Comparative Analysis of Energy Consumption and Carbon Footprint of Additively Manufactured Solid and Lattice structure Tensile Specimens.

Hashim Khan[1] *Muftooh ur Rehman Siddiqi* [2*] Sarah Junaid [2]

[1]Mechanical Engineering Department CECOS University of IT & Emerging Sciences Peshawar
[2] Mechanical, Biomedical and Design Engineering, Aston University, Birmingham B4 7ET, UK

Abstract. Manufacturing significantly contributes to global warming due to its substantial carbon emissions. United Nations sustainable development goals support the reduction of carbon emissions in the manufacturing sector, which can be accomplished by making the manufacturing process sustainable with a minimal carbon footprint. This is also appropriate for novel manufacturing processes such as additive manufacturing. This study introduces the investigation of the additively manufactured specimen. Prior research delves into examining the impact on the energy consumption of solid specimens under distinct printing process parameters. Nonetheless, the influence of electrical energy consumption and total carbon footprint for the additively manufactured solid and lattice structure has yet to be investigated. The current study fills the research gap by assessing layer thickness and infill density on both specimens' electrical energy consumption and total carbon footprint. The presented study offers insight into the impact of layer thickness and infill density for the solid and lattice structure specimens and their comparison of electrical energy consumption and total carbon footprints. The results demonstrated that a rise in an infill density directly correlates with increased energy consumption and carbon footprints. However, rising layer thickness resulted in a reduction in both power consumption and carbon footprints. Furthermore, it was observed that the triangular, octagonal, and hexagonal cellular structures manifest higher power consumption when the infill density is set at 50% and 80%, respectively. Moreover, when assessing a solid specimen at 100% infill density, the total carbon footprint exhibits increases of 12%, 21%, 23%, and 41% in comparison to triangular, octagonal, hexagonal, and square lattice structures, respectively.

1 Introduction

Climate change, an immanent global concern, is substantially influenced by the exploitation and degradation of our planet[1]. Global warming is being expedited by increasing carbon dioxide levels in the atmosphere, which are usually considered as the primary cause[2]. Human activities appeared to be the cause of this surge[3], [4]. Nearly 25% of the planet greenhouse gas emissions and 33% of its energy consumption are associated to industry, with the industrial sector accounting for the majority of these emissions either directly or indirectly [5], [6]. The carbon footprint metric, expressed in carbon dioxide equivalents (CO2e), is used to quantify GHG emissions [7]. To alleviate the emission challenge United Kingdom decided to adopt a set of proposal, The UK aims to become a modern, resource-efficient, and competitive economy with zero net carbon dioxide emissions by 2050[8]. Additive manufacturing, or AM, has gained recognition as a potentially revolutionary technology that can greatly mitigate manufacturing's adverse environmental impacts [9], [10]. Light weight structure and products are in highly demanded these days. Therefore, it is vital to accomplish the highest strength when the products with it minimal weight[11][12]. However, sometimes, reaching the highest strength when the product's weight is at the lowest is not possible. Thus,

* Corresponding author : m.siddiqi5@aston.ac.uk

the material extrusion process gives the opportunity to build complex and porous products that cannot be built by conventional methods[13], [14].This led the development of topology optimization and alleviated the structural constraints in additive manufacturing process[15]. Topology optimization is a technique that determine the optimal mass distribution to manage the load with in a predefined volume domain. The first method is generative design which is also known as density-based and the second method is incorporation of cellular structure by replacing the solid region of component with lattice structure with a specific relative density to attain a optimal mass distribution respectively [12], [16], [17], [18], [19]. Acquiring this approach leveraging high strength to weight ratio, high energy absorbing, high porosity and surface area to volume ratio, suitable for Prosthesis, heat transfer application respectively. It is important to note that manufacturing process are the critical factor that influence the sustainability [20]and it can be evaluated by the level of the measures it is influenced by, such as energy consumption[21], [22]. Recent research article investigated the impact of printing parameters on the energy consumption. Peng et al revealed that layer thickness is the significant factor that contribute significantly to energy consumption[23].Extensive research has been conducted on process parameters and their impact on energy consumption. Several researchers used DOE to optimize the influential process parameters. Nevertheless, till date there is no such investigation present in the literature that thoroughly compare the energy consumption of solid specimen and cellular structure and more importantly their carbon footprint of both printer and material consumed in the process. The study herein tries to compare the electrical energy consumption and total carbon footprint of electrical energy per kWh and PLA per kg Carbon dioxide of solid and lattice structure tensile specimen of the same size in accordance with ASTM standard Type I specimen fabricated through material extrusion technique under various printing process parameters that affect electrical energy consumption. The current study concentrates on manipulating layer thickness and infill density to investigate the electrical energy consumption and carbon footprints of for both solid and cellular structure specimen. Section 3 presents the result and discussion that were collected for different levels of layer thickness and infill density, With the use of data from the printing, the energy spent during MEX is calculated and the carbon footprint is estimated. The level that causes most of the emissions is determined.

