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Electrical Energy Demand Modeling of 3D Printing Technology for Sustainable Manufacture

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ABSTRACT

The advent of 3D printers has been embraced globally within few years of its emergence. The surge in the acceptability of rapid manufacturing RM strategy can be attributed to the depletion and cost of natural resources, waste reduction and sustainability criterion of manufactured parts. This rapidly evolving 3D printing technologies is predicted to grow exponentially especially for the manufacture of customized and geometrically complex products. Therefore, it is appropriate to consider and optimize the resource efficiency of 3D printing technologies at this early stage of this technology development. In this work, the direct electrical energy demand of 3D printing (i.e. fused deposition modeling) was studied and a generic model proposed. The developed model was further validated with the Stratasys Dimension SST FDM in order to evaluate and ascertain the generic application of the model. This work is a further contribution to the existing foundation for electrical energy demand modeling and optimization for the rapidly expanding 3D printing processes.

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1. INTRODUCTION

The sustainability assessment of product and services can be understudied based on key sustainability performance indicators, such as energy intensity and CO_2 emissions and carbon footprint. The Organization for Economic Co-operation and Development (OECD) [1], International Standard Organization [2-4], Cooperative Effort on Process Emission CO2PE! [5], United Nations Environment Program UNEP [6], etc. all define key performance indicators (KPIs) and processes for sustainable manufacturing, which include energy intensity, process efficiency, resource optimization, Life Cycle analysis, sustainable manufacture, etc. Energy intensity is an important performance indicator for resource efficiency and sustainable manufacture [7]. In line with the sustainability agenda, rapid prototyping RP emerged as one of the alternatives to sustainable manufacture of geometrically modeled and complex parts. The basis of this alternative manufacturing process was to improve and optimize the electrical energy consumption and reduce time to market for the manufacture of complex products.

The surge in the acceptability of RM technology can be attributed to the depletion and cost of natural resources, waste reduction and sustainability criterion of manufactured parts. Other known advantages of RM processes especially 3D printing over other manufacturing processes include low production and equipment cost, cheaper inventory, labor, improved quality control since human errors are limited through the use of digital data, and lower set-up cost. This is a major opportunity seized by manufacturers as alternatives to conventional material removal processes for a more efficient and fabrication methods. Also, RP and RM techniques are perceived to be more sustainable than conventional material removal manufacturing methods and also help to shorten the production development steps [8].

The concept of transition from rapid prototyping RP to Rapid Manufacturing RM has been encouraging in recent years, especially for one-off's and small batch production of parts. The research to boost RM

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methodology for mass production of parts is ongoing. The RM technology is new and the development is moving towards more advanced stages in recent times. Despite some reported problems encountered by manufacturers using the RM technology during fabrication of components, for example limitations of part geometry, accuracy, surface finish and repeatability [9], the technology is receiving great attention in the manufacturing arena. The limited number of build materials selection have also been reported [10]. Until part quality improves, it is unlikely that the RM technology will be used to fabricate complex components that are critical to quality, size, safety and aesthetics in industries like aerospace, automobile, space and in other more demanding applications.

1. 1. Prototyping Technologies Rapid prototyping RP or layer manufacturing (LM) is one of the additive manufacturing techniques that involve a layer by layer deposition of materials during part fabrication [9]. This techniques adopt the developed 3-D solid model from Computer Aided Design CAD to generate Numerical Codes (i.e. g-codes) adopted during Computer Aided Manufacturing CAM of the part [11]; and using additive processes, generates a solid-free form physical model in layers, and therefore reducing the amount of material required to produce the part [12]. Furthermore, few researchers also reported and documented the characteristics and benefits of additive manufacturing techniques in literature [13]. This technology was initially developed to produce prototypes of physical models as fast as possible using polymers [8]. Rapid Prototyping do not allow common engineering materials to be processed. For example materials with sufficient mechanical properties like polymers, metals, ceramics, and composites [14].

In RP technology, CAD models are uploaded to specialist software. This software discrete or slices the model in the z-axis so that an RP machine can construct a 3-D model in layers without the need of tooling. The digital data is processed and uploaded to the machine. RP fabricates parts through layer by layer deposition to form the model. Post processing may be required if a support material is used in fabrication. Gibson et al. and Yan et al. [15, 16] defined important steps in the generic fabrication process of RP from CAD-to-part and are as defined in the flow process shown in Figure 1.

