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An Intelligent CRITIC–WASPAS Decision Framework for Sustainable Multi-Material Additive Manufacturing of Architected Structures

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Abstract

Functionally graded multi-material architected structures fabricated by fused deposition modeling (FDM) were investigated to evaluate their multifunctional mechanical and dynamic performance. Sixteen honeycomb configurations incorporating poly(lactic acid) (PLA), thermoplastic polyurethane (TPU), and wood-filled PLA (WWF-PLA) were designed by systematically varying material distribution, cellular geometry, and structural density as integrated architected configurations. Compression, flexural, dynamic mechanical, free-vibration, density reduction, and water absorption tests were conducted, and the experimental responses were objectively evaluated using the CRITIC–WASPAS multi-criteria decision-making framework. Among the investigated configurations, A16 exhibited the highest overall performance, achieving 41.8 MPa compressive strength, 56.4 MPa flexural strength, 1425 MPa storage modulus, 0.162 loss factor ($\tan \delta$), 3.7% damping ratio, and 39% density reduction. Compared with the baseline configuration (A1), A16 demonstrated improvements of 14.5%, 17.0%, 20.8%, 44.6%, 76.2%, and 77.3% in the respective performance metrics. The proposed framework provides an objective approach for ranking integrated architected designs for lightweight multifunctional engineering applications.

Keywords: smart manufacturing; intelligent decision-support systems; data-driven optimization; multi-material additive manufacturing; fused deposition modeling; sustainable manufacturing; CRITIC-WASPAS framework

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1. Introduction

Additive manufacturing (AM) is an emerging technology offering new possibilities for lightweight manufacturing, including functionally graded materials and cellular architecture, which has become an essential component of modern engineering designs in a variety of industries, including aerospace, automotive, biomedical, robotics, and energy-related devices [1–3]. Among different AM techniques, fused deposition modeling (FDM) has attracted the attention of many industry experts and researchers because of low manufacturing costs, material versatility, reduced waste formation during the fabrication process, and the ability to print customized parts with minimized tooling [4–6].

The layer-by-layer fabrication method of FDM allows for printing highly complicated structures with controlled internal architecture, such as architected cells, lattices, and functionally graded materials, which cannot be produced via conventional subtractive manufacturing processes. Modern developments in multi-material FDM have additionally increased design flexibility and opened up new avenues in the field of engineering by allowing the fabrication of systems containing rigid and flexible polymers with controlled stiffness and lightweight features, vibration isolation capability, enhanced heat resistance, and energy absorption properties [7–9]. Overall, multi-material architected structures developed using FDM can be applied in numerous engineering tasks aimed at structural and dynamic performance optimization.

There are many different types of architected structures with unique properties and applications; however, in recent decades, researchers have focused on developing honeycomb geometries, which exhibit the best stiffness-to-weight ratios, high energy absorption capability, effective load distribution, and enhanced deformation capabilities under dynamic loading [10,11]. Honeycomb structures are extensively used in sandwich panels, protective systems, vibration isolators, impact-resistant systems, and support structures due to the possibility of dissipating mechanical energy through elastic and plastic deformation [12–14]. In recent times, more and more researchers have attempted to use viscoelastic polymer materials such as thermoplastic polyurethane (TPU) for increasing damping and vibration mitigation capabilities. In addition, biodegradable and environmentally friendly polymer materials like polylactic acid (PLA) and walnut wood fiber–polymer composite (WWF-PLA) have become an important topic of scientific research due to their environmentally friendly properties, low density, and suitability for processing via FDM technology [15–17]. As a result, multi-material architected cellular structures made from rigid polymer and viscoelastic phases may offer a high potential in engineering designs aimed at enhancing mechanical stability and vibration attenuation capacity of parts under dynamic loads.

Despite the progress made in these areas, finding the right balance of stiffness, light weight, manufacturability, and damping capability still presents a challenge when designing multi-material FDM structures. Most studies currently focus on either the mechanical performance of single-material lattice systems or the structural stiffness of multi-material architected structures without considering their vibrational damping capabilities. In most cases, adding flexible materials enhances the vibration damping capability of such architected structures at the expense of structural stiffness and strength, making them impractical for use in engineering applications. Additionally, the interface compatibility of different materials, weak layer adhesion, printing errors, and uneven stress distribution often compromise the mechanical performance and repeatability of multi-material FDM structures. While some studies have utilized the cellular architecture of multi-material architected FDM structures to enhance energy absorption and dampen vibrations, systematic optimization of functionally graded honeycomb multi-material architected structures remains largely unexplored [10,18]. Our previous study, Subramani [19], investigated functionally graded thermoplastic architectures using the Analytic Hierarchy Process (AHP) to identify an optimal structural configuration based primarily on viscoelastic performance criteria. The present study extends that work in several important aspects. First, a different multi-material system comprising PLA, TPU, and WWF-PLA functionally graded honeycomb structures is investigated experimentally. Second, the engineering assessment is expanded to include compressive strength, flexural strength, dynamic mechanical behavior, free-vibration response, density reduction, and water absorption. Third, the optimization is performed using an objective CRITIC–WASPAS framework, in which criterion weights are determined directly from the experimental data rather than subjective pairwise comparisons. Consequently, this

