Don't Forget Your Electricity Bills! An Empirical Study of Characterizing Energy Consumption of 3D Printers

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Abstract

3D printing is an emerging technique in product manufacturing. Its applications have been expanding vastly in home-based production. Compared to traditional manufacturing techniques, such as Computerized Numeric Control (CNC) machine tools, it is believed that 3D printing is more cost-effective in fabricating personalized products. The product cost estimation in 3D printing mainly takes material expenditure into account, and extensive studies have been performed for reducing filament expense or development of recyclable filaments. However, electricity expenditure is another inevitable cost in the 3D printing process yet an omitted factor in the cost estimation. To this end, this paper introduces the first in-depth study to understand the energy consumption in 3D printing. Specifically, our study comprises of two parts. The first part quantifies both material and electricity use in the 3D printing, and find that the electricity takes upto 32% of the total cost. The second part characterizes the energy consumption and identifies the sensitivity of various parameters. We also share insights and potential solutions to optimize the power consumption of 3D printers.

1. Introduction

Additive manufacturing, also known as 3D printing, is hailed as the third industrial revolution because of the unique ways in which products are conceived, designed, manufactured and distributed to end users [9]. Due to the elegant concept of layer-by-layer fabrication, 3D printing is used to build various complex objects with a wide variety of materials and functions [2]. Compared to conventional subtraction manufacturing techniques (i.e., CNC machining [28]), 3D printing holds the merit of *customization* and *affordability*. 3D printing has been changing market trends resulting in an efficient, responsive, robust and sustainable production paradigm in a wide range of domains including aerospace, automobile, defense, bio-medical, health and energy sectors [19].

3D printing was first proposed in 1987 [26] and is currently becoming a core topic in the manufacturing community. One of the key challenges in 3D printing is to lower the cost of the 3D printed products. Since material expense has been traditionally recognized as the major cost, researchers have explored various methods to minimize the material consumption in the 3D printing process. Existing works can be classified into two categories. The first category underlines reduce material wastes by optimizing the fabrication process. For example, Vanek *et al.* propose a clear support generation approach to reduce the supporting material in 3D printing [23]. Duflou *et al.* investigate many process planning algorithms and compare the material efficiency among them [7]. The second category emphasizes on improving the yield of the 3D printing process. Currently, affordable 3D printing techniques, such as the Fused Deposition Modeling (FDM) type, suffer from an unstable yield rate [20]. There are many on-going works to tackle this challenge ranging from better 3D printer designs to CAD optimization [5].

Energy efficiency is a key factor in the manufacturing industry, and energy consumption is tightly related to the product cost [17]. According to our literature survey, there are few studies focusing on energy consumption in 3D printers. Walls *et al.* compare the power consumption among a few lost-cost 3D printers [24]. A recent study by T. Peng [16] analyzes the energy utilization in the 3D printing process. However, neither of them investigate the sensitivity of energy consumption to the overall cost of printing a 3D product.

In this paper, we assert the significance of electricity cost to the overall expense of 3D printing and thus provide a basis for understanding and managing 3D printer energy consumption. Although the material cost still holds a major share in the overall cost sector, it is equally important to optimize the energy consumption to reduce the cost of printing for less environmental impacts. To this end, we perform an empirical study of characterizing the energy consumption

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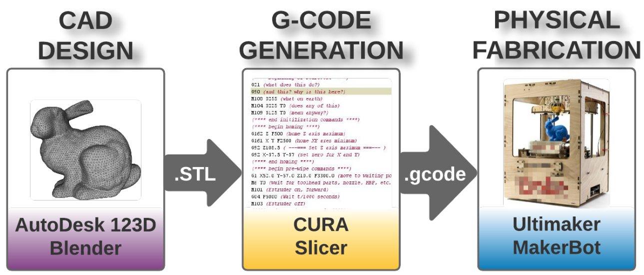


Figure 1. The 3D Printing Process Overview

in an commercially off-the-shelf 3D printer, *Ultimaker 2 Go* [21]. Our study is divided into two parts:

1. We examine the material and electricity use in a 3D printing process to inspect the ratio of electricity cost to net expense. We investigate the cost of a set of fabricated products with different manufacturing setups.
2. We characterize the energy consumption of 3D printers by considering the distribution of power to the various components and quantify its sensitivity to the overall product cost.

