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DESIGN FOR METAL POWDER BED FUSION: EXPLORING PREDICTED PRINT TIME AND COST IMPACTS OF LATTICE STRUCTURES

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Abstract

Effective use of AM necessitates a comprehensive approach that considers the entire manufacturing process, from design through final processing after the print. Each step has different cost drivers that can be used to optimize production costs through thoughtful design choices. For printing, the two primary cost drivers are machine time and material cost. Designers often seek to reduce those through removal of unnecessary material, utilizing techniques such as topology optimization or lattice structures. However, lattice structures have inherent complexity that can impact print time and cost. This paper explores the impact of design choices on three types of lattice structures to be manufactured via laser-based powder bed fusion (LPBF) for a case study component. The type of lattice, unit cell size, and volume fraction of the lattice all are observed to influence the print time of the final designs. The impacts of lattice structure design on print time and cost through build print time simulation are discussed.

NOMENCLATURE

VF	volume fraction
LV	lattice volume
VR	volume replaced by lattice structure

1. Introduction

Lattice structures have been of increasing interest to the engineering community as additive manufacturing (AM) facilitates the manufacture of structures that would be otherwise prohibitively complex. The unique properties that a lattice structure can offer, from energy absorption behavior [1] to acoustic properties [2] to high strength to weight ratios is of interest in engineering applications. This paper documents a study undertaken to explore how printing lattice structures impacts cost and print time for AM components. Lessons learned and key takeaways are highlighted.

Use of lattice structures reduces material use when compared to solid designs, and thus appear to be a promising cost-reduction option. However, recent work on several proprietary applications at the authors' companies suggested the correlation between model weight reduction via lattices and cost reduction may not be as strong as was expected. One such example was identified when the authors obtained print time estimates for a component that had been redesigned to include a lattice structure. Print time estimates for this model with a lattice infill and with a solid infill were compared using parameters and build paths generated in EOS Print. Despite the use of a lattice saving more than 20% of the part's original weight, upon receiving the build estimates, there was no significant difference in time to print before and after the lattice structure replaced the solid design. This result inspired an experiment to further explore the implications of lattices on print time.

2. Literature Review

Previous studies have examined how various aspects of metal powder bed fusion part geometry can affect output parameters such as material usage and print time. Budinoff and Shafae [3] found that part complexity and the associated material savings were not linearly related to print time. They highlighted a need for more study of the effects that highly complex geometry, like latticed parts, can have on print time. Several studies have endeavored to fill this gap in the literature. Flores et al [4] studied the economic and time costs related to several lattice parameters including unit cell size, volume fraction, and lattice type. They found unit cell size and volume fraction to have the biggest impact on print time out of the lattice parameters. In their study, there was very little print time difference dependent on the lattice types used, those being Cubic Truss and Octet Truss. With the parameters they selected, it was found that they could decrease print time by an average of 54.3%, however, they did not observe any occurrences where lattices increased the print time compared to solid parts, unlike the authors of this paper.

2.1 Print Time and Cost Considerations

Several other efforts have been made in the literature to reduce AM print times. One such study by Jiang and Ma [5] looked at optimizing the path an AM laser or extruder would take to manufacture a layer. Path planning deals with the layer-by-layer scanning strategy and can be used to improve a variety of factors, including material strength and print time. Instead of modifying design parameters, this method involves changing the printing strategy of the machine and could be applied to a wide variety of parts, latticed or solid. Bibb et al [6] examined how the geometry present in scanning layers could impact the print times, however they focused on extrusion-based AM. They found that the layer size and area of geometry present in the layer were the biggest drivers of print time. The total perimeter of the geometry had a lesser effect, only impacting it as geometry became smaller and increased in complexity.

Other studies have evaluated drivers of print economics and observed that the larger the mass of the printed component the more it would cost to print. For example, component mass played a strong role in cost models generated by Schneck et al. who observed a relationship between material mass printed and cost, wherein a part that weighed more was generally quoted as being more expensive than a part that weighed less [7]. However, the cost of machine running time was not explored in that study as it was based on quotes received from manufacturers.

Geometry that can and cannot be printed with LPBF has also been an area of previous interest, with a variety of guidelines and studies available to support selection of lattice geometries that should be printable – such guidelines for LPBF geometry [8-10] helped inform the design of the lattices tested in this study, as minimum wall thicknesses of above 0.6-0.7mm and self-supporting structure designs were selected to enable printing with typical LPBF materials and parameters.

