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Direct electrical energy demand in Fused Deposition Modelling

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Abstract

3D printing is predicted to grow and underpin distributed manufacture of customized and geometrically complex products. At this early stage of technology development it is timely to consider and optimize the resource efficiency of these layered manufacturing technologies. In this work, the direct electrical energy demand in one of the most popular technologies, fused deposition modelling was studied and a generic model for direct energy demand in layered manufacture proposed. To explore the variability of energy demand according to machine systems, three different FDM machines were evaluated. The performance of Fused Deposition Modelling was further benchmarked to machining processes in order to throw light on the relative energy demands for alternative manufacturing processes. The work is a foundation for electrical energy demand modelling and optimisation for the rapidly expanding 3D printing processes.

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Keywords: Energy; Rapid prototyping; Fused deposition

1. Introduction – Layered Manufacturing Technologies

Rapid prototyping (RP) or layered manufacturing (LM) are additive manufacturing techniques that build up the product layer by layer [1]. In these techniques the part is fabricated from a 3D solid model produced in Computer Aided Design (CAD) packages. The process is considered to be material efficient because material is added in layers and therefore reducing the amount of material wasted in producing a part compared to material removal processes [2]. Additional characteristics and benefits of additive manufacturing techniques are well documented [3-4]. As rapid prototyping, this technology was initially developed to produce prototypes of physical models as fast as possible using polymers [5]. This largely reduces errors and cycle time in new product development and accelerates time to market. Today, layered manufacturing is growing as a means for 3D printing of customized parts, or as a repair technique for functional high value parts.

In RP technology, CAD models are uploaded to specialist software. This software slices the model in the z-axis so that an RP machine can construct a 3D replica of model in layers without needing tooling. Post processing may be required if support material is used in fabrication.

Various layered manufacturing techniques have been developed, these include Stereo Lithography (SLA), Fused Deposition Modelling (FDM), Ink Jet Printing (IJP), 3D Printing (3DP), Selective laser sintering (SLS), Selective laser melting (SLM), 3D laser cladding process, Laminated object manufacturing (LOM) and Laser chemical vapour deposition (LCVD) [6, 7]. It has been reported that [8] RP can cut costs by up to 70% and reduces time to market of finished parts by 90% when compared to other conventional manufacturing methods. Manufacturing of functional parts through these technologies in 3D printing is predicted to grow and underpin distributed manufacture of customized and geometrically complex products.

1.1. Fused Deposition Modelling

Fused deposition modelling (FDM) was developed by Stratasys Inc. and has grown to become one of the most popular RP processes [4]. In this process, a thermoplastic

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filament is unwound from a spool that supplies material to a heated extrusion nozzle. As the filament passes through the nozzle, it is melted and extruded onto a build platform to form bonded bead which rapidly solidifies. The machine follows hatch strategy for each model cross-sectional layer as generated in the STL file slicing software. When the layer is finished, the build platform then indexes down and another layer is fabricated. The common material used is Acrylonitrile butadiene styrene (ABS), which combines the strength and rigidity of acrylonitrile and styrene polymers with the toughness of polybutadiene rubber. ABS has many daily applications as material, for example for lego bricks, toys, golf club heads, automotive trim components, automotive bumper bars etc.

In the FDM process, fabrication occurs inside a temperature controlled chamber. The heated nozzle is mounted to a motion system that can move in the X-Y plane within the chamber. For the base bridge as a foundation to lay the part and for large overhangs and complex geometries, the nozzle also extrudes support material when required. Thus, the part has to be post processed to remove any support material. For the Stratasys Dimension SST FDM, this is done in a heated bath of detergent which selectively dissolves the support material and leaves the part material. Other FDM machines do not provide this soluble support material and hence the support structures have to be broken down manually.

It is generally acceptable that because FDM and other layered manufacturing technologies are based on material addition they are more material efficient compared to mechanical machining processes. However, the energy intensity of layered manufacturing process has not received much attention. It is timely at this early stage of the technology development to embed resource efficiency in developing and optimizing manufacturing techniques.

