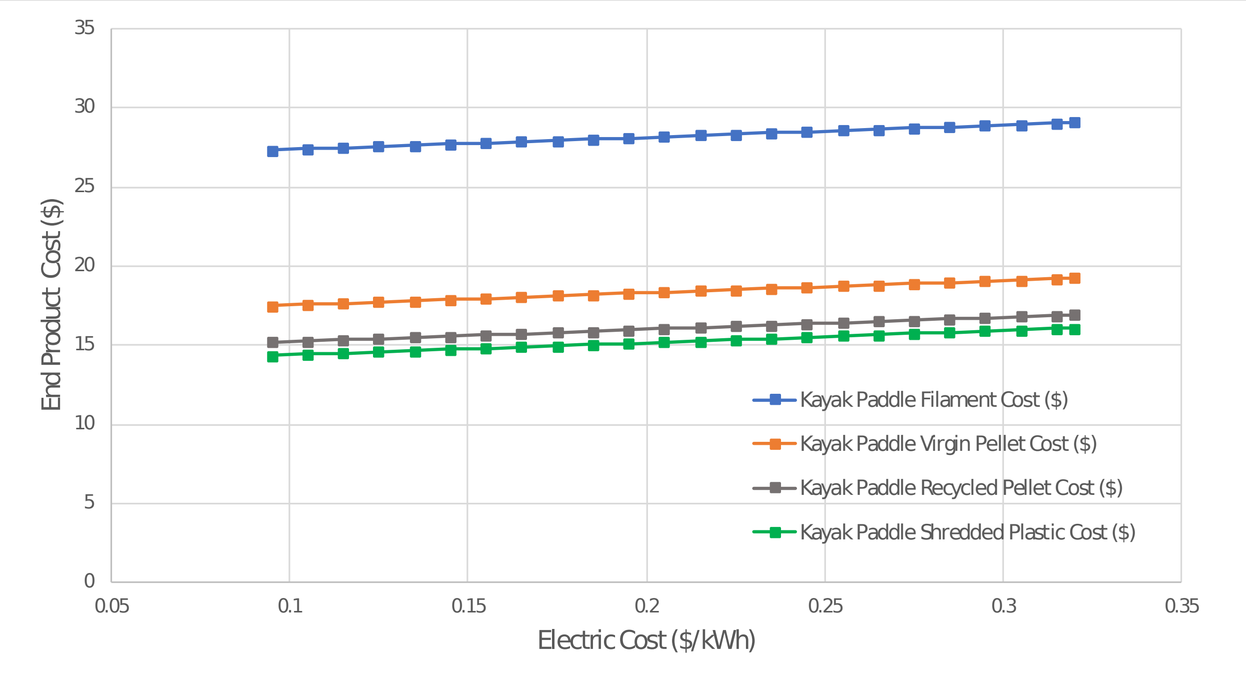


Figure 11. Economic cost to produce a kayak paddles as a function of the cost of electricity