Our experimental results show that the electricity cost is significant, taking up to 32% of the overall manufacturing cost. We also show the energy consumption of each component of the printer and their sensitivity to the overall cost of printing. In addition, we discuss potential approaches to reduce the energy consumption in 3D printers.

2. 3D Printer System Overview

In present market, there is a diverse collection of commercially off-the-shelf 3D printers [24]. In this work, we investigate the Fused Deposition Modeling (FDM) 3D printer, Ultimaker 2 Go because of its open-sourced platform. FDM 3D printers currently constitute more than 90% of the market share in low-cost 3D printers [15].

Fabrication Process: In this part, we present an overview of the standard 3D printing process. As illustrated in Figure 1, there are predominantly three stages involved in the printing process. The first step is to create a 3D design model, which is devised by 3D design tools (e.g., Solidworks) or produced by a 3D scanner. The 3D design is represented as a triangle mesh in the STereoLithography (STL) format. The second step is a computing process that transforms a 3D design file into a set of instruction codes (i.e., G-code), which a 3D printer interprets and executes. This process for a 3D printer is similar to a compiler for a CPU, or a synthesizer for an FPGA. The last step is the manufacturing process, in which the 3D printer fabricates the physical object according to the G-codes.

System Architecture: 3D printer is a hybrid electromechanical machine. As depicted in Figure 2, it comprises of

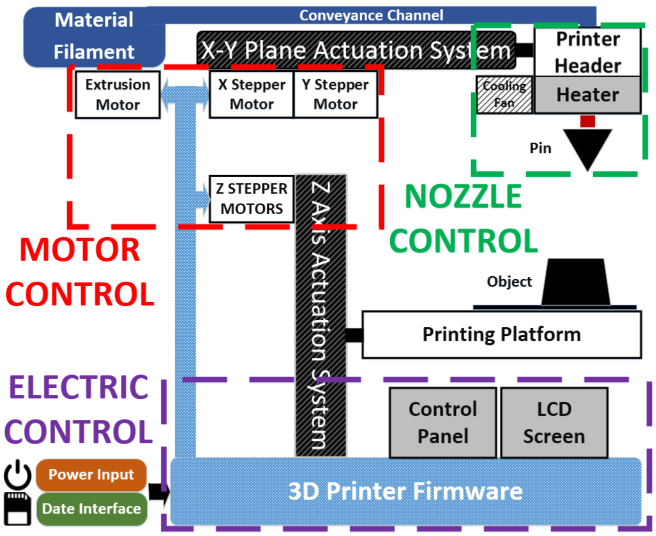


Figure 2. System architecture of a 3D Printer

three major components: an electric control unit, a motion controller and a nozzle that extrudes out the material. The electric control unit is a micro-controller system based on Atmel ATmega 2560. It reads the G-codes (either from a serial port or a mini SD card), and manages the motors, nozzle and the heating/cooling systems in real-time. There is no sophisticated operation system in 3D printers yet, because the current printing task is still a simple-model single-material process. The motion controller includes four NEMA17 stepper motors. The travel speed ranges from 10 to 300mm/s, and the precision is 1 micron. Three motors govern movements along the X-Y-Z directions. The fourth motor manages the material extrusion. The material is fed into the printer in the form of a filament of diameter 2.85mm. The nozzle consists of a brass heater (M4, 25W), a ceramic thermal insulator, a thermistor (PT-100B) and a 12V DC cooling fan. PID controllers stabilize the temperature in the nozzle with values ranging from 100 to 230°C. For simplicity of the analysis, we modified the firmware to disable other auxiliary parts, such as the LCD screen, in our study.