Up-to-date, various RP techniques have been developed. This include Stereo Lithography (SLA), Fused Deposition Modeling (FDM), Ink Jet Printing (IJP), 3-D Printing (3DP), Selective laser sintering (SLS), Selective laser melting (SLM), 3-D laser cladding process, Laminated object manufacturing (LOM) and Laser chemical vapor deposition (LCVD) [10, 17]. For RP manufacturing, Lan et. al. [18] reported

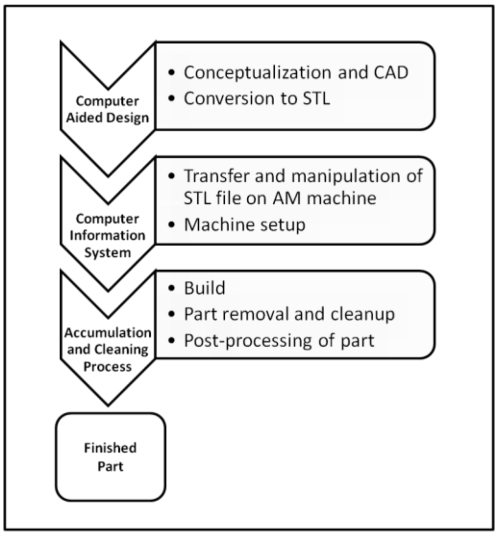

Figure 1. Flow chart of the RP process

that it is possible to obtain up to 70% costs reduction and that it also reduces lag time to market of finished parts by 90% when compared to other conventional manufacturing methods.

The conventional material removal methods are similar to 'Fused Deposition' technology in that they both have the capabilities to fabricate physical parts from CAD models and they both has the tendency to reduce the amount of waste with Rapid Tooling (RT) strategy. The RP and RM technology could greatly benefit the manufacturing industry as a whole, but in particular, small to medium sized enterprise (SME). This is because it can be adopted to fabricate a small number of customized parts faster than conventional manufacturing techniques, significantly reducing the 'time-to-market' however; one of the major problems is the cycle time. The cycle time directly influences the electrical energy demand of the build processes [19].

Few electrical energy models for RP technology have been developed. For example, Balogun et al., [19, 20] developed a new framework for direct energy requirements in FDM by modeling the electrical energy demand of Stratasys Dimension SST FDM a 3D printer. Although, their model is a major contribution to knowledge, it enhances the understanding of the 3D printer process; some of the energy consuming components were not captured in the model. For example, the auxiliary units and preparatory stages energy demand were not properly accounted for. Therefore, and in line with the CO2PE! directives that proposed a systematic approach to energy modeling [5, 21], it is important to modify the proposed electrical energy demand model for Fused Deposition technology in order to estimate the total electrical energy demand and global warming potentials of this new fast developing technology.

1. 2. Research Aim This work is aimed to improve the direct electrical energy model of FDM, Rapid Prototyping (RP) and Rapid Manufacturing (RM) strategy with a view to develop mathematical model or framework for a 3D printing process. In the first instance, the electrical current consumed by the FDM at no-load will be evaluated to categorize their energy states. The results will be validated with direct electrical energy requirements measurement of a 3D printer. The data generated will empower process and product planner with the knowledge base of FDM in order to estimate process efficiency and estimate the corresponding CO_2 emission for Life Cycle Analysis of the machine.

1. 3. Mathematical Model for Direct Energy Requirements The electrical energy requirement for a manufacturing process was studied by Gutowski et al. [22]. The authors proposed a mathematical model for the electrical energy based on the automobile production line. In their model, they categorized the electrical energy demand into two groups i.e. 'Basic State' and 'Cutting State' as stated in Equation (1).

$$E = \left(P_0 + k\dot{v}\right)t \quad (1)$$

where E is total electrical energy in J, P_0 the idle power in watts (W), the rate of material processing in cm^3/s, k a constant with units of kJ/cm^3 and t time in s.

