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Environmental Life Cycle Analysis of Distributed Three-Dimensional Printing and Conventional Manufacturing of Polymer Products

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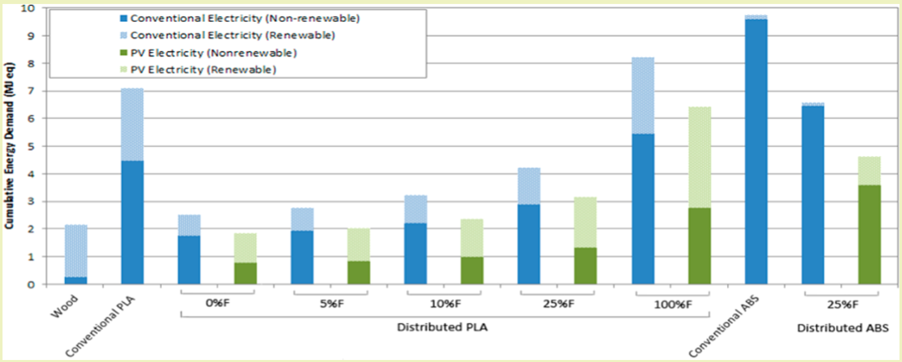

ABSTRACT: With the recent development of the RepRap, an open-source self-replicating rapid prototyper, low-cost three-dimensional (3D) printing is now a technically viable form of distributed manufacturing of polymer-based products. However, the aggregate environmental benefits of distributed manufacturing are not clear due to scale reductions and the potential for increases in embodied energy. To quantify the environmental impact of distributed manufacturing using 3D printers, a life cycle analysis was performed on three plastic products. The embodied energy and emissions from conventional large-scale production in low-labor cost countries and shipping are compared to experimental measurements on a RepRap with and without solar photovoltaic (PV) power fabricating products with acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). The results indicate that the cumulative energy demand of manufacturing polymer products can be reduced by 41−64% (55−74% with PV) and concomitant emission reductions using distributed manufacturing with existing low-cost open-source 3D printers when using <25% fill PLA. Less pronounced positive environmental results are observed with ABS, which demands higher temperatures for the print bed and extruder. Overall, the results indicate that distributed manufacturing using open-source 3D printers has the potential to have a lower environmental impact than conventional manufacturing for a variety of products.

KEYWORDS: *Life cycle analysis, 3D printing, Additive manufacturing, Distributed manufacturing, Desktop manufacturing, RepRap, Open source hardware, Cumulative energy demand*

■ INTRODUCTION

Centralized mass manufacturing of polymer-based products has reduced economic costs while creating a need to mitigate the concomitant environmental burden. The benefits of large-scale manufacturing are well-established and include reduction in costs due to economies of scale from (i) purchasing (bulk buying of materials, supplies, and components through long-term contracts), (ii) increased specialization of employees and managers, (iii) favorable financing in terms of interest, access to capital, and variety of financial instruments, (iv) marketing, and (v) purely technological advantage of returns to scale in the production function.[1−3] The last advantage is in part due to lower embodied energy during manufacturing of a given product because of scale. These advantages have created a general trend toward large-scale manufacturing in low-labor cost countries, especially for inexpensive plastic products.[4,5] The environmental burden that plastics consumption has on the environment is well-established due to their slow decomposition rate and pollution of land, water, and air.[6−8] With annual global production of 245 million tons increasing by approximately 6% per year, there is a clear need to reduce the global environmental impact of plastic consumption.[9]

One new potential method of reducing the environmental impact of plastic products is to use distributed manufacturing with low-cost open-source 3D printers,[10−13] as the nature of 3D printing allows for the fabrication of extremely complex geometries, customization, and minimization of production waste compared to subtractive manufacturing, while maximizing material utilization.[16] The technological development of 3D printers has been substantial[14,15] in industries such as biomedicine with the ability to print artificial bones and aerospace to produce lightweight, increasingly complex, and sturdy parts; however, the costs of 3D printers have historically been too expensive to be feasible for distributed or home-based

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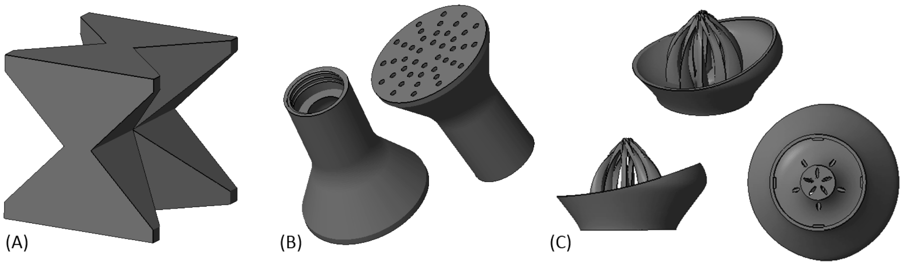

Figure 1. Naef building block[23] (A), water spout[24] (B), and juicer[25] (C).

manufacturing.[16] Recently, several open-source (OS) models of commercial rapid prototypers have been developed,[16] which offer an alternative model of low-cost production. The most successful of these is the self-replicating rapid prototyper (RepRap), which can be built from printed parts, open-source electronics, and common hardware for under $500.[17,18] The RepRap, has opened the door of additive layer manufacturing to a wide range of potential users due to cost and simplicity while making distributed small-scale production technically feasible.[10,19] The ability to change fill composition allows more complicated shapes to be produced with structural integrity while minimizing material use. This property combined with the potential reduction in embodied energy of transportation made available by distributed manufacturing allow for the possibility that it could be less energy and emission intensive than conventional manufacturing. However, the aggregate environmental benefits of distributed manufacturing are not clear due the potential for increases in the overall embodied energy from reduction in scale (e.g., thermodynamic limitations to working with smaller volumes).