Generality in this study: We emphasize the validity of our results not only for the aforementioned model but for any other 3D printer operating on same or different 3D printing process [4], provided that the architecture is inclined towards Figure 2. The main difference between the processes lies in the operation of layers deposited to create parts and the material usage. The system architecture in Figure 2 is applicable to all extrusion-type 3D printers since they operate on the same principle of creating objects by adding layers of material, i.e., additive manufacturing [3]. Extrusion-type printers currently constitute major market share due to its low-cost and rapid prototyping. Particularly, we compared *Ultimaker 2 Go* and *Ultimaker Original*, two FDM printers being released 3 years apart [21]. We observe that the architecture

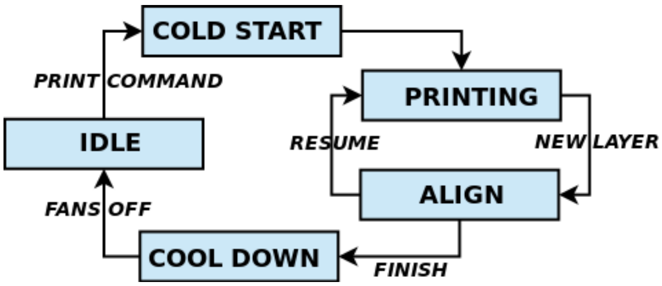


Figure 3. The Working State Transition Diagram

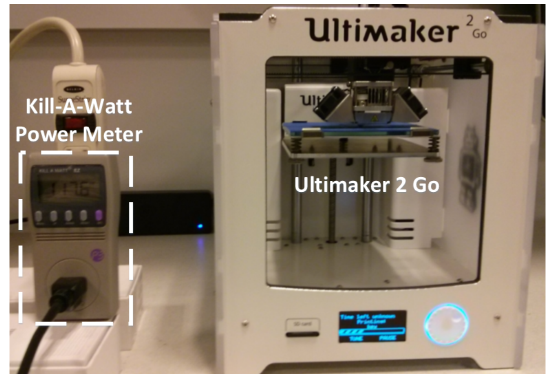


Figure 4. Experimental setup.

of 3D printer remains the same, even though the *Ultimaker 2 Go* firmware was updated to introduce more functionality for user-friendly interaction and smooth operation. No change was found in parameters such as layer resolution, speed and nozzle temperature. Therefore, we believe that the significance and sensitivity of components in an FDM-type 3D printer to overall energy consumption will remain valid for all extrusion-type 3D printers for next few years unless there is a breakthrough which significantly modifies system architecture.

Working States: The 3D printer has five working states. The state transitions depend on the G-Code instructions and printing conditions. Figure 3 shows the state transition diagram. Each state is described as follows:

- **IDLE**: The default state of the 3D printer when the printer is powered on. In this state, the motors, fan and the heat-head are turned off. User has the option to choose a print model or perform any maintenance check before the manufacturing process.
- **COLD START**: The starting state of a printing process where the nozzle heats up from room temperature (e.g. 25°C) to the material-melting temperature (e.g. 230°C). This state initiates immediately after the print command is given.
- **ALIGN**: The state where the nozzle moves to a specific X-Y coordinate without extruding any material. The Z and extruding motors are powered off, and therefore no material is extruded. The nozzle travel speed in this state is faster than the PRINTING state.
- **PRINTING**: The fabrication state in which every component of the printer is functional. During this state, the nozzle maintains the temperature at 230°C while extruding the filament and motors remain in full-fledged motion. The motors move the nozzle to different coordinates based on the interpreted G-codes to print various layers of the product.
- **COOL DOWN**: This is the edge state of printing process, initiated after the PRINTING state. The nozzle aligns itself to the origin and the fan continues to be in function to cool down the heat-head/nozzle.

3. Study One: Exploring Electricity Cost

Experimental Setup: The aim of Study One is to answer the question: What is the proportion of electricity cost in the overall expense of a 3D printed product?

