Article

Open Source Waste Plastic Granulator

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Abstract: In order to accelerate deployment of distributed recycling by providing low-cost feed stocks of granulated post-consumer waste plastic, this study analyzes an open source waste plastic granulator system. It is designed, built and tested for its ability to convert post-consumer waste, 3-D printed products and waste into polymer feedstock for recyclebots of fused particle/granule printers. The technical specifications of the device are quantified in terms of power consumption (380 to 404W for PET and PLA, respectively) and particle size distribution. The open source device can be fabricated for less than USD$2000 in materials. The experimentally-measured power use is only a minor contribution to the overall embodied energy of distributed recycling of waste plastic. The resultant plastic particle size distributions were found to be appropriate for use in both recyclebots and direct material extrusion 3-D printers. Simple retrofits are shown to reduce sound levels during operation by 4dB-5dB for the vacuum. These results indicate that the open source waste plastic granulator is an appropriate technology for community, library, makespace, fab lab or small business-based distributed recycling.

Keywords: 3-D printing; additive manufacturing; distributed manufacturing; distributed recycling; granulator; shredder; open hardware; fab lab; open-source; polymers; recycling; waste plastic; extruder; upcycle; circular economy

1. Introduction

The open-source release of the self-replicating rapid prototyper (RepRap) 3-D printer [1-3] greatly expanded access to additive manufacturing (AM) because of several orders of magnitude reduction in costs [4]. As open-source RepRap 3-D printers spawned hundreds of clones, fused filament fabrication (FFF) enabled a shift in the trend from centralized to consumer (or prosumer) distributed manufacturing [4-8]. Consumers now use RepRaps or pre-built desktop 3-D printers to manufacture all manner of products from toys to household items less expensively than purchasing them from conventional brick and mortar or online retailers [9-11]. The peer-reviewed business literature now recognizes this potential shift in manufacturing [12-14], which is brought on not only by the open source sharing of 3-D printer designs, but now more importantly because of millions of freely shared digital designs of other products that are 3-D printable [9]. Any level of consumer from scientific research funders to arthritis patients [15] can earn a high return on investment (ROI) [16] for distributed manufacturing with commercial polymer 3-D printing filament based on downloaded substitution values [17]. However, commercial 3-D printing filament is still sold for roughly an order of magnitude more than the cost of the raw materials of virgin plastic pellets. This has reduced adoption of AM at the prosumer level [18]. There are two methods to overcome this artificial cost barrier for wider spread distributed manufacturing: 1) use distributed recycling to make filament and 2) skip the entire process of fusing filament into a 3-D printed object by printing directly from polymer granules, shards or particles.

3-D printing filament can be manufactured economically using distributed means with an open source waste plastic extruder (often called a recyclebot) [19]). Recycling is a well-known environmental benefit and performing distributed recycling of plastic waste into filament decreases the embodied energy of filament by 90% compared to traditional centralized filament manufacturing using fossil fuels as inputs [20-22]. Using distributed recycling fits into the circular economy paradigm [23-26] as it eliminates most embodied energy and pollution from transportation between processing steps. Many open source commercial and non-commercial recyclebots have been developed [27] including a 3-D printable version [28]. Many research groups and companies have demonstrated that pre-consumer and post-consumer waste polymers can be recycled into 3-D printing filaments, including:

- polylactic acid (PLA) [28-32]
- acrylonitrile butadiene styrene (ABS) [24,33-36],
- high-density polyethylene (HDPE) [19,37,38],
- polypropylene (PP) [38],
- polystyrene (PS) [38],
- polyethylene terephthalate (PET) [39],
- linear low density polyethylene (LLDPE) and low density polyethylene (LDPE) [40],
- elastomers [8],

In addition, filaments can be made from polymer composites using carbon reinforced plastic [41] and various types of waste wood [42,43]. Unfortunately, each melt-solidification degrades the mechanical properties of the resultant 3-D print [44,45] recycling is limited to about five cycles [46,47] without use some means of reinforcement or blending with virgin materials. The potential for such distributed recycling could be either completely distributed (where the consumer recycles their own plastic in their home or business) or part of a local closed-loop supply chain [48].

The second method, however, eliminates the need for filament entirely as 3-D printers have been developed that can print directly from particles, pellets, flakes, regrind, or shreds of recycled plastic. These fused particle fabrication (FPF) or fused granular fabrication (FGF) 3-D printers and are becoming established in the academic [49-54], maker [55-57], and commercial venues (e.g. GigabotX, PartDaddy, Cheetah Pro, David, Erecto-Struder, etc.). FPF/FGF printing is possible with recycled materials [58-60] as is using FGF printing of molds for distributed injection molding of larger replicate products [60].

Both the widespread deployment of distributed recycling with recyclebots and FPF/FGF are being restricted because of the lack of accessibility of low-cost pelletizers and choppers to turn post-consumer plastic products into polymer feedstock. In general, these are large industrial machines not conducive for makerspaces, fab labs, research or consumer use because of their high throughputs, noise and capital costs. In order to provide a low-cost tool for making polymer feedstock from post-consumer waste this study follows the open-source hardware design paradigm [61,62], which has proven so successful for 3-D printing in general. An open source waste plastic granulator system is designed, built and tested for its ability to convert post-consumer waste, 3-D printed products and 3-D printer waste into polymer feedstock for recyclebots of FGF/FPF printers. Then the technical specifications of the device are quantified in terms of power consumption and particle size of the output. In order for the device to operate in a fab lab (or similar environment) a noise reduction system is added and analyzed. The results are presented and discussed.