The mathematical models proposed by researchers [22-25] on electrical energy demand is an indication that electrical energy of manufacturing machines can be categorized based on machine states or the operations been performed. Therefore, in line with this principle, the model can be modified to reflect the operations of fabricating a part using RP and RM processes. Thus, Equation (1) can be modified to Equation (2).

$$E = P_0 t_s + e_b V_R t_b \quad (2)$$

where E is the direct energy requirement in J for RP and RM processes, P_0 the idle power in W, t_s the set up time in s, e_b the specific binding or sintering energy (RP/RM process dependent) in Ws/mm^3, V_R the volumetric manufacturing rate in mm^3/s and t_b the build time in s.

The mathematical model in Equation (2) is applicable to different types of RP and RM processes. The idea is to define a generic process dependant model that can be used to estimate electrical energy demand based on RP and RM processes. Therefore, it is necessary to understudy the machine components and auxiliary units that make up the 'Basic' or 'Idle' state power, P_0 and to define the specific binding or sintering energy e_b for the materials which for RP and RM is usually 'Acrylonitrile butadiene styrene ABS plastics'. Note that the volumetric manufacturing rate V_R is machine dependent and could vary depending on the deposition rate of the RM machine nozzle.

2. EXPERIMENTAL METHOD

2. 1. Modeling the Electrical Energy States of FDM

This work is built on the published work of Balogun et al. [19, 20] to investigate and classify build process and electrical energy profile for FDM machine. Series of pre-tests were carried out at no-load and during the build stages. As the FDM machine was switched 'ON' the electric current consumption for the machine states were measured and categorized into groups. This method allows the electric current consumptions to be differentiated at each stages of the machine process.

The electric current consumption was measured with the Fluke 345 power quality clamp meter. The machine cycle was repeated three times to generate and compare recorded electric current profile at each state. It is important to note that the power consumed during post processing operations was ignored. This is because the post processing is a separate activity that involves washing, dissolving and separation of the support materials from the fabricated part. This is done in order to enhance the physical outlook of the finished component.

As the FDM machine start-up, it was observed that it took the machine 270 s to attain temperature of 68°C within the build chamber as shown in Figure 2. This process occurred just once in the course of a day or when the machine is 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 next operation.

Three energy profiles were recorded, one for each build as depicted in Figures 2 and 3. The FDM machine underwent a number of operative states from being switched 'ON'.

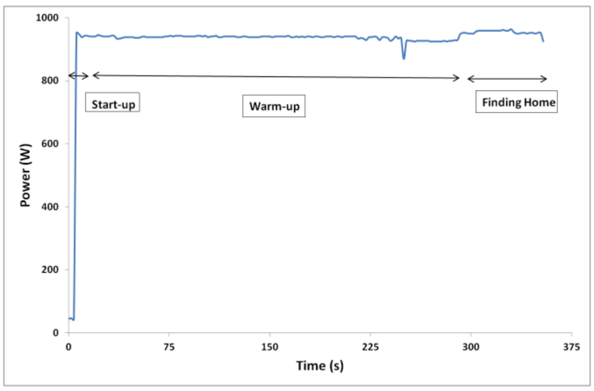

Figure 2. Power-time curve at no-load for FDM machine at room temperature for test 1

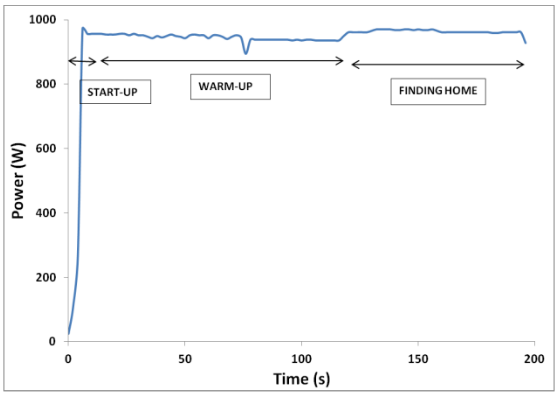

Figure 3. Power-time curve of FDM after warm-up for test 2

These operative states were observed on each of the energy profiles recorded. The states were: start up; idle; set up; and build. There was a period of 20 minutes delay between each test. This time was assumed to be the time it would take the operator to load and unload the part and send in the next CAD file to build.

