Structural Performance and Optimization of 3D-Printed PLA Lattice Structures for Sustainable Design in Load-Bearing Applications

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ABSTRACT

This study explores the structural performance and optimization of 3D-printed Polylactic Acid (PLA) lattice structures, focusing on octapeak, hexstar, and dodecahedron designs, for potential load-bearing applications. Through compression testing, the load-displacement behavior of each structure type was analyzed, examining key characteristics such as peak load capacity, deformation patterns, and failure modes. The Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) was employed to assess each configuration based on two primary criteria: compressive strength and mass. This analysis yielded insights that were structure-type specific as well as overall across all nine samples. Among the hexstar configurations, sample 4 attained the highest rank due to its exceptional load-bearing capacity, making it the optimal choice for high-strength applications. Within the octapeak and dodecahedron groups, samples 2 and 7, respectively, demonstrated balanced performance, suitable for applications prioritizing mass efficiency over maximum strength. In the overall ranking, hexstar emerged as the top-performing structure, with its configurations consistently balancing strength and mass effectively, while octapeak and dodecahedron offered viable alternatives for lighter, less load-intensive uses. The findings demonstrate the utility of the PROMETHEE method in optimizing lattice structure configurations for specific engineering applications, thus contributing to the advancement of sustainable design in additive manufacturing. This research provides a framework for selecting 3D-printed structures that meet application-specific criteria for compressive strength and material efficiency.

Keywords-3D-printed PLA structures; lattice structures; compressive strength; PROMETHEE; load-bearing applications; structural performance analysis; sustainable design

I. INTRODUCTION

PLA is a material that has gained significant popularity in the field of additive manufacturing, particularly in the context of three-dimensional printing [1]. As a biodegradable thermoplastic derived from renewable resources such as corn starch and sugarcane, PLA presents an environmentally friendly alternative to petroleum-based plastics [2]. Its ease of processing, minimal warping, and high dimensional accuracy make it ideal for rapid prototyping and functional parts in educational, industrial, and research applications [3, 4]. However, its relatively low melting point and limited flexibility impose limitations on its use in high-temperature or high-stress environments [5]. Its structural potential, coupled with its low density, renders it an optimal choice in sectors such as aerospace, automotive, and biomedical engineering, where durability and lightweight properties are paramount [6]. The design of 3D-printed structures, particularly lattice configurations such as octapeak and dodecahedron, directly impacts their load-bearing performance [7, 8]. These structures can be engineered to balance strength and mass, thereby optimizing them for specific applications. However, identifying the optimal configuration of these lattice designs requires a careful analysis of multiple performance criteria, including compressive strength and mass [9–11]. This study uses the PROMETHEE method [12] as a Multi-Criteria Decision-Making (MCDM) approach to evaluate and rank 3D-printed PLA structures based on their load-bearing capabilities and mass. The PROMETHEE method offers a structured and preference-based ranking system, enabling a nuanced assessment of trade-offs between conflicting criteria. In contrast to conventional approaches such as TOPSIS or AHP, which often oversimplify preference modeling, PROMETHEE allows for a more flexible and accurate evaluation of trade-offs between multiple criteria, making it well-suited for analyzing structural performance and sustainable design optimization. The present study aims to identify the most efficient structure that maximizes compressive strength while minimizing mass by applying PROMETHEE [13]. The findings of this study contribute to the understanding of how lattice geometry and material properties influence structural performance, offering insights for sustainable and optimized design in load-bearing applications. This study introduces a novel approach by integrating the PROMETHEE method into the optimization of 3D-printed PLA lattice structures for load-bearing applications. A distinguishing feature of this study is its adoption of a systematic and preference-based multi-criteria decision-making approach, which stands in contrast to the predominant focus on experimental evaluations in prior research. This approach enables the ranking of configurations based on their performance in terms of compressive strength and mass. This quantitative framework underscores trade-offs and provides a reproducible methodology for sustainable design in additive manufacturing.