This study evaluates the potential of using a distributed network of 3D printers to produce three types of plastic components and products. A preliminary life cycle analysis (LCA) of energy consumption and greenhouse gas (GHG) emissions is performed for distributed manufacturing using low-cost open-source 3D printers and compared to conventional manufacturing overseas with shipping. This comparison was done to represent a realistic approach to manufacturing, as distributed manufacturing has the advantage of being done within the home for products typically produced overseas. To further evaluate the distributed manufacturing system, a distributed electricity generation system using solar photovoltaic (PV) technology was quantified, as the embodied emissions are highly dependent on the grid emission intensity, and PV systems can be scaled to match distributed manufacturing loads.[20] These results are evaluated and discussed to draw conclusions about the viability and environmental performance of distributed manufacturing.

■ METHODS

Production Methods. The production methods used in this study represent the most common 3D printing protocols in the open-source community. The RepRap (Prusa Mendell variant) with a 200 mm × 200 mm × 140 mm (height) build envelope was used to print all product/product components using the thermoplastics: acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA).[21] PLA is a thermoplastic aliphatic polyester derived from renewable resources, such as corn starch, making it a good alternative plastic due to its low environmental impact.[22] The ABS extruder temperature was 230 °C, and the bed temperature was 110 °C. PLA was printed using an extruder temperature of 185 °C, with a first layer bed temperature of 63 °C to ensure adhesion, followed by print bed temperature of 60 °C. Energy measurements were taken using a multimeter (±0.005 kW h) during initial heating (to raise both the print bed and the extruder nozzle to the necessary temperature for printing) and while printing each individual object.

Three products were chosen based on increasing complexity, commercial availability, frequent printing by those in the 3D printing community, and open-source 3D .stl file availability for free online. The following were 3D printed with 45° fill using a rectilinear pattern in ABS and PLA: a "block", a "water spout", and a "juicer" (Figure 1). The three products, which are all likely to be printed by the 3D printing owners for simple economic benefits, were chosen to represent classes of products to test specific variables. The first was chosen to test both the effects of fill percentage on environmental impact without impacting the functionality of the product and for changing material selection, the second for the ability to replace larger products with a combination of recycled objects and specialized 3D prints, and the third to represent a geometrically complex yet functional product.

The Naef building block is a simple, but expensive, toy that is typically handcrafted in Switzerland from hardwood. The fill percentage was varied to include 0, 5, 10, 25, and 100% fill, as seen in Figure 2, within the PLA block in order to determine the relationship between fill percentage and environmental impact. The ABS blocks were printed only at 25% fill.

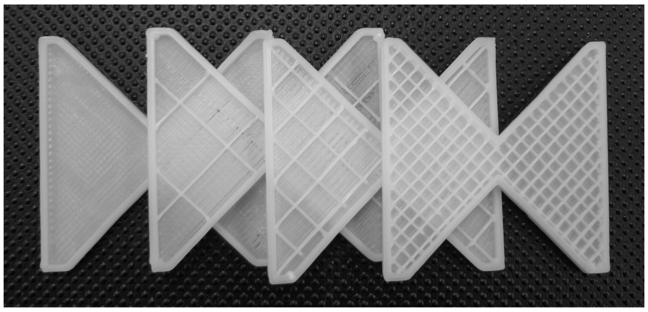

Figure 2. Example of fill percentages for Naef blocks 0, 5, 10, and 25% (left to right), represented in Figure 1a.

The water spout attaches to a postconsumer 2 L bottle and can be used to water plants replacing a typical gardening watering can. PLA and ABS were printed at 100% fill to ensure leak protection.

The citrus juicer is used to produce juice from oranges, grapefruits, lemons, limes, and other citrus fruit. The plastic juicer is fixed upon a postconsumer glass jar for collection similar to commercial products. A 15% fill was used in order to reduce the amount of plastic used to produce it, while maintaining the necessary functional mechanical strength.

Life-Cycle Analysis Methods. Life-cycle impact assessment was used here to quantify the difference in environmental impact between distributed and conventional manufacturing.[26] Similar studies compare and improve the environmental impact of various goods, production methods, fuel sources, etc., such as lubricants[27] and cement.[28] The life cycle impact assessment (LCIA) methods were implemented in the EcoInvent v2.0 database using the program SimaPro 7.2: Cumulative energy demand (CED 1.07) and IPCC GWP 2007 100a (global warming potential over 100 years in kg CO_2 equivalent emissions) for each product. Each input in EcoInvent v2.0 is cumulative, containing all environmental burdens up to the input. A "cradle-to-gate" analysis was done (from raw material extraction to the product exiting the factory gate), with the gate located in the United States (including shipping to U.S. if overseas, packaging not included). The functional unit was assumed to be 1:1 and was input by kilograms required to create each individual product based on fill. The inputs of the LCIA are shown in Table 1.

