

Analysis of Lattice Unit Cells for Additive Manufacturing

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14. ABSTRACT Additive manufacturing (AM), otherwise known as 3D printing, is an attractive manufacturing method due to its low cost, lightweight, rapid manufacturing characteristics. It is increasingly being used as an alternative to traditional machining, or subtractive manufacturing, methods with its ability to easily fabricate complex geometries. Additionally, AM offers unique weight reduction design opportunities due to its additive manner of fabrication such as latticing of parts. Latticed parts reduce weight through bulk material reduction while maintaining part strength. However, weight reduction is not the only use for latticing. This concept has gained increased interest for dielectric printing where by latticing a material the bulk material properties can be changed. This paper presents a study of different lattice structures and their unit cells, specifically how to design for a specific fill percentage.						
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CONTENTS

CONTENTS	iii
FIGURES	v
TABLES	vii
1. Introduction	1
2. Background.....	1
2.1 Additive Manufacturing.....	1
2.2 Lattices for AM	1
3. Lattice Density Analysis	2
4. Summary	8
5. Future Work	8
REFERENCES	9

FIGURES

Fig. 1	TPMS unit cells.	2
Fig. 2	Graph unit cells.	3
Fig. 3	Graph unit cells are defined by some line path graph like the grey lines seen in (a). When applied with some thickness these become beams, called out in (b).	3
Fig. 4	The unit cell thickness is varied in relation to the unit cell size. The % fill volume for the different unit cells can vary widely for a given thickness/unit cell size. Each line is a different unit cell type	4
Fig. 5	The unit cell thickness is varied in relation to the unit cell size. The % fill volume for the different unit cells can vary widely for a given thickness/unit cell size. Each line is a different unit cell type	4
Fig. 6	The unit cell thickness is varied in relation to the unit cell size. The % fill volume for the different unit cells can vary widely for a given thickness/unit cell size. Each line is a different unit cell type	5
Fig. 7	TPMS unit cells.	5
Fig. 8	Graph unit cells.	6

TABLES

Fig. 1 Lookup table for the lattice % fill volume. Each row is a ratio of thickness to unit cell size and each column is a different lattice type. This table can be used to design a lattice with a specific % fill volume..... 7

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ANALYSIS OF LATTICE UNIT CELLS FOR ADDITIVE MANUFACTURING

1. Introduction

Additive manufacturing (AM), otherwise known as 3D printing, is an attractive manufacturing method due to its low cost, lightweight, rapid manufacturing characteristics. It is increasingly being used as an alternative to traditional machining, or subtractive manufacturing, methods with its ability to easily fabricate complex geometries. Additionally, AM offers unique weight reduction design opportunities due to its additive manner of fabrication such as latticing of parts. Latticed parts reduce weight through bulk material reduction while maintaining part strength. However, weight reduction is not the only use for latticing. This concept has gained increased interest for dielectric printing where by latticing a material the bulk material properties can be changed. This paper presents a study of different lattice structures and their unit cells, specifically how to design for a specific fill percentage.

2. Background

2.1 Additive Manufacturing

Additive manufacturing is a broad term that encompasses fabrication methods, which create a part through additive methods, building a part layer by layer. This is in contrast to subtractive manufacturing, otherwise known as traditional manufacturing, where parts are built by removing material until the desired part is achieved. Due to the additive method of fabrication, AM is capable of fabricating complex, abnormally shaped parts with relative ease that would be impossible, or at least immensely difficult, for subtractive manufacturing to achieve. This ability to utilize all of the 3 dimensional design space is one of the big draws for AM and is why it has become such an attractive manufacturing method.

AM is not a single fabrication process. Instead, multiple AM processes exist, each fabricating parts in an additive manner but with different methods of building parts. The 7 main types of additive manufacturing are material extrusion, material jetting, binder jetting, vat photopolymerization, powder bed fusion, directed energy deposition, and sheet lamination. While the different AM processes are not critical to the lattice density analysis conducted and discussed in Section 3, it is important to note that the different AM processes will affect lattice selection due to the manufacturability concerns with different processes. However, manufacturability of lattices in different AM processes is outside the scope of this paper and will be analyzed in future work.