1.2. Research Aim

This work was aimed at investigating the direct electrical energy requirements of Rapid Prototyping (RP) and Rapid Manufacturing (RM) with a view to understand how the energy demand varies for different FDM machines (machines based on the same process mechanism), develop a mathematical model or framework for electrical energy modeling in 3D printing process and comparing the electrical energy intensity of material additive process to that of mechanical machining.

The electrical energy requirement for a manufacturing process was studied by Gutowski et al [9]. The authors proposed a mathematical model for the electrical energy based on machine tools on a Toyota automobile production line. In their model, they categorized the electrical energy demand into two groups i.e. ‘Basic State’ and ‘Cutting State’. Along these lines the vision for this work was to use energy monitoring and event streaming to study the energy demand for fused deposition modelling and explore the effect of different FDM machines available at Manchester but made by different systems developers. To put this in context, energy demand for Fused Deposition Modelling was benchmarked to using a high speed milling machine to machine a similar component. The contribution would help to assess the energy efficiency of FDM technology and identify priority areas for improvement.

2. Energy Demand in Fused Deposition Modelling

2.1. Energy States of Fused Deposition Modelling Machine

In order to investigate and classify build process activities and energy profile for FDM machines, a series of reference machine states were studied during the fabrication processes. The FDM machine was switched ON and the current consumption for the machine states was measured and categorised. This method allows the current consumption to be differentiated at each stage of the build process. The current consumption was measured with the Fluke 345 Power Quality Clamp Meter. The machine cycle was repeated three times (on different days) to generate and compare current profile at each state. The current consumption was measured from ‘Start-up’ i.e at room temperature for each day. From the current recorded during the operation of the machine, the power demand was calculated taking into account the voltage. The power profile shown in Figure 1 is a representative of the current profile ultimately measured on a Stratasys Dimension SST FDM when building a first component starting from room temperature. The energy demand is the area under the Power – Time graph plotted for each build cycle.

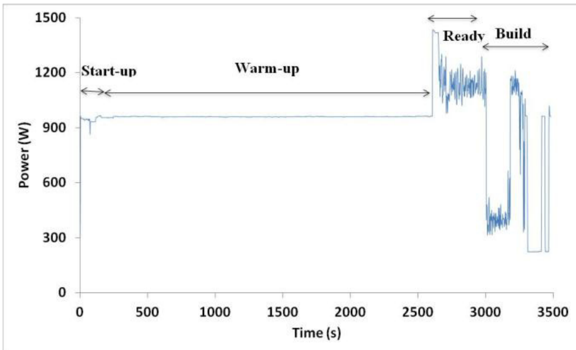

Fig. 1. Power-time curve for Stratasys Dimension SST FDM machine building from room temperature

As the FDM machine Starts-up, it took the machine 270 seconds to attain a temperature of 68°C within the build chamber. This start-up time is marked in Figure 1. This process occurred just once in the course of a day or after the machine had been switched off and allowed to cool back down to room temperature. However, once the machine has acquired the required temperature, it takes less time to be ready for the next build. From the first build test on the Stratasys Dimension SST FDM as shown in Figure 1, there were four different electrical energy consumption states in the FDM build process.

- *Start Up State* - This state occurs after the power up and initial start-up of the machine.
- *Warm Up State:* This state occurs after the Start-up. The machine is heated up initially until the build chamber reaches between 61°C to 68°C inside chamber temperature. The Warm-up stage continues until the filament materials attain a temperature of 102°C to enable extrusion through the build nozzle or nozzles. The melting point of Acrylonitrile butadiene styreneplastics ABS material is about 105 °C.
- *Ready State:* At this state, the nozzle finds the home position by referencing the x, y and z-axes and positions itself to a point just about to start building. The machine could be at this state for longer than necessary depending on the operator's speed to load the SLICE file.
- *Build State:* The fabrication of the part commences at this state. This state encompasses any operation that the machine does from receiving the SLICE file (part program) to part completion. The peaks and the troughs observed during building are a result of the nozzle movement and material deposition by the FDM machine. The peaks and higher energy periods are when the nozzle is extruding material and actually building the layers of the model. The lower energy periods are when the nozzle returns to its start point to begin building another layer.