2. Design Concept

The design of the open source waste plastic granulator system is divided into four separate sub-systems, each responsible for parts of the machine that serve a specific function:

1. Power Transmission: This system encompasses all machine parts needed to convert the electrical energy being input to the system into mechanical energy, as well as transmit that mechanical energy to the plastic cutting/granulation system.
2. Plastic Cutting/Granulation: This system is the one that directly interacts with the plastic in order to cut it into small chunks. It is responsible for cutting plastic as well as ejecting granules after they have reached a uniform size.
3. Material Guidance/Structural: This system involves any parts that keep the plastic feedstock inside of the proper cutting area during operation or guide the feedstock during its journey. It includes the hopper chute, the hopper lip, the granulation chamber lip, any mechanism used to hold the hopper to the granulation chamber, and the upper surfaces of the granulation chamber.
4. Electrical: This system encompasses all of the components required to convert electrical energy from mains power into rotational energy, as well as any other electrical peripherals present on the machine. This includes the electrical box, safety switches, circuit board, motor, and a microcontroller.

Together, these systems operate all with the end goal of transforming plastic recyclables into usable 3-D printing feedstock in the form of granules (or particles). The main concepts and parts in each sub-system will be described but the full open hardware details including the bill of materials (BOM), drawings for custom parts, CAD files, build instructions and design reports of previous versions are housed at the Open Science Framework [63].

2.1. Power Transmission System

The power transmission system transfers rotational mechanical energy from the motor spindle to the cutting rotor shaft. As a first step towards designing this subsystem of the machine the design team made the decision that a one-phase AC motor would be used to supply mechanical power to the machine. This method of mechanical power delivery is the most reliable and easiest way for an individual to drive a machine from their home circuitry. Pulleys and belts are used to convey power to the cutting rotor; belts are not only inexpensive when compared to a gearbox, but are also more user friendly since they are easy to install, maintain and adjust once assembled. An isolated view of the 3-D model for the power transmission subsystem and all of its components can be seen in Figure 1.

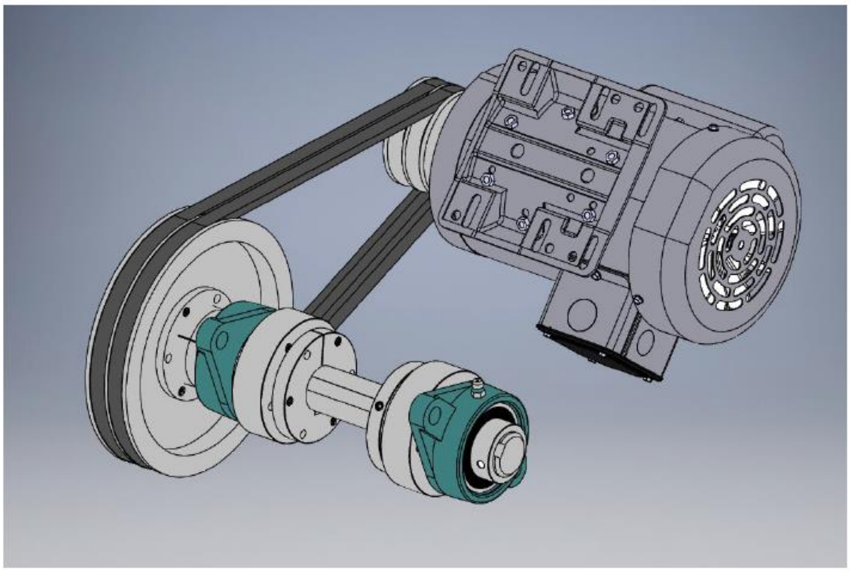

Figure 1: Power transmission system design of the open source waste plastic granulator.

As seen in the Figure 1, the parts of the power transmission system are as follows: AC Motor, pulleys, belts, flange-mount bearings, rotor shaft, quick-disconnect (QD) bushings, and weld-on hubs (plus mounting hardware). The motor selected to drive the granulator is a 1.5 HP motor with a spindle speed of ~1800 RPM. On a previous version of the open source waste plastic granulator, the optimal rotor speed for cutting was found to be around 750 RPM [62]; this speed was also used for this design as well, leading to a set ratio of pulley diameters of about 1:2.4. A 3.95″ (100.33 mm) diameter pulley was chosen to connect to the motor spindle using a quick-disconnect style bushing. An 8.75″ (222.25 mm) diameter pulley was used to attach to the cutting rotor shaft, also with a quick-disconnect bushing. Both pulleys have two channels for v-belts to ensure there is no slippage during operation. In order to keep the cutting rotor shaft spinning about its major axis two large flange-mount bearings were used. In order to connect the shaft to the cutting rotor, QD bushings were used in conjunction with weld-on hubs to clamp to the shaft. These components were then bolted to the cutting rotor so that the blades would spin with the shaft (see Figure 2).

2.2. Plastic Cutting System

The plastic cutting subsystem is, out of all of the subsystems, the most directly related to the overall function of the machine as it is responsible for transforming plastic waste/recyclables into granules of a specific size. In order to do this, the design team picked out many different forms that would satisfy the subsystem's purpose, and compared them using a decision matrix (details of which are found in the OSF database [62]). From the decision matrix, the best option was found to be the fly knife design, consisting of two large rotating blades (fly knives) that pass close to a fixed blade during operation (Figure 2). Shear force on the plastic between the blades is the main cutting method.

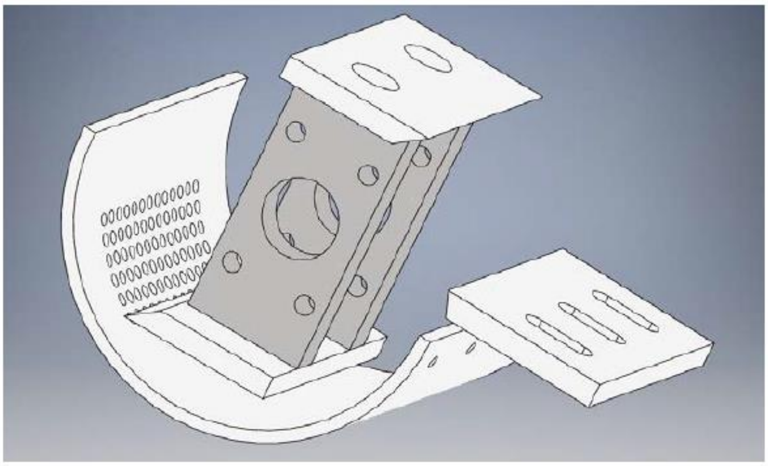

Figure 2: Plastic cutting system design of the open source waste plastic granulator.