2.2 Lattices for AM

Lattice structures, in the context of 3D printing, are repeated geometric patterns used to fill a part or volume in 3 dimensions [1]. All lattice structures can be broken down to a unit cell, which is the repeating structure in the lattice pattern, otherwise named the lattice type. There are several different types of lattices

but for this study we focus on triply periodic minimal surfaces (TPMS) and graph lattice types. Two variables control the unit cell of a lattice: unit cell size and thickness. The unit cell size, as the name suggests, defines the size of the unit cell to be repeated through a volume to create the lattice structure, effectively the size of the bounding box for a single lattice cell. The thickness variable controls the thickness of the walls for a TPMS lattice and the beam thickness in a graph unit cell (beam definition is discussed in Section 2.2.2). These two variables will be explored in the analysis section, Section 3, to determine how they control the unit cell's density, otherwise known as % fill volume.

2.2.1 TPMS Unit Cells

The TPMS lattice types investigated in this study are gyroid, schwarz, diamond, lidinoid, splitP, and neovius. The unit cell for each of these lattice types are shown in Fig. 1. TPMS unit cells are all defined by equations as described in [2].

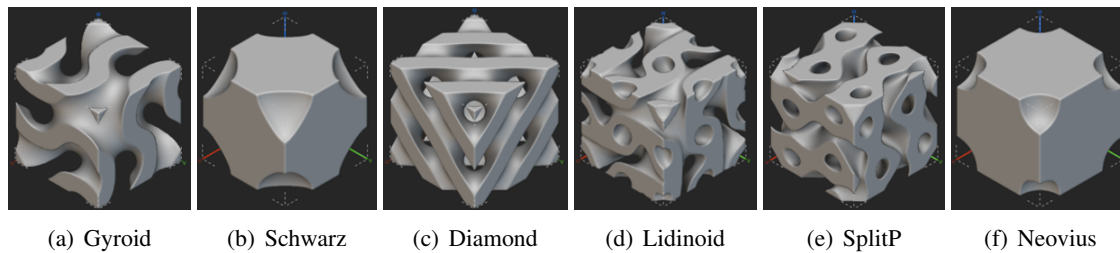


Fig. 1 — TPMS unit cells.

2.2.2 Graph Unit Cells

The graph lattice types investigated in this study are simple cubic, body centered cubic, face centered cubic, diamond (not the same as the TPMS diamond), fluorite, octet, truncated cube, truncated octahedron, kelvin cell, isoTruss, re-entrant, and Weaire-Phelan. The unit cell for each of these lattice types are shown in Fig. 2. Graph unit cells are defined by some line path within the unit cell, which when applied with some thickness are referred to as beams. For example, the graph unit cell of Fig. 2(b) is a unit cell containing lines from the center of the unit cell to the corners of the bounding box of the unit cell, shown in Fig. 3(a). Applied with a thickness these lines become beams, highlighted in Fig. 3(b).

3. Lattice Density Analysis

Each lattice type has a different unit cell density (% fill volume). The unit cell % fill volume refers to the amount of material contained within a unit cell or the ratio of material to air in a unit cell. For a unit cell of solid material (i.e. no lattice applied) the % fill volume would be 100%. Thus, applying a lattice would reduce the fill volume to some percentage under 100%. As we see in Fig. 1 and Fig. 2 each lattice type has a different unit cell density. So, if we apply two different lattice types to a part and look at the % fill volume of both, with the same unit cell size and thickness between the two, we would see different % fill volumes