Not shown in Figure 1 is *Post Processing* for which Stratasys Dimension SST FDM uses soluble supports, a water-based solution designed to simply wash away the support material enabling support removal from complex models. The solution for removing support material can be NaOH and will be in a powered tank usually operated at a warm solution temperature and with washing mechanically assisted by ultrasonic vibration. This adds energy demand.

During the first build, it was observed that the electrical energy demand to power up the FDM machine from Start-up state to Build state was 897 Wh. Figure 2 shows that Start-up, Warm-up, Ready and Build energy demand states consumed 3%, 14%, 73% and 10% respectively when the FDM machine was started from room temperature to part completion.

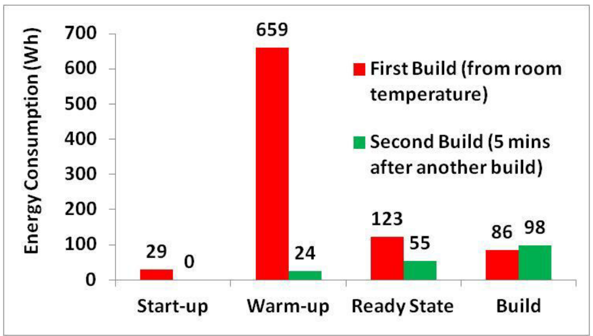

Fig. 2. Power-time curve for Stratasys Dimension SST FDM machine building from room temperature

After the first build and allowing the machine to cool down for 5 minutes (this time is assumed the period for unloading and loading a new model for build) the same part was fabricated again. This was done to compare the effect of temperature on the total electrical energy demand. As expected, the energy for the warm-up state reduced by 96% as shown in Figure 2. This is a clear indication that batching jobs and building more than one part can reduce the electrical energy per part considerably.

2.2. New Framework for direct energy requirements in FDM

Following the increasingly common classification of manufacturing process energy states after Gutowski et al [9] and the Cooperative Effort on Process Emissions in Manufacturing CO2PE! [10] into Basic and Tip energy, a generic equation for direct electrical energy requirements in layered manufacturing is proposed as shown in Equation 1. This is based on Basic and Value Adding energy states.

$$E = P_b t_b + P_{va} t_{va} \quad (1)$$

Where, E is the total electrical energy in J, P_b, P_{va} represents basic and value adding power in W, and t_b, t_{va} are the corresponding time for basic and value adding operations in *seconds*. Equation 1 can be expanded for the value adding energy demand as shown in Equation 2.

$$\boldsymbol{E = P_b t_b + e_m V_R t_{va}} \quad (2)$$

Where $\boldsymbol{E}$ is the direct energy requirement in J for RP and RM processes, $\boldsymbol{P_b}$ is the basic power in W consumed for non value adding activities, $\boldsymbol{t_b}$ is the basic energy state duration in s, $\boldsymbol{e_m}$ is the specific material printing energy as determined by the materials and process mechanism in Ws/mm^3, $\boldsymbol{V_R}$ is the volumetric manufacturing rate in mm^3/s and $\boldsymbol{t_{va}}$ is the actual build time in s. The value $\boldsymbol{P_b}$ and $\boldsymbol{t_b}$ can be expanded into start-up state, warm up state, ready state, basic state, nozzle positioning and post processing power demand. These can be measured for particular machines.

2.3. Benchmarking of 3 different FDM technologies

To explore the variability of energy demand according to machine system concepts, 3 different FDM machines available at Manchester were used to build a simple standardized model, shown in Figure 3, of 9,000 mm^3 volume. Table 1 shows the specifications of the machines used, while Figure 4 and 5 shows the images of the FDM machines. The Stratasys Dimension SST and the Dentford Inspire D290 are standard size machines with enclosed build champers while the PP3DP is a miniature open chamber machine as evident in Figure 5, from the size of the filament diameter in relation to the machine envelope.