From Figures 2 and 3 and according to Balogun et al. [19] it has been shown that on the FDM, there were three different electrical energy consumption states in the process leading to preparing the machine for fabrication of a part. This energy states includes the 'start-up state' (i.e. occurs at the power up and initial start-up of the machine), 'warm-up state' (i.e. occurs after the start-up and during the process of heating up the machine until both the build and stock materials attained a temperature of 102^{o}C and the build chamber reaches temperatures between 61^{o}C to 68^{o}C), and the 'ready state' (i.e. the nozzles locates the home position by referencing the x, y and z-axes coordinates and position itself to a point just about to receive the CAD model to start the build process). The machine could be at this state for longer than necessary depending on the operator's efficiency to load the CAD model through the available platform. The 'build' state is incorporated during a complete cycle to fabricate a part. The fabrication of the part commences at this state. This state encompassed any operation that the machine does from CAD initialization to part completion.

The electrical energy states classification and grouping is important to gain understanding as to how electrical energy is consumed by the FDM machine. Therefore, considering Figures 2 and 3, and if all energy states are incorporated, Equation (2) can thus be modified into a mathematical model specific to FDM as shown in Equation (3).

$$E_t = \left(\frac{P_s t_s}{n}\right) + P_w t_w + P_r t_r + P_b t_{cy} + E_s + P_p t_p \quad (3)$$

where

$$E_s = e_b M \quad (4)$$

Here, E_t is the direct total energy requirement per build in *J*; P_s P_w, P_r, P_b and P_p are the start-up state, warm up state, ready state, basic state and post processing power demand in *W* respectively, and t_s, t_w, t_r, t_{cy} and t_p the start-up state, set up state, ready state, total cycle and post processing time in *s* respectively. *n* is the number of builds occurring from machine power-up to power-down, E_s specific sintering energy in *J*, e_b the embodied specific energy per unit mass in *Wh/g* and *M* the total mass of part in *g*. Note that $P_p t_p$ is ignored (zero)

From Figure 2, it is observed that it took the FDM machine 270 *s* to warm-up and be ready to build while Figure 3 reveals that it took the machine shorter time to attain the build environment temperature of 68^{o}C after the machine had only cooled down for few minutes before the next build states.

In this work, assumption is made that the start-up process is activated only once in a particular day. This assumption was necessary for profitability of the FDM machine and reducing or eliminating the electricity consumption due to 'start-up'. The resulted start-up electrical energy demand for low production, small batch or one off part will dominate the total energy demand throughout the build process. However, for high productivity operations and as the quantity of part fabricated increases, this will be negligible. Also, since FDM is an RP process that can be used for the fabrication of one-off part in a cycle, the machine could be termed as not-efficient since the electrical energy demand could be considerably higher when compared to an RM processes. However, if the FDM produces more than 10 parts from power-up to power-down cycle time, the energy demand for the start-up will be negligible. Therefore, the need to normalize the start-up energy demand by the quantity n produced in a cycle as in Equation (3).

During the first test, it was observed that the electrical energy demand to power up the FDM machine from 'start-up' state to 'ready' state at no-load was 90.53 *Wh*, with start-up, ready (finding home) and warm-up states demands 4%, 26% and 70% respectively as shown in Figure 4a when the FDM machine was started from room temperature. After the first test, the machine was powered down and allowed to cool down for 20 minutes. This time, as previously stated, was assumed a period of loading and unloading new part to be fabricated.

The FDM machine was powered up again and the electrical current demanded at no-load measured. The result shows that 49.37 *Wh* of electrical energy was demanded to take the machine to the 'ready' state.

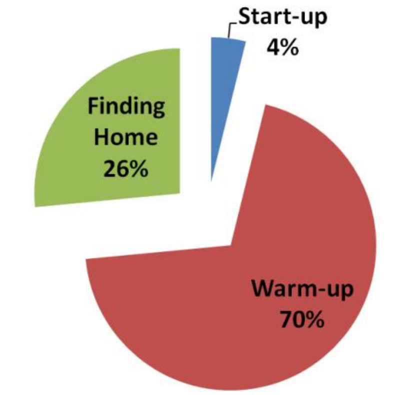

Figure 4(a). Energy demand of FDM with Start-up from room temperature

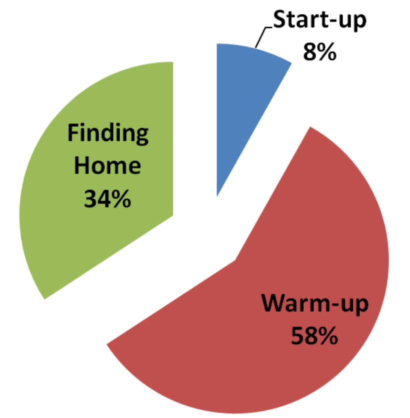

Figure 4(b). Energy demand of FDM with Start-up after initial warm-up.