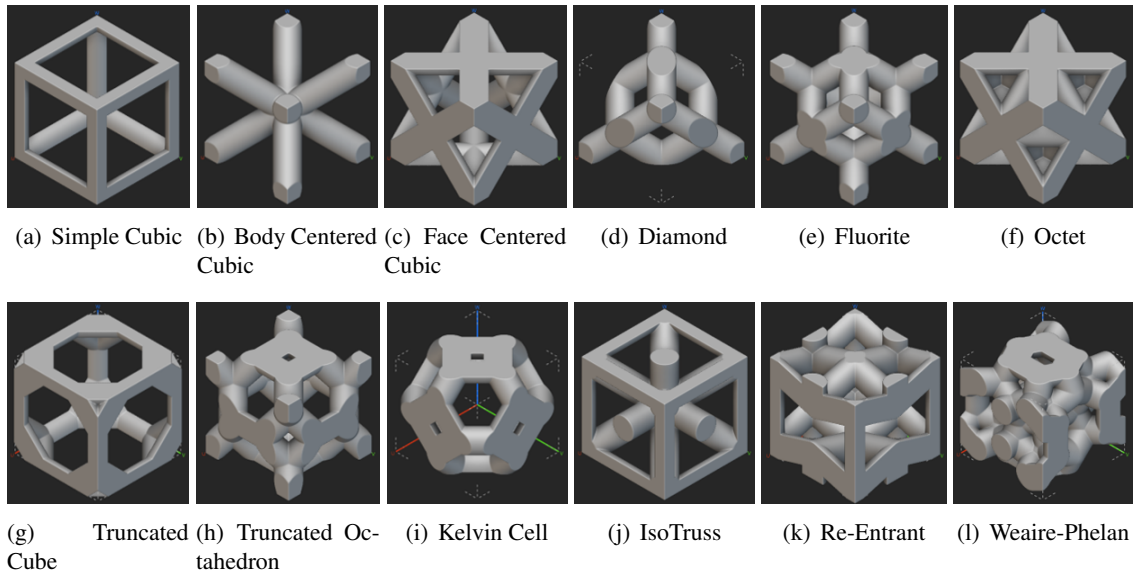


Fig. 2 — Graph unit cells.

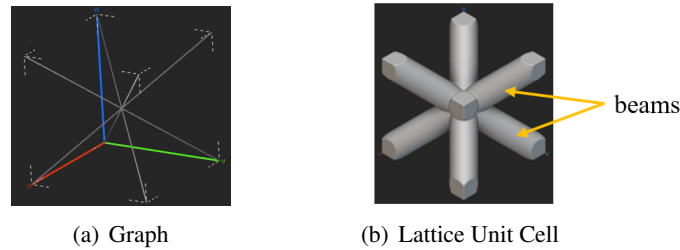


Fig. 3 — Graph unit cells are defined by some line path graph like the grey lines seen in (a). When applied with some thickness these become beams, called out in (b).

for the total part. This is shown in Fig. 4 where each line is a different lattice type showing the variability of the fill volumes.

Isolating the TPMS unit cells, shown in Fig. 5, a thickness of $1/2$ of unit cell size or greater becomes a solid block or 100% fill volume. However, if we look at Fig. 6 there is a wider spread of % fill volume for thickness values above $1/10$ th of unit cell size. This means if we want to maintain the same % fill volume but switch lattice type either the thickness or unit cell size needs to be varied to compensate.

Lookup charts like Fig. 7 and Fig. 8 simplify the process of determining the required ratio of thickness to unit cell size for a desired % fill volume and vice versa. Alternatively, a lookup table, Table 1, is included containing the same data.

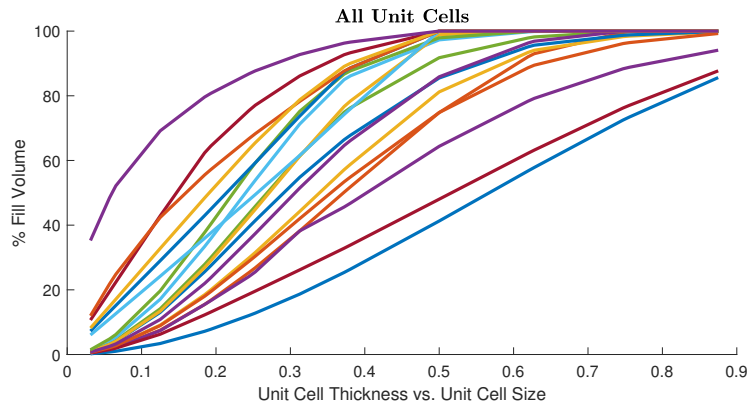


Fig. 4 — The unit cell thickness is varied in relation to the unit cell size. The % fill volume for the different unit cells can vary widely for a given thickness/unit cell size. Each line is a different unit cell type