Table 1. Inputs for LCIA

distributed manufacturing
electricity, production mix U.S./U.S.
OR
electricity, PV, at 3 kWp slanted-roof, a-Si, panel, mounted/CH
polylactide, granulate, NatureWorks Nebraska, U.S.
OR
acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER
conventional manufacturing
electricity, production mix U.S./U.S.
OR
electricity, PV, at 3 kWp slanted-roof, a-Si, panel, mounted/CH
polylactide, granulate, NatureWorks Nebraska, U.S.
OR
acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER
injection molding/RER
transoceanic freight ship/international

Distributed Manufacturing Methods. Distributed manufacturing was quantified using the electricity consumption of the RepRap and the material inputs by weight for ABS or PLA. The U.S. electricity production mix or 3 kWp a-Si panel electricity PV profile from Switzerland was used as an input for energy. In addition to the inputs for the materials were the NatureWorks polylactide from Nebraska and acrylonitrile-butadiene-styrene copolymer from Switzerland. Plastic production was assumed to be in the U.S. for the distributed case. U.S. eco-profiles were used when available; otherwise, European eco-profiles were used.

Conventional Manufacturing Methods. Conventional manufacturing was input using Table 1 assuming a 100% fill and based on the mass of a functionally tested object obtained experimentally. The inputs used for conventional manufacturing were material inputs PLA or ABS, as done for distributed assuming production of plastics in China, in addition to injection molding (Switzerland ecoprofile) and shipping 9213 km using (transoceanic freight ship, international) from Shanghai, China to Seattle, WA.[29] The injection molding was done with the European eco-profile due to limitations on Chinese inputs, this would underestimate the energy use and emissions due to higher regulations in Europe and the large dependence of China on coal-fired electricity. The injection molding input states that the finished product is 99.3% of its input, this was considered in the analysis for both the material input and the injection mold.

One additional version of the conventional manufacturing was done for the case of the "block" to consider wood using inputs (ecoprofile for sawn timber, hardwood, kiln dried $U = 10\%$, Switzerland) using a wooden cube with 2 in. sides and shipping 6275 km using (transoceanic freight ship, international) using the approximate distance from Bern, Switzerland, to New York, NY.[29] Additional processing is unknown for the case of the wood block and is thus underestimated in this study.

Additional Assumptions. Processing for each of these cases should be assumed to underestimate total cumulative energy demand and emissions, as additional processing may be required for consumer use (i.e., sanding, finishing, etc). Overseas shipping distance is an underestimate due to taking a straight-line trip across the ocean. Shipping over land, infrastructure, molds, packaging, and waste were not included in this analysis, thus underestimating the embodied energy of traditional manufacturing and are left for future work. The materials PLA and ABS were used as an example for each product but may not be the ideal materials for these products or may require additional coatings to make them food-grade or child-safe.

RESULTS AND DISCUSSION

Measured experimental values from the RepRap are shown in the fifth column "measured energy" in Table 2 and were used as inputs for the LCIA as outlined above and compared to

Table 2. Experimental Values (total energy), Conventional (conv), and Distributed (distr) Manufacturing Total Cumulative Energy Demand Values for Using SimaPro (CED), Emission Values in Global Warming Potential (GWP), and for Distributed Manufacturing with and without the Use of Solar PV to Provide Low Emission Intensity Electricity

	1	2	3	4	5	6	7	8	9	10	11	12
product	method	fill	material	measured energy	CED	Δ from conv	CED w/ PV	Δ from conv	GWP	Δ from conv	GWP w/ PV	Δ from conv
		%	(PLA/ ABS)	kWh	MJ eq	%	MJ eq	%	kg CO_2 eq	%	kg CO_2 eq	%
blocks	conv	100	PLA		7.09				0.26			
	distr	0	PLA	0.09	2.52	−64.5	1.84	−74.0	0.11	−57.7	0.05	−80.8
	distr	5	PLA	0.1	2.77	−60.9	2.02	−71.5	0.12	−53.8	0.06	−76.9
	distr	10	PLA	0.11	3.21	−54.7	2.38	−66.4	0.14	−46.2	0.07	−73.1
	distr	25	PLA	0.14	4.22	−40.5	3.16	−55.4	0.19	−26.9	0.09	−65.4
	distr	100	PLA	0.24	8.23	16.1	6.42	−9.4	0.35	34.6	0.19	−26.9
	conv	100	ABS		9.76				0.44			
	distr	25	ABS	0.26	6.58	−32.6	4.62	−52.7	0.34	−22.7	0.17	−61.4
spout	conv	100	PLA		1.93				0.07			
	distr	100	PLA	0.1	2.55	32.1	1.80	−6.7	0.12	71.4	0.05	−28.6
	conv	100	ABS		2.38				0.11			
	distr	100	ABS	0.19	4.20	76.5	2.77	16.4	0.22	100	0.09	−18.2
juicer	conv	100	PLA		11.58				0.43			
	distr	15	PLA	0.31	8.66	−25.2	6.32	−45.4	0.39	−9.3	0.18	−58.1
	conv	100	ABS		13.71				0.62			
	distr	15	ABS	0.52	12.96	−5.5	9.03	−34.1	0.68	9.7	0.32	−48.4