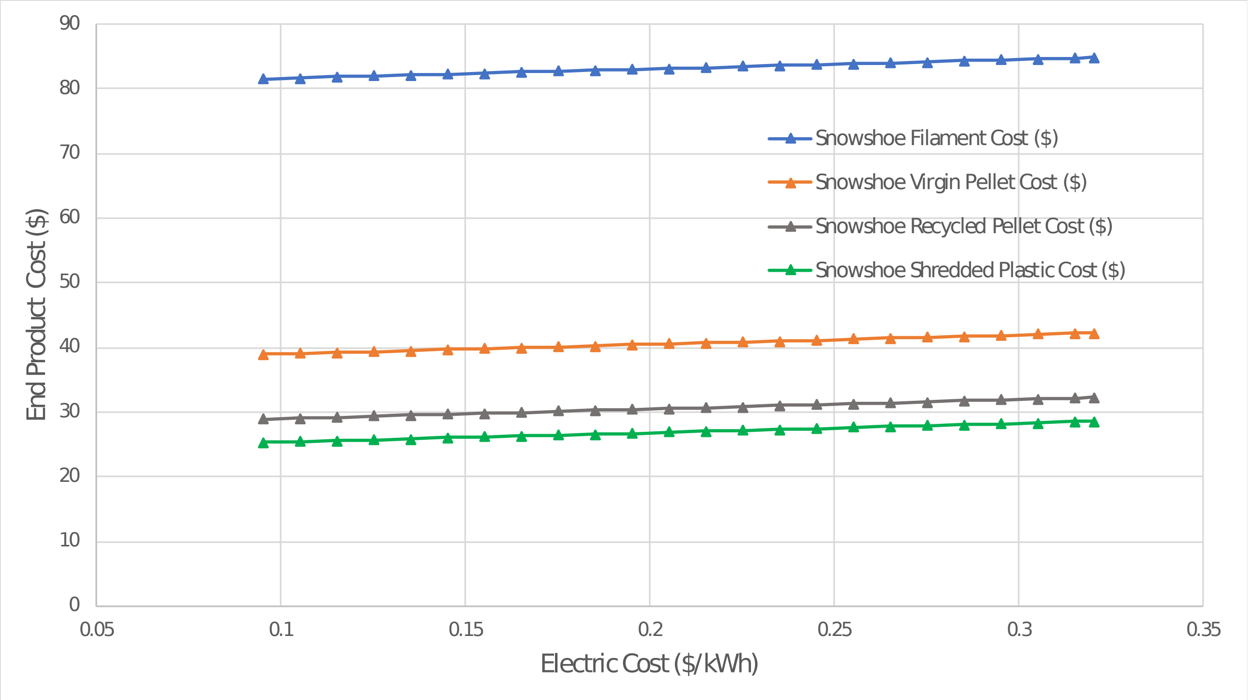


Figure 12. Economic cost to produce a snowshoe set as a function of the cost of electricity

First, it is clear that when looking at the costs of all three case study products the costs of using a Gigabot X to produce products from pellets or shredded plastic is significantly less than using filament regardless of the electricity costs found in the U.S. Despite the size of the Gigabot X, it uses 0.85 kWh/hr, which is less than operating a small microwave or hair dryer. This efficiency could be improved further in the future using several approaches such as a chemically appropriate bed to avoid heating, an insulated bottom to the heated bed, zone heating of the heated bed, an enclosure and more insulation on the hotend.

Comparing the Figures 10 through 12 it is clear that all products increase in cost as the price of electricity increases, however, in Figure 11, which displays cost data for the kayak paddles, the slightly steeper trend lines than compared to Figure 10 and 12 are due to the smaller (by weight) kayak paddles have a product cost that is more dependent on electric costs than larger products. In general, as material costs decrease, electric costs increase as a fraction of total product cost. This becomes increasingly important when using low-cost recycled plastics, where the material costs are brought close to zero. The magnitude of this effect can be seen in Table 3.

Table 3. Electric costs for operating the Gigabot X as a percent of total product cost at U.S. high and low values of electric prices. Note: It is assumed that the user pays out of pocket for the shredded plastic for which the only cost was the average cost of electricity to operate the shredder.

	Filament	**Virgin Pellets**	**Recycled Pellets**	**Shredded Plastic**
Avg. % Elec. Costs Low	2.24%	6.24%	13.61%	35.35%
Avg. % Elec. Costs High	7.14%	17.72%	29.83%	43.45%

The costs of all the products can be compared in Figures 13 -15 assuming the average U.S. electric rate. These costs only include the material and electrical costs (e.g. marginal costs), whereas the machine costs are detailed in the next section.

