

RELATIVE ENERGY CONSUMPTION OF LOW-COST 3D PRINTERS

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ABSTRACT

The potential of low cost, 3D printing to support distributed manufacture in remote, rural communities has been noted by several observers. However the economic practicality of such proposals has not yet been clearly established and although some overheads, such as capital or consumables, are easily quantified the energy costs are less clear. Motivated by the need to understand the energy and power trade-off's inherent in 3D printing this paper reports the results of an initial study to evaluate the relative performance of three popular, low-cost models. Direct measurement of the electrical power required to build the same benchmark part demonstrates that there is both significance variance in the average power required and that the total energy consumption varies dramatically with the build parameters (i.e. layer thickness and platform temperature). In other words the research suggests that although 3D printed parts created on different machines might appear physically identical, their energy costs will be anything but. Far from completely characterizing the energy trade-off's inherent in 3D printing this initial study only highlights the need for further work to fully understand the energy implications of varying air temperature, print speed, layer resolution, filament diameter and print head temperature.

Keywords: additive manufacture, energy consumption, fused-filament fabrication.

1 INTRODUCTION

Additive manufacture (AM) is defined as, "...a collection of production techniques enabling the layer-by-layer manufacture of components using digital data and raw materials as inputs" (Baumers *et al.* 2011). AM is growing rapidly and has the potential to change manufacturing industry dramatically in the coming years. AM technologies have advanced substantially since the conception of the idea in the late 1980s, and recent developments have led to the integration of the technologies into a range of small scale 3D Printers which are now commonly available for prices affordable by consumers. The pace of development is high for example recently a robotic platform which is capable of performing subtractive, additive and formative manufacture in one process has been produced (Keating and Oxman 2013). This enables the parts to be produced without a requirement for support material, which reduces both time and cost involved. The merits of AM are (i) it can reduce the time span between product conception and manufacture by 60-90%, whilst reducing costs by as much as 70% (Waterman and Dickens 1994), (ii) it does not require the skill of experienced model-makers (Upcraft and Fletcher 2003), (iii) it offers a method of rapid production of complex shapes, and low quantity production of individually tailored products at a unit cost that is comparable to other processes (Baumers *et al.* 2011), and (iv) scrap material, worn tooling and cutting fluids are all minimal (Sreenivasan and Bourell 2010).

Since 2006 there has been a large growth in low-cost "desktop" 3D printers, which stemmed from open-source projects and the expiry of a number of key patents. These factors have combined to create a dramatic growth in the number of small start-up companies producing commercialised desktop 3D Printers (Makerbot 2013, Ultimaker 2013). Through the nature of 3D printing and the file types associated with it, sharing CAD models is easy and has readily led to the development of an "open source" community within the field. A number of papers have suggested that the future may see individuals moving to self-manufacturing, whereby they produce items they require by themselves without the dependence on commercial manufacturing (Berman 2012).

However in order for these machines to be viable in rural, 3rd world environments, 3D Printing must be economically feasible (Wittbrodt *et al.* 2013). In addition to the capital and raw materials, energy usage is a factor required to fully assess both the environmental impacts and running costs.

Since most of the low cost 3D printers use Fused-Filament Fabrication (FFF) technology, this study is focused on the evaluation of the power and energy consumption of three FFF printers. The subsequent sections of this paper briefly survey related literature, detail the experimental process used, present the results and conclude with a discussion of the findings and the need for further work.

2 RELATED LITERATURE

The literature on Additive Manufacture focuses largely on commercial applications, and the system's role in the rapid development of technology, primarily within small batch applications. The rapid expansion in low cost systems is not well reflected in academic literature which is focused on the industrial AM processes of Selective Laser Sintering (SLS) and Stereo lithography (SLA). SLS and SLA are both processes which utilize bonding of thin layers using lasers to sinter/melt or catalyze material, and although they can produce higher quality models, they are complex and require expensive machines. Compared to SLS and SLA, FFF systems are very cheap and can produce parts with layer thicknesses of 0.1mm (Makerbot 2013) by laying extruded thermoplastic in very thin layers from a nozzle which is kept at a measured temperature (Luo *et al.* 1999). 3D prints from FFF machines can be smoothed with compounds such as acetone and dichloromethane, depending of the material used (Wittbrodt *et al.* 2013).