We use the Kill-A-Watt [12] power meter to quantify the energy consumed while printing different models. The experimental setup is shown in Figure 4. We select four different design testbenches in our experiment - a ring, a robot, a cup and a sculpture. The testbench is characterized in Table 1. The models vary from 7MB to 20MB in G-code size, comprising of hundreds to thousands of layers, and chosen from four different domains. In our experiments, we set the nominal printing speed to 150 mm/sec, and the temperature to 230°C. Above parameters were observed to be safe for printing of any design on a 3D printer without affecting the quality of the model [13]. Printing defects and damages to nozzle were observed during prolonged printing at temperature below 210°C. We further elaborate the sensitivity of these parameters in relation to energy consumption in Section 4. The electricity cost is estimated by the standard residential electricity price due to wide home-use scenario of 3D printers. We used the most common bracket for electricity cost in U.S. [22], which aligns with the global average. We chose a highly accepted buying option for the filament [8] to calculate the material expense to improve the generality of our work.

Table 1. Design Testbench Description.

Name	G-code Size	No. of Triangles	No. of Layers	Description
Ring	8.2MB	1088	832	Intricate geometry
Robot	9.5MB	3290	838	Hobby item
Cup	12.1MB	5352	1094	Commercial product
Sculp.	18.9MB	7510	2715	Intricate art

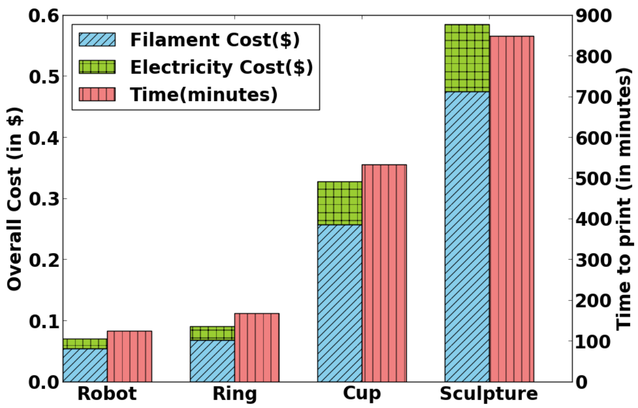


Figure 5. Cost and time statistics for printing different models.

Results: We investigate the impact of electricity cost on the overall manufacturing cost by considering two aspects, i.e., design complexity and fabrication quality.

- **Complexity Impact**: The test results are shown in Figure 5. We observe that the fabrication duration depends on the design complexity, and the overall fabrication cost is proportional to the printing duration. *By taking a closer look at the cost breakdown, we find that the electricity cost takes 28% on average, and up to 32% portion in the overall expense to print a 3D model.* Design complexity refers to structural complexity of a model or the valuation of information embedded in the design as captured by intelligent computer aided design systems [6]. One of the prominent parameter relative to 3D design model is number of layers. As observed from Table 1, sculpture model was observed to have twice the number of layer as the cup. Increase in the number of layer associate with either having numerous amount of standard shapes or having increase in number of faces, arcs or irregular shapes with varying parameters of speed, extrusion amount set to each layer. This leads to extra acceleration and deceleration in the motors for precise movement of nozzle for different layers. Our results show that the design complexity has a significant impact on the electricity consumption, as more complex designs require more time for manufacturing leading to increase in overall energy consumption, which further enhances the overall expense of the product.
- **Resolution Impact**: We investigate how the printing quality, i.e., resolution, affects the fabrication cost. We set different resolutions varying from 250 to 2 microns in the 3D printing process. Figure 6 shows the results on four different design products. The red line indicates the material usage while the blue line corresponds to energy consumption which is directly proportional to the electricity cost. *We observe that as the fabrication quality increments, electricity cost unanimously increases on all models, while the material cost remains the same.* Increase in resolution of a model is coherent to its design complexity. As a design is converted from coarse to fine-grained, the instructions for the 3D printer to print the model increases leading to increase in overall size of G-code file. These instructions comprise of machine recognized commands specifying parameters such as layer count, extrusion amount, feed rate and temperature for individual layers of the model. These parameters suffer change in order to increase the density and precision of movement of the nozzle, thereby increasing the overall energy consumption. Since electricity cost is a time related quantity, significant increase in the time for high quality print leads to rise in expense for production of a 3D model. The abnormality in the filament mass for Figure 6(d), is observed for excessive time consuming and solid designs, where a small change in resolution can lead to significant variation in total amount of filament consumed. This characteristic was not observed for hollow designs (e.g. cup) since change in material expenditure upon increasing resolution is trivial.