2 Materials and Methods

To determine the carbon footprint of solid and lattice structure specimen in compliance with ASTM standard D634-14 type I Specimen. A hexagonal, octagonal, triangular, square cellular structure along with the solid specimen were printed using material extrusion (MEX) 3D printing technique by melting a 1.75mm diameter PLA filament through a nozzle of 0.4mm diameter. An open source CURA 5.40 software were used to translate CAD geometry into G-Codes. The current study focuses on the impact of printing parameters on the energy consumption ultimately the carbon footprints and their outcomes were carefully examined. In this context previous research regarding printing parameters effects the printing time and ultimately the electrical energy consumption of printed samples. Markos et al. inferred that layer thickness; infill density and raster angle significantly affects the energy consumption[24]. Shubhada et al. optimize the printing parameters against the energy consumption as they are 0.14 mm layer thickness, 65% Infill% and 92.52 mm/s printing speed[25]. Based on the above findings it is crucial to conduct investigation on the carbon footprint of additively manufactured solid and cellular structure specimen under distinct printing parameters. This will explore a thorough understanding of carbon footprints of additively manufactured specimen under influential printing parameters. A summary of the printing process parameters is outlined in the **Table *1***. Moreover, the printing parameters that significantly impact the energy consumption were evaluated at certain levels; layer thickness (0.10mm, 0.15mm, 0.20mm, 0.30mm,) and infill density (50%, 80%, 100%) respectively to estimate the printing time for each specimen. Notably, the printing time and mass of the specimen is calculated for each sample including solid and cellular structure. The current drawing of the printer was calculated with the help of Ammeter as shown in the **Figure *1***. Moreover, the average value has been taken to calculate the actual power consumption of the printer for each specimen. Furthermore, the carbon footprint for electrical energy consumption in United Kingdom with an average of 162g of carbon dioxide per kilowatt hour [26]and mostly the material is imported from china and their production carbon footprint of PLA is 1.8 kg CO_2 and this values varies in different regions of the world wise[27]. On the basis of the above data the carbon footprint of electrical energy and material consumed were calculated. Moreover, the data has been plotted and presented against each level of layer thickness and infill density.

Table 1. Printing Process Parameters

Printing Process Parameters	
Nozzle Diameter	$0.4mm$
Nozzle Temperature	215℃
Bed Temperature	60℃
Raster angle	45°
Build Direction	Horizontal
Printing Speed	$60\ ^{mm}/_{sec}$
Infill Pattern	Line
Layer thickness	$0.1, 0.15, 0.20, 0.30, 0.40$
Infill Density	50%, 80%, 100%

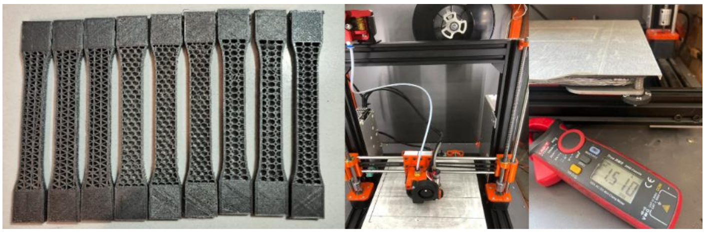

Figure 1 Measuring the current consumption of the printer

3 Result and Discussion

3.1 Impact of layer thickness and infill density on electrical energy consumption

The impact of layer thickness and infill density on electrical energy consumption is shown in Figure 2. It has been observed that the increase in the infill density raises the electrical energy consumption. Nevertheless, as the layer thickness increases, the electrical energy consumption decreases. Moreover, the depicted figures contain a solid and different cellular structure specimen plot for different levels of infill density. It is worthwhile to note that, for the first two levels of infill density triangular and octagonal lattice structure specimen has the highest power consumption followed by the hexagonal. At the same time, the square lattice structure has the lowest value of power consumption, followed by the solid specimen. It is obvious that when the infill density rises to 100%, then, the solid specimen experiences a sharp rise in electrical energy consumption compared to lattice structures. It is pertinent to note that, at 100% infill density, the power consumption of both triangular and octagonal hexagonal, square cellular structures is reduced by 12%, 23%, and 35%, respectively. The current finding suggests that layer thickness is the influential factor in electrical energy consumption, and it is in line with the reported literature [28].