Sreenivasan and Bourell (2010), who conducted a sustainability study of the process of SLS, suggest that materials and consumption of energy of a fabrication process are the prevailing factors of sustainability. There have been a number of efforts within academia to evaluate the energy usage in AM processes, but few have discussed low cost FFF technology. One of the first instances whereby the energy consumption within AM was analyzed was carried out by Luo *et al.* (1999), who studied the environmental impacts of FFF, along with the other two major polymeric AM processes: SLS and SLA. They reported varying energy usage across FFF, SLA and SLS machines. Another study which evaluated energy usage within FFF was conducted by Mognol *et al.* (2006). They investigated the effects of part build orientation on energy consumption for the same three processes, and they reported that negating support material in industrial FFF processes is the key to reducing energy consumption. It was seen that the FFF process was the least energy intensive process of the three for the printed part. The machines used in the study all utilized different AM technology and so this comparison does not take into account a range of FFF low cost 3D Printers.

An important study comparing the SLS and injection moulding (IM) processes was carried out by Telenko and Seepersad (2012), who produced a comparative lifecycle inventory of these two processes. They concluded that the production volume at which both processes consumed relatively equal amounts of energy for their test was between 150 and 300 parts, indicating that SLS can be used effectively for small production runs up to this value. They do state, however, that both processes consume energy at different points in the supply chain. The AM process consumes far more energy in production than IM, but does not require tooling which is costly and energy intensive to produce. It is seen that FFF processes, especially desktop machines, produce parts with significantly less energy consumption than either of these two processes, but part quality is significantly reduced. Baumers *et al.* (2011) suggested that AM is found to be effective in its use of the energy inputs to the process, especially in comparison to other production processes. Table 1 summarized the most relevant results found by Gutowski *et al.* (2006), who aimed to outline the electrical energy requirements for a variety of fabrication processes in a single table. Although these estimated figures based on past research, the table shows that variations of these processes demand a wide range of power values.

The review of current literature showed that there is presently extensive work still to be carried out through academia into a range of areas within Additive Manufacture. Since energy consumption is the largest component of operating costs in the use of small scale AM machines, more in-depth studies are required to reduce specific energy usage of the individual parts. More pertinent to this paper, research into aspects of Fused-Filament Fabrication is required, and definitely into low-cost desktop AM.

Table 1: Estimated process energy consumption (Gutowski *et al.* 2006).

Process	Average Estimated Power Required (kW)
Injection Moulding	10.76 to 71.40
Various Machining	2.8 to 194.8

3 HYPOTHESIS AND METHODOLOGY

The aim of this study is to evaluate the energy uses and requirements of common desktop 3D printers which utilize Fused-Filament Fabrication, and benchmark the performance of such devices at the end of 2013. The hypothesis to be tested is whether: “*Low cost 3D printers have roughly similar (within 5% variation) energy requirements regardless of model or build settings*”. To test this hypothesis three different low cost 3D printers were used to produce the same “benchmark” component. The machines used were (approximate 2013 market price in brackets): Ultimaker-Original (\$1,200), Makerbot-Replicator-2X (\$2,799), and Makerbot-Cupcake-CNC (\$455). The Makerbot Replicator 2X utilises two separate print heads, to extrude in two colours of filament. To ensure comparative testing however, only one of the two extruders was used. To study the effects of different process parameters on energy consumption two Makerbot-Replicator-2Xs were used to print the benchmark part at maximum speed but with different process setting. One used a layer thickness of 0.1mm and a build platform temperature of 50°C, while the other used a layer thickness of 0.3mm and a build platform temperature of 110°C. These machines are referred to as Makerbot-Replicator-2X -1 and -2 respectively.

The electrical energy consumption was measured using an “efergy hub” (efergy 2013). This nonintrusive energy monitoring device is designed to be a flexible device that could record the power consumed by an entire building or a single appliance. The device works by transmitting a signal from a Hall effect current sensor attached to the live electricity feed of an appliance to a hub device, which then uploads the data to an online platform. From here, data on power and energy usage can be both viewed in real-time and stored for later referral. The instantaneous power usage was recorded every twelve seconds and the time taken to print the object was recorded by a timer. This recording of instantaneous power over time allows the production of a graph of power over time, from which the total energy requirements can be calculated.