Another consideration for this study was that of quantifying costs for materials and printing time. Typical powder costs for 316L powder for AM in 2023 are around 100 dollars per kilogram [11], with some variation depending on the powder characteristics and the quantity purchased. LPBF machine time costs are estimated within the authors' industry, which has stringent quality standards, at $50-150 per hour, depending on the size and scale of machine and the project quality requirements. Rates within this range were observed in other studies for multi-laser large machines in [12]. As engineers seek to understand the value trade-off between increasing machine time via building a complex lattice and reducing weight and therefore material, these values guide discussions, as 1 kg of weight savings may be considered approximately cost equivalent to 1 hour of print time, with both being considered as approximately $100.

2.2 Lattice Design Considerations

In previous lattice structure work, volume fraction is used as a way to compare lattice geometry of different styles consistently [13]. Volume fraction is the percentage of material in a unit cell of the lattice compared to the material in a fully dense cube of the same size. This parameter offers a way to compare different lattice geometries. Lattice volume fractions were selected based on covering a range of those expected to be printable based on minimum wall thickness. This range includes volume fractions of 0.45, 0.50, 0.55, and 0.65. This range was above the minimum observed to be printable for BCC lattices [14].

A unit cell is used to refer to a section of the lattice that fully represents the geometry without repetition. The lattice is effectively a pattern of unit cells. A range of 2mm to 10mm unit cell sizes are commonly used in the literature [2,4,9,15,16]. This study evaluated a selection of unit cell sizes within the previously mentioned range, including 3mm, 5mm, and 7mm. These were informed by the geometry constraints for printability via LPBF [8-10].

Informed by the literature, the authors sought to further explore the impacts of several lattice parameters including unit cell size, volume fraction, and lattice type.

3. Materials and Methods

Lattice structures come in a variety of geometries, including two-dimensional lattices, triply periodic minimum surfaces (TPMS), and strut-based. Two-dimensional lattices are essentially a two-dimensional pattern that is extruded to generate a solid area. TPMS are lattices that periodically repeat in three dimensions while minimizing surface area. They are controlled by mathematical equations. Strut-based lattices involve a truss-like structure and are considered traditional lattices and the most common lattices. For this study, the impact of lattice type on print time was explored by testing one of each type of lattice. A variety of lattice independent variables were selected for this comparison, including volume fraction, unit cell size, and lattice type. Lattice types were limited to those expected to be printable based upon factors like unit cell size and geometric considerations, as discussed in Section 2. Final lattices selections can be found in the below list and their images are in Figure 1:

a. TPMS Gyroid (gyroid)
b. Hexagonal Honeycomb (honeycomb)
c. Body Centered Cubic (BCC)

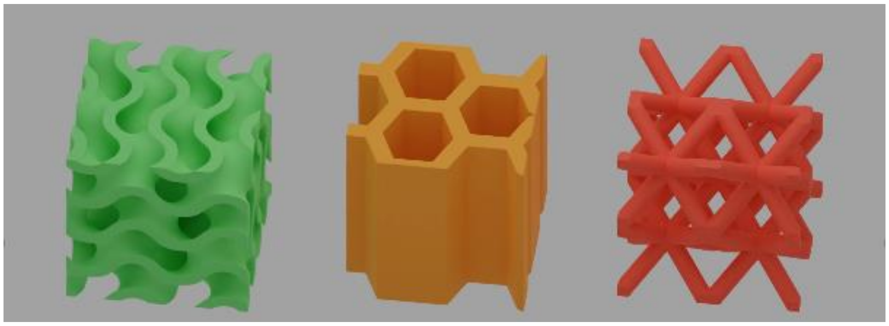

FIGURE 1: GYROID, HONEYCOMB, AND BCC LATTICES.

The TPMS gyroid was selected for its superior yield strength properties, the BCC strut-based lattice was selected because it is commonly available in CAD and has good printability, and the honeycomb lattice was selected due to mechanical property performance and easy powder removal. The gyroid and honeycomb lattices were also of interest due to their consideration in designs for the author's case study application.