work focuses on establishing an integrated experimental and objective evaluation methodology for multifunctional architected FDM structures rather than introducing a new optimization algorithm. Furthermore, research gaps exist in the development of decision-making processes capable of optimizing the design of these structures by evaluating multiple design parameters and performance criteria. Therefore, there is a need for optimized multi-material architected structures with high vibration damping capabilities in lightweight additive manufacturing processes based on integrated process–structure–performance analyses and multi-criteria decision-making techniques.

Recent advances in additively manufactured architected structures have shown promising results in enhancing the functional performance of these structures through hybrid materials, lattice geometry optimization, and functionally graded designs. For instance, O’Keefe et al. [20] found that architected cellular structures produced using additive manufacturing possess high stiffness-to-weight ratios and can effectively control their deformation capabilities, which make them ideal for lightweight structural designs and efficient energy absorption. Similarly, Khizar et al. [21] highlighted that architected structures such as honeycombs and lattices have high mechanical efficiency because they redistribute stress through their periodic cellular architecture while minimizing structural mass. In the domain of polymer additive manufacturing, Sagar et al. [22] examined the mechanical performance of FDM-printed PLA structures and found that print orientation, raster structure, and layer adhesion significantly influence the tensile and compressive capabilities of the printed parts. Ulkir et al. [23] showed that the internal infill geometry and printing parameters directly influence the stiffness, anisotropic deformation, and failure mode of FDM structures. While these studies provided insights into the relationship between the printing process and the geometric structure of FDM-printed parts, most studies focused on the static performance of the printed parts rather than their vibrational damping capability.

In an effort to overcome the limitation of insufficient damping performance of rigid thermoplastics, some researchers have integrated flexible viscoelastic materials into AM architectures. Ye et al. [24] developed multi-material structures based on rigid PLA and soft TPU lattices and found that energy dissipation was improved due to the deformation of viscoelastic TPU-rich regions. Along similar lines, Pandey et al. [25] showed that hybrid polymer architectures featuring both rigid and soft polymers are capable of achieving superior vibration mitigation performance due to shear deformations at interfaces and hysteretic energy dissipation behaviors. Another study by Yurtbasi et al. [26] showed that the presence of TPU in cellular structures fabricated through dual-nozzle FDM leads to improved impact energy absorption and resonant response suppression compared with monolithic polymer counterparts. Very recently, Tabril et al. [27] also proved that a well-considered distribution of functionally graded materials in multi-material lattice structures can contribute greatly to stress transmission and deformation control. Additionally, it was demonstrated that flexible polymeric interlayers in architected honeycomb cores (Bian et al. [28]) can enhance the vibration isolation performance due to local deformations and progressive energy dissipation in cellular regions. Even though several works have shown promising results related to multi-material AM, most of the previous studies were confined to simple lattice architectures without systematic optimization of material distribution schemes through multi-criteria evaluations.

At the same time, there has been rising interest in the use of sustainable composite materials in additive manufacturing processes because of their lightweight nature, biodegradability, and low environmental impact. For instance, Bhattacharjee et al. [29] reported that wood fiber-reinforced PLA composite structures manufactured using FDM exhibit enhanced dimensional stability and stiffness compared with neat PLA structures. Also, Teriya et al. [30] showed that natural fiber-reinforced thermoplastic composites possess favorable specific mechanical properties as well as lower environmental impact when used in lightweight applications. However, the inclusion of natural fiber fillers in polymers can lead to some problems related to weak interlayer bonding, higher porosity, and non-uniformity of printing. Thus, researchers have considered hybrid material combinations involving both rigid biocomposites and flexible polymers. Notwithstanding substantial developments in multi-material additive manufacturing and architected cellular structures, several vital challenges continue to exist in the present literature. Firstly, most research studies focus primarily on either the static mechanical properties or energy absorption capability of single-material lattices, whereas relatively few works explore the joint optimization of stiffness retention, lightweight design, damping augmentation, and manufacturing capability of functionally graded multi-material FDM structures. Secondly, although many earlier studies on vibration damping have used simple lattice architectures or homogeneous materials, the impact of material grading and architected honeycomb architectures on the dynamic behavior of these materials has not been sufficiently studied. Although flexible polymers like TPU have been added to rigid thermoplastics to enhance energy dissipation, excessive introduction of viscoelastic components may significantly decrease stiffness and structural integrity, limiting the application in engineering. Thirdly, the interface between rigid and flexible polymers, stress transfer in graded materials, and vibration mitigation mechanisms in architected honeycombs require further investigation. The final constraint in the existing literature relates to the absence of an integrated optimization framework to analyze various conflicting performance parameters. Additive manufacturing optimization research typically involves single-response optimization, which does not adequately consider the multiple requirements of multifunctional structures. For example, the dynamic damping performance, mechanical robustness, reduced weight, and environmental stability of the structure should be analyzed simultaneously. Thus, there is still a necessity to develop a comprehensive optimization methodology based on the process–structure–performance approach of functionally graded multi-material FDM structures using multi-criteria decision-making techniques.