  The observations from both the aforementioned aspects enhance the magnitude of reducing electricity cost to scale down the overall expense of production. Section 4 reveals the sensitivity of parameters to energy consumption for better understanding of energy model of the 3D printer.

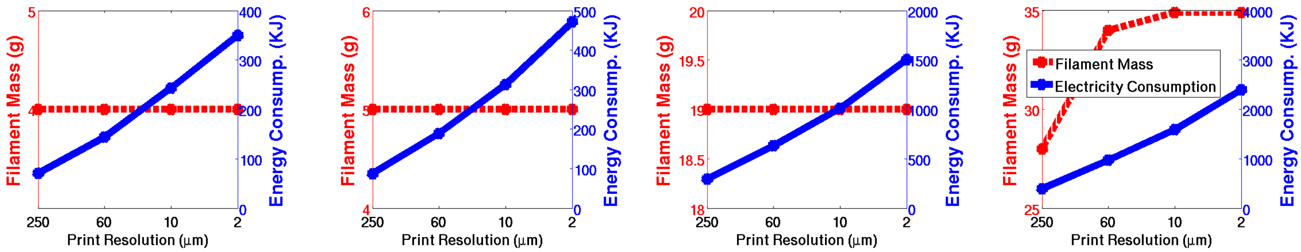
4. Study Two: Energy Characterization

The aim of Study Two is to understand the energy model in a 3D printer. We devise a benchmark to characterize the energy consumption in each significant part of the printer. The benchmark approach is discussed in the following section.

Benchmark Approach: Motion, heating and cooling are the three major consumers of energy[1]. We designed the benchmark to test the energy consumption of the motors, heater and the fans.

- **Motor TestBench:** Motor is the central electromechanical part in the 3D printer, and its configuration impacts both product quality and energy consumption. This testbench includes a task specifically to examine the energy characteristics of motor. In *Ultimaker 2 Go*, there are three NEMA17 stepper motors that govern the movements of the extruder along the X,Y and Z axes. They work on Pulse-Width-Modulation (PWM) mechanism. Based on an algorithm called Leib-Ramp, the firmware builds acceleration/deceleration step profiles and dynamically sends the appropriate step value to the stepper mo-

[1] The energy consumption in the electric control unit is not significant according to our preliminary observation and related datasheets [21].



(a) Printing a Robot (b) Printing a Ring (c) Printing a Cup (d) Priting a Sculpture

Figure 6. Filament and energy cost of printing various products.

tors. In this study, we will investigate the power consumed by these motors at different print velocities[2].

- **Heating TestBench:** Heating is another pivotal part in the 3D printer. Heating setup is determined by the melting temperature of the material. To obtain the heating characteristics, the heating testbench examines how the sensitivity of heating part changes with different temperatures. In this testbench, the nozzle remains steady and the temperature is varied from 100 to 230°C to obtain the readings[3]. No power is consumed by the motors in this testbench.
- **Cooling TestBench:** The main component in the cooling part are the fans. In this testbench, we vary the fan speed while printing and notice the changes in the power consumed by the fans. Since the fans remain functional for the entire printing period and beyond, quantifying the power consumed by the fans is important. Also, it helps to understand the portion the fan takes in the total energy consumption.

Evaluation: We use the testbench devised above to characterize the energy consumed by various components at different stages of printing.