All three lattice types were tested for all the selected volume fraction and unit cell size values. When varying the unit cell size, volume fraction was held constant at 50%. When varying the volume fraction, unit cell size was held constant at 5mm. A list of all the parameters tested can be seen in Table 1.

TABLE 1: LIST OF STUDY PARAMETERS

Lattice Type	Unit Cell Size	Volume Fraction
Gyroid	3mmx3mmx3mm	45%
BCC	5mmx5mmx5mm	50%
Hexagonal Honeycomb	7mmx7mmx7mm	55%
		65%

In order to further explore the lattice structures, a sample part was chosen from an assembly that the authors were redesigning. While the technical details are proprietary, the component was to approximately retain its external envelope, but its mass could be reduced, making an internal lattice structure of interest. This made it a good candidate for this study.

Once the component had been identified, it was then modified by shelling it and filling it with a lattice. Shelling a part involves keeping the outer surfaces the same but hollowing out the insides to reduce volume and material usage. Shells are commonly paired with lattices as they allow for the outer surfaces of the part to remain the same and the solid outer layer provides mechanical strength benefits to the lattice [9]. For this part a modified shell was used in which the top and bottom surfaces were removed entirely to aid with powder removal. This was done using the CAD software Creo. The original and shelled versions of the part can be seen in Figure 2. This part was then transferred to nTop where the various lattices were added to the part. The final files were then exported for printing preparation via EOS Print.

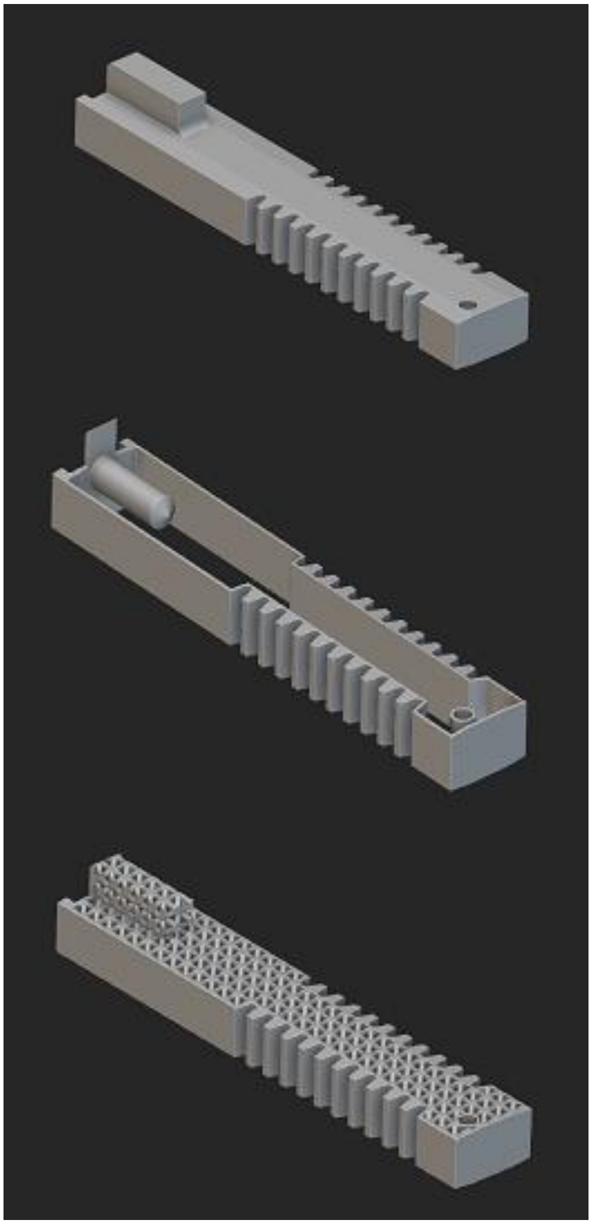

FIGURE 2: IMAGE OF COMPONENT USED FOR TEST CASES, SHOWING IT AS A SOLID, A SHELL, AND WITH A LATTICE.