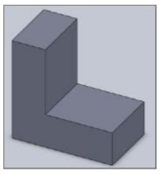

Fig. 3. Simple model fabricated on 3 FDM machines to study energy demand

Table 1. FDM Machines investigated

	Stratasys Dimension SST FDM	Dentford Inspire D290	PP3DP
Size (mm)	914 x 686 x 1041	720 x 850 x 1650	245 x 260 x 350
Model Material	ABS	ABS & PLA Plastic	ABS
Build Envelope (mm)	203 x 203 x 305	255 x 290 x 320	140 x 140 x 135
Software	Catalyst	TierTime Model Wizard	TierTime Model Wizard
Jetting heads	2 nozzles	2 nozzles	1 nozzle
Layer thickness (mm)	0.254	0.100	0.150
Rated Power (KW)	1.6	2.0	0.22

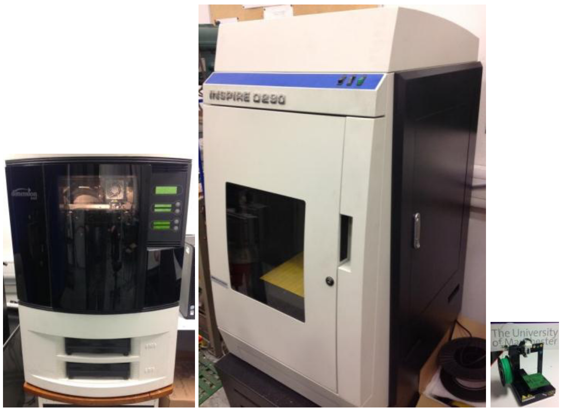

Fig. 4. From left Dimension SST FDM, Dentford Inspire D290 and PP3DPP

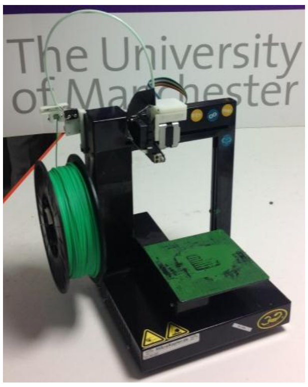

Fig. 5. Detailed view of low cost FDM machine model PP3DPP

Figure 6, 7 and 8 represents the power profile measured to fabricate the same part starting the machines from room temperature. It can be observed that the power demand for the three FDM machines follows similar trend as modelled in Equation 1 and 2. From data input there is a drop in the power as the machine processes the data that has been fed, then, there is a spike in the power as the machine begins to extrude material and build the part.

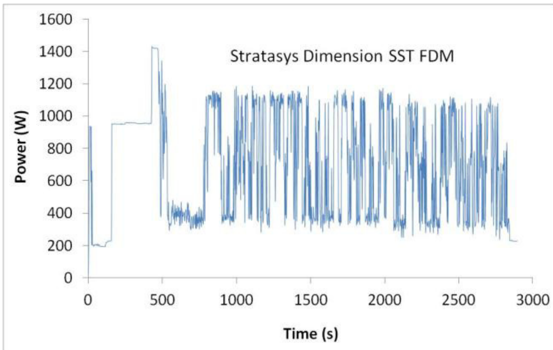

Fig. 6. Power-time curve for Stratasys Dimension SST machine building from room temperature.

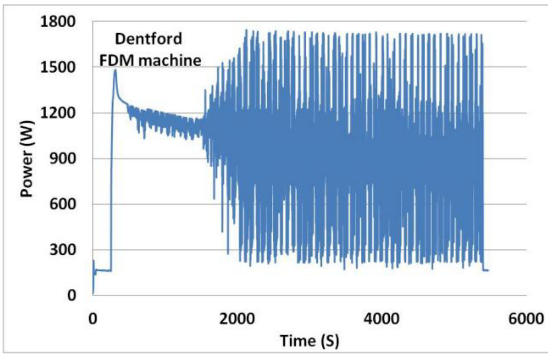

Fig. 7. Power-time plot for Dentford Inspire D290 machine building from room temperature