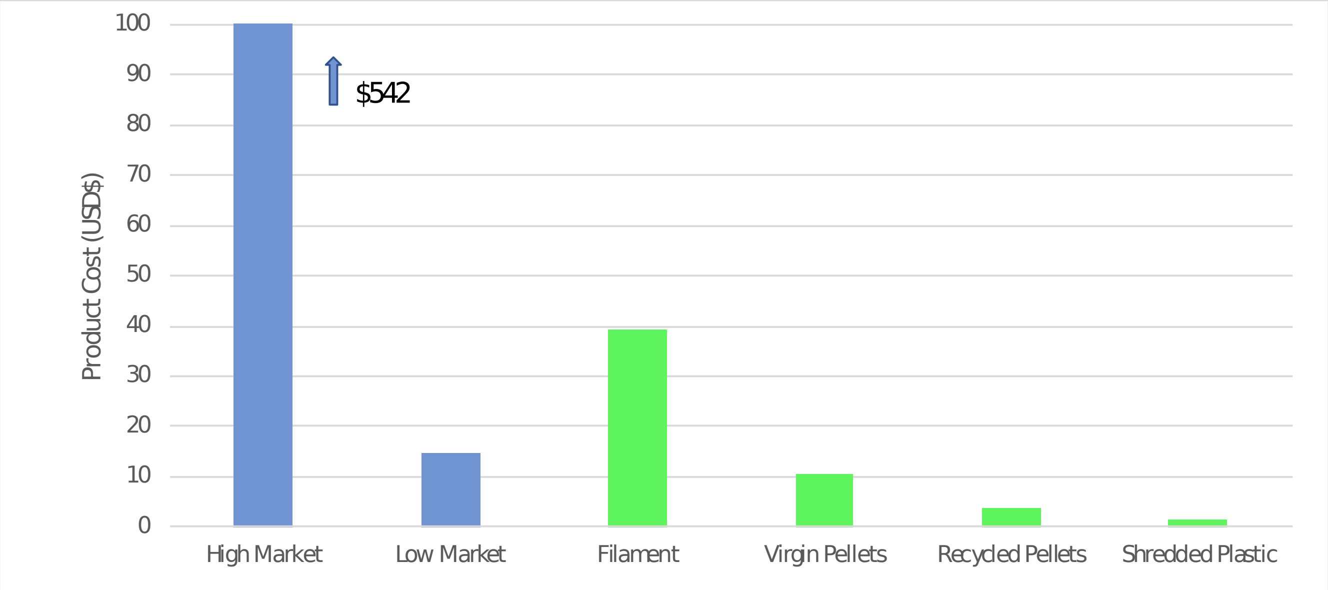


Figure 13. Skateboard, product cost by source.