The AM-focused CAD software, nTop, does not have the native ability to control a lattice's volume fraction; so, to create lattices with the specified volume fractions this calculation was performed manually. This was done by calculating the volume fraction (VF, Equation (1)) after the lattice had been generated and then adjusting the wall thickness to get this volume fraction within 1% of the desired value. For the lattices and parameters used in this study, the relationship between volume fraction and wall thickness for a given unit cell size was found to be approximately linear and can be seen in Figure 3.

$$VF = \frac{LV}{VR} \tag{1}$$

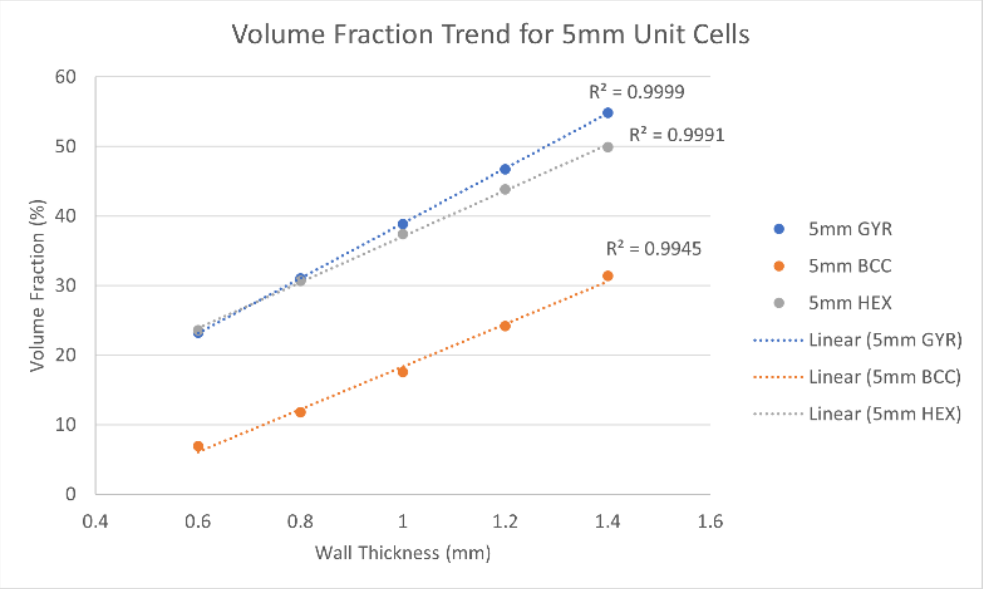

FIGURE 3: PLOT SHOWING THE RELATIONSHIP BETWEEN WALL THICKNESS AND VOLUME FRACTION

For most unit cells, the definition is consistent between CAD software packages, such as Creo and nTop. However, the hexagonal honeycomb lattice definition varies. During this study it was observed that nTop's definition of a hexagonal honeycomb unit cell differs from Creo. Creo's hexagonal honeycomb unit cell is a hexagon bounded by a square of the given unit cell dimensions, while nTop's contains the hexagon as well as sides of following hexagons. For this paper, the Creo definition of a Hexagonal Honeycomb lattice is used because it was most appropriate for the application. This can be replicated in nTop by scaling the V dimension of the unit cell shown in Figure 4 by geometrically determined factor of 1.5485.

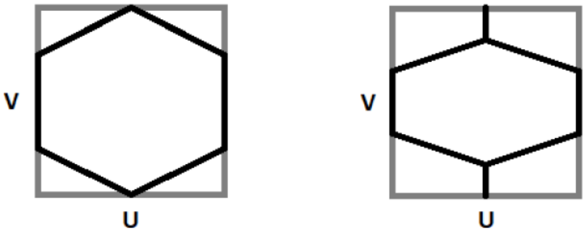

FIGURE 4: HEXAGONAL HONEYCOMB UNIT CELLS OF CREO (LEFT) AND NTOP (RIGHT)

The parameter set used for processing each lattice structure was held constant for this experiment. All print time estimates for a model with a lattice infill and with a solid infill were compared using the EOS 316L 040 FlexM291 1.00 parameters and build paths generated in EOSPrint. Each model was located on the build plate in the center, without supports or rafts.

4. Results and Discussion

This work generated print simulations for thirteen versions of a component. Each version was centered on the build plate of an EOS M290 and its printing was simulated. Each version was simulated as printing by itself with no raft or supports to avoid those factors impacting the results. Based upon data generated by each simulation, several trends can be observed about the impact of various lattice structure design aspects. These trends can be seen in Figures 5 and 6.