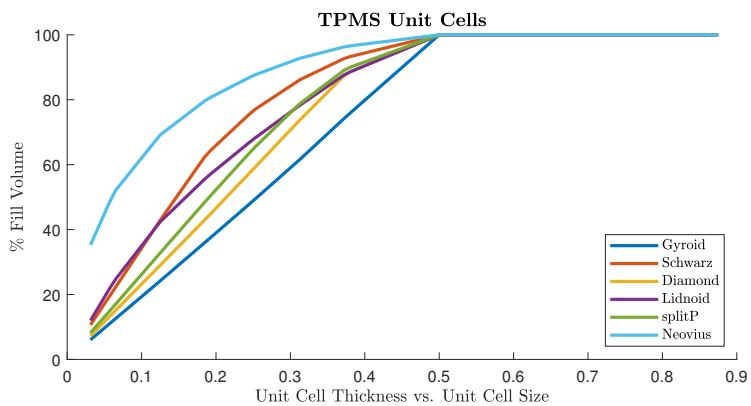


Fig. 5 — The unit cell thickness is varied in relation to the unit cell size. The % fill volume for the different unit cells can vary widely for a given thickness/unit cell size. Each line is a different unit cell type

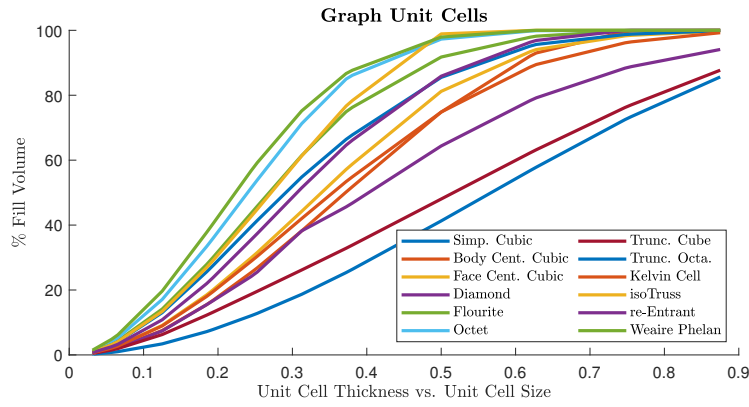
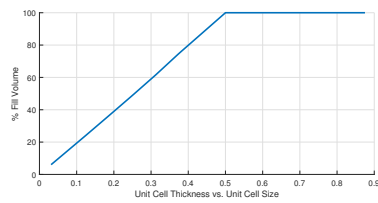
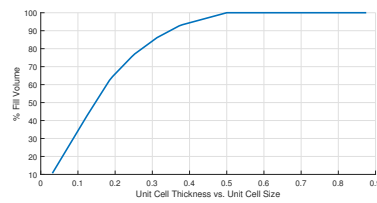


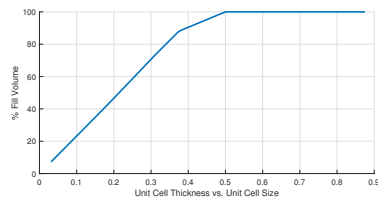
Fig. 6 — The unit cell thickness is varied in relation to the unit cell size. The % fill volume for the different unit cells can vary widely for a given thickness/unit cell size. Each line is a different unit cell type



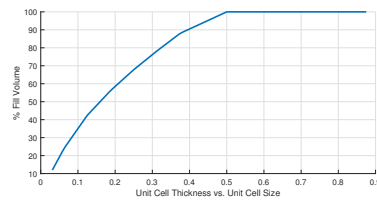
(a) Gyroid



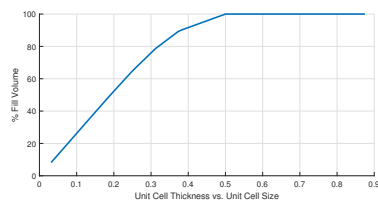
(b) Schwarz



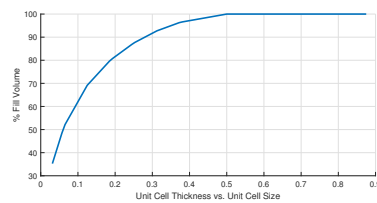
(c) Diamond (TPMS)



(d) Lidinoid



(e) SplitP



(f) Neovius

Fig. 7 — TPMS unit cells.