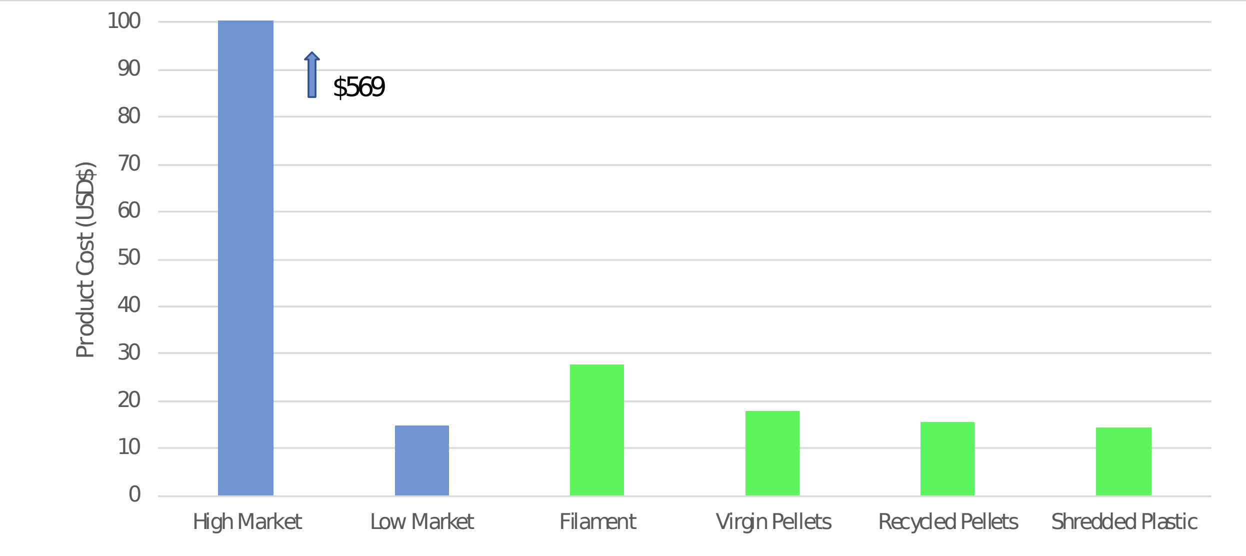


Figure 14. Kayak Paddle, product cost by source.

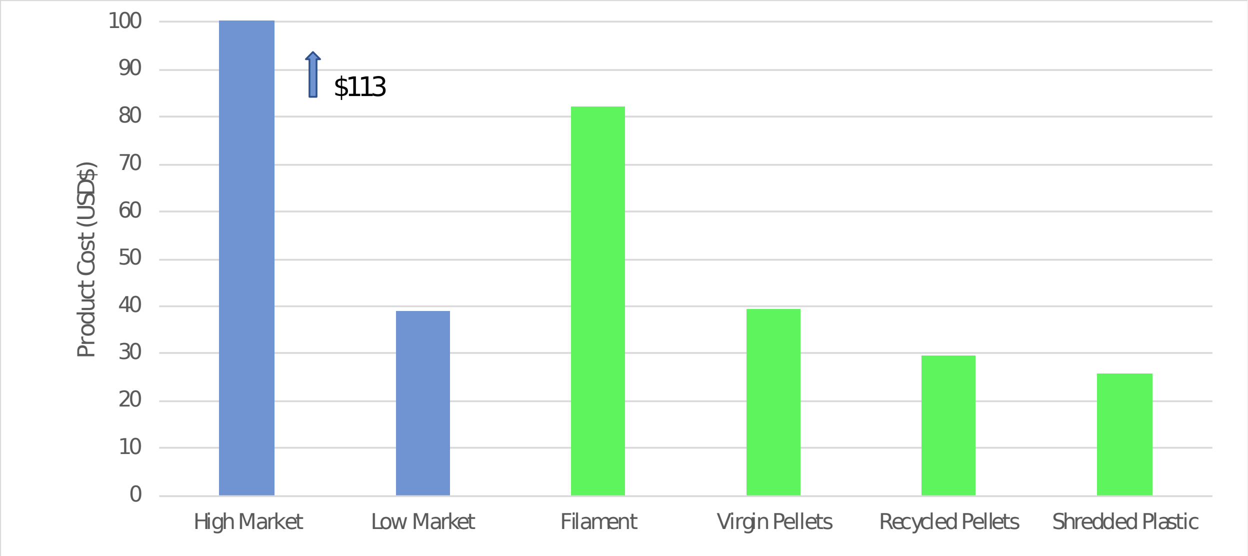


Figure 15. Snowshoe, product cost by source

The cost of the skateboard, kayak paddles, and snowshoes for commercial high and low prices, and distributed manufacturing with the Gigabot X with filament (purchased and cut up), virgin pellets, recycled pellets, and shredded plastic are shown in Figure 13-15. Please note the y-axis scale is limited to 100USD so the lower cost methods of manufacturing can be compared. As can be seen in Figures 13-15, any form of distributed manufacturing is significantly less costly than the high market price. The cost of filament is higher than the cost of the low market commercial products because of the high markup costs on commercial filament. In all cases, the use of shredded recycled plastic was less costly than the lowest commercial price product available on Amazon. Thus the marginal cost of producing any of the case study products is less than purchasing it.