The plastic cutting system, consists of four separate components (plus mounting hardware). Two blade arms will connect to the cutting rotor shaft (shown in Figure 2) and will spin with the shaft. Connected to either end of each blade arm in the configuration shown below are two fly knives, which will contact the plastic within the cutting chamber and shear through it. To help with the cutting of the plastic granules, there are two more pieces in this system that both interact with the rotating fly knives, the granulation screen and the bed blade. As the fly knives rotate in the granulation chamber they will pass very close to the fixed bed blade on the right side of Figure 2.

This is where the large pieces entering the cutting chamber will be sheared for the first time. In our design, all stress-bearing components related to this large cutting force were designed to be able to cut ⅞″ (22.2 mm) cubes of nylon mill stock. Once large pieces have been cut for the first time by the bed blade, they will accumulate on the surface of the granulation screen. The clearance between the tip of the fly knives during rotation and the inside of the screen in ~⅛″ (3 mm), which means that any larger granules will get pinched between the screen and the blade and be sheared to a smaller size. Once the granules are smaller than ~¼″ (6 mm) in all dimensions they are pulled through the holes located in the granulation screen and into a collection chamber by a vacuum. In order to make the blade arms rotate, as described in Section 2.1, weld-on hubs attached to the shaft were bolted onto the blade arms.

2.3. Material Guidance

The material guidance system is responsible for containing the waste plastic both before and after the cutting operation. In addition to guiding materials, this system also serves as the structure upon which all other subsystems are constructed. The feedstock is guided using a sloped tube as shown in Figure 3.

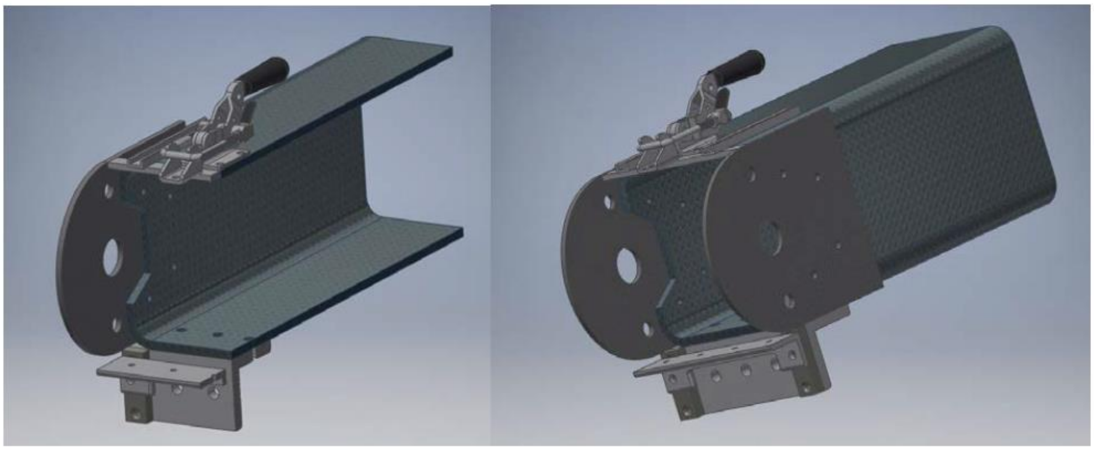

Figure 3 Material guidance system (cut section and completed) for the open source waste plastic granulator.

Overall, the main component used for material guidance is a large steel square tube that not only provides a smooth, enclosed surface for the waste plastic to slide on while it is on its way to be cut, but also a very strong and rigid structure that can be built upon. Attached to this large (8" (203 mm) width) square tube are several other components that support the plastic cutting and power transmission systems. The two large rounded plates attached to the vertical faces of the tube are what hold the bearings from the power transmission system in place. The angle iron on the bottom part of the tube serves two purposes. The larger piece holds the fixed bed blade in place during operation, as well as clamping to the second piece of angle iron shown, which secures the granulation screen in place for cutting. The materials on the top of the tube are all responsible for holding the opposite side of the granulation screen in place and allows the user to disconnect the granulation screen quickly from one side. This system also includes a secondary tube acting as a hopper for funnelling material directly from the user's hand into the machine as well as a server rack cart that is used to house the main cutting mechanism, however, these components are not shown above for clarity.

2.4. Electrical

The electrical system in the machine serves three purposes, powering the motor, powering the granule extraction vacuum, and monitoring the power consumption of the machine. These functions are accomplished simply since both the vacuum and the motor require no more than a simple on/off control scheme. Both the vacuum and the motor are connected directly to 120VAC mains power and use simple switches to control them. In addition, an emergency-stop switch is included in the circuitry to cut power to the whole machine if necessary. The final accessory included in the electronic circuit for this machine is a multimeter that provides a digital readout with information on the power consumption of the machine. All of the components in the electrical system were designed to operate using less than 15 Amps during steady-state conditions so that the machine could be run off of a standard in-home wall outlet. A circuit diagram for the electrical system is included in Figure 4.