II. MATERIALS AND METHODS

A. Material Used

The material used for the fabrication of the sample was PLA filament (MakerBot® PLA, 1.75 mm diameter), which is characterized by its biodegradable and environmentally friendly properties. The selection of PLA was made on the basis of its suitability for sustainable designs and compatibility with 3D printing processes. The specimens were manufactured with the printer of the School of Mechanical and Automotive Engineering (SMAE)-500CF 3D. The printer supports Fused Deposition Modeling (FDM) technology and is designed for composite materials, including PLA, PETG, PLA-CF, and PETG-CF with a build volume of 500 mm × 500 mm × 300 mm, maximum print speed of 120 mm/s, and maximum nozzle temperature of 350 °C, thereby enabling the fabrication of high-precision lattice structures. The specimens were designed with three distinct lattice structures, namely octapeak, hexstar, and dodecahedron [14], and were fabricated with varying edge lengths (6, 8, and 10 mm) and shell thicknesses (1.2, 1.6, and 2.0 mm). Compression tests were conducted in accordance with ASTM D695 standards, which delineate the testing methodologies for the evaluation of the compressive properties of polymer materials. A Zwick/Roell Z050 Universal Testing Machine with a 50 kN load cell was used for the compression tests which were conducted at a constant displacement rate of 1 mm/min. The failure criterion was defined as the maximum load (peak force) recorded during the test, which represents the compressive strength of each specimen. This value indicates failure due to brittle collapse or structural deformation under load. The mass of each sample was measured with an analytical balance (Shimadzu AUW220D) with an accuracy of ±0.01 g, ensuring precise data collection.

B. Structure Design

Three distinct structures were selected for testing, based on their unique geometric configurations, each of which has the potential to affect compressive strength and mass differently, as shown in Figure 1. Each structure is characterized by the following features:

- Octapeak: This structure is distinguished by a combination of octahedral and pyramid-like shapes that contribute to both rigidity and light mass properties. It is anticipated that this interconnected triangular geometry will yield moderate compressive strength.
- Hexstar: The hexstar structure is distinguished by its star-shaped cross-section, which integrates hexagonal elements with radial symmetry. The hypothesis is that this design will yield high compressive strength, as the interconnected arms and central core provide strong load-bearing capabilities.
- Dodecahedron: The dodecahedron features a regular polyhedral form with twelve pentagonal faces, and it is expected to exhibit balanced strength characteristics due to its symmetrical and evenly distributed load-bearing surfaces.

(a)

(b)

(c)

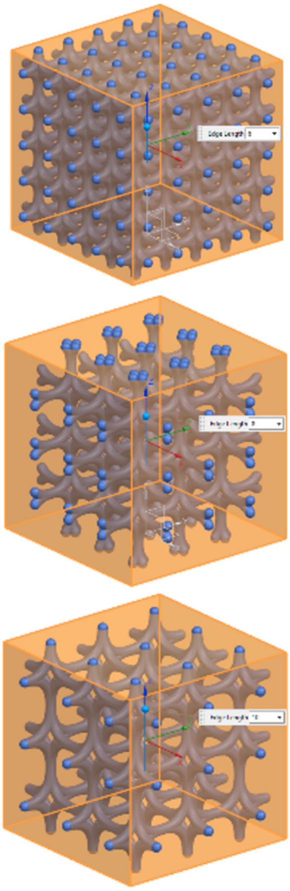
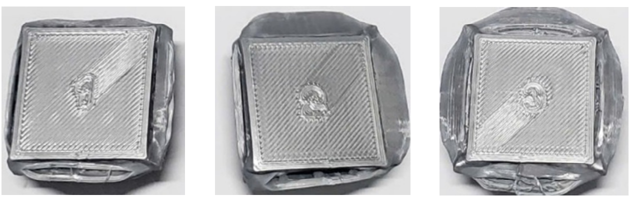


Fig. 1. CAD models of 3D-printed structures: (a) octapeak, (b) hexstar, (c) dodecahedron.

The design and fabrication of each structure was conducted with distinct parameter settings, aiming to investigate the impact of structural geometry on the material's compressive performance and mass, as presented in Figure 2.



(a) (b) (c)

Fig. 2. Physical appearance of 3D-printed structures after compression testing: (a) octapeak, (b) hexstar, (c) dodecahedron.