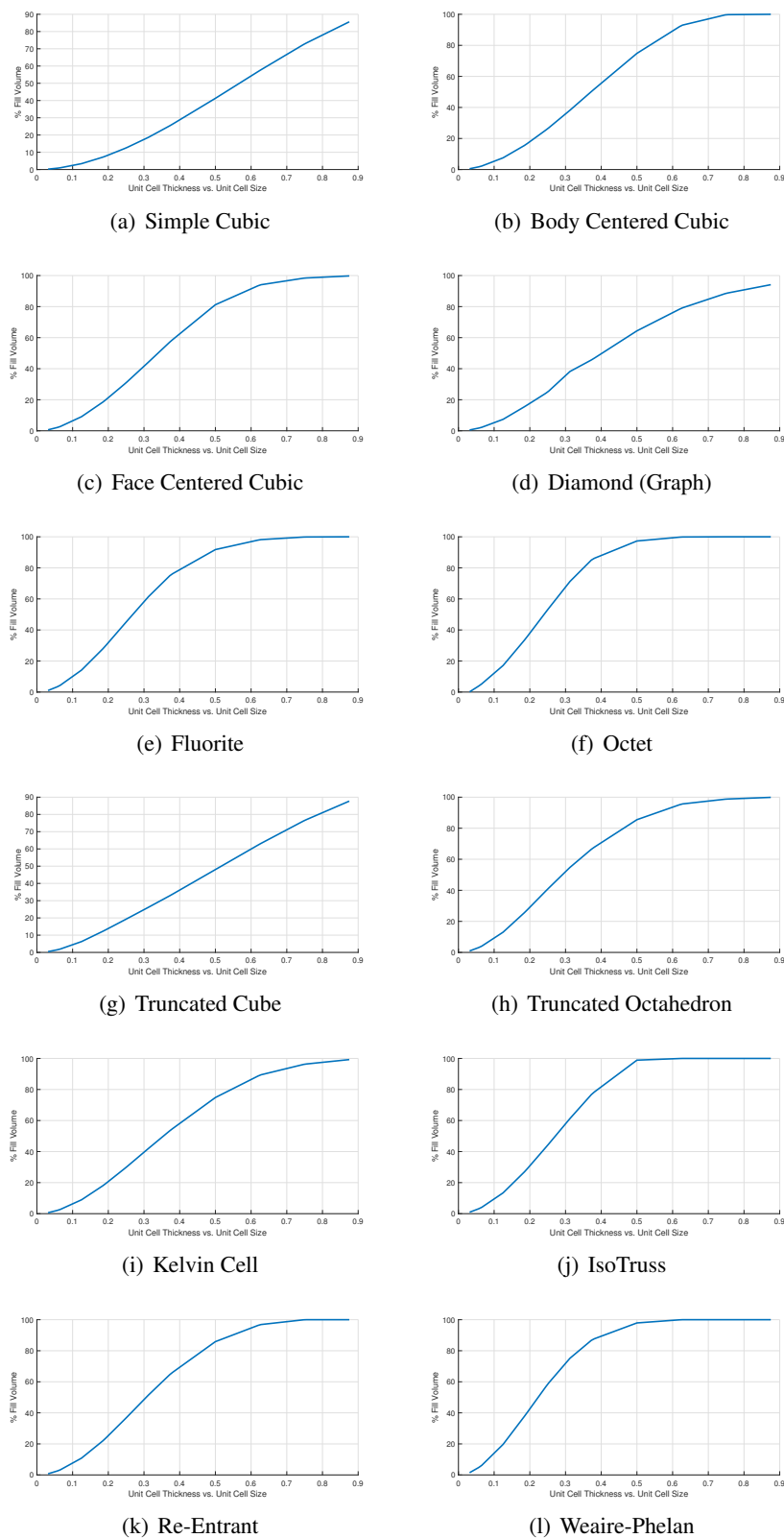


Fig. 8 — Graph unit cells.

Table 1 — Lookup table for the lattice % fill volume. Each row is a ratio of thickness to unit cell size and each column is a different lattice type. This table can be used to design a lattice with a specific % fill volume.