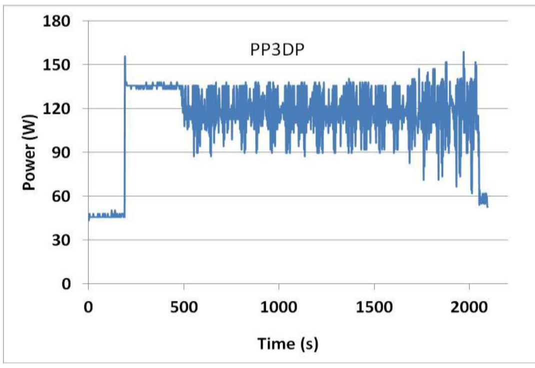

Fig. 8. Power-time plot for PP3DP machine building from room temperature

From Figures 6, 7 and 8 the machine with the largest area under the Power – Time curve has the highest energy demand. These areas are extracted and the results are summarized in Figure 9. Inspire D290 uses a lot more energy compared to the Stratasys Dimension SST FDM machine, while the miniature open Fused Deposition modeling machine has the least energy demand. It however, needs to be noted that the machine functionality has some differences; the Stratasys Dimension SST allows easy support material, while the Dentford Inspire D290 builds a honey comb structure and saves material. Comparing similar standard size machines it is clear from Figure 9 that the energy can be higher by 256% for one standard size FDM machine technology and design. When the cheapest miniature machine with open build envelope which is not temperature controlled is compared to the Inspire D290, the energy demand is over 20 times lower. Clearly there is significant opportunity for improving the energy demand of different FDM technologies.

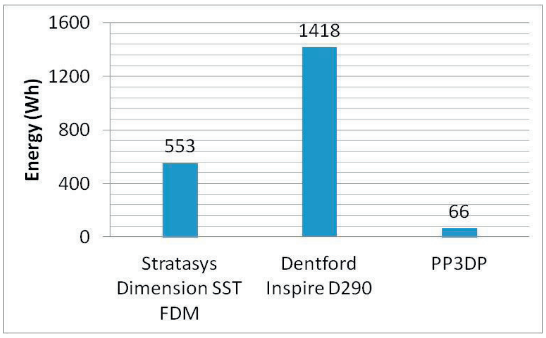

Fig. 9. Energy demand for 3D printing a similar model on different FDM machines (first build from room temperature)

3. Energy Demand for 3D printing versus Machining

A further study was set up to compare the energy demand in additive manufacture to that in subtractive manufacture. Similar volume of ABS material was milled (in this case 9000 mm^3) during end-milling operation on Mikron HSM 400 Machining centre. The high speed milling machine was chosen because when geometric complexity is not an issue the machine can be used for rapid fabrication of prototypes. Thus, this part of the study compares alternative manufacturing process in terms of resource efficiency. The cutting and process parameters used on the Mikron HSM 400 Machining centre are stated in Table 2.

Table 2. Parameters for milling on Mikron HSM 400 Machining centre

Machine spindle	HVC140-SB-10-15/42-3F-HSK-E40
Workpiece Material	ABS
Spindle speed (RPM)	9549
Feedrate (mm/min)	1910
Depth of cut (mm)	0.5
Tool diameter (mm)	10
Number of cutting edges on tool	4

The current profile as recorded by the Fluke 345 power clamp meter, was converted into a power profile for the end-milling operation and is shown in Figure 10. The area under the power-time graph and the total energy demand when end-milling ABS was 114 Wh.

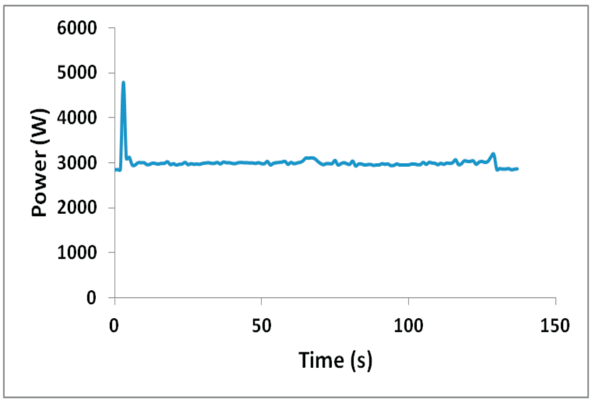

Fig. 10. Power profile end-milling 9000 mm^3 on Mikron HSM 400 Machining centre

The result of the analysis was benchmarked with the FDM machine as shown in Table 3. The result shows that the Basic power required for keeping the Mikron HSM 400 running was 90% of that required by the FDM machine. This is as a result of various electricity consuming auxiliary units that keep the Mikron HSM 400 functional for example, un-loaded motors, pumps, lights, computer. The Ready state of the FDM consumed 57% more power than the Mikron HSM 400.