To evaluate the economic potential of the greenest (least environmental impact scenario) a distributed recycling scenario [85-88] is assumed that fab lab users would grind their own waste plastic on site and then use it directly in the Gigabot X. Based on the four capacity factor scenarios the economics for the green fab lab using a single Gigabot X are summarized in Table 4 for a skateboard deck. The skateboard deck is the least complicated because there are no factors related to the purchased components (e.g. the costs of the aluminum poles needed for the kayak paddles would fluctuate significantly based on source location and tariffs and fees associated with current trading disputes). Market research shows the low and high costs for simple and highly customized skateboard decks are $14.80 [89] and $542 [90], respectively. The same data is shown for kayak paddles and snowshoes in Table 5 and 6, respectively. The low and high value savings found in column five, Table’s 4-6, use the low and high cost comparisons found for the most similar objects on Amazon.

Table 4. Skateboard 12 hr. print

Scenario	**Capacity Factor (%)**	**Prints per year**	**Prints over lifetime**	**USD$ saved/ year Low-high**	**USD$ saved/life-time Low-high**	**Payback time Low-high (years)**	**ROI Low-high (%)**
Continuous	100.0	730	10950	$ 9,263.70	$ 138,955.50	1.89	53
				$ 394,119.70	$ 5,911,795.50	0.04	2,273
One new start per day	50.0	365	5475	$ 4,631.85	$ 69,477.75	3.78	26
				$ 197,059.85	$ 2,955,897.75	0.09	1,124
Two starts per day	100.0	730	10950	$ 9,263.70	$ 138,955.50	1.89	53
				$ 394,119.70	$ 5,911,795.50	0.04	2,273
Max per one 8 hour shift	50.0	365	5475	$ 4,631.85	$ 69,477.75	3.78	26
				$ 197,059.85	$ 2,955,897.75	0.09	1,124
One new print weekly	7.1	52	780	$ 659.88	$ 9,898.20	--	--
				$ 28,074.28	$ 421,114.20	0.62	161

As can be seen in Table 4 all scenarios with the exception of making only a single print per week (using a capacity factor of 7.1%) produced a profit. Some of these profits were quite substantial. So for example, a fab lab with a Gigabot X operating only as a skateboard deck manufacturer could expect to see a more than $2.9m profit over the lifetime of the device even if operating only a single 8-hour shift for labor a day and selling at the high value or over $69,000 at the low value. In reality, the market would likely be within these two extremes and a fab lab wishing to enter such a business would need to determine what salary they could afford to provide while still maintaining profitability. The worker, would of course only need to start and clear prints along with fix any major problems during a print. Thus, a worker could do other tasks (e.g. man the welcome desk at the fab lab, operate multiple Gigabots, etc.), which would make the marginal cost of operating a Gigabot X small.

The economics are similar for the case of a Gigabot X being used to only fabricate snowshoes. Based on the four capacity factor scenarios the economics for the green fab lab using a single Gigabot X with distributed recycled shredded waste are summarized in Table 5 for the snowshoes designed in this study. Market research shows the high and low costs for readily available commercial snow shoes are $39 [92] and $112.99 [91], respectively. Again, only the extreme case of producing only 1 per week was not economic. The ROI for all other capacity factors ranged from 10 to 240% without including labor. For this case study there is some assembly required as shown in Figure 6, so if the snowshoes were either sold as kits or fully assembled the profit per snowshoe pair would be more towards the lower end value even with customizability benefits related to 3D printing are taken into account.

Table 5. Snowshoe 9 hour (18 hours for a set of two) print.