- **Energy Division:** We first examine the energy distribution in 3D printers to understand the energy model in each part. To this end, we breakdown the energy component in each part and construct the energy sector in Figure 7. The result illustrates that motors, heating and cooling consumes 51.7%, 41.4% and 6.9%, of the overall energy consumption, respectively. These portions were computed during the PRINTING state (specified in Section 2), since all the components remain functional during printing. Due to evaluation of energy consumption of the components in same state, i.e., time being a constant entity for each one, the energy distribution can be generalized for any 3D design. During experimentation, we used testbench models for individually separating the motor, heat-head, fan and analyzed the power consumption associated with it. Magnitude of each component to energy consumption assists us in deriving proper process planning algorithms for refined printing by examining the component where most efficiency is possible. We characterize each component in more detail in the following discussions.

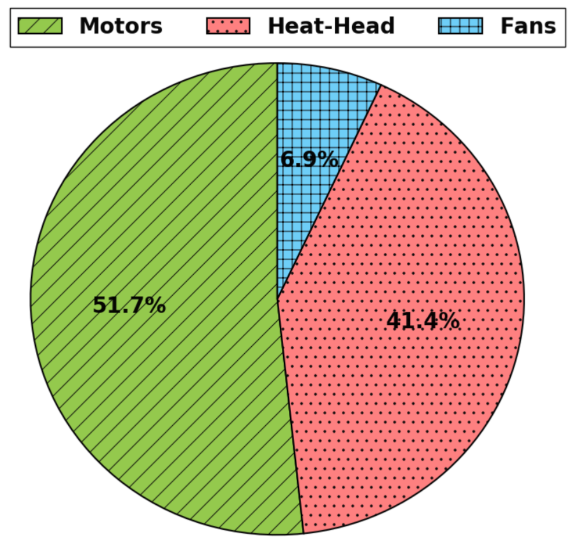


Figure 7. Energy sector in the 3D printing process.

- **Motor Sensitivity Analysis:** We investigate the power characteristics of the motors based on the motor testbench. The power consumption of the motors is determined by the motion velocity which has a wide configurable range. In this experiment, we examine the power characteristics of the motors by obtaining readings at different velocities ranging from 10 to 150 mm/sec. The results are depicted in Figure 8. *We observe that the power consumption of motor (the red dash line) increases at both low and high speed settings.* Specifically, the stepper motor NEMA17 reaches the lower power at the velocity of 100 mm/sec. A 3D printer recognizes instruction commands (G-code) and instructs the nozzle to move in a specific direction with explicit speed and other parameters specified in the command. To perform experiments,

[2] We obtain the power consumed by the motors by subtracting the power consumed by other components such as the fans and the heat-head from the overall power consumption.

[3] We examine the temperature under 210°C to explore the temperature sensitivity and its impact on energy consumption.

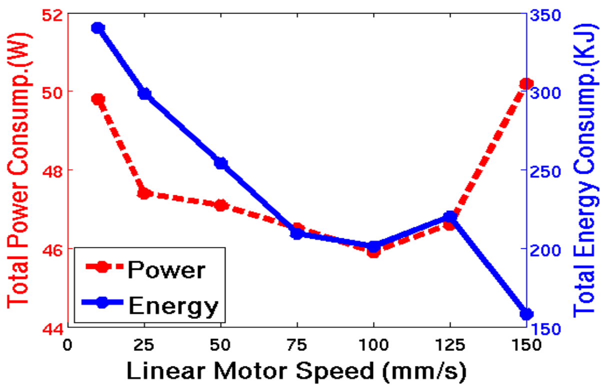


Figure 8. Motor power characterization with different running velocities.