First, the volume fraction of a lattice structure appears to be correlated with print time. An increase in volume fraction is correlated with an increase in print time. This is apparent for all lattice types evaluated in this work. The relationship appears to be close to linear as trend line R squared values are over 0.99 for each type of lattice.

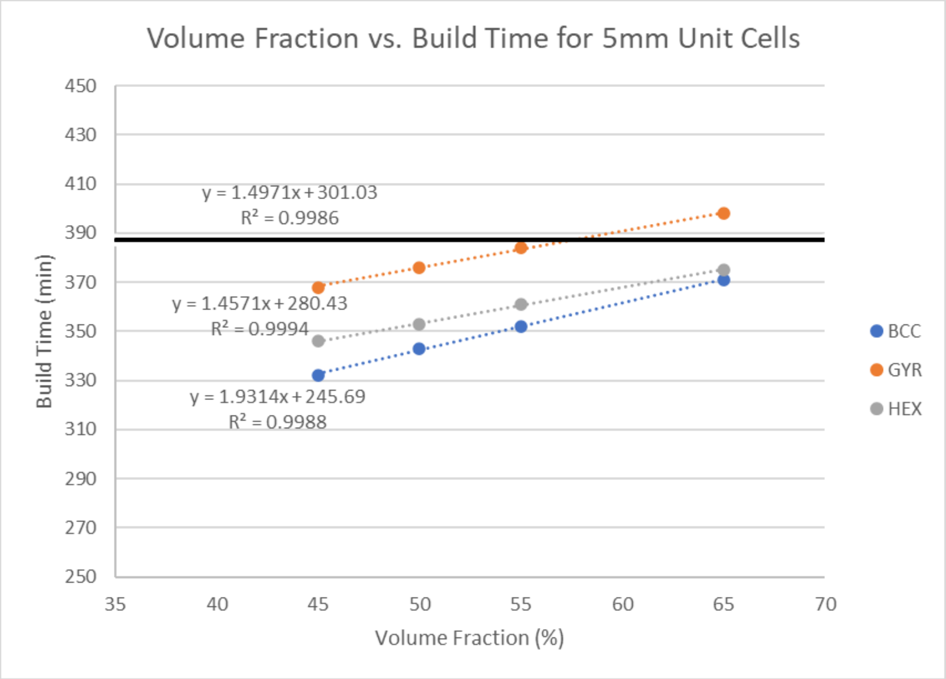

FIGURE 5: PLOT SHOWING THE IMPACT OF VOLUME FRACTION ON PRINT TIME FOR 5MM UNIT CELL SIZE. SOLID BLACK LINE REPRESENTS SOLID DESIGN WITHOUT A LATTICE.

Additionally, this works demonstrated that larger unit cell sizes are correlated with shorter print times. Based upon print times for unit cells of a range of sizes at a constant 50% volume fraction, a correlation between unit cell size and print time can also be seen. For each type of lattice examined, print time appears to decrease as unit cell size increases.