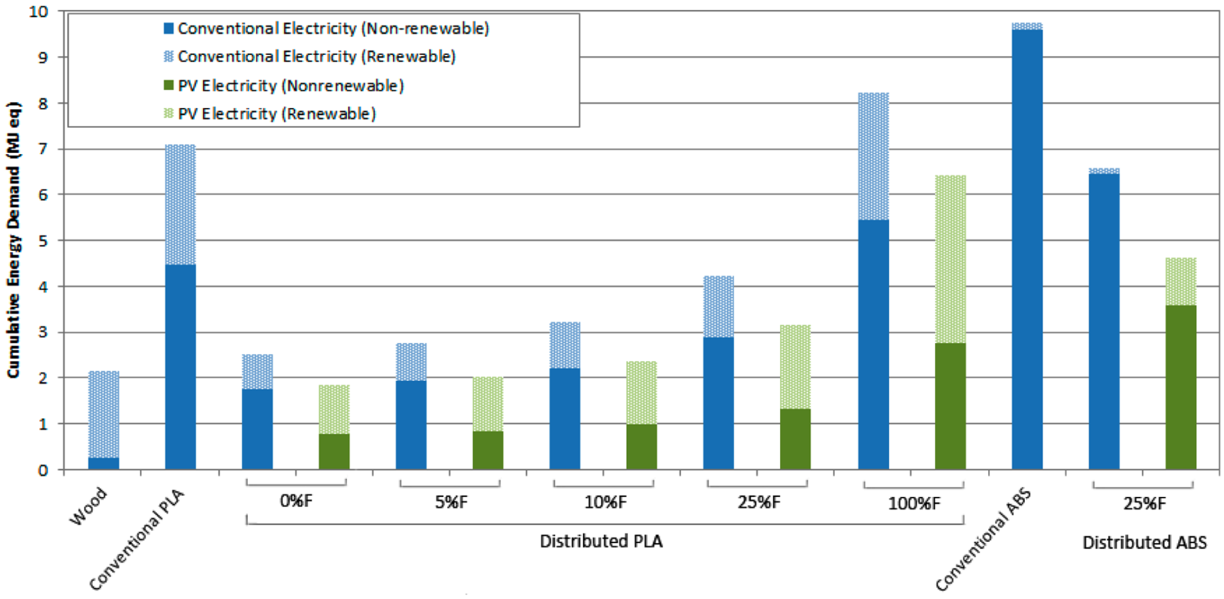

Figure 3. CED of the blocks showing wood, conventional PLA, ABS at 100% fill, distributed PLA from 0 to 100% fill, and distributed ABS 25% fill, along with the effect of PV electricity.

conventional methods as described for cumulative energy demand (CED) and greenhouse gas emissions in global warming potential over 100 years (GWP; Table 2).

The environmental impacts of the distributed manufacturing cases were minimized using a solar PV array to provide electricity following recommendations by Pearce et al. that would allow for 3D printing fabrication in most locations in the world.[19] It has been well established that PV technology is a sustainable source of energy that significantly reduces environmental impact of electricity use and is amenable to distributed generation[30,31] and the embodied energy of PV decreases as advancements are made.[32] PV technology has the potential to prevent a significant amount of emissions[33] as it produces less than 89% of the air emissions from conventional electricity sources.[31] Although there are no commercial PV-powered RepRap 3D printers, proof of concepts already exist and the open-source development community that supports the RepRap has been experimenting with variants.[34] These variants would enable distributed manufacturing even in remote communities without access to the conventional electric grid.

Naef Building Block. The results for the block prints had the CED and emissions compared to conventional and wood synthesis (Table 2 and Figures 3−5). In Figures 3, 6, and 8, the CED is split into two categories: renewable and nonrenewable energy sources involved to display the level of sustainable energy for each case. Renewable consists of renewable biomass, wind, solar, and water energy sources that are part of the conventional energy mix and does not directly relate to the PV-powered systems. Nonrenewable consists of nonrenewable energy sources fossil fuels, nuclear, and biomass. The CED for the blocks can be found in Table 2 and Figure 3. The CED for the conventional method for PLA and ABS at 100% fill was found to be 7.09 and 9.76 MJ, respectively, which is a factor of roughly four times the embodied energy of the wood case. The CED for the distributed 25% ABS block was a 33−53% decrease over conventional polymer production. As expected, as shown in Figure 4 there is a linear trend between fill ratio and energy use for blocks printed in PLA with and without PV. The addition of a PV system results in a saving of emissions from the traditional energy source between 22 and 27%. The CED values under the PV distributed system were less than the conventional manufacturing values for all fill percentages, while the traditional energy source distributed system is less than the conventional below 79% fill. In general when printing with RepRaps, the typical print is done at 25% fill or less, depending on the structural integrity needed, with the majority of prints being 15% or less. Producing goods with less than a 79% fill is easily achieved by the average 3D printer for this reason, implying that distributed manufacturing will have less of an environmental impact than conventional for almost all print jobs.