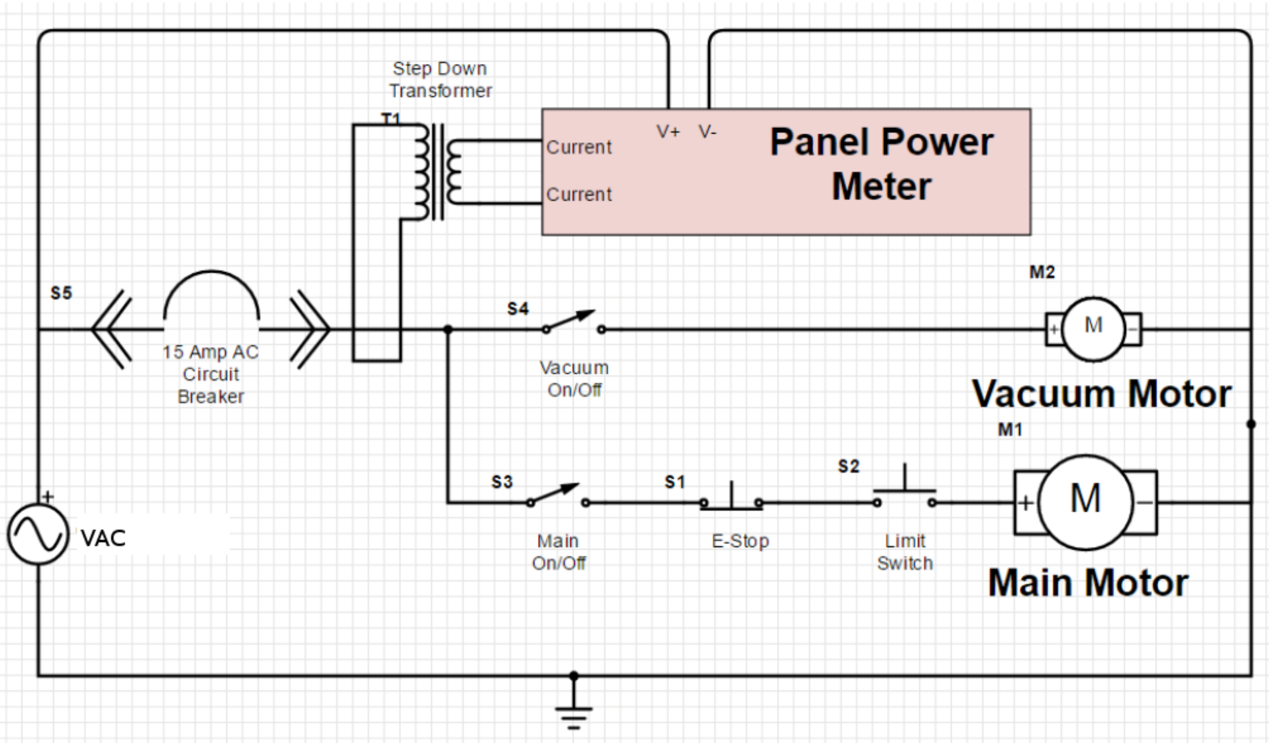

Figure 4: Circuit Diagram for electrical control system of the open source waste plastic granulator.

2.5. Peripheral Parts Assembly

Together, the four systems described in Section 2.1-2.4 work together to achieve the overall objective of the design of the open source waste plastic granulator. Other than getting the material from place to place, all of the actual manipulation of the plastic to transform it from stock material into feedstock occurs due to the cutting and power transmission systems. An overall view of the machine's core systems are shown in Figure 5.

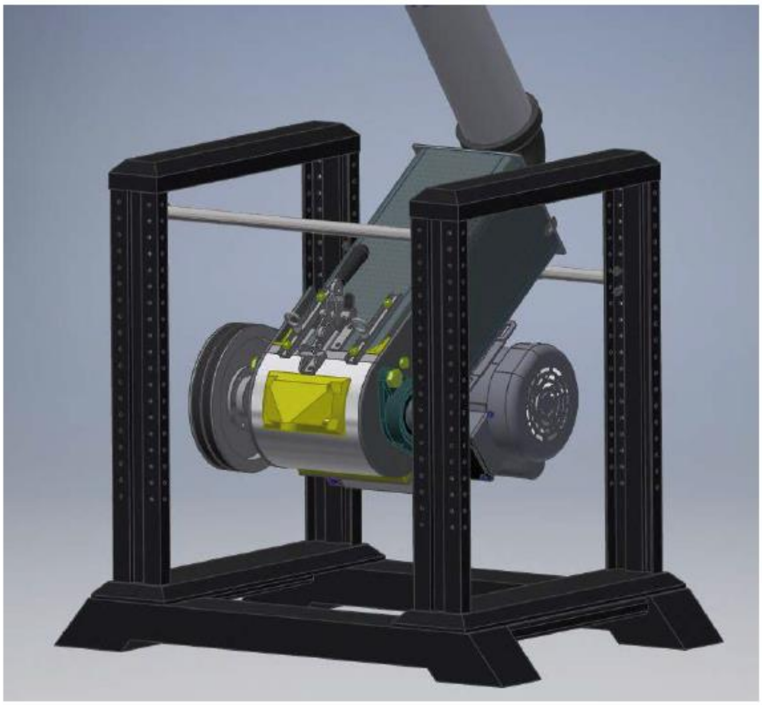

Figure 5: Overall design setup of the open source waste plastic granulator.

Figure 5 shows the assembly of the three mechanical design systems, including all of the parts explained earlier as well some 3-D printed parts and several parts not shown before. As can be seen in the above picture the server rack cart that was mentioned in the material guidance system is housing the main systems of the granulator. It holds the machine components so that the major axis of the large square tube is angled to allow plastic pieces to slide into the cutting mechanism. To accomplish this, several standard size ½″ (12.7 mm)) steel pipes are attached to the server rack using u-bolts. The pipe in the rear (as shown in Figure 5) is attached directly to the bottom of the steel tube using pipe straps, while the pipe in the front is attached via nylon strapping to the eye-bolts shown on the top of the steel tube in the above figure. This is done to allow the builder of the machine to easily add a vibration-dampening spring at the front attachment point to mitigate any rotational imbalance that may be present in the machine. The hopper consists of the large tube sticking out of the top of the server rack as well as a plate that allows it to attach to the back of the square steel tube/main machine body. This allows users to safely place materials into the machine for cutting. The bend that materials will have to pass through in order to get from the machine's opening to the cutting mechanism ensures that a user cannot accidentally place their hands/arms inside the machine while it is cutting as well as stops granules from flying out of the machine during operation. To highlight the interaction between all three main mechanical systems a cutaway view showing the assembled granulation chamber in Figure 6.