C. *Variable Factors*

In order to systematically examine the effects of different design parameters on the compressive strength and mass of the 3D-printed samples, two primary variables were modified:

- Structures were printed with edge lengths of 6 mm, 8 mm, and 10 mm to assess the influence of size on mechanical properties. It was hypothesized that larger edge lengths would increase volume, mass, and compressive strength.
- Shell thickness was also varied, with structures printed at 1.2 mm, 1.6 mm, and 2 mm thickness to assess the impact on material distribution. Shell thicknesses of 1.2 mm, 1.6 mm, and 2 mm were applied to evaluate material distribution. It is generally accepted that thicker shells enhance strength, though they concomitantly increase mass. Conversely, thinner shells have been demonstrated to reduce structural integrity.

These variables were meticulously chosen to observe their individual and combined effects on the compressive strength and mass of the PLA samples, thereby facilitating a comprehensive analysis of each structural configuration.

D. *Measurement Metrics*

In order to assess the performance of each 3D-printed specimen, two critical metrics were evaluated:

- Compressive strength (MPa): This metric quantifies the maximum stress that each structure can withstand before failing under compressive load. This metric was measured using a compression testing machine, where samples were loaded in a controlled environment until structural failure occurred. The compressive strength of each sample was calculated by dividing the peak force experienced during testing by the cross-sectional area at the point of failure.
- Mass (g): The mass of each sample was measured using a precision scale. The significance of mass is particularly pronounced in applications that demand lightweight components, as it directly impacts portability and energy efficiency in mechanical systems. The objective of this study is to identify designs that achieve an optimal balance between compressive strength and minimized mass. To this end, the mass of each sample was recorded.

This study uses a systematic variation approach, encompassing edge length and shell thickness, to comprehensively assess the trade-offs associated with optimizing 3D-printed PLA structures for applications that demand both durability and lightness. The experimental design encompasses a meticulous measurement of compressive strength and mass, providing a comprehensive understanding of the trade-offs involved in the optimization process. The factors and their levels were selected to encompass a broad spectrum of practical cutting conditions. The Taguchi experimental design yielded a total of nine experimental runs as presented in Table I.

TABLE I. EXPERIMENTAL RESULTS

No.	Struct. Type	Edge Length (mm)	Shell Thickness (mm)	Ultimate Compressive Stress (MPa)	Mass (g)
1	Oct	6	1.2	334.1	13
2	Oct	8	1.6	368.6	12
3	Oct	10	2	463.9	14
4	Hex	6	1.6	1,786.5	32
5	Hex	8	2	1,200.7	24
6	Hex	10	1.2	529.3	17
7	Dod	6	2	999.2	23
8	Dod	8	1.2	383.9	16
9	Dod	10	1.6	355.6	15

III. RESEARCH METHODOLOGY

This study uses the PROMETHEE method to analyze and rank 3D-printed PLA lattice structures, namely the octapeak, hexstar, and dodecahedron designs, based on two key criteria: compressive strength and mass. PROMETHEE, a widely used MCDM method, facilitates pair-wise comparisons across criteria and generates rankings of alternatives based on their respective preference flows. This methodological approach furnishes a lucid and systematic modus operandi for the identification of optimal configurations that achieve an equilibrium between strength and mass requirements.

A. Application of the PROMETHEE Method

This study uσes the PROMETHEE method to assess 3D-printed PLA lattice structures (octapeak, hexstar, and dodecahedron) in terms of compressive strength and mass. PROMETHEE facilitates structured, preference-based ranking through pairwise comparisons of alternatives across multiple criteria, rendering it particularly well-suited for analyzing the balance between structural strength and material efficiency.

1) Computational Steps and Formulas in the PROMETHEE Method

The first step in the process is to define the criteria and preference functions:

- Criteria: Compressive strength C1, higher values are preferred and Mass C2, lower values are preferred.
- Preference functions: For each criterion, a preference function P(a,b) is defined to measure the degree of preference of alternative a over b.