The disintegrated analysis in Figure 4b revealed that 'start-up', 'ready' (finding home) and 'warm-up' energy states demanded 8%, 34% and 58% respectively. This result implies that after the initial 'start-up', 33.2% of electrical energy can be saved if the machine is not allowed to cool back down to room temperature. The reason for this is that for the first warm-up, it took the build environment of FDM machine 270 *s* to attain a temperature of 68^{o}C while at the second 'start-up', the 'warm-up' state lasted only 110 *s*.

The European plastic trade association reported an average of 26.48 *kWh* of energy for industrial production of 1 *kg* of ABS resin in Europe [26-28]. Therefore, the embodied energy for ABS is 26.48 *kWh/kg*. From first law of thermodynamics, that energy cannot be created nor destroyed; rather energy can be changed from one state to another. It follows that it will take 26.48 *kWh* to transform 1 *kg* of ABS from state to state.

If the density of ABS is 1.04 g/cm^3 and the volume of the part is 9,000 *mm^3* (evaluated geometrically with the Solidworks CAD software), then the mass can be calculated as in Equation (5) thus:

$$M = \rho \times \upsilon \qquad (5)$$

where M represents total mass of part in g, ρ is the density of material (ABS) 1.04 *g/cm^3* and υ the total volume of part to be fabricated in *cm^3*.

Substituting for density and volume in Equation (5), M = 9.36 g. Therefore, from Equation (4), Specific sintering energy E_s for 9.36 g can be estimated thus:

$$E_s = \left(\frac{26.48 \times 1000\ Wh}{1000\ g}\right) \times 9.36\ g = 247.85\ Wh$$

Thus, sintering energy E_s for ABS can be estimated if the total mass of the component is known as in Equation (5b).

$$E_s = 26.48 \times \rho \times \upsilon \qquad (5b)$$

where E_s is the Sintering energy in *Wh*
Substitute Equation (5b) into Equation (3):

$$E_t = \left(\frac{P_s t_s}{n}\right) + P_w t_w + P_r t_r + P_b t_{cy} + (26.48 \times \rho \times \upsilon) + P_p t_p \qquad (6)$$

Equation (6) represents the total electrical energy demand model to fabricate a part on FDM machines.

3. VALIDATION OF DIRECT ENERGY MODEL DURING 3D PRINTING PROCESSES

In order to validate the mathematical model proposed, a component part was designed on CAD software and fabricated on an RP Stratasys Dimension SST FDM machine. The CAD part was loaded to the FDM machine through Catalyst software. This software is the interaction interface of the RP Stratasys Dimension SST FDM machine. The total volume of the part fabricated was 9000 mm^3. The electrical current consumption was measured with the Fluke 435 power clamp meter and the power profile obtained is as shown in Figure 5.

The power profile recorded in Figure 5 ignored the start-up state.

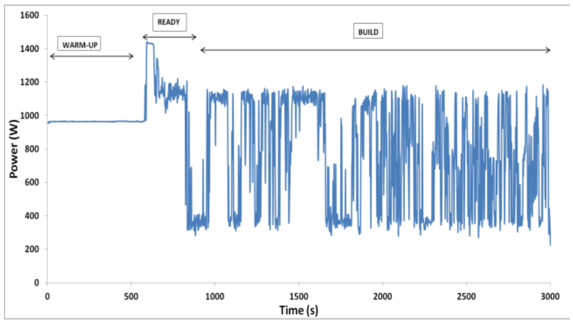

Figure 5. Power profile to fabricate 9000 mm3 volume on FDM after first warm-up

This is because the machine had already gone through this state in the previous test. It also to be noted that the start-up stage occurs only once unless the FDM machine is turned off for every production cycle. Also, the warm-up states increases from 92 *s* in the second test to 564 *s*. This is to enable the machine attain a temperature of 75°F for the build chamber and 266°F for both the build and support materials. At these temperatures, the flow rate of the build and support materials are stable and maintained in a 75°F environment. The contribution for each of the electrical energy states recorded is depicted in Figure 6.