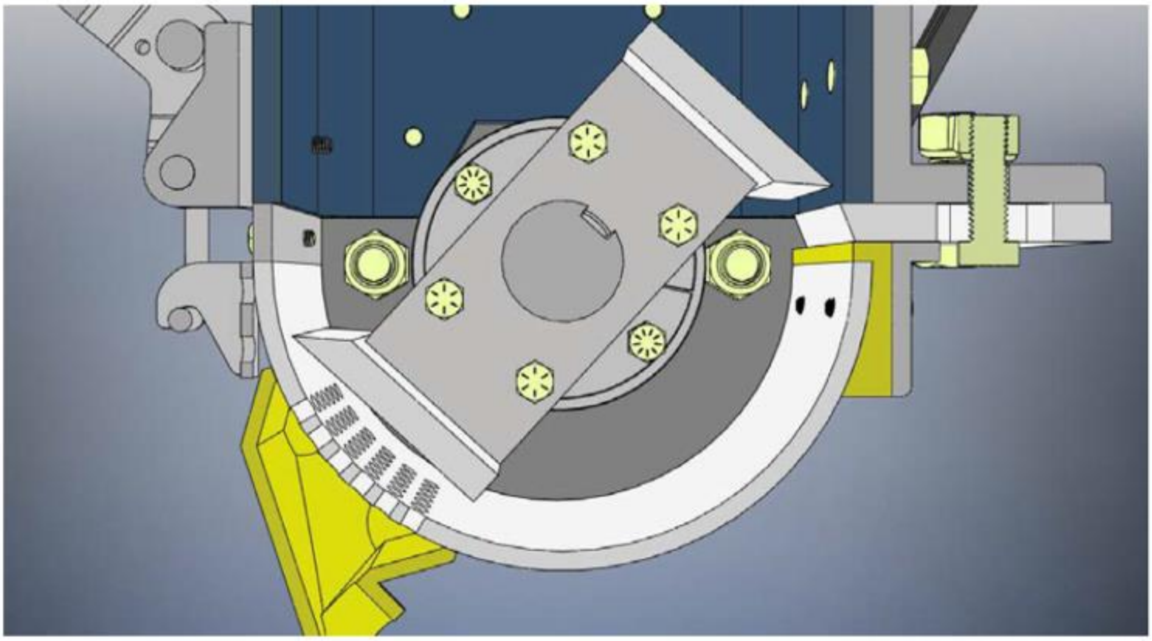

Figure 6: Cutaway of mechanical systems in the open source waste plastic granulator.

2.4 Cutting Force Design Analysis

The cutting operation that takes place during the operation of the granulator is unpredictable so a simulation was run of the cutting forces that occur during the operation of the granulator [62]. These forces are important because they allow for the calculation of the stresses that occur inside the key stress-bearing elements of the design. The method and findings are in the OSF database [62].

The stress levels inside the blade arm as well as the fly knife bolts are well below the acceptable level for steel materials. In order to achieve this, it was determined that the blade arms must be made out of ¾ ″ (19 mm) x 2.5″ (63.5 mm) steel flat stock, and that the bolts must be ⅜ ″ - 16 UNC (9.525 mm) grade 8 hex cap screws. Previous simulations found that a 1/2″ (12.7 mm) thick piece of angle iron with side lengths of 3″ (76.2 mm) would be suitably strong for this piece. ¼ ″ (6.35 mm) - 20 UNC bolts were selected despite being over engineered because they proved inexpensive for this application. After iterating the simulation to find the optimal size for the bed blade mounting bolts, both locations were considered and ½ ″ (912.7 mm) -12 UNC grade 8 hex cap bolts were chosen.

Standard fatigue analysis [64] was performed and it was found that the Grade 9 bolts responsible for attaching the fly knife blades to the blade arms are predicted to fail due to fatigue before infinite life. That being said however, the analysis done assumes that a ¾ ″ (19 mm) nylon block will enter the machine once every time one knife rotates, which, for normal operation is very unlikely. For normal use the stresses present will never reach the values used for analysis. However, users planning on using this machine for nylon recycling should replace these bolts every month in order to avoid failure due to fatigue. The maximum torque acting on the cutting rotor during operation is slightly less than 1500 N-m, or about 13000 in-lbs. In order to attach the cutting rotor to the shaft two SK type QD bushings were chosen, since each bushing can support a torque of 7000 in-lbs. Together, these two bushings can support a maximum torque of 14000 in-lbs, a torque which should never be exceeded during the normal operation of the machine. In conclusion, the design simulation indicated that the technology as designed would be able to cut a maximum thickness of nylon stock of 3/4″ (19 mm), i.e. a cube measuring 3/4″ (19 mm) on each side is the largest piece of plastic stock that should be inserted into the machine.

3. Material and methods

3.1 Technical specifications: Power consumption and particle size

The power consumption operating the granulator as measured with an open-source printed circuit board and Arduino Nano attached to the power supply to measure the power output of the while it was processing different materials. During each of the power recording sessions, thermoplastic was inserted at a rate the granulator could handle. This rate is not measured, as it highly depends on the geometry and density of the inserted plastic.