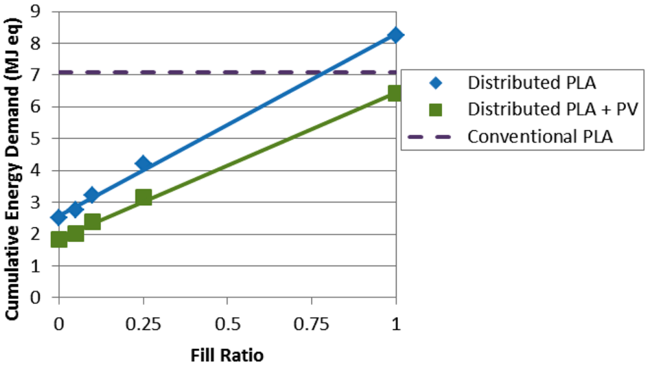

Figure 4. Blocks—fill ratio vs energy demand. The conventional value is included for comparison purposes at 100% fill. If other fill percentages were possible for the conventional method, this value would no longer be a constant function, but change based upon fill.

The emissions for the blocks are shown in Table 2 and Figure 5. The emissions for the conventional ABS block are 0.44 kg CO_2 eq, while the distributed case without and with PV had 23 and 61% savings in emissions respectively at 25% fill. The distributed manufacturing cases have the lowest emission values compared to traditional manufacturing for all cases, except for distributed without PV for 100%. Again, it is clear for this particular product that 100% fill is unnecessary. This implies that without PV, distributed manufacturing should be

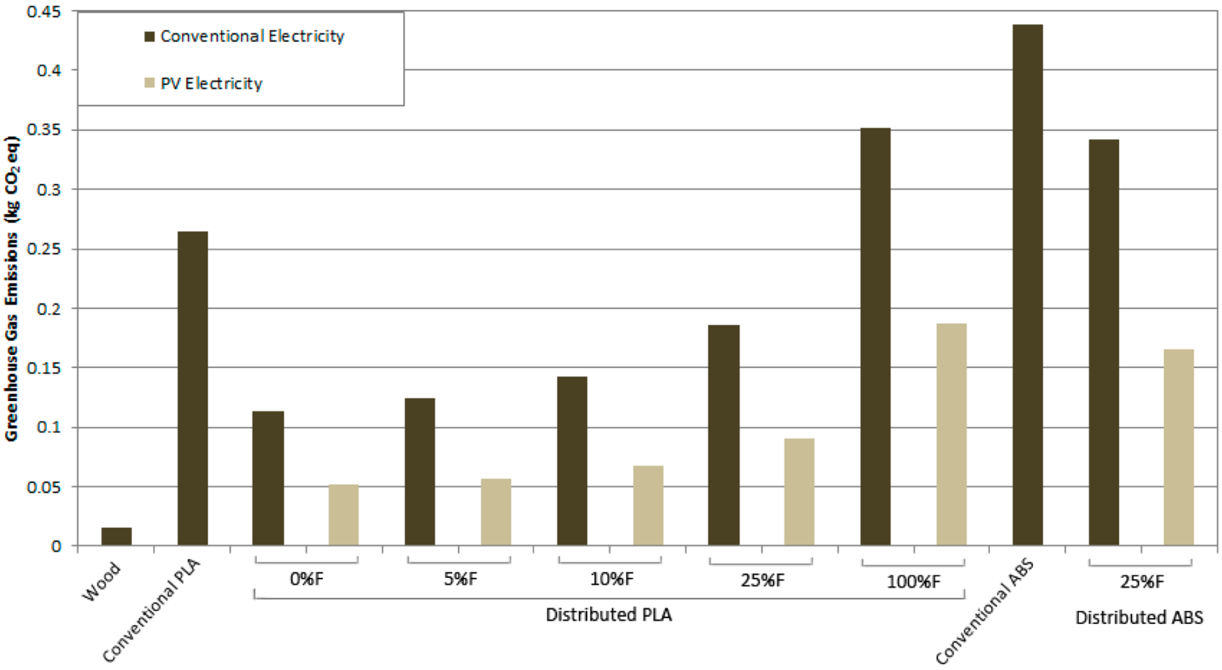

Figure 5. Greenhouse gas emissions in kg CO_2 eq (GWP 100a) for the block for wood, conventional PLA and ABS 100% fill, distributed PLA from 0 to 100% fill, and distributed ABS 25% fill, along with the effect of PV electricity.

done at the smallest percent fill acceptable for an application in order to reduce energy consumption and concomitant GHG emissions. This also reduces print time and the costs associated with energy and materials for a given product. With the use of PV, distributed manufacturing minimizes the emissions for manufacturing compared to the conventional methods. The wood block has the lowest emissions out of all cases due to being handmade and made from potentially renewable resources, but if this product was to switched to plastic, distributed PLA + PV at 0 or 5% fill should be considered as the CED is even slightly lower than the wood value for these cases. Mechanically acceptable blocks were printed with 0% fill. Since PLA is made from renewable organic materials, is biodegradable, and has a high green design ranking among plastics, it would make a good alternative to wood.[22] Similar products with the same potential would be other toys or household goods in addition to other products that could be made lightweight by replacing the inside with a hatch fill to provide structural integrity.

Water Spout. The distributed manufactured water spout not only replaces a centralized manufactured one, but also provides the interesting complexity of allowing for the reuse of a 2 L bottle, while replacing a conventional watering can. The comparison was done between the distributed case and the conventional case for manufacturing (Figures 6 and 7). It is important to stress that this analysis was done for a spout using both distributed and conventional manufacturing. In addition, a comparison to a full watering can was included because in reality the spout created would actually be replacing a full watering can that would use more material and energy to create than for a simple spout replacement. A 210 g 2 L watering can[35] made in China using injection molding in PLA or ABS would require a cumulative energy demand of 19.8 or 27.4 MJ and emissions of 0.738 or 1.23 kg CO_2 eq, respectively.