The subsequent step involves the calculation of preference indices. The third step entails the determination of positive and negative flow scores and the final step involves the calculation of net flow score. The detailed formulas for these calculations have been comprehensively presented by authors in [13, 15]. The computed results, including intermediate steps and rankings, are summarized in Table II. This behavior indicates that, while octapeak possesses a satisfactory initial load-bearing capacity, its performance under continuous compression is constrained due to the presence of stress concentration points within its geometry. The load capacity of the specimens exhibited variation due to differences in shell thickness and edge length. It was observed that thicker shells or shorter edge lengths generally resulted in better load retention, as shown in Figure 3.

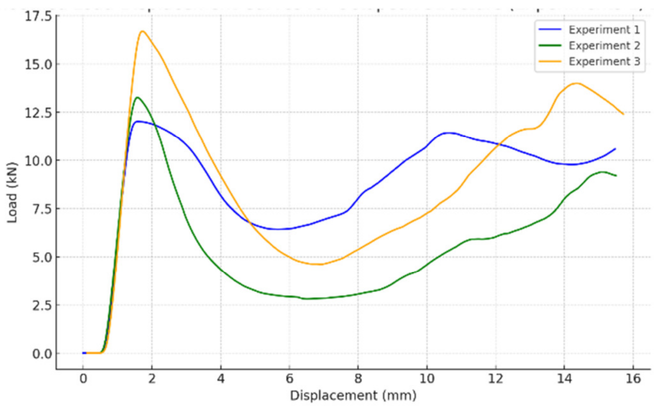


Fig. 3. Load-displacement curves for octapeak structure.

TABLE II. EXPERIMENTAL RESULTS

No.	Structure Type	Edge Length (mm)	Shell Thickness (mm)	Ultimate Compressive Stress (MPa)	Mass (g)	Pref. Compressive	Pref. Mass	Positive Flow	Negative Flow	Net Flow	Ranking
1	Oct	6	1.2	334.1	13	334.1	0.077	334.18	379.42	-45.24	5
2	Oct	8	1.6	368.6	12	368.6	0.083	368.68	344.91	23.77	2
3	Oct	10	2	463.9	14	463.9	0.071	463.97	249.62	214.35	8
4	Hex	6	1.6	1,786.5	32	1,786.5	0.031	1,786.53	-1,072.94	2,859.47	1
5	Hex	8	2	1,200.7	24	1,200.7	0.042	1,200.74	-487.15	1,687.89	4
6	Hex	10	1.2	529.3	17	529.3	0.059	529.36	184.23	345.12	6
7	Dod	6	2	999.2	23	999.2	0.043	999.24	-285.65	1,284.89	3
8	Dod	8	1.2	383.9	16	383.9	0.063	383.96	329.63	54.33	9
9	Dod	10	1.6	355.6	15	355.6	0.067	355.67	357.93	-2.26	7

B. Hexstar Structure

The hexstar structure demonstrates a notably robust load-bearing capacity, as evidenced by the higher and more gradual peak in the load-displacement curves. In contrast to octapeak, hexstar demonstrates a prolonged capacity to bear loads over an expanded displacement range, thereby evidencing enhanced structural resilience. Following the attainment of the maximum load, hexstar's curves demonstrate a gradual decline, suggesting controlled deformation. This trend underscores the structural stability imparted by the interconnected arms within the hexstar design, which efficaciously distribute compressive forces and retard the onset of buckling or fracturing. The uniformity observed across experimental trials indicates that the hexstar structure possesses the capacity to adequately withstand elevated loads, rendering it well-suited for applications necessitating sustained load-bearing capabilities, as presented in Figure 4.

C. Dodecahedron Structure

The load-displacement curves of the dodecahedron structure indicate a lower peak load in comparison to both the octapeak and hexstar structures. The curves generally show a rapid rise followed by a noticeable peak, after which the load decreases sharply. This precipitous decline is indicative of early buckling or failure, which is likely attributable to the dodecahedron's complex, open-cell design, which distributes load less effectively than hexstar. Furthermore, the post-peak deviation observed in the dodecahedron curves indicates structural instability, suggesting a propensity for compression-induced failure, as shown in Figure 5. The comparatively diminished load-bearing capacity and accelerated failure of the dodecahedron suggest that it might be more suitable for applications that prioritize material efficiency over structural strength.

