Energy consumption and carbon footprint analysis of Fused Deposition Modelling: A case study of RP Stratasys Dimension…

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Energy consumption and carbon footprint analysis of Fused Deposition Modelling: A case study of RP Stratasys Dimension SST FDM

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Abstract— It is envisaged and expected that professional engineers, process and product developers plays an active role in the sustainable development of manufacturing activities to overcome the global challenges of depletion of natural resources, environmental pollution and damage to the ecosystems. This however calls for the necessity of the industry to adapt and improve on the various manufacturing processes employed for their products not only to keep up with global competition by reducing its variable costs, but also for the sustainable manufacture of their products. Rapid prototyping is one of the new 3D and additive manufacturing technology available globally. This technology has been viewed as a sustainable technology since it optimises electrical energy demand and promotes zero waste technology. This overstretched hypothesis need to be tested. This work evaluate the direct electrical energy demand in fused deposition modelling FDM machine using the Stratasys Dimension SST FDM as a case study and as a panacea to understudy the electrical energy requirement and carbon footprint for rapid prototyping.

Index Terms— Stratasys Dimension SST, Fused deposition modelling, energy demand, sustainable manufacture, carbon footprint, Rapid Prototyping

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1 Introduction

PROFESSIONAL engineers are increasingly expected to play an active role in sustainable development, overcoming global challenges, such as depletion of resources, environmental pollution, rapid population growth and damage to ecosystems [1]. The necessity for the industry to adapt and improve its manufacturing processes is not only to keep up with global competition by reducing its variable costs but also to be more sustainable in becoming increasingly important.

In 2011, 32 % of the electrical energy in the United Kingdom was consumed by industry [2]. This energy has been generated using carbon based fuels that emit carbon emissions. The European Union [3] has imposed carbon reduction targets on their member states in an attempt to mitigate its impact on the environment. The Energy Information Administration EIA [4] reported that 42.6 % of the world total electrical energy was consumed by the industries in 2011. Hence the need for the development of newer technologies to curb the increasing trend of CO2 emission and waste.

Rapid Prototyping RP machines and Rapid Manufacturing RM machines are some of the new manufacturing technologies developed that have few input requirements and zero waste. They are perceived to be the future of manufacturing since they are viewed as a sustainable technology.

Rapid prototyping (RP) and rapid manufacturing (RM) technologies were developed in the 1980s and they are a recent development in the manufacturing industry [5]. Stratasys patented the rapid prototyping process known as fused deposition modelling (FDM) [6, 7]. The process creates parts layer by layer by extruding thermoplastic material (ABS plastic, polycarbonate, PPSF) in a liquid state. This process is relatively simple but its use is limited to thermoplastic materials.

RP is the fabrication of parts for functional prototypes, whereas RM is the fabrication of end-use parts using RP techniques. There are multiple different types of the technology available, which are capable of producing physical parts from CAD models through the addition of material layers, which therefore reduces the amount of waste material that is produced. However, it is believed that the RP technology could greatly benefit the manufacturing industry as a whole, but in particular, small to medium sized enterprise (SME) [8]. This is because it can fabricate a small number of customised parts faster than conventional manufacturing techniques, significantly reducing the 'time to market' and cost.

Since its conception, despite being a ground breaking technology, the pace that RP has moved towards RM has been slow and overall uptake has been extremely low when comparing it to more frequently used conventional manufacturing methods. Different software, design and fabrication issues have been observed in all the current available techniques and these have not yet been fully corrected. It is unlikely that in the near future, the technology will replace other more widely used manufacturing methods as parts fabricated using these techniques generally have a poorer surface finish [9]. At present, there are a limited number of materials available but research is on-going [10]. Until part quality improves, it is unlikely that the technology will be widely used especially in more demanding applications.