The AC power measurement board collects data from both input legs of the 220 VAC power input to the control electronics. Each leg’s corresponding voltage is measured by direct connection, and current is measured using 100A non-invasive current transformers. Each leg’s measurements are hooked into a channel of the board where the measurements are made using a dedicated Analog Devices ADE7757 energy metering integrated circuit (IC). The IC meets the IEC61036 accuracy requirements for power measurements. The ADE7757 transmits the wattage signal through its CF pin, and is captured by the on-board Arduino Nano. The values are operated on by a linear calibration, and then written to a microSD card, with time stamps generated by the on-board real time clock.

The size characteristics of the particles for the resultant granulated material were quantified using digital imaging and the open source Fiji/ImageJ using techniques discussed previously [60].

3.2. Noise reduction

Sound pressure levels were measured using a free field array microphone positioned in front of the vacuum inlet of the machine. The measurements were logged using a National Instruments compact DAQ data acquisition system in conjunction with custom LabVIEW software. Multiple positions were considered before finalizing on the position in Figure 7 due to repeatability and high signal-to-noise ratio. All trials were performed using this microphone position Sources of sound in the machine includes the shear cutting mechanism in the granulator and the shop vacuum. Although the microphone location was not in the operator ear position, it was appropriately placed for before/after insertion loss measurements.

Figure 7: Sound measurement test setup depicting the microphone in one of the test locations

Tests were performed to find the sound pressure levels of the open source waste plastic granulator system including the auxiliary devices such as the vacuum pump and the individual contributions as well. It was determined that the vacuum pump was the loudest source with a distinct peak in the 250 Hz one third octave band. Panel gaps in the enclosure for the granulator provides leakage paths for the sound and hence it was decided to seal these gaps appropriately. The inner lining of the walls were packed with open-celled foam to increase sound absorption and transmission loss as shown in Figure 8.

Figure 8: Granulator panel gaps filled with sound proofing material

Using the initial acoustic measurements, an expansion chamber was designed (Figure 9) that could be attached to the 5-gallon bucket shop vacuum, and a 3-D model was produced to utilize PVC and a 3-D printable components to reduce noise from the operation of the device. As 250Hz was the chosen frequency one third octave band for attenuation, the double tuned expansion chamber design was chosen as it provides good transmission loss around the frequency of interest while having good attenuation around the octave bands as well [65]. However, the muffler aids in higher frequency attenuation and by lining the inner walls of the muffler with fiberglass foam.

Figure 9: Comparison between CAD of chamber and finished expansion chamber.

4. Results

4.1 Technical specifications for particle size and energy use

Figure 10 shows the resultant particles and particle size distribution, where it is clear that the majority of particles are fines with total areas under 10 mm^2. These particle sizes are appropriate for the majority of recyclebots as well as direct material extruder based 3-D printers such as the Gigabot X [58-60].

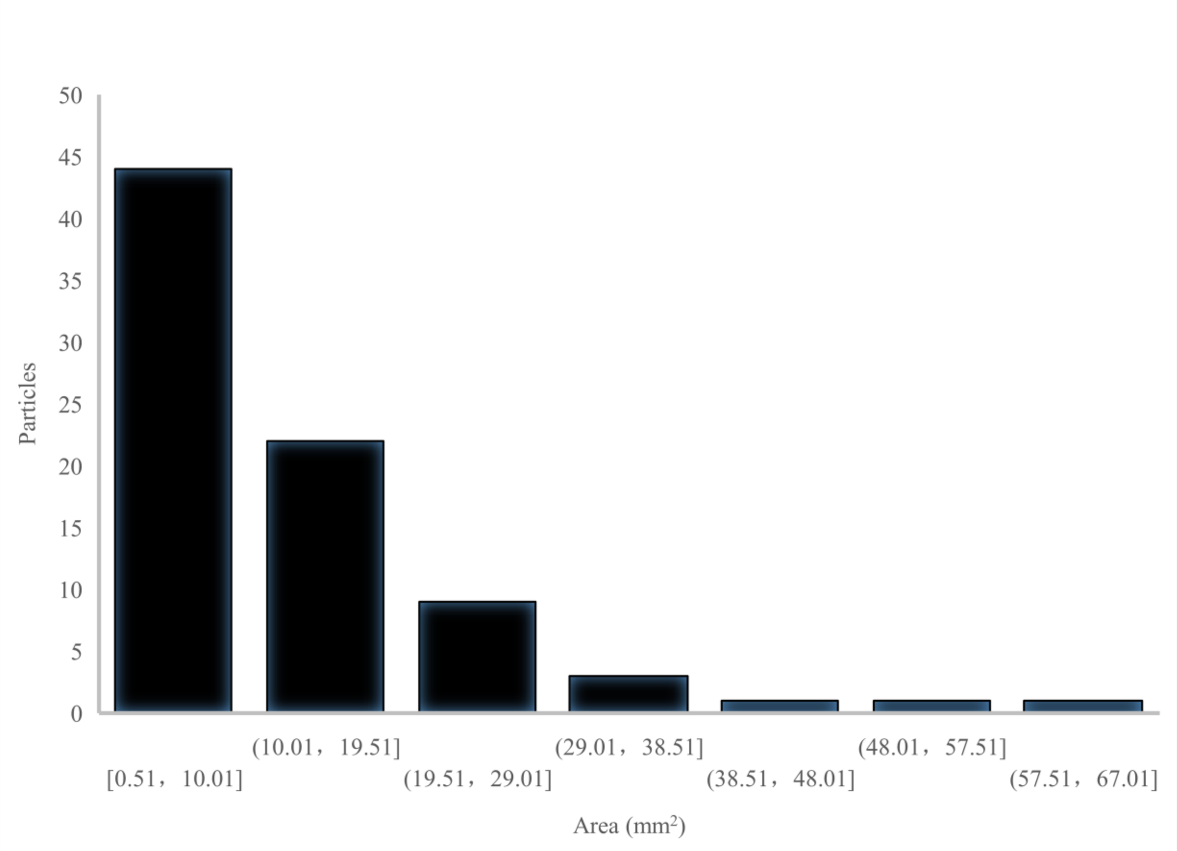

Figure 10. Resultant particle size distribution in mm^2 after shredding in the open source granulator.