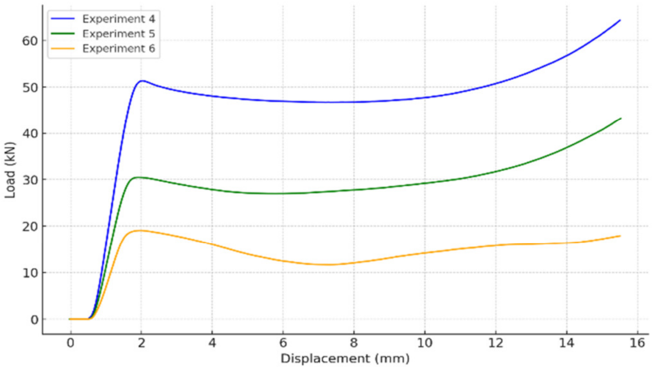


Fig. 4. Load-displacement curves for hexstar structure.

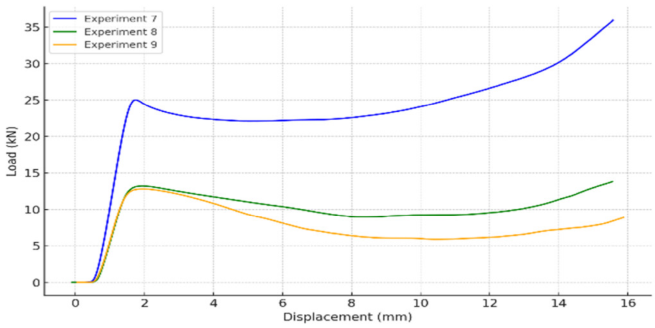


Fig. 5. Load-displacement curves for dodecahedron structure.

A comparative analysis of the three structures reveals a discernible hierarchy in their load-bearing capacity. Hexstar exhibits the highest compressive strength and structural resilience, as evidenced by its design, featuring interconnected arms that enable it to withstand greater forces without immediate failure. The gradual decline in load after the peak indicates effective load distribution and controlled deformation, making hexstar suitable for applications that demand strength and durability. Octapeak, while offering moderate load-bearing capacity, exhibits a tendency for stress concentration and localized buckling. This structure may be preferable for lighter applications where maintaining a lower mass is essential, but the load requirements are less demanding than those for hexstar. dodecahedron exhibits the lowest compressive strength, as indicated by the sharp decline in load after the peak. This design demonstrates susceptibility to early buckling and structural instability under sustained compression, which could be advantageous in non-load-bearing applications or situations where minimizing material use is critical. In summary, hexstar emerges as the most robust structure for compressive applications, while octapeak and dodecahedron offer trade-offs between strength and mass, each suited to different types of applications. The results of this study highlight the importance of selecting a structure based on the specific requirements of load-bearing and material efficiency.

D. Analysis by Structure Type with the PROMETHEE Method

1) Octapeak

Within the octapeak group, sample 2 (edge length 8 mm, shell thickness 1.6 mm) achieved the highest ranking with a PROMETHEE score of 2, indicating an optimal balance of compressive strength (368.6 MPa) and relatively low mass (12 g). Sample 1 (edge length 6 mm, shell thickness 1.2 mm) attained a ranking of 5, indicating that while it offers a lighter mass (13 g), its compressive strength (334.1 MPa) is comparatively lower. Sample 3 (edge length 10 mm, shell thickness 2 mm) is the least favorable within the octapeak category, with a rank of 8 due to its higher mass (14 g) and moderate compressive strength (463.9 MPa). This ranking suggests that octapeak structures with moderate edge length and shell thickness, such as Sample 2, achieve the best balance in the PROMETHEE analysis, indicating suitability for lightmass applications with moderate strength requirements.

2) Hexstar

In the present study, sample 4 (6 mm edge length, 1.6 mm shell thickness) was found to demonstrate the highest levels of compressive strength (1786.5 MPa) and mass (32 g), thereby positioning it as the optimal candidate for applications that prioritize strength. Sample 5 (8 mm, 2 mm) achieves a 4th-place ranking, exhibiting a balanced performance between strength (1200.7 MPa) and mass (24 g). Sample 6 (10 mm, 1.2 mm) exhibits lower strength (529.3 MPa) but higher mass (17 g). Overall, hexstar structures demonstrate a commendable performance, with Sample 4 being particularly noteworthy for its applications requiring high strength in scenarios where mass is less significant.