Thickness	Simple cubic	Body Centered Cubic	Face Centered Cubic	Diamond (Graph)	Flourite	Octet	Truncated Cube	Truncated Octahedron	Keivin Cell	IsoTruss	Re-Entrant	Weaire Phelan	Gyroid	Schwarz	Diamond (TPMS)	Lidnoid	SplitP	Neovius
0.0313	0.23	0.51	0.63	0.51	1.01	0.13	0.46	0.95	0.63	0.95	0.75	1.46	6.04	10.65	7.24	11.98	8.18	35.26
0.0398	0.41	0.92	1.12	0.92	1.8	1.38	0.81	1.68	1.12	1.69	1.34	2.57	7.69	13.58	9.22	15.25	10.41	39.65
0.0483	0.59	1.32	1.61	1.32	2.58	2.64	1.16	2.41	1.61	2.43	1.93	3.69	9.34	16.51	11.21	18.52	12.64	44.05
0.0569	0.77	1.73	2.11	1.73	3.37	3.89	1.51	3.14	2.1	3.17	2.52	4.8	10.99	19.44	13.19	21.8	14.87	48.44
0.0654	1.01	2.26	2.74	2.25	4.36	5.29	1.95	4.05	2.72	4.11	3.28	6.19	12.64	22.37	15.17	24.81	17.1	52.17
0.0739	1.35	3.01	3.64	2.98	5.76	6.98	2.57	5.34	3.61	5.44	4.35	8.12	14.29	25.3	17.15	27.32	19.35	54.6
0.0824	1.69	3.76	4.55	3.71	7.16	8.66	3.18	6.62	4.5	6.76	5.43	10.04	15.95	28.23	19.12	29.83	21.59	57.03
0.091	2.03	4.52	5.46	4.44	8.55	10.35	3.8	7.9	5.38	8.09	6.51	11.97	17.6	31.16	21.1	32.35	23.83	59.46
0.0995	2.38	5.27	6.36	5.18	9.95	12.03	4.42	9.18	6.27	9.42	7.59	13.89	19.25	34.09	23.07	34.86	26.08	61.89
0.108	2.72	6.03	7.27	5.91	11.34	13.72	5.04	10.46	7.16	10.74	8.67	15.82	20.9	37.02	25.05	37.37	28.32	64.32
0.1165	3.06	6.78	8.18	6.64	12.74	15.4	5.66	11.74	8.05	12.07	9.75	17.74	22.56	39.96	27.02	39.88	30.57	66.74
0.125	3.4	7.54	9.09	7.38	14.14	17.09	6.27	13.03	8.94	13.4	10.83	19.67	24.21	42.88	29	42.39	32.81	69.17
0.1336	3.94	8.67	10.43	8.53	16.1	19.42	7.13	14.82	10.23	15.33	12.42	22.25	25.88	45.67	30.99	44.27	35.04	70.66
0.1421	4.48	9.8	11.77	9.69	18.06	21.75	7.98	16.62	11.53	17.25	14.01	24.83	27.56	48.45	32.99	46.14	37.27	72.15
0.1506	5.02	10.94	13.11	10.84	20.02	24.07	8.84	18.41	12.82	19.18	15.6	27.41	29.24	51.23	34.98	48.02	39.5	73.64
0.1591	5.56	12.07	14.45	12	21.98	26.4	9.69	20.2	14.12	21.11	17.19	29.99	30.91	54.01	36.97	49.89	41.72	75.13
0.1677	6.1	13.21	15.8	13.16	23.94	28.73	10.54	21.99	15.41	23.03	18.78	32.57	32.59	56.79	38.97	51.77	43.95	76.63
0.1762	6.63	14.34	17.14	14.31	25.9	31.06	11.4	23.79	16.71	24.96	20.37	35.14	34.26	59.57	40.96	53.65	46.18	78.12
0.1847	7.17	15.48	18.48	15.47	27.86	33.39	12.25	25.58	18	26.89	21.96	37.72	35.94	62.36	42.96	55.52	48.41	79.61
0.1932	7.82	16.81	20.02	16.68	30.02	35.88	13.15	27.51	19.48	29.04	23.78	40.39	37.63	64.5	44.98	57.21	50.58	80.77
0.2017	8.53	18.23	21.66	17.92	32.28	38.46	14.07	29.5	21.03	31.3	25.73	43.11	39.32	66.32	47.03	58.8	52.72	81.78
0.2103	9.24	19.65	23.31	19.16	34.54	41.04	14.99	31.5	22.59	33.56	27.67	45.82	41.01	68.15	49.07	60.39	54.87	82.78
0.2188	9.94	21.08	24.95	20.4	36.81	43.62	15.91	33.49	24.15	35.82	29.61	48.54	42.7	69.97	51.11	61.98	57.01	83.79
0.2273	10.65	22.5	26.59	21.64	39.07	46.2	16.84	35.48	25.7	38.08	31.56	51.25	44.39	71.8	53.16	63.57	59.15	84.79