Since natural resources are increasingly becoming expensive, sustainability is becoming increasingly important to manufacturers. This has led to manufacturers looking for alternative and more efficient techniques. As a result, there has been a surge and interest in RP and RM technologies because they produce almost zero waste and are perceived to be more sustainable than material removal manufacturing methods [11]. This means that there is a need for the manufacturing industry to gain a fuller understanding of the sustainability criterion of these technologies in order to evaluate the electrical energy requirement of fabricating a part using these methods. This knowledge could potentially lead to more efficient operation of RP and RM machines and a more widespread uptake of the technology. There is at present few work conducted on the direct electrical energy

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requirements [11, 12] and carbon footprint of RP and RM. The technology is simply presumed to be more sustainable than conventional manufacturing methods as there is less waste material produced. The environmental impact is not known, nor is it clear what the most efficient way to operate an RP/RM machine. It is hoped that this work could lead to an improvement in the understanding of the electrical energy requirements and carbon footprint of RP and RM technologies.

1.1 Research Aim

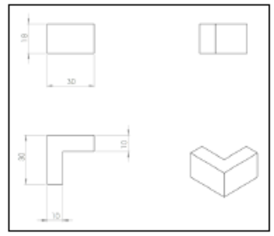
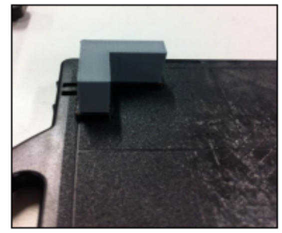
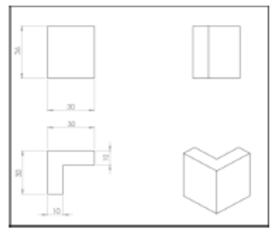
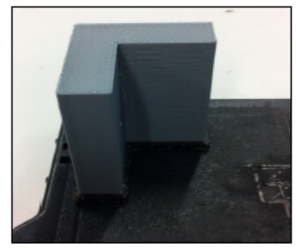
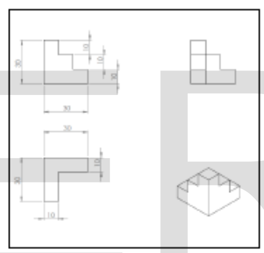
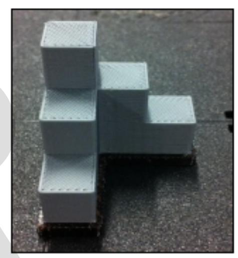
The aim of this work is to investigate the electrical energy demand of RP Stratasys Dimension SST FDM in order to determine the sustainability values and suggest areas of improvement for resource efficiency. To achieve this, a simple component was built on the RP Stratasys Dimension SST FDM and the electrical energy consumed for printing the simple components was evaluated. This further led to the analysis of the carbon footprint as a result of the fabricated parts moved across globes.

2 Experimental Analysis

Detailed Three preliminary electrical energy consumption tests were conducted on a RP Stratasys Dimension SST FDM machine. The machine built a small model three times with the electrical current consumption measured using the Fluke 345 Power Quality Clamp Meter at each build cycle. Each model was fabricated and post processed three times for data repeatability and good experimental practice. The electrical energy consumption tests were carried out for building and for the post processing of the three different models in order to investigate the energy demand at different machine states and their respective carbon footprints.

The three simple parts as shown in Table 1 were designed using CAD software, Solidworks, and were fabricated on a RP Stratasys Dimension SST FDM machine. Figure 1 and 2 shows the FDM machine used.

TABLE 1
CAD Drawing and Picture of Each Model

Model	Dimensioned Drawing	Fabricated Model
1		
2		
3		

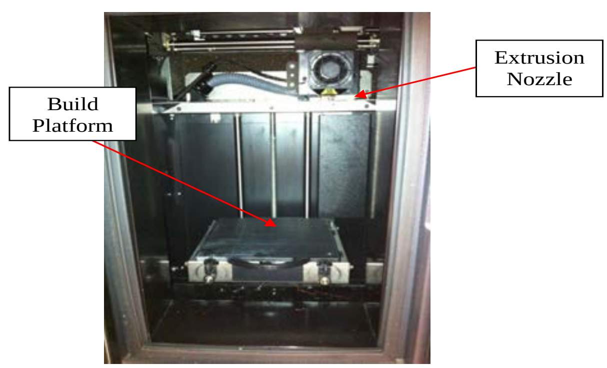


Fig. 2. RP Stratasys Dimension SST FDM machine work space

The post processor as shown in Figure 3 is an Ultrawave Precision Ultrasonic Cleaning machine that is used to wash, clean and remove all support materials attached to the fabricated part.