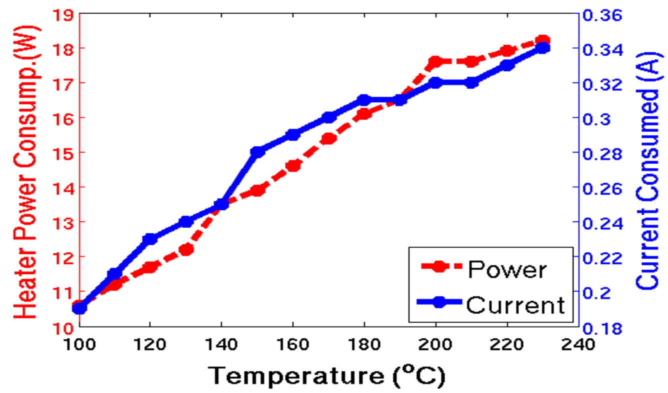


Figure 9. Heating energy characterization with different temperatures.

we uploaded the G-code to 3D printer and controlled the speed using the console provided in the printer. Variation in the speed results in machine recognized speed from the G-code to nullify and further commands are send to either accelerate or decelerate according to our variations. This anomaly in speed from optimum value, leads to rise in power consumption when the printing process is expedited or eased. Energy consumption curve (the blue solid line) portray that increase in the speed from minimum to maximum results in an exponential decrease in energy consumption. Energy being a time related quantity suffers from a significant change at lower speed setup since the time to print increases exponentially. The abnormality between 100 mm/sec and 125 mm/sec result from increase in power but not sufficient decrease in time to lower the energy consumption. Therefore, it suggests the manufacturing industries to investigate the effect of path planning on motor speed for energy efficient 3D printers.

- **Temperature Sensitivity Analysis:** Since the heating part takes a significant portion (as high as 41%) in the energy cost sector, we further investigate the characteristics of the heating process. There are different filament materials with different melting temperatures. Therefore, we change the temperature setup from 100 to 230°C, and examine the power and electric current changes. As shown in Figure 9, both power (dash) and current (solid) linearly increase with temperature. *From our observations in Figure 9, the end to end change in temperature setup results in maximum reduction of 8 watts of power.* While it is possible to reduce the heating energy by fine-tuning the temperature profile in the fabrication process, motor component remains the predominant factor (Figure 7) for reducing overall energy consumption through implementation of process planning algorithms recommended in Section 5.
- **Fan Sensitivity Analysis:** We test the cooling energy consumed by the fans following the setup specified in cooling testbench. The fan is switched on and off according to PID temperature controls in the firmware. We configure the speed of fan from 10 to 100 mm/sec, and monitor the power consumption. The results are shown in Figure 10. We observe that the power curve in the fans seem to be a piece-wise linear curve, and 75 mm/sec is the turning point. The readings for 75 mm/sec and 100 mm/sec lies in the accepted error range. Evaluation of primary components for energy consumption is important for understanding the energy model of 3D printer in designing finest quality print. By observing the fan curve, we conceived the efficiency of the fans and its relation to power consumption. *We witness that varying the fan speed from 100 mm/sec to 10 mm/sec will lead to maximum decrease in 4 watts of power, although inducing deleterious effects to 3D printer.* Therefore, for optimal printing and functioning of the printer, fan speed is recommended to be at 100 mm/sec or 75 mm/sec.

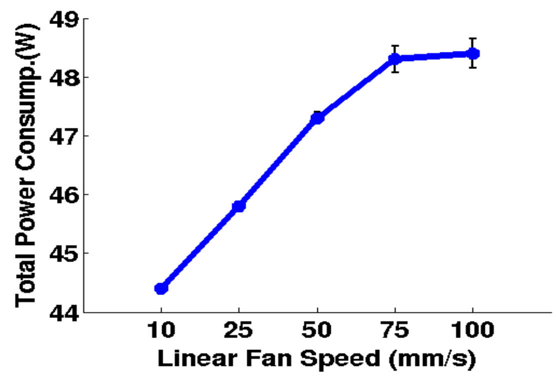


Figure 10. Cooling power characterization with different fan speeds.

- **Temporal Power Profile:** Finally, we perform a study to profile the power variation through different stages of the fabrication process. This further investigation provide insights to the energy consumption in different working states of a 3D printer (defined in Section 2). We use the sculpture benchmark and repeat the test for 10 times.