One of the parameters that could not be controlled in this study was the software used to convert CAD file to a STL file type from which G-codes are produced for the part. Ultimaker Original and Makerbot Replicator 2X use ‘Makerware’ which includes inbuilt slicing software. This is well developed slicing software required for dividing the CAD file into thin layers, which are then relayed to the 3D Printer. The Makerbot Cupcake CNC required the G-code to be produced through “ReplicatorG”, another product of an open source project. The G-code for the part was generated using “Skeinforge Standard” within “ReplicatorG” version 0028.

The rationale for benchmark (Figure 1) using an extruded profile for a part were (i) the shape should require support material when built in the direction of extrusion (which will minimise consumption of electrical energy as observed by Mognol *et al.* (2006)), (ii) to include a degree of repeatability, the test part was designed to be symmetrical and with a consistent cross section, and (iii) the part has a range of directional changes to ensure 3D Printer was utilising all degrees of freedom frequently which would vary power values more regularly to provide distinct results.

For each test, recordings were made of the air temperature, as this could effect the rate of cooling of machine parts. Also recorded was the temperature of the extruder heads of the machine. This temperature was required for the melting of the filament material used in the experiment, which was Acrylonitrile Butadiene Styrene (ABS) for all of the machines. The Makerbot Replicator 2X contains a heated print platform, the flat area that the object is printed on to. This feature is utilised to allow the material to bond to the print surface more readily and prevent warpage of the printed object. This temperature was recorded for each of the machines to which it applied. The energy consumption results obtained from the data collected from these experiments are analysed in the next section.

4 RESULTS

This section provides an overview of the data collected from each 3D Printer. Table 2 gives a summary of machine parameters used in the printing of the benchmark part on the four machines. The temperature of extruder was a constant value, set in the system software, and fluctuated between 220 and 230°C on all of the machines. More significant variance, however, came in filament, as the Makerbot-Replicator-2X use 1.75mm diameter while the other machines used a 3mm filament.

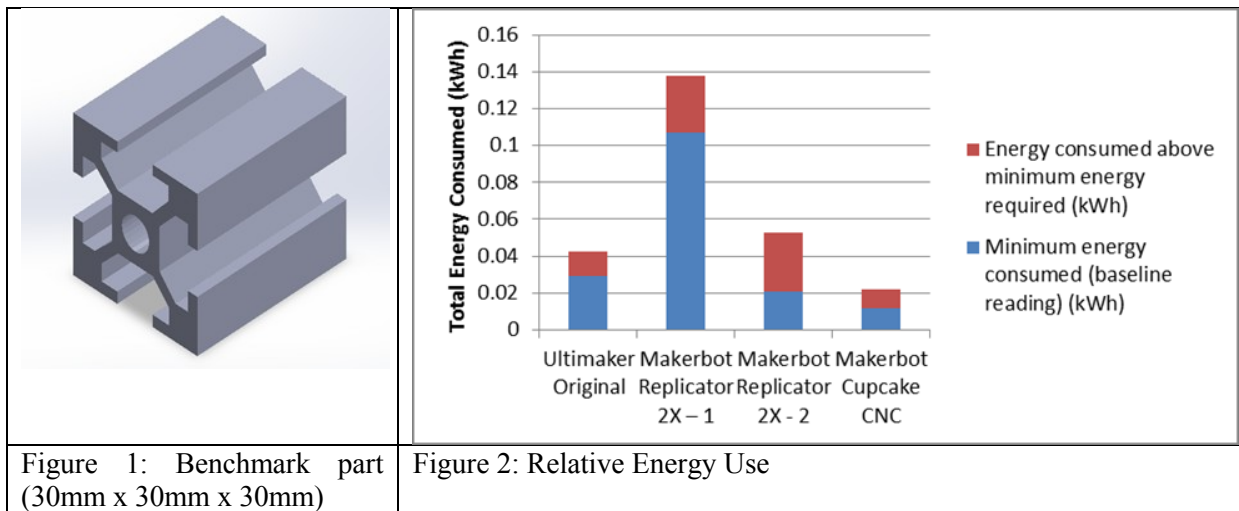


Figure 1: Benchmark part (30mm x 30mm x 30mm)