0.2358	11.36	23.92	28.23	22.88	41.33	48.78	17.76	37.48	27.26	40.34	33.5	53.97	46.08	73.62	55.2	65.16	61.3	85.8
0.2444	12.06	25.35	29.87	24.12	43.59	51.36	18.68	39.47	28.82	42.6	35.44	56.68	47.77	75.45	57.25	66.76	63.44	86.8
0.2529	12.81	26.84	31.57	25.55	45.84	53.91	19.61	41.43	30.41	44.89	37.41	59.25	49.47	77.1	59.3	68.29	65.5	87.71
0.2614	13.65	28.46	33.38	27.36	48.07	56.39	20.54	43.34	32.07	47.24	39.42	61.53	51.2	78.39	61.36	69.72	67.39	88.43
0.2699	14.49	30.09	35.19	29.17	50.3	58.86	21.48	45.25	33.73	49.58	41.43	63.8	52.93	79.68	63.47	71.14	69.29	89.15
0.2784	15.32	31.71	37	30.98	52.53	61.34	22.42	47.16	35.38	51.93	43.44	66.08	54.65	80.97	65.48	72.57	71.18	89.87
0.287	16.16	33.34	38.81	32.79	54.75	63.82	23.36	49.07	37.04	54.27	45.45	68.36	56.38	82.26	67.54	73.99	73.08	90.59
0.2955	17	34.97	40.62	34.6	56.98	66.3	24.3	50.98	38.7	56.62	47.46	70.63	58.1	83.55	69.6	75.42	74.97	91.31
0.304	17.84	36.59	42.43	36.41	59.21	68.78	25.24	52.89	40.36	58.96	49.47	72.91	59.83	84.84	71.66	76.84	76.86	92.03
0.3125	18.67	38.22	44.24	38.21	61.44	71.26	26.17	54.8	42.02	61.31	51.48	75.19	61.56	86.12	73.72	78.27	78.76	92.75
0.3211	19.63	39.93	46.08	39.27	63.36	73.22	27.13	56.45	43.64	63.5	53.35	76.83	63.37	87.06	75.68	79.6	80.23	93.26
0.3296	20.59	41.63	47.92	40.32	65.29	75.18	28.08	58.11	45.27	65.7	55.23	78.47	65.18	88	77.64	80.94	81.7	93.76
0.3381	21.54	43.34	49.76	41.38	67.21	77.14	29.04	59.77	46.89	67.89	57.11	80.11	66.99	88.94	79.6	82.28	83.18	94.26
0.3466	22.5	45.05	51.61	42.44	69.14	79.1	29.99	61.43	48.52	70.09	58.98	81.75	68.79	89.88	81.56	83.62	84.65	94.76
0.3551	23.45	46.76	53.45	43.49	71.06	81.06	30.95	63.09	50.14	72.29	60.86	83.4	70.6	90.81	83.51	84.96	86.13	95.27
0.3637	24.41	48.47	55.29	44.55	72.99	83.02	31.9	64.74	51.77	74.48	62.73	85.04	72.41	91.75	85.47	86.3	87.6	95.77
0.3722	25.36	50.18	57.13	45.6	74.91	84.98	32.86	66.4	53.39	76.68	64.61	86.68	74.22	92.69	87.43	87.64	89.07	96.27
0.3807	26.39	51.84	58.81	46.79	76.29	86.16	33.85	67.8	54.88	78.38	66.17	87.71	75.97	93.32	88.62	88.62	90.04	96.6
0.3892	27.46	53.48	60.41	48.05	77.4	86.96	34.86	69.06	56.31	79.85	67.58	88.44	77.69	93.8	89.44	89.44	90.75	96.85
0.3978	28.52	55.12	62.01	49.3	78.5	87.75	35.88	70.33	57.73	81.31	68.99	89.17	79.4	94.27	90.25	90.25	91.46	97.09
0.4063	29.58	56.77	63.61	50.56	79.61	88.55	36.89	71.59	59.16	82.78	70.39	89.89	81.12	94.75	91.06	91.06	92.17	97.33
0.4148	30.65	58.41	65.21	51.81	80.71	89.35	37.9	72.86	60.58	84.24	71.8	90.62	82.84	95.23	91.88	91.88	92.88	97.57
0.4233	31.71	60.05	66.81	53.07	81.82	90.14	38.91	74.12	62.01	85.71	73.21	91.35	84.55	95.71	92.69	92.69	93.6	97.82
0.4318	32.77	61.69	68.41	54.33	82.93	90.94	39.93	75.39	63.43	87.17	74.62	92.08	86.27	96.18	93.5	93.5	94.31	98.06
0.4404	33.84	63.33	70.01	55.58	84.03	91.73	40.94	76.65	64.85	88.64	76.02	92.81	87.99	96.66	94.31	94.31	95.02	98.3