This power draw of the open source waste plastic granulator was processed and its results appear below in a Table 1. The average power varied depending on the type of plastic and would be expected to change based on the type of feedstock (e.g. large solid blocks vs flakes).

Table 1: Power consumption details

	PLA (Polylactic acid)	PET (Polyethylene terephthalate)
Average power	403.6 W	383.9 W

4.2 Noise reduction results

The noise reduction modifications to the granulator were verified with sound level measurements and are as shown in Figure 11. Compared to the earlier design, a 4dB overall reduction in sound levels was achieved with attenuation at the 250Hz one third octave band particularly. As the focus of the noise reduction was concentrated towards the vacuum, 5 dB reduction was achieved here.

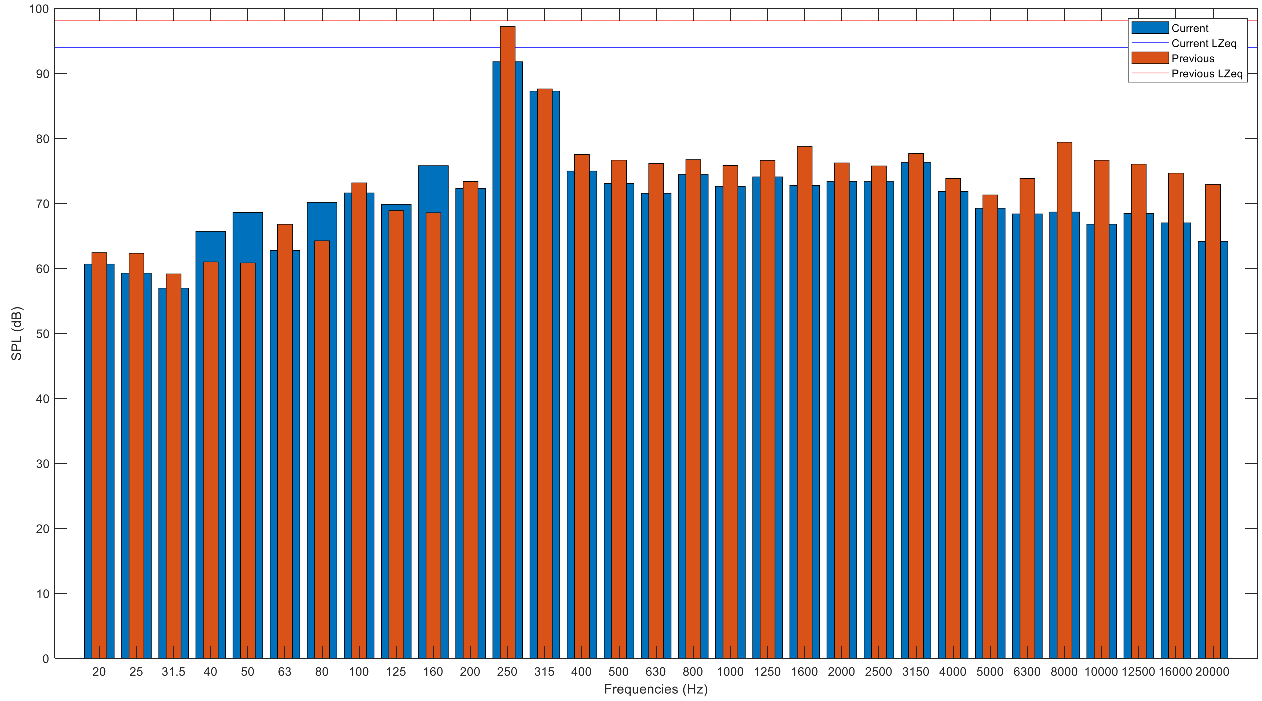

Figure 11: Results of the sound reduction redesign showing a bar plot of 1/3 octave noise measurements.

5. Discussion

5.1 Technical specifications for particle size, through put, and energy use

The particle sizes demonstrated in Figure 18 are small enough to use in a wide array of recyclebots (both commerical and homemade) as well as for direct printing via FPF/FGF as demonstrated in [58-60].

The volumes that the device can process are appropriate for small businesses [13], community centers, libraries, makespaces, and fab labs [59,66] that could potentially become community distributed recycling centers. There are challenges with this approach throughout the world. So although, libraries in Finland for example routinely offer their patrons free 3-D printing services, many countries do not. In addition, the actual reycling process can be challenging due to lack of appropriate information in specific countries. For example, China has a sophisticated recycling symbol system [67] that covers a wide range of waste plastics, the U.S. grous most of its polymers together in only 1 of 7 categories (7- “other”) [68]. In order to have low-cost distributed recycling waste plastics need to be appropriately labeled. The open source 3-D printer community has already devised a voluntary recycling code based on China's comprehensive system [68]. To have a more widespread impact and reach a cradle-to-cradle material cycle [69] regulations that demand that manufacturers identify the materials in their products appears necessary [70].

The power draw for the open source waste plastic granulator is relatively mild, drawing as much power as 3-4 conventional incandescent light bulbs. Coupling this low power use to the rapid throughput of the technology results in a relatively low embodied energy of electricity for grinding plastic with this machine. This is close to values that have been reported for commercial devices used in previous studies of distributed recycling using additive manufacturing [20,21].

5.2 Noise reduction

Sealing the exhaust port of the suction vacuum with the muffler did reduce the noise levels experienced, which make the system more amenable to non-production facility based applications like mixed-use fab labs. As stated in the results, a 4 dB overall reduction from the granulator and the suction vacuum combined was obtained and hence the muffler served the intended purpose. However, efforts to control granulator noise were not as successful and this was possibly due to existing panel gaps in the enclosure. They were not sealed off due to need for ease of access. Future work is needed to explore other methods of sound reduction.