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Fig. 3. Ultrawave Precision Ultrasonic Cleaning Machine

The Ultrawave cleaner uses a combination of ultrasonic waves, heat and a detergent to remove any excess support material used during fabrication without damaging the model itself.

During each build test, the electrical current consumed by the machine was measured using a Fluke 345 Power Quality Clamp Meter. The Fluke 345 power clamp meter was clamped to the power cable of the machines to record the event stream and electric current flowing during the build and the post processing cycle. The area under the power-time profile was evaluated as the total electrical energy for each of the build states and CO_2 attributable to electrical energy consumption estimated.

In the second build test, the models were designed to test the effects of volume and complexity/shape on the build time and therefore the electrical energy consumed. Therefore for these build tests, two simple models were designed. The first model (as shown in Table 1) has a volume of 9,000 mm^3 (Model 1) and the second model has a volume of 18,000 mm^3 (Model 2).

The third build test is designed to test the correlation between the complexity/shape to build time and energy demand. The third model was designed with a volume of 9,000 mm^3 (Model 3) and having a complex design. The CAD drawing and picture of each model is shown in Table 1.

3 Results and Discussions

The results of the three build tests indicated that the first build consumed the most electrical energy and had the largest equivalent CO2 due to the electrical energy usage. This can be attributed to the significant start-up phase observed between 0 seconds and 2500 seconds, annotated in Figure 4. At 2500 seconds, data was immediately imputed to the machine for it to set up for a build. At 2608 seconds during the first build there is a spike in power consumption to 1435 W. The actual build time for the first cycle was approximately 800 seconds. In builds 2 and 3, data was fed to the machine whilst it was in standby. During set up, a small amount of electrical energy was required to heat up the machine, and again there were spikes in power consumption to 1432 W in test 2 and 1446 W in test 3. The actual build time was approximately the same for both at around 800 seconds. This preliminary analysis enabled an insight into the power consumption trends of a typical RP FDM machine.

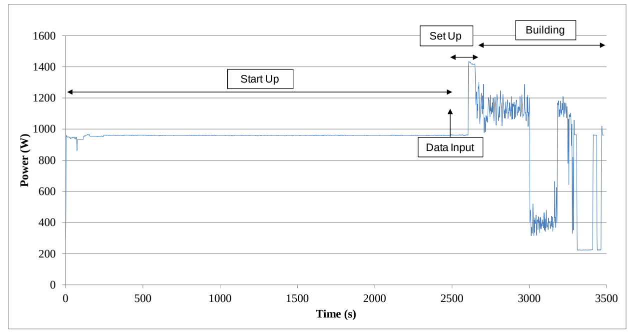

Fig. 4. Chart showing the energy profile, power against time for test 1.

3.1 RP Stratasys Dimension SST FDM Machine States

Balogun and Mativenga [13] proposed three-states machining processes. These states are termed 'basic', 'ready' and 'cutting' states. The authors reported that most manufacturing equipment would exhibit these three states during their use phase. This is also in agreement with the work of Gutowski et al., [14] which reported that manufacturing processes are made up of a series of processing steps since high production situations are usually automated. For some processes, each of these steps can be integrated into a single piece of equipment. Likewise in FDM machines, and as previously reported by Balogun et al., [11], preliminary tests carried out revealed that there were a number of different energy usage states prevalent during different stages of part fabrication. The five states that were observed include:

1. Start Up State - This state was only during initial start-up. The machine heated up and the nozzles reached a ready position (finding home).
2. Ready State - This standby state was when the machine was idle and ready to build. CAD data could be fed to the machine to be fabricated.
3. Set Up State - This state was when the machine received geometrical data and it prepared to build. It began when data was input and was until part fabrication began.
4. Build State - This state was when part fabrication occurred. This state encompassed any operation that the machine does from part fabrication beginning to part completion.
5. Post Processing - This state was when the fabricated part needed to post processed and any excess support material was removed from the model. Items will be set outside of the paragraphs.