For the purpose of this work where the concern is mostly the maximum electrical energy demand per build, it is important to consider the peaks and troughs of all energy profile by their averages. At the build stage for example, the electrical energy demand is evaluated by considering the average power demand with respect to the build stage total time. This ensures that all peaks and troughs of the power profile are considered as shown in Figure 5.

The energy state recorded revealed that 33.96%, 30.95%, 20.62%, 13.94% and 0.54% for the build, basic, warm-up, ready and start-up states, respectively. The machine basic energy demand was 31% of the total electrical energy requirement of the process. This percentage is consumed by the auxiliary units of the FDM machine which includes loaded and unloaded motors, lights, computer user interface, etc. This further proves dominating effect of machine basic/ set-up state contributions to the electrical energy demand and the need for further improvement at the machine design stages to optimize energy efficiency.

The power demand of each state was measured with the Fluke 435 power meter and the result shown in Table 1.

The total energy demand on FDM machine calculated using Equation (6) was 729.92 Wh. The power profile measured by the Fluke 435 Clamp meter gave values which led to an area under the power-time graph of 685.09 Wh.

The deviation of the prediction of the theoretical estimation of the model from the experimental measurement was 6%. These values further prove that the energy model as stated in Equation (6) can be used as a generic and robust estimate of the energy requirements for 3D printer machines. Note that the post process energy demand was ignored in the energy estimation.

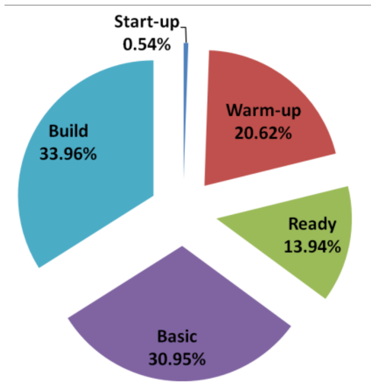

Figure 6. Energy demand during fabrication of 9000 mm3 volume part.

4. CONCLUSION

This work proposed the direct electrical energy consumption model for the of FDM 3D printer machine. The total electrical energy demand was validated with a simple 3D model printed. Similar volume of ABS was fabricated on the Stratasys Dimension SST FDM machine. The resulted electrical energy demand for each process was benchmarked. The following conclusion can be deduced from the study:

i. The proposed total electrical energy demand model to fabricate a part on the FDM machines is as stated in Equation (6) below:

$$E_t = \left(\frac{P_s t_s}{n}\right) + P_w t_w + P_r t_r + P_b t_{cy} + (26.48 \times \rho \times \upsilon) + P_p t_p \quad (6)$$

Note: The electrical energy demand for the post processing operation $P_b t_b$ is ignored in this case since it is an independent and separate equipment from the FDM machine. However, for an all encompassing energy demand model, it is included.

ii. The sintering energy E_s for ABS can be estimated if the total mass of the component is known as in Equation (5b) thus;

$$E_s = 26.48 \times \rho \times \upsilon \quad (5b)$$

iii. The generic sintering energy E_s can also be estimated for any type of build material adopted as stated in Equation (4) thus:

$$E_s = e_b \times \rho \times \upsilon \quad (4)$$

TABLE 1. Total energy demand results

	Start-up state	Warm-up state	Ready state	Basic (Set-up) state	E_s (Wh)	Total Energy (Wh) Theoretical (from model)	Total Energy (Wh) Area under garph (measured)	Error (%)
Power (W)	715.72	963.94	934.14	270.00				
Time (s)	20.00	562.00	392.00	3012.00				6.14
Energy (Wh)	3.98	150.48	101.72	225.90	247.85	729.92	685.09	

iv. The variation between the theoretical electrical energy estimation and the area under the graph as obtained from the direct power measurement was 6%. The proposed model can therefore be said to be generic and process specific for FDM 3D printer machines and can be used to estimate the total electrical energy requirements for part manufacture and for sustainable process planning.