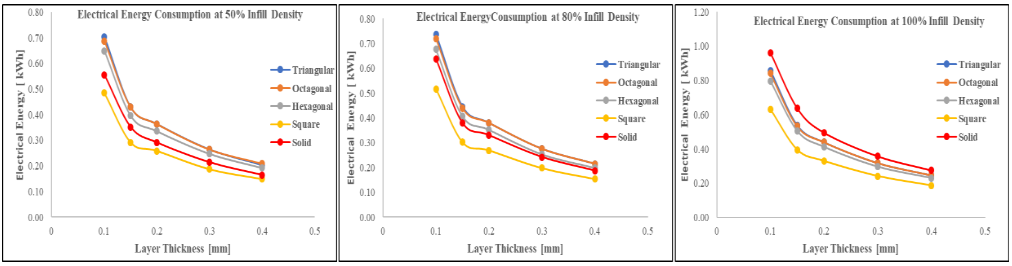

Figure 2. Electrical energy consumption against different layer thickness for each infill density level

3.2 Total Carbon footprints of additively manufactured specimen

The total carbon footprint of additively manufactured solid and cellular structure specimens via material extrusion technique is shown in Figure 3. As the infill density increases, the total carbon footprint rises substantially. However, varying material deposition thickness to a higher level yields a significant decline in the total carbon footprint. It is due to the fact that a thicker layer minimizes the print time substantially[29]. It is important to note that higher infill density significantly impacts the weight of the part[28]. Therefore, the total carbon footprint of the sample surges drastically at the maximum infill density. This trend can be seen for each layer thickness, thereby showing that infill density is a substantial parameter that increases the weight of the sample. Furthermore, the presented figures outline a solid and triangular, octagonal, hexagonal, and square lattice structure specimen total carbon footprint at various levels of layer thickness. It has been observed from the figure that when the infill density is lower than 100%, the carbon footprint of the square lattice structure has the least value followed by the solid specimen. Contrary to that, a gradual increase in the layer thickness resulted in the carbon footprint being marginally higher for solid structures than for the lattice structures specimen. Notably, at the highest level of infill density, the solid specimen yielded the highest carbon footprint in comparison with the lattice structure. Moreover, the carbon footprint is gradually decreasing as the layer thickness increases, and this trend can be seen for all levels of infill density. It vital to mentioned that, at 100% infill density the percentage decrease in the carbon footprint of the triangular octagonal, hexagonal and square is 21%, 21.5%, 23% and 41% respectively.

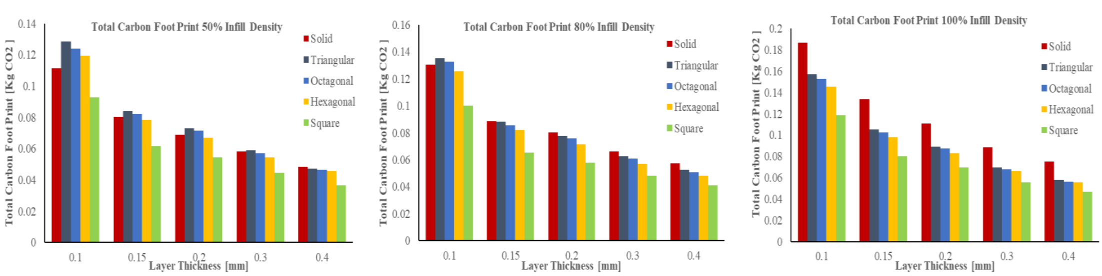

Figure 3. Total Carbon footprint of additively manufactured sample

4 Conclusion

In this work, meticulous investigation of the effect of layer thickness and infill density on the electrical energy consumption and, more importantly, the total carbon footprint of consumed electrical energy and material, specifically PLA-made solid and various cellular structure specimens, fabricated with the MEX 3D printing process was conducted and the conclusion drawn from the present study as the electrical energy consumed in the process lowers when the layer thickness rises. Although it increases with an increase in the infill density. Moreover, the solid specimen has the highest value of energy consumption at 100% infill density and it is 12% 12% and 23% and 35% for triangular, octagonal, hexagonal, square lattice structures respectively. The carbon footprint increases with the rise in infill density. The difference between the solid and lattice structures decreases as the infill density rises and becomes higher among the other specimens when the infill density is maximum. At 100% infill density, the total carbon footprint of the solid specimen is 21%,21.5%, 23% and 41% higher than triangular, octagonal, hexagonal and square structures, respectively. The study opens the opportunity to further investigates the strength to weight ratio of each lattice structure meticulously, compare their carbon footprint and optimize the process parameters, mechanical behavior and their geometrical parameters to accomplish the design requirement of material extrusion printed products.