It was important to classify each of these states in order to gain an understanding of their contribution to the total electrical energy consumed by the machine. The states that were observed were general states. Each state is made up of various energy consuming elements and a fraction of the total energy

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demand during machine use phase.

As can be observed in Figure 5, an FDM machine takes a considerable amount of time and energy for non-value adding processes i.e. start up, warm up, set up and ready energy states. The non-value added processes consume 64 % of the total energy demand during initial build cycle. It can therefore be deduced that for high productivity operations, the amount of time and energy consumed for non-value adding processes is not important, however, for low productivity operations; there will be a significant electrical energy requirement for the non-value added processes hence cost of the product will be higher compared with that for high volume production. This is so because cost of the electrical energy will be distributed across the total number of part produced. Since FDM is an RP process and not an RM process, it could be used for building just one part in a power cycle and this is not as energy efficient as building several parts during one power cycle. This means that it is more energy efficient to use the machine ten times in a day than to use it only once as a smaller proportion of the start-up energy is required for a build.

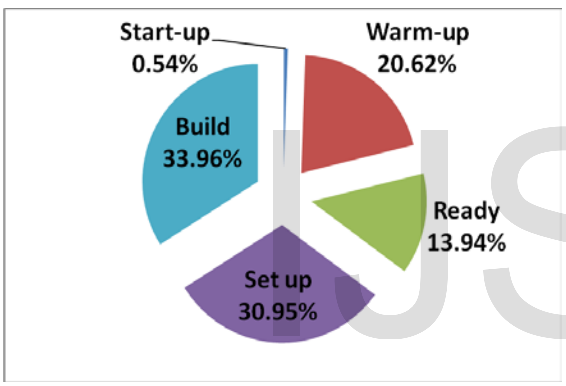

Fig. 5. Electrical energy consumption ratio at each state

Figure 6 and 7 shows the electrical energy demand power profile for test 2 and test 3 respectively. As can be seen, it is clear that the energy demand for both tests 2 and 3 are similar. This is due to the fact that after the first build on the FDM machines, the power demand for start-up, warm-up and ready states becomes 'zero' since the machine is already in the ready state waiting for data input. Therefore, the FDM machines energy demand can be reduced by over 60 % if it is used to build more than one part.

The peaks and the troughs observed on all of the energy profiles 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 is returning to its start point to begin building another layer.

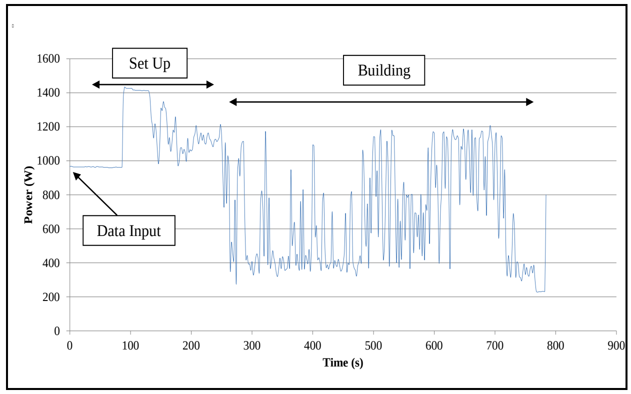

Fig. 6. Chart showing the energy profile, power against time for test 2.

It can be observed form Figure 7 and 8 that at the point of the data input, there is a drop in the power as the machine processes the data that has been fed through the user interface of the computer, then, there is then a spike in the power as the machine begins to extrude material and build the part.