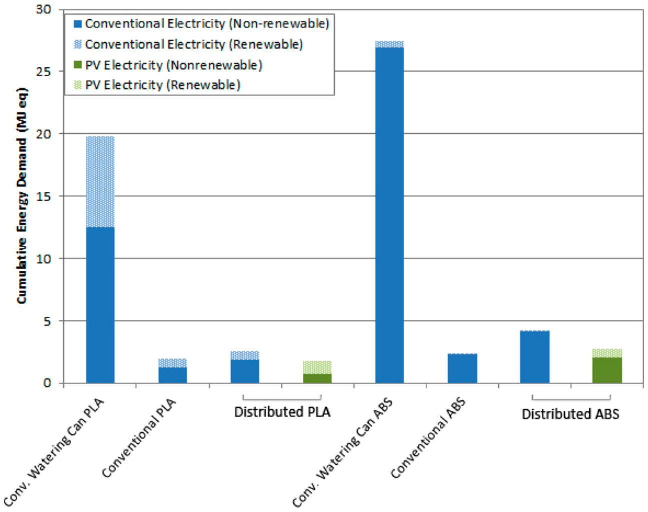

Figure 6. CED showing a typical watering can in PLA and ABS, and values for the spout in conventional PLA and ABS at 100% fill and distributed PLA and ABS at 100% fill, along with the effect of PV electricity.

While the CED and emissions values are higher than the conventional method listed because of 100% fill, a full watering can under conventional methods would require 6.5 times more energy than distributed for ABS and 7.5 times more for PLA, due to the amount of plastic and processing required to make the entire can. The distributed values were minimized for PLA and ABS using PV. PLA with PV resulted in a 6.7% cumulative energy savings over the conventional spout production, while ABS with PV was 16.4% larger than the cumulative energy for conventional. Using the same fill percentage (100%) for distributed and conventional manufacturing resulted in conventional having lower CED values for all cases except distributed PLA + PV. The emissions were reduced using distributed manufacturing PLA + PV and ABS + PV, as shown in Figure 7. The results imply that reducing the amount of raw materials used in production by replacing a large volume object with a postconsumer good that requires little to no additional

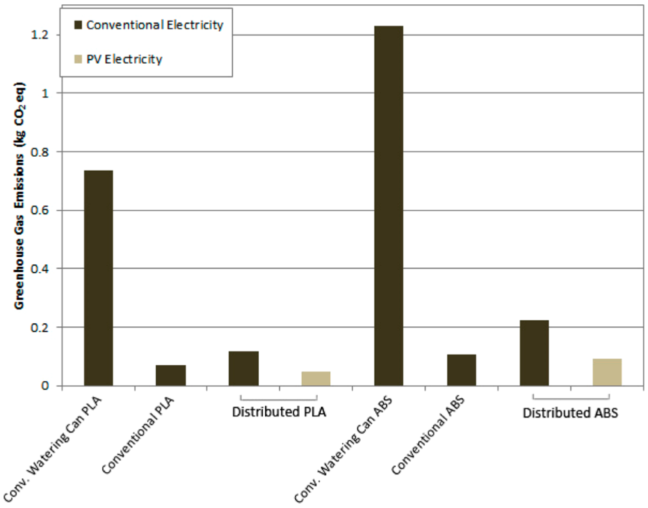

Figure 7. Greenhouse gas emissions in kg CO_2 eq (GWP 100a) for a typical watering can in PLA and ABS and values for the spout in conventional PLA and ABS 100% fill and distributed PLA and ABS at 100% fill, along with the effect of PV electricity.

processing will dramatically decrease the environmental impact associated with the end product.

Citrus Juicer. Distributed PLA and ABS juicers at 15% fill and made with conventional electricity decreased CED values by 25% and 6%, respectively (Figure 8). The addition of a PV system reduced the values an additional 20−29%. Similar results were produced for emissions as can be seen in Figure 9. The energy is minimized using distributed manufacturing for the juicer and is made possible by using a smaller fill percentage. This not only reduces material used in the product itself but also the environmental impact of the processing and embodied energy use in the raw material extraction and transportation. The use of PV to power the RepRap minimizes both the emissions and the energy use for distributed manufacturing even further.

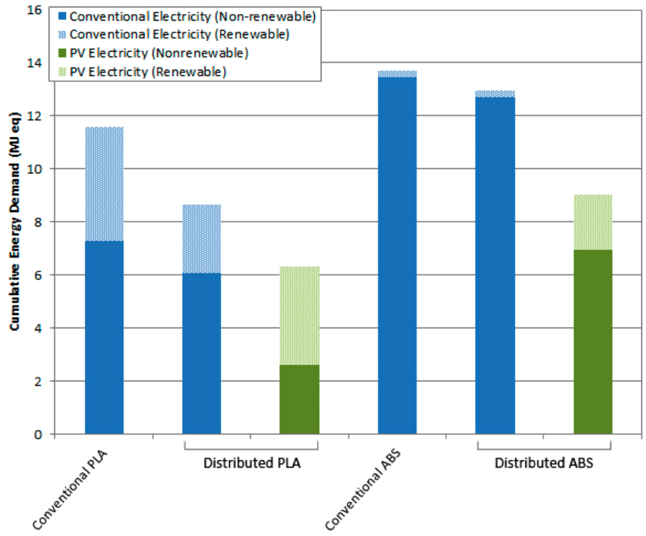

Figure 8. CED of the juicer showing conventional PLA and ABS at 100% fill and distributed PLA and ABS at 15% fill, along with the effect of PV electricity.