5.3 Future work

This technology is an open source technology built on prior designs [71] and will continue to evolve in the traditional open source fashion. There are thus several areas of future work to improve on the design of the open source waste plastic granulator. First, the cost of the materials for the device is US$1,943.11, which limits its accessibility throughout many applications. The breakdown in the cost of the materials can be seen in Figure 12.

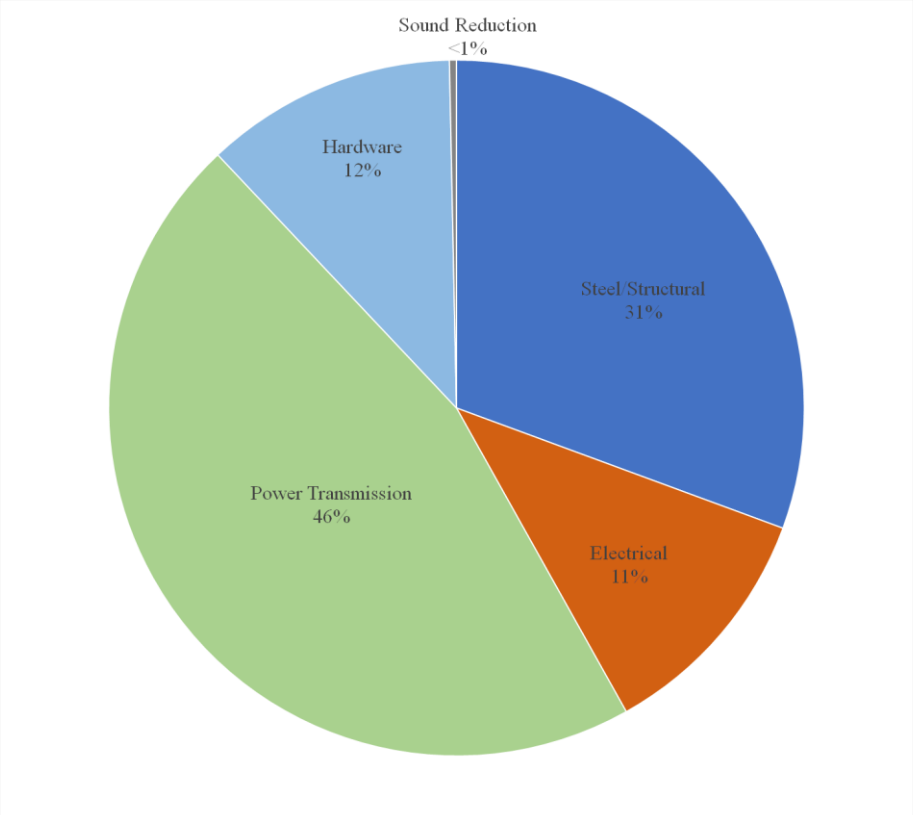

Figure 12. Cost breakdown of the bill of materials for the open source granulator.

To further drive down costs, additional components should be redesigned to use digital manufacturing technologies, the mass of parts should be minimized to maintain the necessary mechanical integrity (which is most easily done in the reduction of structural steel that makes up nearly a third of the cost), and the volume footprint of the device should be reduced. These costs were for retail purchased materials and would be expected to drop significantly if an open hardware company built the devices at even modest scale.

6. Conclusions

This study successfully demonstrate the designs, build and testing of an open source waste plastic granulator for its ability to convert post-consumer waste, 3-D printed products and 3-D printer waste into polymer feedstock for recyclebots of fused particle/granule printers. The device can be built from open source plans using materials that cost less than US$2000. The device has a power consumption (380 to 404W for PET and PLA, the most common post-consumer plastic waste and most popular 3-D printer plastic, respectively). With this device, granules can be produced with a particle size distribution consistent with distributed recycling and manufacturing using open source recyclebots and 3-D printers. Simple retrofits for the open source waste plastic granulator are shown to reduce sound levels during operation by 4dB and 5dB for the vacuum. It can be concluded that the open source waste plastic granulator is an appropriate technology for community, library, makespace, fab lab or small business-based distributed recycling

Author Contributions: Conceptualization, Joshua M. Pearce; Data curation, Arvind Ravindran, Sean Scsavnicki, Walker Nelson , Peter Gorecki , Shane Oberloier and Theresa K. Meyer ; Formal analysis, Arvind Ravindran, Walker Nelson , Peter Gorecki , Shane Oberloier , Theresa K. Meyer , Andrew R. Barnard and Joshua M. Pearce; Funding acquisition, Joshua M. Pearce; Investigation, Arvind Ravindran, Sean Scsavnicki , Walker Nelson , Peter Gorecki , Shane Oberloier and Theresa K. Meyer ; Methodology, Arvind Ravindran, Walker Nelson , Peter Gorecki , Shane Oberloier and Theresa K. Meyer ; Resources, Andrew R. Barnard and Joshua M. Pearce; Supervision, Joshua M. Pearce; Validation, Arvind Ravindran, Sean Scsavnicki , Walker Nelson , Peter Gorecki , Shane Oberloier and Theresa K. Meyer ; Visualization, Arvind Ravindran, Walker Nelson and Peter Gorecki ; Writing – original draft, Arvind Ravindran and Joshua M. Pearce; Writing – review & editing, Arvind Ravindran, Sean Scsavnicki , Walker Nelson , Peter Gorecki , Shane Oberloier , Theresa K. Meyer , Andrew R. Barnard and Joshua M. Pearce.

Funding: This research was funded by the Witte Endowment.

Acknowledgments: The authors would like to acknowledge technical support from Paul Fraley.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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