References

1. J. Wang and K. Dong, "What drives environmental degradation? Evidence from 14 Sub-Saharan African countries," *Sci. Total Environ.*, vol. 656, pp. 165–173, 2019, doi: https://doi.org/10.1016/j.scitotenv.2018.11.354.
2. L. Al-Ghussain, "Global warming: review on driving forces and mitigation," *Environ. Prog. \& Sustain. Energy*, vol. 38, no. 1, pp. 13–21, 2019, doi: https://doi.org/10.1002/ep.13041.
3. M. K. Anser, "Impact of energy consumption and human activities on carbon emissions in Pakistan: application of STIRPAT model," *Environ. Sci. Pollut. Res.*, vol. 26, no. 13, pp. 13453–13463, 2019, doi: 10.1007/s11356-019-04859-y.
4. J. Fang, J. Zhu, S. Wang, C. Yue, and H. Shen, "Global warming, human-induced carbon emissions, and their uncertainties," *Sci. China Earth Sci.*, vol. 54, no. 10, pp. 1458–1468, 2011, doi: 10.1007/s11430-011-4292-0.
5. L. Cozzi *et al.*, "World Energy Outlook 2020," vol. 2050, no. October, pp. 213–250, 2020, [Online]. Available: https://www.oecd-ilibrary.org/energy/world-energy-outlook-2020_557a761b-en
6. Intergovernmental Panel on Climate Change, *Climate Change 2021 – The Physical Science Basis*. 2023. doi: 10.1017/9781009157896.
7. T. Wiedmann and J. Minx, "A Definition of ' Carbon Footprint," *Science (80-.).*, vol. 1, no. 01, pp. 1–11, 2007, [Online]. Available: http://www.censa.org.uk/docs/ISA-UK_Report_07-01_carbon_footprint.pdf
8. N. Burnett, T. Edwards, and N. Watson, "The UK's plans and progress to reach net zero by 2050," *House Commons Libr.*, no. November, p. 1, 2023, [Online]. Available: https://commonslibrary.parliament.uk/research-briefings/cbp-9888/#:~:text=Download full report-,The UK is committed to reaching net zero by 2050,warming and resultant climate change.
9. J. Poelma and J. Rolland, "Rethinking digital manufacturing with polymers," *Science (80-.).*, vol. 358, no. 6369, pp. 1384–1385, 2017, doi: 10.1126/science.aaq1351.
10. E. MacDonald and R. Wicker, "Multiprocess 3D printing for increasing component functionality," *Science (80-.).*, vol. 353, no. 6307, p. aaf2093, 2016, doi: 10.1126/science.aaf2093.
11. D. Barba, E. Alabort, and R. C. Reed, "Synthetic bone: Design by additive manufacturing," *Acta Biomater.*, vol. 97, pp. 637–656, 2019, doi: https://doi.org/10.1016/j.actbio.2019.07.049.
12. E. A. A. Alkebsi, H. Ameddah, T. Outtas, and A. Almutawakel, "Design of graded lattice structures in turbine blades using topology optimization," *Int. J. Comput. Integr. Manuf.*, vol. 34, pp. 370–384, 2021, [Online]. Available: https://api.semanticscholar.org/CorpusID:233029360
13. P. Pradel, R. Bibb, Z. Zhu, and J. Moultrie, "Exploring the Impact of Shape Complexity on Build Time for Material Extrusion and Material Jetting," in *Industrializing Additive Manufacturing - Proceedings of Additive*

Manufacturing in Products and Applications - AMPA2017, M. Meboldt and C. Klahn, Eds., Cham: Springer International Publishing, 2018, pp. 24–33.