The emissions are lower for the distributed manufacturing systems using current printing practices for all cases except the ABS juicer without PV. This is due to the relatively large amount of energy needed to keep the heated build platform at operating temperature for the ABS. Future work is necessary to reduce the energy needed for the build platform and will be discussed below.

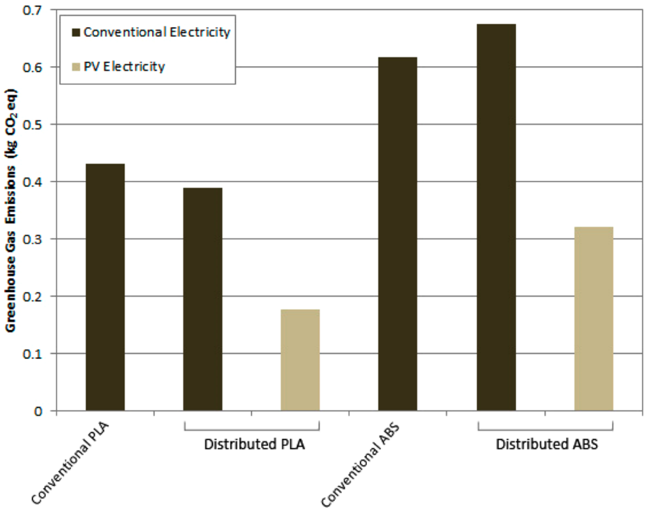

Figure 9. Greenhouse gas emissions in kg CO_2 eq (GWP 100a) for the juicer for conventional PLA and ABS 100% fill and distributed PLA and ABS at 15% fill, along with the effect of PV electricity.

■ DISCUSSION

Overall the results of this preliminary LCA indicate that distributed manufacturing with a RepRap 3D printer will have less environmental impact than conventional manufacturing due to (1) the ability to adjust the internal fill of a product, (2) the ease of adapting to PV power, (3) the ability to further reduce environmental impact using improvements in energy efficiency of printing technology and recycling filament.

Adjusting Fill Percentage. Conventional manufacturing is limited on internal manipulation of a product, with the use of the RepRap, this is no longer a barrier to improved material efficiency. The use of 3D printers allows for previously impossible shapes under conventional manufacturing methods (e.g., injection molding) along with the ability to manipulate the inside of an object during production in multiple ways, such as, adding internal parts or fill composition, which can be altered by pattern (rectilinear, honeycomb, etc.), angle, or percentage, along with adding solid fill layers when necessary.[10,18,36] This ability has the potential to reduce additional machining during processing, since holes and other needs that were impossible using methods similar to injection molding had to previously be done using tools, such as, drill presses. These steps can now be created during the design step, with the digital design files shared and automatically produced using any open-source 3D printer.[10]

The results of this study show that distributed manufacturing with a 3D printer requires less cumulative energy than conventional manufacturing when products are made from PLA and ABS for a fill composition less than 0.79. For many products or components that do not have a need for significant mechanical strength, it may be possible to print considerably below 79% fill, indicating that it is possible to 3D print products at a lower environmental impact than conventional manufacturing.

Distributed Power with Photovoltaic Technology. When distributed manufacturing is used in conjunction with a solar PV system, the cumulative energy is further decreased. It should be pointed out that the benefit of solar power could also be applied to the conventional system, although the scale of PV necessary for conventional manufacturing makes this more technically difficult due to the high energy requirements associated to mass-scale production and the more challenging storage necessary to provide continuous production. In addition, the embodied energy of roof-mounted PV is lower than that of large-scale centralized PV systems because of the additional energy associated with relatively cement- and metal-intensive ground-mounted racking.[37] From a perspective of minimizing environmental impact PV is much more practical for distributed manufacturing. Finally, distributed manufacturing would normally occur during the day, when PV power is available without storage, while centralized manufacturing is normally a 24 h/day process used to accelerate the payback of the substantial capital equipment costs.

Energy Efficiency in 3D Printing. The results of this study indicate that although open-source 3D printers can be used in distributed manufacturing to reduce the environmental impact it is still necessary to reduce the energy needed for the build platform to make the environmental benefits clear for distributed manufacturing of plastic products in all cases. There is already some initial experiments in the open-source 3D printer community indicating potential improvements or partial solutions including: (i) integrating dynamic temperature control during printing to allow for reduced bed temperatures after the first several layers have good adherence to the substrate, (ii) similarly printing on rafts so again the heated bed can be turned off shortly after laying down the raft (this technique has the advantage of reducing cooling-related stress in the main object that can cause warping for tall print jobs), (iii) better insulation (higher R value) under the bottom of the bed, (iv) using zoned heating so only the parts of the bed under the part are heated, or (v) using a controlled environmental chamber to insulate the entire RepRap from cold ambient temperatures or drafts. In addition, alternative substrates and chemical surface treatments of conventional substrates (e.g., glass) have only begun to be explored. For example, ABS can be printed directly on an acrylic with no heating and PLA can be printed directly on any surfaces covered with blue painters tape with no heating. These last techniques offer the potential to completely eliminate the need for a heated platform, which would not only reduce the energy and emissions associated with distributed manufacturing, but also reduce the capital costs and complexity of the RepRaps. Finally, it should be pointed out that if more products are printed simultaneously on the heating bed, it is possible to reduce the energy to print even further due to the initial heating energy being dispersed among more individual products. For example, when printing two blocks simultaneously under the same conditions and settings as a single block made out of PLA at 10% fill under conventional electricity, there was an energy savings of 4% and an emission reduction of 5% over printing a single block.