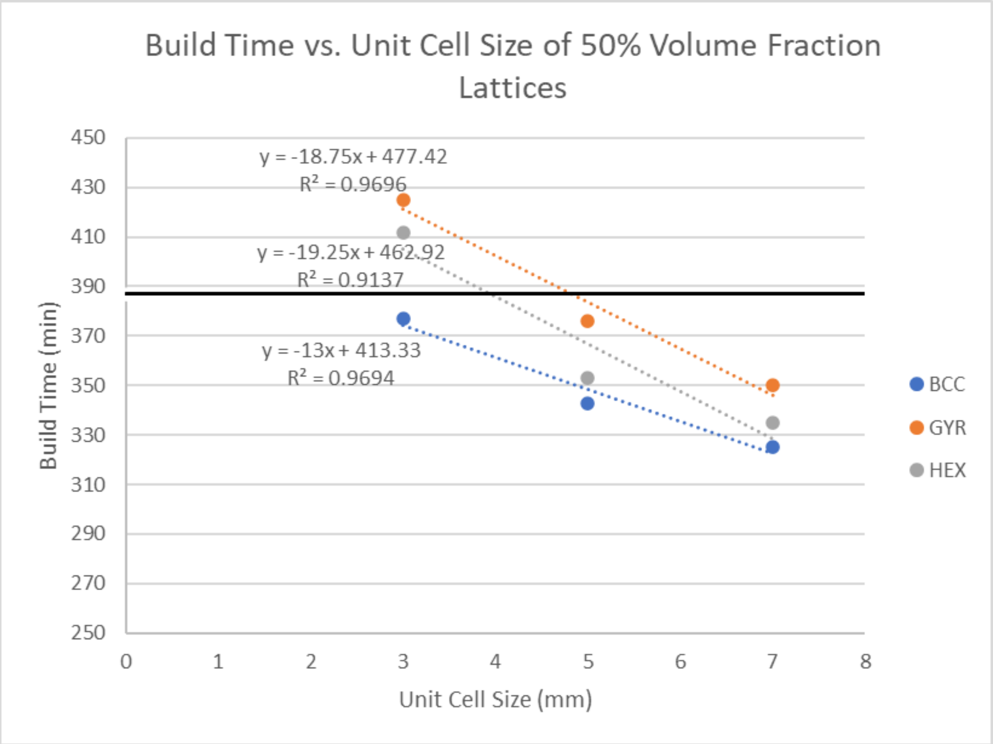

FIGURE 6: PLOT SHOWING THE IMPACT OF UNIT CELL SIZE ON PRINT TIME FOR 0.50 VOLUME FRACTION. SOLID BLACK LINE REPRESENTS SOLID DESIGN WITHOUT A LATTICE.

Print time is also impacted by the type of lattice used. The lattice types used in this study all had different print times across constant volume fractions and unit cell sizes. BCC was consistently the fastest of the three, followed by hexagonal honeycomb. The gyroid lattice was consistently the slowest. It does appear from the trend lines that this may change at higher volume fractions, where the hexagonal honeycomb may become faster than BCC.

Finally, not all lattice designs will print faster than a solid part. In Figures 5 and 6 it can be seen that several of the latticed parts have a longer print time than the solid control part. Lattice designs with smaller unit cell sizes, larger volume fractions, or slower printing lattices are more susceptible to this. It may now be an important design step to consider whether adding a certain lattice to a part will improve the print time, since this can't be assumed to be a given of using a lattice.

The trends in the lattice print times are due to the scanning strategy of the EOS Print software for the selected build parameters. Print time for each model was made up of recoat time, which is the time to spread powder for each layer, and exposure time, which is the time for the laser to scan each cross section. The recoat time was identical for each model as they are all the same height. The exposure time drove all print time variation.

Exposure time includes the time when the laser is scanning all cross sections of the component. However, it is not simply scanning all areas one time, or all lattices of the same volume fraction would have an equivalent print time. There is an additional step where the laser scans the outer contour of each layer in the parameter set used for this work. This is believed to be a driver of the time difference. The contour takes longer when the outer contour for each cross section is longer – such as when the laser must trace the gyroid structure. This effect of contours has been observed in other studies. Pauzon et al. [15] found that including contours in the print parameters increased print time of AM parts, with latticed parts experiencing this effect the most.

5. Cost Impact of Lattice Design Choices

Cost impacts of lattice structures on printing are considered in two ways for this study. The first is through the cost of material. As mentioned in Section 2, material costs for 316L powder are estimated at $100. The second is through cost of print time. The cost for an hour of printing time has been estimated at $100, also discussed in Section 2. A simple way to consider the impact of printing time cost and weight is that one kilogram of weight savings is roughly equivalent to one hour of print time, and both are approximately $100.

Each component printed in this study is relatively light, ranging from 0.26kg (for the lattices at 45% volume fraction) to 0.34kg (lattices at 65% volume fraction). The cost savings of the lightest lattice when compared to the heaviest lattice (0.34kg-0.26kg=0.08kg, 0.08kg*$100/kg = $8) are $8 if the material cost is assumed to be $100/kg.

The range of print times for this study had a maximum of 425 minutes (3mm gyroid at 50% volume) and a minimum of 325 minutes (7mm BCC at 50% volume). This means that there was a 1.67 hour difference between the longest and shortest print time. At 1.67 hours at $100 per hour, this means the cost savings between the longest and shortest print time is $167.

This outcome shows that lattice design choices can have a greater economic impact than weight savings alone in this case study. The difference in material cost between the heaviest and lightest lattice only saved $8, while the difference in print time cost between the fastest and slowest to print lattice saved about $167, which is almost 21 times the impact of saving extra weight. This large cost impact demonstrates why consideration of print time during design is important.