3) Dodecahedron

In the context of the present study, sample 7 (6 mm edge length, 2 mm shell thickness) was found to be the most optimal specimen, ranking third overall and first within the dodecahedron group. This specimen exhibited a noteworthy strength of 999.2 MPa and a moderate mass of 23 g, characteristics that render it particularly well-suited for balanced applications. Samples 8 and 9 (8 mm and 10 mm, with 1.2 mm and 1.6 mm shell thicknesses, respectively) rank 9th and 7th, with lower strengths (383.9 MPa and 355.6 MPa) but lighter masses (16 g and 15 g, respectively). Dodecahedron structures are particularly well-suited for applications that prioritize mass reduction, with sample 7 offering an optimal balance of strength and weight.

4) Overall Analysis

The top performer is characterized by its exceptional performance metrics, which are outlined below. In sample 4 (hexstar), with an edge length of 6 mm and shell thickness of 1.6 mm, the highest PROMETHEE ranking was achieved across all structure types, with a value of 1. This sample's high compressive strength and moderate mass make it the most viable choice for load-bearing applications requiring maximum durability. The balanced options, in contrast, include samples from each structure type that provide balanced performance in different scenarios. For example, sample 2 (octapeak) and sample 7 (dodecahedron) both rank within the top three, indicating that they offer competitive performance in terms of mass efficiency and adequate strength. Conversely, lower-ranked samples, specifically samples 8 and 9 (dodecahedron) and sample 3 (octapeak), exhibited inferior performance metrics across various evaluation criteria. Samples 8 and 9 (dodecahedron) and sample 3 (octapeak) received the lowest rankings in the overall PROMETHEE analysis. These configurations exhibit limited compressive strength, rendering them less suitable for load-bearing applications but potentially useful in lightweight, non-structural applications. The PROMETHEE analysis underscores hexstar as the most structurally robust design, with sample 4 attaining the highest overall ranking. Octapeak and dodecahedron offer alternatives for applications where mass is a primary concern rather than strength, with octapeak's sample 2 and dodecahedron's sample 7 as the most optimal configurations within their respective types. This comprehensive ranking provides a clear guide for selecting structures based on application-specific needs for strength and mass balance.

IV. CONCLUSIONS

This study evaluated the structural performance and optimization of 3D-printed Polylactic Acid (PLA) lattice structures using the Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) method for multi-criteria decision-making. The results demonstrated that the hexstar structure, with a compressive strength of 1786.5 MPa, outperformed other designs and surpassed prior studies [3], where similar lattice configurations achieved strengths of approximately 1500 MPa. The octapeak design exhibited an optimal balance of light mass (12 g) and reasonable strength (368.6 MPa), aligning with observations in [7] regarding the suitability of PLA for mass-sensitive applications.The integration of PROMETHEE further distinguishes this work by providing a quantitative framework for evaluating structural performance, advancing beyond empirical-only methods highlighted in [12] and [14]. This approach offers a robust and reproducible methodology for optimizing lattice designs, particularly in sustainable engineering applications where strength-to-mass ratios are critical. The octapeak structure, particularly sample 2 (8 mm edge length, 1.6 mm shell thickness), achieves a good balance between moderate compressive strength and low mass, making it a viable choice for applications where mass efficiency is prioritized alongside adequate strength. Likewise, the dodecahedron structure (sample 7, 6 mm edge length, 2 mm shell thickness) exhibits a balanced compromise between compressive strength and mass, positioning it as a viable alternative for lightmass applications with moderate strength requirements. In summary, the PROMETHEE analysis provides a comprehensive ranking of the structures, guiding the selection of 3D-printed PLA lattice configurations based on specific application requirements for strength and mass balance. This work demonstrates the effectiveness of the PROMETHEE method in assessing multi-criteria design choices and offers a foundation for optimizing PLA structures in sustainable, load-bearing applications.

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