Scenario	**Capacity Factor (%)**	**Prints per year**	**Prints over life-time**	**USD$ saved/ year Low-high**	**USD$ saved/ lifetime Low-high**	**Payback time Low-high (years)**	**ROI Low-high (%)**
Continuous	100.0	486	7300	$ 5,918.84	$ 88,782.60	2.96	34
				$ 41,927.31	$ 628,909.60	0.42	240
One new start per day	75.0	365	5475	$ 4,439.13	$ 66,586.95	3.94	25
				$ 31,445.48	$ 471,682.20	0.56	180
Two starts per day	100.0	486	7300	$ 5,918.84	$ 88,782.60	2.96	34
				$ 41,927.31	$ 628,909.60	0.42	240
Max per one 8 hour shift	37.5	182.5	2737.5	$ 2,219.57	$ 33,293.48	7.88	10
				$ 15,722.74	$ 235,841.10	1.11	90
One new print weekly	10.7	52	780	$ 632.42	$ 9,486.36	--	--
				$ 4,479.90	$ 67,198.56	3.91	25

The economics for producing kayak paddles is less clear as there is less of a direct comparison. First, there is not a comparable product as the wettability of the treated ABS provided an advantage over a standard kayak paddle as shown in Figure 10. This is an advantage for the 3D printed paddle because the need for a drip guard is eliminated as the paddle itself sheds water more easily. In addition, the commercial paddle is slightly more flexible indicating that to make an exact economic comparison more research is needed to choose an apples-to-apples comparison, potentially with composites of ABS and TPEs. On other performance metrics both paddles were comparable (e.g. ability to float if dropped, ease of use, and weight).

Figure 10. Comparing wetting of the 3D printed kayak paddle (left) and a commercial paddle (right).

Second, and perhaps more importantly, the cost of kayak paddles is dominated by the bar shown in an assembled kayak paddle in Figure 11. The aluminum pipe used for the cost comparison of the 3D printed kayak paddle was the worst-case scenario (e.g. single retail price at a local hardware store in the UP of Michigan). Market research shows the low and high cost for kayak paddles is $14.99 [93] and $569 [94], respectively. The cost of the aluminum pole alone was $13, which left very little room for any additional costs to meet the lowest cost commercial paddle. Based on the four capacity factor scenarios the economics for the green fab lab using a single Gigabot X and locally shredded plastic are summarized in Table 6 for kayak paddles.

Figure 11. Assembled kayak paddle shown in use.

As can be seen in Table 6, none of the low-cost comparisons provide a payback or an ROI. The paybacks and ROIs were much better for the high cost scenarios, providing an ROI for example of 7% for even a single print per week which is what would be expected for long term investments on a balanced portfolio on the U.S. stock market. If operated optimally on 8 hour shifts this jumps to 77%

ROI and over 230% if operated continually.

Table 6. Paddles 4 hour (8 for set) print

Scenario	**Capacity Factor (%)**	**Prints per year**	**Prints over life-time**	**USD$ saved/ year Low-high**	**USD$ saved/ lifetime Low-high**	**Payback time Low-high (years)**	**ROI Low-high (%)**
Continuous	100.0	1095	16425	$ (208.05)	$ (3,120.75)	--	--
				$ 606,432.90	$ 9,096,493.50	0.43	233
One new start per day	33.3	365	5475	$ (69.35)	$ (1,040.25)	--	--
				$ 202,144.30	$ 3,032,164.50	1.30	77
Two starts per day	66.7	730	10950	$ (138.70)	$ (2,080.50)	--	--
				$ 404,288.60	$ 6,064,329.00	0.65	154
Max per one 8 hour shift	33.3	365	5475	$ (69.35)	$ (1,040.25)	--	--
				$ 202,144.30	$ 3,032,164.50	1.30	77
One new print weekly	4.8	52	780	$ (9.88)	$ (148.20)	--	--
				$ 28,798.64	$ 431,979.60	9.12	7

5. Discussion

Like most manufacturing equipment purchases, the potential cost benefit of the Gigabot X system is dependent on the relative value of the manufactured components, the cost of materials and the maximum capacity factor at which the system can be successfully operated. However, among AM systems there exist potential incentives due to the Gigabot X systems unique ability to use recycled waste plastics without the need to first turn these plastics into commercial grade filament.