Figure 2: Relative Energy Use

3D Printer	Extruder Temperature	Print Platform Temperature	Environment Temperature	Filament
Ultimaker Original	230°C	N/A	18.5°C	ABS 3mm
Makerbot Replicator 2X – 1	220°C	50°C	18.5°C	ABS 1.75mm
Makerbot Replicator 2X - 2	220°C	110°C	19.5°C	ABS 1.75mm
Makerbot Cupcake CNC	230°C	N/A	19.5°C	ABS 3mm

Table 2: Machine Parameters

3D Printer	Mean Power Consumption (kW)	Power Baseline (kW)	Energy Baseline (kWh)	Energy used above baseline (kWh)	Total Energy Used (kWh)	Total Time
Ultimaker Original	0.063	0.043	0.029	0.0135	0.0425	40 mins, 25 secs
Makerbot Replicator 2X – 1	0.083	0.064	0.107	0.031	0.138	99 mins, 55 secs
Makerbot Replicator 2X - 2	0.122	0.048	0.021	0.032	0.053	26 mins, 5 secs
Makerbot Cupcake CNC	0.046	0.025	0.012	0.01	0.022	28 mins, 50 secs

Table 3: Experiment Results

Table 3 provides a summary of the overall results. Perhaps the most striking figures are those for the total energy consumed by each machine during the build of the benchmark part. This ranged from 0.022 kWh to 0.138 kWh and suggests that the Makerbot-Replicator-2X-1 used over six times as much energy as the Makerbot- Cupcake-CNC. Comparing the two Replicators it is not surprising, given the smaller layer thickness (i.e. 0.1 vs 0.3mm) that the build time of 1 is much greater than 2 but interesting that the energy usage does not scale linearly. The relative energy usage by the four 3D Printers is illustrated in Figure 2.

Figure 3 shows the Power vs Time plots for that underlie the figures in Table 3. It is interesting to note that all the graphs have a characteristic baseline power consumption below which no reading are recorded. The baseline represents the power used to run each machine's controller and energize the stepper motors (which consume power regardless of their motion). The fluctuations above the baseline value are believed to be caused by the heating elements in the print heads and, in two machines, the build table as they switch on and off in response to thermocouple inputs. The fact that the peaks of each graph are relatively frequent suggests that heating efficiency (e.g. print head insulation and the

thermal inertia of the build table) is a more important contributing factor to overall energy consumption than many other factors such as the movement of the axes. The machines, in particular the Makerbot-Replicator-2X-1, commonly returned relatively steady values when a peak due to heating was not observed. This machine returned to a baseline of between 40 and 75 watts to power controller and motors and peaked to 180 watts when heating was occurring. The fluctuation were caused largely by heating elements in the head and table switching on-and-off in response to thermocouple readings. It is interesting to note that the Replicator with the higher table temperature (ie. machine-1 was 50°C, machine-2 was 110°C) is drawing power for heating far more frequently.