The cycle time to process similar volume of materials was approximately 22 times higher to fabricate 9000 mm^3 on the FDM machine when compared with machining on the Mikron HSM 400 centre. Taking the power and cycle time into account, the FDM machine demanded 6 times more energy processing the same volume of material compared to the Mikron HSM 400 machining centre. Reflecting on these results it can be proposed that the biggest challenges for FDM and layered manufacturing technologies if they are to be as resource efficient as machining is to address the high cycle time and low fabrication rate.

Table 3. Energy benchmarking FDM versus mechanical milling

	FDM machine	Mikron HSM 400 milling machine	% difference FDM/Milling
Basic Power (W)	270	2904	9%
Ready Power (W)	934	401	233%
Total Cycle Time (s)	3012	137	2198%
Total energy demand (Wh)	685	114	601%

The ultrasonic cleaning tank for the Stratasys Dimension SST demanded about 250W. The solution is operated in a tank that has ultrasonic vibration and a heater. The Stratasys Dimension SST FDM model that was benchmarked to mechanical milling was washed in approximately 3600 s. This adds another 250Wh to the energy demand for FDM, thus making a total energy demand of 935 Wh for the data given in Table 3. Thus considering the post processing energy demand, the FDM machine required 8 times more energy compared to using a milling machine. A step change in the build rate of FDM machines and layered manufacturing machines will help to significantly bridge the gap in relation to energy efficiency compared to material removal processes.

Conclusions

This work presented an evaluation of the direct electrical energy demand in Fused Deposition Modelling, one of the most popular 3D printing technologies. The following conclusions can be deduced from the study:

1. When standard size enclosed chamber FDM machines are used for the first build, the energy demand required raising the temperature within the build chamber and preparing the machine for extrusion can be a very large proportion of the total energy demand in building the first component or set of nested components. The warm up time for the FDM machine is considerably high. This could be an area of improvement to meet the goals of energy efficiency. New temperature ramp up cycles and heaters can be designed to reduce this energy demand.
2. Given that in terms of production planning, first builds in FDM processes are associated with a higher energy demand due to the thermo ramp-up cycles, nesting of parts and in one build and planning jobs back-to-back can help reduce the energy demand per part.
3. For FDM machines using the soluble support removal process, the energy demand for the cleaning process is not insignificant; this is due to the need to elevate solution temperature and to induce ultrasonic vibration for enhanced cleaning. The energy for cleaning was 35% of the build energy for the case considered.
4. The energy demand in FDM can be modelled as Basic energy demand by the machine and Value Adding energy for the extrusion process. A framework can be developed by monitoring current usage and event streaming the activities performed by the machine.
5. While for FDM machines, the long build cycle time is the major challenge that need to be addressed in order to reduce energy intensity of manufacture, for mechanical machine tools reducing the Basic Power and energy demand can have significant impact on the energy efficiency.
6. Considering one 3D printing technology such as FDM, there is a major difference in energy demand for different machine platforms. This is evident that significant opportunities exist for system developers to radically improve the energy efficiency of 3D printing technologies.
7. A step change in the build rate of FDM and other layered manufacturing machines will help to significantly bridge the gap in relation to energy efficiency compared to material removal processes.
8. When compared with the alternative machining process, although, the basic energy demand of the Mikron HSM 400 machining centre was 90% higher than the FDM machine it needed 6 times lower energy compared to FDM in building the same part. This was mainly due to the relatively high cycle time for the FDM and low manufacturing rate.
9. In Life Cycle Analysis (LCA) it is more accurate to include the fabrication rates if the environmental impact of layered manufacturing processes is to be accurately captured.

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