14. L. A. Dobrzański, A. D. Dobrzańska-Danikiewicz, and T. G. Gaweł, "Computer-aided design and selective laser melting of porous biomimetic materials," *Adv. Mater. Process. Technol.*, vol. 3, no. 1, pp. 70–82, 2017, doi: 10.1080/2374068X.2016.1247339.
15. D. I. Stoia, L. Marsavina, and E. Linul, "Mode I Fracture Toughness of Polyamide and Alumide Samples obtained by Selective Laser Sintering Additive Process," *Polymers (Basel).*, vol. 12, no. 3, 2020, doi: 10.3390/polym12030640.
16. J. P. Groen and O. Sigmund, "Homogenization-based topology optimization for high-resolution manufacturable microstructures," *Int. J. Numer. Methods Eng.*, vol. 113, pp. 1148–1163, 2018, [Online]. Available: https://api.semanticscholar.org/CorpusID:53069749
17. E. Alabort, D. Barba, and R. C. Reed, "Design of metallic bone by additive manufacturing," *Scr. Mater.*, 2019, [Online]. Available: https://api.semanticscholar.org/CorpusID:139287749
18. C. Li, I. Y. Kim, and J. Jeswiet, "Conceptual and detailed design of an automotive engine cradle by using topology, shape, and size optimization," *Struct. Multidiscip. Optim.*, vol. 51, no. 2, pp. 547–564, 2015, doi: 10.1007/s00158-014-1151-6.
19. S. Oh, Y. Jung, S. Kim, I. Lee, and N. Kang, "Deep Generative Design: Integration of Topology Optimization and Generative Models," *J. Mech. Des.*, 2019, [Online]. Available: https://api.semanticscholar.org/CorpusID:159040324
20. Z. Ahmadi-Gh and A. Bello-Pintado, "Why is manufacturing not more sustainable? The effects of different sustainability practices on sustainability outcomes and competitive advantage," *J. Clean. Prod.*, vol. 337, p. 130392, 2022, doi: https://doi.org/10.1016/j.jclepro.2022.130392.
21. A. H. Gutierrez-Osorio, L. Ruiz-Huerta, A. Caballero-Ruiz, H. R. Siller, and V. Borja, "Energy consumption analysis for additive manufacturing processes," *Int. J. Adv. Manuf. Technol.*, vol. 105, no. 1, pp. 1735–1743, 2019, doi: 10.1007/s00170-019-04409-3.
22. C. Liu *et al.*, "Does green environmental innovation really matter for carbon-free economy? Nexus among green technological innovation, green international trade, and green power generation," *Environ. Sci. Pollut. Res.*, vol. 29, no. 45, pp. 67504–67512, 2022, doi: 10.1007/s11356-022-22040-w.
23. T. Peng and F. Yan, "Dual-objective Analysis for Desktop FDM Printers: Energy Consumption and Surface Roughness," *Procedia CIRP*, vol. 69, pp. 106–111, 2018, doi: 10.1016/j.procir.2017.11.084.
24. M. Petousis, N. Vidakis, N. Mountakis, E. Karapidakis, and A. Moutsopoulou, "Functionality Versus Sustainability for PLA in MEX 3D Printing: The Impact of Generic Process Control Factors on Flexural Response and Energy Efficiency," *Polymers (Basel).*, vol. 15, no. 5, 2023, doi: 10.3390/polym15051232.
25. S. S. Warke and V. S. Puranik, "Optimizing Energy Consumption, Surface Quality, and Production Time in Fused Deposition Modeling Based 3D Printing of Polylactic Acid Polymers," *J. Mater. Eng. Perform.*, 2023, doi: 10.1007/s11665-023-08255-z.
26. Simon Evans, "Analysis: UK electricity from fossil fuels drops to lowest level since 1957." [Online]. Available: https://www.carbonbrief.org/analysis-uk-electricity-from-fossil-fuels-drops-to-lowest-level-since-1957/
27. A. Abdelshafy, A. Hermann, S. Herres-Pawlis, and G. Walther, "Investigating the opportunities of establishing a regional bio-based polylactic acid supply chain: A case study from North Rhine-Westphalia," *Chemie Ing. Tech.*, vol. 94, no. 9, pp. 1307–1307, 2022, doi: 10.1002/cite.202255120.
28. D. S. c Nectarios Vidakis a, Markos Petousis a, Emmanuel Karapidakis b, Nikolaos Mountakis a, Constantine David c, "Energy consumption versus strength in MEX 3D printing of polylactic acid," *Adv. Ind. Manuf. Eng.*, vol. 6, 2023.
29. N. Vidakis, M. Petousis, E. Karapidakis, N. Mountakis, C. David, and D. Sagris, "Energy consumption versus strength in MEX 3D printing of polylactic acid," *Adv. Ind. Manuf. Eng.*, vol. 6, no. December 2022, p. 100119, 2023, doi: 10.1016/j.aime.2023.100119.