Distributed Recycling. Distributed recycling is also being developed to recycle postconsumer products into filament for a 3D printer using RecycleBots, which could further reduce cost, environmental impact, and resources required for distributed manufacturing.[38−41] The open-source small-scale models of commercial plastic extruders currently under development that could potentially be used for RecycleBots include named RecycleBots,[42,43] the MiniRecycleBot,[44] the Filabot,[45] and the Lyman filament extruder.[46] If the juicer is produced with similar print electricity consumption in recycled-HDPE, it would cost only about 4 cents, instead of $2.76 using commercial PLA filament for distributed manufacturing or $7−25 for commercially available products.[41] All other products (water spout, blocks), under the same conditions, use less electricity to produce and material, meaning that any of these items can be produced for only a few pennies, even at 100% fill. Similarly, for the water spout (watering rose) or the watering can, which can be bought retail for about $10, using the distributed water spout can save over 99%. If the blocks are compared to a set 16 Naef wood blocks which retail for $160, a set of 16 blocks using recycled filament would cost less than 64 cents, for over $159 savings. Previous work has already shown that open-source 3D printing can provide even more dramatic cost savings for customized and specialized products such as scientific instruments.[47,48] In fact the capital cost of the printers can relatively easily be recouped printing a single high-value scientific research tool.[47−49]

Limitations and Future Work. This was a study on a limited number of products and future work is necessary to quantify the CEDs and emissions of distributed vs conventional manufacturing of other types of products. An ideal study would consist of a cradle-to-grave analysis for both conventional and distributed manufacturing, including all infrastructure, packaging, and transportation. Most importantly, a more detailed study needs to evaluate the embodied energy in equipment (both for conventional and distributed) as the largest difference between the two manufacturing styles is that the equipment investment is radically diverse as noted above. This study will be difficult as although the allocation of embodied energy in conventional manufacturing is straightforward and just divided among a number of identical products, 3D is far more versatile and can print thousands of products under schedules that could vary widely. For distributed manufacturing, analysis of more products being printed on several different types of 3D printers would allow for a more generalizable average estimates of energy and emissions for use of 3D printers. For conventional manufacturing, a more accurate analysis could be done by communicating with plastics manufacturers to determine any additional inputs or processes required for manufacturing as would analyzing specific products from several manufacturers. Finally, limitations with EcoInvent currently consist of a lack of available and reliable inputs for China; as these inputs become available, the limitations can be minimized as the EcoInvent database grows.

These order of magnitude reductions in cost represent a clear economic incentive for driving distributed manufacturing and indicate that the rapid growth in open-source 3D printing and distributed manufacturing will likely continue. However, in the examples above, the personal labor costs are not included in the distributed manufacturing cost (or recycling cost), where as the retail costs include the labor costs and the cost of manufacturing equipment capital, operations, and maintenance. Future work is needed to investigate the social acceptability of distributed manufacturing and to provide more detailed economic analysis of distributed 3D printed costs, operations, and maintenance per part manufactured or over the printer's life cycle.

3D printing has the potential to alter the mode of manufacturing as it enables individuals to make high-value complex products within their own homes with minimal labor and capital investments. In addition, these products can be ultracustomized representing not only an alternative but a superior value to buying similar mass-produced items over the internet or off the shelf in a retail store. Most plastic goods can already be produced using a RepRap or variant, and research and development is underway on using other printing materials. Since the RepRap community is open-source, this allows anyone to build and use their own 3D printer and create any item that is shared under appropriate licenses on the internet. This culture of open-source design sharing is already established. For example, Thingiverse, a database of designs for real physical objects, the vast majority of which can be printed on a RepRap, currently (August 2013) houses over 135 000 items and is growing at an exponential rate.[50] These designs are generally shared with some form of open license, thereby adding value to owners of 3D printers. As this database and other similar efforts continue to grow, the value of access to 3D printing expands and thus creates a positive feedback loop following a classic network effect.

The results of this LCA study indicate that the environmental impact of manufacturing polymer products can be reduced using distributed manufacturing with existing low-cost open-source 3D printers when using PLA. This indicates that distributed manufacturing is technically viable and environmentally beneficial because of both reduced energy consumption and greenhouse gas emissions. These positive environmental results for distributed manufacturing are expanded to ABS, which demands hotter bed and extruder temperatures when low emission intensity sources of power are utilized such as solar photovoltaic technology. The results indicate that the ability of RepRaps and similar 3D printers to vary fill percentage has the potential to significantly diminish environmental impact of many products. In addition, it seems clear that as the relatively immature RepRap technology continues to improve as it evolves these environmental impacts will be further reduced. It can be concluded from the results of this study that open-source additive layer distributed manufacturing is both viable and beneficial from an ecological perspective.

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Notes

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