v. The warm up time for the FDM 3D printer machine is considerably high. This can be an area of improvement for energy efficiency and sustainable manufacture to meet the requirement for the UNEP sustainability agenda.

vi. Since energy demand is time dependent, new heating methods could be designed to reduce the warm-up time.

vii. Also, since FDM is an RP process that can be used for the fabrication of one-off part in a cycle, the machine could be termed as not-efficient since the electrical energy demand could be considerably higher when compared to an RM processes. However, if the FDM produces more than 10 parts from power-up to power-down cycle time, the electrical energy demand for the start-up will be negligible. Therefore, the need to normalize the start-up energy demand by the quantity *n* produced in a cycle.

viii. For resource efficiency it is recommended that 3D printers are not allowed to cool down to room temperature before the next part is fabricated. This is so because 33.2% of the electrical energy can be saved.

ix. To improve the sustainability and resource efficiency of the FDM 3D printer machines, it is important that more research should be directed towards the reduction of cycle time and also improving the surface finish of the fabricated components.

5. REFERENCES:

1. Toolkit, S.M., "Organization for economic co-operation and development", France: http://www.oecd.org/innovation/green/toolkit/.[accessed 8/12/12], (2010).
2. ISO, 2011. International Standard Organisation, Win the energy challenge with ISO50001:2011, available: www.iso.org/iso/iso_50001_energy.pdf, accessed 01-09-2015.
3. ISO14955-2, Methods of evaluating energy efficiency of machine tools and machine components. http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=55294. Accessed 14th may 2015.
4. ISO I, "14020: 2000. Environmental labels and declarations-general principles geneva, switzerland2000", (2000).
5. Ostaeyen JV, CO2PE! (Cooperative effort on process emissions in manufacturing) Taxonomy. www.mech.kuleuven.be/co2pe!/taxonomy.php. Accessed January 2016.
6. UNEP, UNEP's Resource Efficiency Programme. Available: http://www.unep.org/resourceefficiency/Home/UNEPsResource EfficiencyProgramme/tabid/55552/Default.aspx. Accessed 26/07 2013.
7. Madan, J., Mani, M. and Lyons, K.W., "Characterizing energy consumption of the injection molding process", in ASME International Manufacturing Science and Engineering Conference collocated with the 41st North American Manufacturing Research Conference, American Society of Mechanical Engineers., (2013).
8. Santos, E.C., Shiomi, M., Osakada, K. and Laoui, T., "Rapid manufacturing of metal components by laser forming", ***International Journal of Machine Tools and Manufacture***, Vol. 46, No. 12, (2006), 1459-1468.
9. Hopkinson, N., Hague, R. and Dickens, P., "Introduction to rapid manufacturing", ***Rapid Manufacturing: An Industrial Revolution for the Digital Age***, (2006), 1-4.
10. Hague, R. and Reeves, P., "Rapid prototyping, tooling and manufacturing", iSmithers Rapra Publishing, Vol. 117, (2000).
11. Tarang, Y.E., "3d printing additive manufacturing", ***International Education and Research Journal***, Vol. 1, No. 4, (2015), 21-23.
12. Levy, G.N., Schindel, R. and Kruth, J.-P., "Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state of the art and future perspectives", ***CIRP Annals-Manufacturing Technology***, Vol. 52, No. 2, (2003), 589-609.
13. Holmstrom, J., Partanen, J., Tuomi, J. and Walter, M., "Rapid manufacturing in the spare parts supply chain: Alternative approaches to capacity deployment", ***Journal of Manufacturing Technology Management***, Vol. 21, No. 6, (2010), 687-697.
14. Kruth, J.-P., Levy, G., Klocke, F. and Childs, T., "Consolidation phenomena in laser and powder-bed based layered manufacturing", ***CIRP Annals-Manufacturing Technology***, Vol. 56, No. 2, (2007), 730-759.
15. Gibson, I., Rosen, D. and Stucker, B., "Additive manufacturing technologies: 3d printing, rapid prototyping, and direct digital manufacturing, Springer, (2014).
16. Yan, Y., Li, S., Zhang, R., Lin, F., Wu, R., Lu, Q., Xiong, Z. and Wang, X., "Rapid prototyping and manufacturing technology: Principle, representative technics, applications, and development trends", ***Tsinghua Science & Technology***, Vol. 14, (2009), 1-12.
17. Mellor, S., Hao, L. and Zhang, D., "Additive manufacturing: A framework for implementation", ***International Journal of Production Economics***, Vol. 149, (2014), 194-201.
18. Lan, H., Ding, Y., Hong, J., Huang, H. and Lu, B., "A web-based manufacturing service system for rapid product development", ***Computers in Industry***, Vol. 54, No. 1, (2004), 51-67.
19. Balogun, V.A., Kirkwood, N.D. and Mativenga, P.T., "Energy consumption in Fused Deposition Modelling machine: a case study of RP Stratasys Dimension SST FDM", ***International Journal of Scientific & Engineering Research***, Vol. 6, No. 8 (2015), 442–447.
20. Balogun, V.A., Kirkwood, N. and Mativenga, P.T., "Energy consumption and carbon footprint analysis of fused deposition modelling: A case study of rp stratasys dimension SST FDM".
21. Kellens, K., Dewulf, W., Overcash, M., Hauschild, M.Z. and Duflou, J.R., "Methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (uplci) co2pe! Initiative (cooperative effort on process emissions