Table 2. Energy consumption in different working states

STATE	POWER (W)	CURRENT (A)
IDLE	2.2	0.04
COLD START	48.7	0.66
ALIGN	21	0.29
PRINTING	47	0.67
COOL DOWN	3.3	0.06

Both power and electric current is measured, and the test results are summarized in Table 2. We identify significant variation (from 2.2 to 47W) in power consumption between IDLE, ALIGN and PRINTING state. This suggests that through implementation of appropriate runtime power management techniques, PRINTING state can be transitioned to ALIGN or IDLE state when nozzle is stationary for a long period of time. Shift in state upon meeting conditional requirements set by manufacturer, can significantly improve energy efficiency of 3D printers.

From initial knowledge of sensitivity of aforementioned parameters and awareness of power consumption in transition states of 3D printer, the manufacturing process can be enhanced to conserve more energy provided that appropriate techniques are implemented. We further explain our insight to refined printing in Section 5.

5. Insights and Recommendations

Our study shows that electricity costs contribute significantly to the overall cost of 3D printing, especially while printing high-resolution products. Therefore, improving energy-efficiency is important to make the 3D printing process economically feasible in the long-term run. In addition, energy use is also a critical factor considering environmental sustainability and technology portability of 3D printers.

We propose the following approaches to potentially improve the energy-efficiency of 3D printers. The proposed approaches include changes only from a computer systems perspective. Methods to alter the electrical, mechanical or material behavior of the constituting components is beyond the scope of this work.

Energy Profile Simulator: A user can convert a 3D model to printer classified instructions (G-code) through diverse design tools. These tools provide user the ability to modify the design while displaying information such as time and material required for the model. But they still remain insufficient in providing any information about energy consumption or electricity cost. User's lack of knowledge about above parameters leads to inability in modifying the design for efficient printing. Therefore, an energy profile simulator is suggested to estimate the energy/power consumption characteristics of fabricating a 3D design in a 3D printer. This simulator is conceived to be one step forward in improving the manufacturing process as 3D printing is heading towards rapid production [1].

Process Planning Algorithms: Results in Section 3 and 4 indicate that the electricity cost is directly proportional to the time taken to print. Therefore, motion speed is a key tuning factor to optimize the energy from the software and algorithms perspective. We would like to point out that the maximal motion doesn't necessarily yield the best energy efficiency. Similar observations is also confirmed by the research work [14, 25] in the robotic community. Considering the large plan design in a fabrication process, we believe that formulating the energy model with process parameters (such as motor travel speed, temperature setup, movement compensation) in 3D printers is a promising approach to reduce energy consumption.

Runtime Power Management: A 3D printer is an emerging *cyber-physical* system. Runtime power management remains under-explored on 3D printers. Considering the distinct delays between electrical components and mechanical components, there is a considerable room to optimize runtime power management in 3D printers. Based on our observations, all motors consume power when the nozzle is moving along a single-axis direction. Considering that the current design of the electrical control unit is still in the state-machine paradigm, it is worthwhile to explore an operation-system paradigm to enhance runtime power management [27, 11]. Hardware enhancement techniques, such as power gating [10], dynamic voltage and frequency scaling [18] can provide flexibility in power management and further improve the energy efficiency of 3D printers.

6. Conclusion

In this paper, we performed the first in-depth analysis of energy consumption of 3D printers. We surprisingly found that the electricity cost is unignorable and takes 32% of overall expense of the product in current 3D printing. We broke down the energy consumption that revealed motor and heating dominates the energy sector. We further examined the sensitivity of system factors to energy consumption, including motor velocity, heating temperature, cooling power and printing resolution. Our results have provided the clues to optimize power of 3D printers, and implied a few potential solutions to reduce energy consumption. Considering that 3D printing cost has multi-fold economic and environmental impacts, we hope that our findings of this study can serve as the reference to understand and optimize energy consumption of 3D printers. Moreover, better energy-efficiency can promote the use of 3D printers into some energy-constrained scenarios, such as battery-powered portable 3D printers.

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