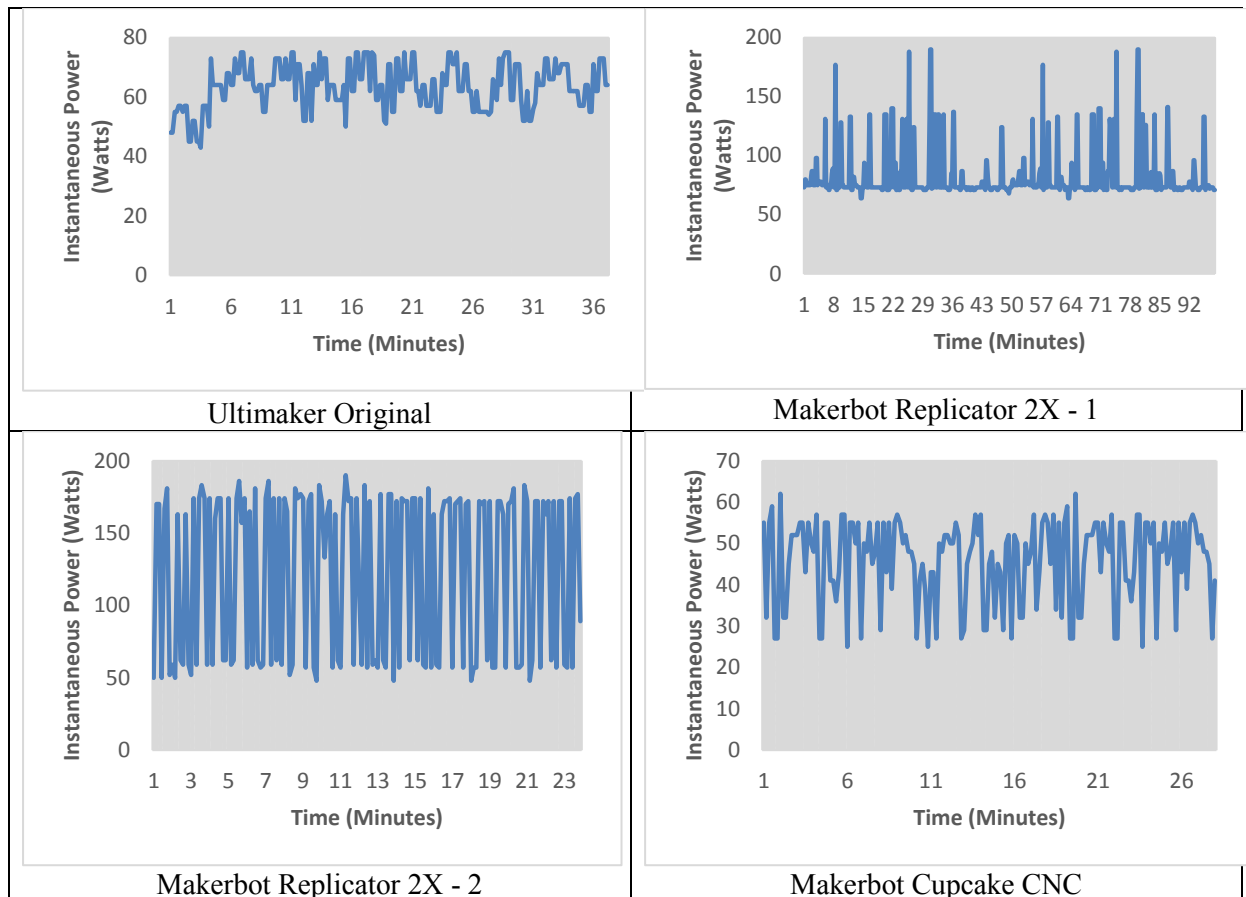


Figure 3: Power-Time Graphs of Each 3D Printers.

The Makerbot-Cupcake-CNC recorded the smallest baseline power value of all the machines, a reading of 25 Watts. In contrast the Makerbot-Replicator-2X produced peak demands of 190 Watts (this is assumed to be the point at which heating of both the build platform and the extruder was occurring). Another interesting observation is the standard deviation of each set of results. Makerbot-Replicator-2X-2 has a standard deviation that is substantially higher than the other machines. The less expensive machines proved to have a much smaller fluctuation in power values recorded. It can be seen that the aggregated energy consumption was highest in Makerbot-Replicator-2X-1, whilst average instantaneous power consumption was highest in Makerbot-Replicator-2X-2.

5 DISCUSSION AND FUTURE WORK

The results of this initial investigation into the energy requirements for low cost 3D Printers show that it is highly varied, and thus the hypothesis that desktop 3D printers consume roughly similar quantity of electrical energy can be refuted. Since the setup parameters of the 3D Printer have a dramatic impact on the overall power requirements, there is a need for operator training and guidance to enable production of high quality parts with low energy consumption. However before this can be done further studies are required to strengthen this result due to the clear limitations of this initial study. The main limitations of this initial study are (i) accuracy of energy measuring device used varied

around 7%, and only sampled at twelve seconds intervals, (ii) no repeatability test were carried out within this study, and (iii) only the time spent in printing was evaluated; ideally the overall time including warm up time should be recorded. More experiments are needed to identify the most influential parameters such as print speed, layer thickness and build heating temperature to enable the energy implications of these to be related to the resulting part quality. For example the mass of the printed parts should be recorded to assess the volume of ABS used in the build. More experimentation is also required for currently uncontrolled factors such as software used, air temperature, temperature of extruder head, motors efficiency and filament diameter. Also comparative benchmarking energy consumption levels of different desktop AM systems such as SLA devices with FFF devices is required. As the 3D printer market matures these will become significant consumer concerns and consequently the authors hope this work will inspire further work to define this important performance parameter.

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