in manufacturing). Part 2: Case studies", ***The International Journal of Life Cycle Assessment***, Vol. 17, No. 2, (2012), 242-251.

22. Gutowski, T., Dahmus, J. and Thiriez, A., "Electrical energy requirements for manufacturing processes", in 13th CIRP international conference on life cycle engineering. Vol. 31, (2006), 623-638.
23. Balogun, V.A. and Mativenga, P.T., "Modelling of direct energy requirements in mechanical machining processes", ***Journal of Cleaner Production***, Vol. 41, (2013), 179-186.
24. Dietmair, A. and Verl, A., "Energy consumption modeling and optimization for production machines", in IEEE International Conference on Sustainable Energy Technologies., (2008), 574-579.
25. Seow, Y. and Rahimifard, S., "A framework for modelling energy consumption within manufacturing systems", ***CIRP Journal of Manufacturing Science and Technology***, Vol. 4, No. 3, (2011), 258-264.
26. Shen, L. and Patel, M.K., "Life cycle assessment of polysaccharide materials: A review", ***Journal of Polymers and the Environment***, Vol. 16, No. 2, (2008), 154-167.
27. Hammond, G.P. and Jones, C.I., "Embodied energy and carbon in construction materials", ***Proceedings of the Institution of Civil Engineers-Energy***, Vol. 161, No. 2, (2008), 87-98.
28. Boustead, I., "Eco-profiles of the european plastics industry: Polyethylene and polypropylene. Report 3, APME, (1993).

Electrical Energy Demand Modeling of 3D Printing Technology for Sustainable Manufacture

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چکیده

ظهور پرینترهای سه بعدی (3D) در سطح جهان در چند سال اخیر استفاده از آن را با استقبال چشم‌گیری مواجه ساخته است. افزایش پذیرش استراتژی تولید سریع (RM) را می‌توان به کاهش هزینه منابع طبیعی، کاهش پس‌ماند و معیارهای پایداری قطعات تولید شده نسبت داد. سرعت رشد این فناوری (چاپ سه بعدی) در حال تحول، به‌ویژه برای تولید محصولات سفارشی و شکل‌های هندسی پیچیده به صورت نمایی پیش بینی شده است. بنابراین، مناسب است که برای بهینه سازی بهره‌وری منابع فناوری‌های چاپ سه بعدی در این مرحله اولیه این توسعه فناوری اقدام شود. در این مقاله، تقاضای مستقیم انرژی الکتریکی (به عنوان مثال مدل سازی رسوب ذوب)، مورد مطالعه قرار گرفته و یک مدل عمومی ارائه شده است. صحه‌گذاری مدل مورد نظر بانرم‌افزار SST FDM Stratasys انجام شد. این کار کمک بیشتری به داده‌های موجود برای مدل سازی تقاضای انرژی الکتریکی و بهینه سازی برای سرعت در حال گسترش فرآیندهای چاپ سه بعدی می‌باشد.

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