If the lattice designs are compared to a solid version of the component with no lattice, there are several additional observations. Table 2 shows how the lattices compare with the solid design. The lattice design with the lowest volume had a total cost 16.1% less than that of the solid part. (All the 45% volume fraction parts would theoretically have the same lowest volume, so the BCC part was selected for this comparison due to it having the lowest print time of that volume fraction set.) The part with the fastest print time had a total cost 17.6% less than that of the solid part. The part with the slowest print time had a total cost 6.5% higher than that of the solid part, despite reducing the material cost by 39%. From this table it can be observed that improving print time has a larger impact than material reduction alone. This is understandable because material cost ranges from 6.7% to 3.8% of the total cost of a component, assuming only the printed material is considered as a cost and the rest of the material in the build chamber is considered to be recycled.

TABLE 2: PART COST COMPARISON, SHOWN TO NEAREST DOLLAR

Part	Material Cost	Print Time Cost	Total Cost	% Total Cost Due to Material
Solid	$46	$645	$691	6.7%
5mm, 45% VF BCC (Lowest Volume)	$26	$553	$579	4.7%
7mm, 50% VF BCC (Fastest Print Time)	$28	$541	$569	4.9%
3mm 50% VF Gyroid (Slowest Print Time)	$28	$708	$736	3.8%

6. Limitations and Future Work

Print times for all lattices examined in this work were generated via a simulation in EOSPrint for an EOS M290 single-laser system and used standard EOS-developed parameters for the same material, 316L. This parameter set has one contour pass during the scanning of cross sections. Aside from contours, there may be other aspects of the scanning, such as path, hatch spacing, or acceleration rates of the laser that may also cause differences in printing time. Considerations like trave time of the laser when off and number of accelerations or decelerations were not explicitly explored. Other parameter sets may perform differently, especially if they have a different number of contour passes or different scanning patterns. Scanning patterns for other AM systems may differ from EOS and provide different outcomes. Additionally, removal of contour passes would reduce print times. If contour passes are not included, the only area the laser would need to scan on each layer would be the cross section. This would lead to print times driven primarily by volume fraction, as higher volume fraction would require more scanning. There may also be some deviation from the simulated print time values during manufacturing and future work could involve printing the components to verify accuracy of predictions.

Finally, this study considered only printed material volume for material costs, and all other powder material used during the build process was assumed to be recycled. True rates of powder reuse vary and practitioners may need to consider adding on an additional cost for material that is used during printing and cannot be recycled, even though it was not joined to create a printed component.

7. Conclusion

This study has evaluated the influence of different lattice parameters on print time to progress understanding of the impacts of lattice structure design choices. Results support the conclusions that increasing volume fraction and decreasing unit cell size both lead to longer print time, regardless of lattice type. It can also be observed that lattice type impacts print time even when unit cell size and volume fraction are held constant. The BCC lattice had the fastest print times in the range of unit cell sizes and volume fractions evaluated during this study, followed by the hexagonal honeycomb. The gyroid lattice was typically the slowest to print. These results were observed for lattice unit cell sizes ranging from 3 to 7 millimeters at volume fractions ranging from 45% to 65%. Additionally, this case study demonstrates how lattice design choices can have a larger impact on cost than material removal alone. It also demonstrates how lattice designs can in some cases cost more to manufacture than solid designs, highlighting the importance of considering the whole AM process during design.

8. Future Work

The concepts in this paper were explored for one printer using one type of build setup software. Future work could explore alternative printers, such as multi-laser machines like the EOS M400-4. It could also explore alternative printer brands, such as SLM Solutions. Many alternative brands utilize different scanning strategies, which could dramatically impact print time. For example, another brand, Seurat, manufactures their own LPBF systems and build preparation software. Seurat utilizes a scanning strategy that enables printing much larger areas at one time, which could change the economics of lattice design choices. It would also be valuable to see how accurate these estimates are when compared to experimental build time results, as print time estimates can differ from actual build time a user experiences.

Exploration of alternative materials would also be beneficial to build a more comprehensive understanding of the impacts of such parameters on the design space. Some materials may require a different number of contour passes, which would significantly change the results of this type of study. It is also possible that some printers or material types may not require contour passes at all. Given the large impact of a contour pass, organizations printing lattices may also explore development of new build parameters that intentionally omit contour passes.

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