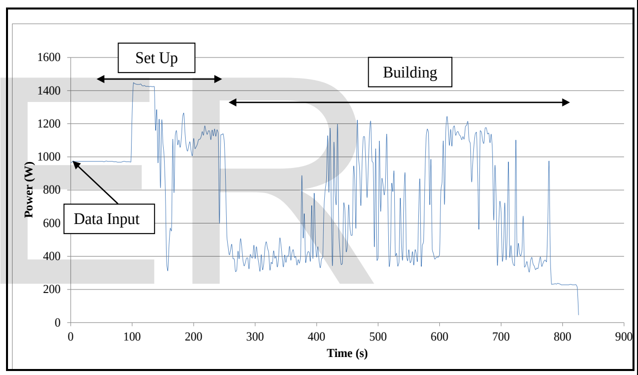

Fig. 7. Chart showing the energy profile, power against time for test 3.

3.2 Carbon Emission Analysis of RP Stratasys Dimension SST FDM Machine

In order to evaluate the carbon footprint as a result of the electrical energy demand, the total electrical energy consumed during the build cycle was converted to the equivalent CO_2 attributed to energy use. Jeswiet and Kara [15], proposed a model (and also adopted by Balogun et al., [12] to estimate the carbon footprint derived from electricity generation as shown in Equation 1. The authors adopted the use of the "Carbon Emission Signature" (CESTM) to specify the CO_2 intensity or emission per unit of energy generated.

$$Carbon\ emission[kgCO_2] = EC_{part}[GJ] \times CES^{TM}[kgCO_2/GJ] \tag{1}$$

Where ECpart represent the electrical energy consumed to produce a component or manufactured product and CESTM is the carbon emission signature calculated for the energy mix at a particular year and for a particular country.

An average carbon intensity factor of 0.4 kgCO2/GJ for the United Kingdom [12] is adopted in the estimation of the carbon footprint of the FDM processes proposed in this paper. In this paper, the electrical energy required for building each test pieces was calculated from the area under the power-time domain characteristic graph for the cycle time that the machine was used.

Figure 8 shows the post process power profile. The total electrical energy consumed for post processing the built part is estimated from the power – time profile shown in Figure 8. Two gradual drops in power are observed, one from 0s to 2700s and one from 2700 s to 3600 s. The two power increases are attributed to the heater being briefly switched on to maintain the temperature of the tank. Post processing electrical energy demand is the same for every build.

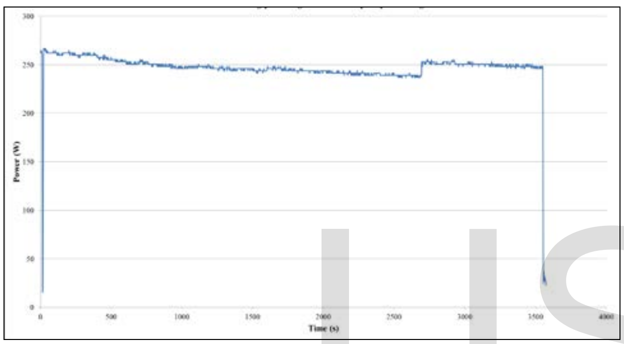

Fig. 8. Electrical energy profile for post processing

Figure 9 show the electrical energy usage after the fabrication of the test pieces of model 1, 2 and 3. It can be observed from Figure 9 that building model 2 consumed 1077 Wh for the first build and 1016 Wh for the second build. This was because it took significantly longer time to build model 2 than the other two models (see Figure 1). This was expected as model 2 doubled the volume of the other two models. From the energy profiles, it is important to note that the actual build time for model 2 of around 4000 s, is about double that of model 1 at 2000 s.