0.4489	34.9	64.97	71.61	56.84	85.14	92.53	41.95	77.92	66.28	90.1	77.43	93.54	89.7	97.14	95.13	95.13	95.73	98.54
0.4574	35.96	66.62	73.21	58.09	86.24	93.32	42.97	79.18	67.7	91.57	78.84	94.27	91.42	97.62	95.94	95.94	96.44	98.79
0.4659	37.03	68.26	74.81	59.35	87.35	94.12	43.98	80.44	69.13	93.03	80.24	95	93.14	98.09	96.75	96.75	97.15	99.03
0.4745	38.09	69.9	76.41	60.61	88.46	94.92	44.99	81.71	70.55	94.5	81.65	95.73	94.85	98.57	97.56	97.56	97.87	99.27
0.483	39.16	71.54	78.01	61.86	89.56	95.71	46.01	82.97	71.98	95.96	83.06	96.45	96.57	99.05	98.38	98.38	98.58	99.52
0.4915	40.22	73.18	79.6	63.12	90.67	96.51	47.02	84.24	73.4	97.43	84.47	97.18	98.29	99.52	99.19	99.19	99.29	99.76
0.5	41.28	74.82	81.2	64.37	91.77	97.3	48.03	85.5	74.82	98.89	85.87	97.91	100	100	100	100	100	100
0.5085	42.39	76.05	82.07	65.37	92.21	97.48	49.05	86.19	75.81	98.97	86.62	98.05	100	100	100	100	100	100
0.5171	43.49	77.28	82.94	66.37	92.64	97.65	50.06	86.88	76.8	99.04	87.36	98.2	100	100	100	100	100	100
0.5256	44.6	78.52	83.82	67.36	93.08	97.83	51.07	87.56	77.79	99.12	88.11	98.34	100	100	100	100	100	100
0.5341	45.7	79.75	84.69	68.36	93.51	98	52.09	88.25	78.77	99.19	88.86	98.48	100	100	100	100	100	100
0.5426	46.81	80.98	85.56	69.36	93.95	98.18	53.1	88.94	79.76	99.27	89.6	98.62	100	100	100	100	100	100
0.5512	47.91	82.21	86.43	70.35	94.39	98.36	54.12	89.63	80.75	99.34	90.35	98.77	100	100	100	100	100	100
0.5597	49.02	83.44	87.3	71.35	94.82	98.53	55.13	90.31	81.74	99.42	91.09	98.91	100	100	100	100	100	100
0.5682	50.12	84.67	88.17	72.35	95.26	98.71	56.14	91	82.73	9								

4. Summary

This paper presented the analysis of different lattice types and their unit cell. It was shown how the ratio between thickness and unit cell size determines the percent fill volume of material vs. air for a given lattice type. Using the same thickness and unit cell size values results in different fill volumes depending on the lattice type used. This led to the development of a lookup table and plots to provide a simple method to switch between one lattice and another while maintaining the same volume infill.

5. Future Work

Future work will build upon this analysis to include the manufacturability of these lattice types in different AM processes. Due to how the different additive processes work, a lattice that can be fabricated in one process may not work in another. The goal of this future work is to provide a guideline for which lattice types manufacture well in the different AM processes as well as any unit cell size and thickness limitations. That work combined with this paper will provide a simplified design process of how to choose and design an appropriate lattice for a particular AM process.

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