Tables 4 through 6 summarize the potential cost benefits of manufacturing and selling case study products at current market prices using the greenest option of locally-sourced recycled waste plastic and on site shredding. The labor costs were not included as those would be highly variable throughout the locations of fab labs all over the world. For example the high-end of costs could be for professional machinists in European markets using the Gigabot X as one of the tools in their specialty shops; whereas the low end could come from using ‘free’ secretary time for reloading polymer feedstock in the printer while otherwise answering phones or manning a front desk. It should be noted that the vast majority of the time the Gigabot X would run unattended during its long prints so the actual labor involved in printing a pre-designed object is minimal. In addition to the labor costs, the profit and markup were similarly excluded as again this would be highly variable depending on the market. However, using the foundational economic information found here, fab labs or other small and medium sized enterprises (SMEs) can quickly determine if the labor rates they use would make the use of a Gigabot X a useful investment for their enterprise by providing a high enough profit potential. In addition, the results here can be used for direct self-production as in distributed manufacturing-based case studies of consumers [48, 83, 95, 96]. Although the Gigabot X could be used as a ‘factory in a box’ for a single product as shown here, most likely it would be used to print a wide variety of products even in a given fab lab. It would also be used for prototyping new products, which in general would provide much more value per hour of printing times shown here. The Gigabot X system, coupled with usage of shredded waste plastic, lends itself to being particularly beneficial in developing economies where poor access to many commercial products is limited [97-105]. There is thus an urgent need for a low cost open source shredder. Several have been developed already [106-108] and there may be a larger version to be made available for fab labs operating several Gigabot X 3D printers simultaneously.

This study had several limitations. First, only a few types of products were investigated over a single run. Additional research would be necessary to optimize each individual product and to analyze the economics of a Gigabot X-based fab lab using many waste polymer feed stocks as well as a realistic basket of large products appropriate for the Gigabot platform. These might include furniture, tools, lower limb prosthetics, medical models or tools, manufacturing fixtures and jigs, or specialized casings or shrouds for equipment. In addition, products that have higher functionality, but our based on a Gigabot X print should be investigated. For example, the skateboard deck could be used for a 3D printable electric skateboard [109] with a higher retail value of $750-$1000 [110].

Further research needs to be conducted both in factoring the impact of labor costs and or employment opportunities provided by the Gigabot X. In locations with unstable electric grids, the usage of solar photovoltaic systems could potentially provide not only a stable power source, but additional cost savings when coupled with shredded waste plastic. There has been significant progress in this area of solar powered distributed manufacturing with AM systems [37, 111-115], and users have already taken the Gigabot off grid with solar photovoltaic-battery systems [116].

6. Conclusions

This study found that the Gigabot X, an open source industrial FPF/FGF 3D printer, has significant economic potential when used as a distributed recycling/manufacturing system using recyclable feed stocks in the green fab lab context. The results showed that FPF/FGF 3D printing is capable of producing large high-value sporting goods products with the three case studies. The system was shown to be relatively energy efficient so that the costs of electricity were not overly important for such manufactured products unless they were small. In all cases a substantial economic savings was observed when comparing the materials and energy related costs to commercial goods. This was even the case when the 3D printed products were substantially customized. Using locally-sourced shredded plastic represented not only the best environmental option, but also the most economic. For some of the case study products analyzed even the lowest capacity factor (starting only one print per week) represented a profit when comparing to the more legitimate high-end product. When comparing to the low-end in general the Gigabot X needed to be used at a higher capacity. For some products the profit potential and return on investment was substantial (e.g. over 1000%) for high capacity use of a Gigabot X. These results clearly show that the economic benefit of distributed recycling and on demand production of large, functional objects using an integrated FPF/FGF tool to promote circular manufacturing.

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