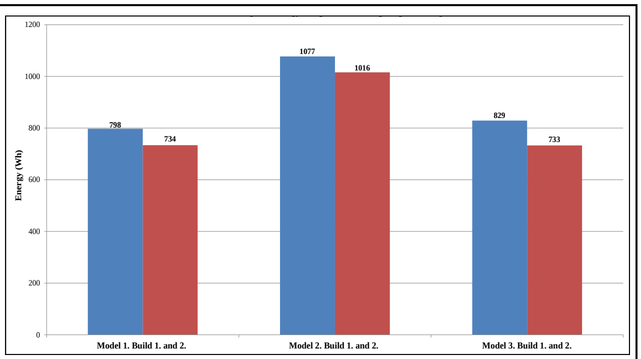

Fig. 9. Electrical energy use per build and post processing for all models

Figure 10 show the carbon footprint per build for models 1, 2 and 3 estimated with Equation 1. It can be observed that volume of build is directly proportional to the carbon footprint produced during the build processes. Hence the carbon footprint of model 2 is considerably higher by over 25%. This is because the larger the model, the longer its build time.

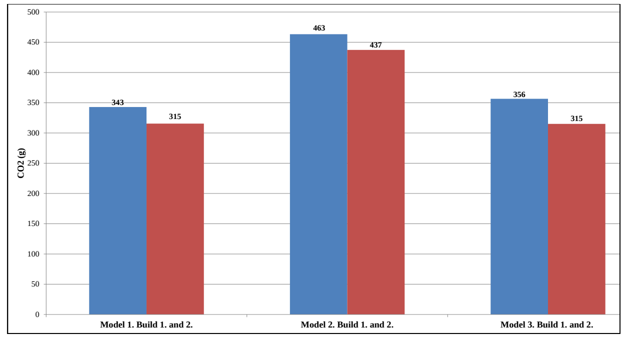

Fig. 10. Estimated carbon footprint per build and post processing of all models

Interestingly, there was approximately a 10-15 % drop in the energy consumed between the first and second build of each model for all three tests. This can be explained by the shorter set up times required for the second model in each of the three tests and this can be viewed on all the energy profiles. It is likely that this is because CAD data had already been input into the machine from the first build and it is not required to be re-analysed again. It is important to consider that in manufacturing applications, it is likely that an RP/RM machine would be building the same design on a regular basis, eliminating the need to re-analyse the data.

4 Conclusion

RM is set to revolutionise the manufacturing industry, bringing it into a digital age. It is a technology that could transform the engineering world making it easier to fabricate parts to a specification of choice in a short period of time. Although development of the technologies has been slow, recent progress has increased the likelihood of a more widespread uptake.

When comparing a build on the FDM machine to the use of a standard 100 W light bulb, the RP Stratasys Dimension SST FDM machine that was used as a case study is quite energy efficient. It has been reported that in the UK the average emissions from electricity generation fell from 718 gCO_2eq/kWh in 1990 to 500 gCO_2eq/kWh in 2008 [16]. Therefore assuming an average of 500 gCO2eq/kWh for emissions from generation and using Equation 1 to estimate emissions from consumptions, a 100 W light bulb would produce 750 kg of CO_2 at the generating station during that year if left 'ON' constantly for a year [17]. This then means that the FDM machine would have to build up to 31,666 times model to produce the same amount of CO2 of a 100 W light bulb. This roughly translates to 4 builds a day for a year.

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It is important to investigate the scenarios that RP and RM techniques are more efficient and productive than conventional manufacturing methods. It takes a long time to fabricate a large part using some RP and RM and this means that it could well make more sense to use conventional manufacturing methods such as machining. A comparative analysis should be undertaken to assess when conventional techniques should be selected ahead of RP and RM.

The key knowledge gained from this investigation is as follows:

- Build time is related to part volume and part complexity. A larger volume or a more complex part results in an increase in the build time and therefore the electrical energy and carbon footprint.
- A shorter set up time was observed during the second build of each model. As stated, this could be a result of data processing and further investigation is required to justify this statement.
- Post processing accounts for a significant fraction of the total energy required and carbon footprint.

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