For instance, Faci et al. [31] examined graded PLA/TPU cellular structures and observed that material optimization considerably enhances the damping capacity of such structures without compromising compressive strength. In addition, MCDM has recently become an efficient tool for optimizing additive manufacturing processes with conflicting criteria. For instance, Khan et al. [32] adopted a TOPSIS-based optimization strategy to select the best FDM process parameters by balancing mechanical and surface quality criteria. Likewise, Atalay et al. [33] applied CRITIC-based optimization to rank high-performance composite designs based on various engineering criteria. Nonetheless, despite these advances, the use of architected honeycombs with functionally graded multi-materials and advanced data-driven optimization strategies such as CRITIC-WASPAS to assess the vibration damping performance, mechanical stiffness, density reduction, and manufacturing capability of structures remains unexplored.

The motivation behind conducting this research lies in the increasing need for lightweight yet highly functional structures that can provide better vibration isolation while maintaining adequate mechanical strength and manufacturability properties. More specifically, various industries, such as transportation, robotics, aerospace, automotive

systems, protective engineering, and lightweight structures, among others, require additively manufactured parts that are tailored according to their dynamic properties to ensure resonance avoidance and prevent vibration propagation. In this sense, architected honeycomb structures made with multi-material FDM show great promise because they allow for controlling the material layout, internal structure, deformation modes, and dissipation channels. Moreover, the use of environmentally friendly materials, such as biodegradable PLA, flexible TPU, and wood-reinforced PLA (WWF-PLA) composites, provides additional benefits for sustainability and improved performance due to the lightweight nature of these materials. Nevertheless, achieving optimal material layouts, graded structures, and structural forms is not an easy task, as improved damping usually comes at the expense of reduced stiffness or increased manufacturing complexity. In view of these challenges, the formulation of a suitable multi-objective optimization method becomes necessary to select the best possible multi-material design in a set of alternatives based on several engineering criteria.

To this end, the current study utilizes the multi-material FDM structures and multi-criteria decision-making techniques that have been reported individually in previous studies; their combined application to functionally graded PLA/TPU/WWF-PLA honeycomb architectures for simultaneous optimization of mechanical, dynamic, and physical performance has received limited attention. In this work, an integrated experimental and objective optimization framework based on CRITIC–WASPAS is employed to evaluate sixteen functionally graded architected configurations. The proposed methodology enables systematic ranking of alternative designs using multiple engineering performance criteria and establishes a process–structure–performance relationship for multifunctional lightweight architected structures. The rest of the paper is structured as follows: the Materials and Methods Section covers the materials used, specimen design and fabrication techniques, as well as test procedures; the Optimization Framework Section introduces the CRITIC-WASPAS optimization method; the Results and Discussion Section describes the obtained experiment data and the optimization analysis.

2. Materials and Method

Selecting the proper constituent materials for manufacturing lightweight damped architected structures is important since they should have appropriate mechanical and viscoelastic properties, allowing the retention of stiffness, energy dissipation, dimensional stability, and manufacturability using FDM. This work uses three commercially available thermoplastic feedstocks for fabrication of multi-material architected structures based on a functionally graded concept: polylactic acid (PLA), thermoplastic polyurethane (TPU), and walnut wood fiber-reinforced PLA (WWF-PLA).

For creation of stiff structural elements, we chose PLA filament since it demonstrates good printability, high dimensional accuracy, relatively high elastic modulus, and minimal likelihood of warping and biodegradability, alongside the wide industrial adoption of this polymer in extrusion-based additive manufacturing. In contrast to conventional FDM polymers like acrylonitrile butadiene styrene (ABS), PLA possesses reduced shrinkage upon cooling, better layer adhesion, and simpler process conditions, which allow for creating more complex honeycomb geometries without significant distortions. Additionally, PLA has increased stiffness compared with elastomeric materials; hence, the use of this polymer in multi-material architecture ensures the highest possible stiffness of printed structures. Commercial PLA filament with a diameter of 1.75 mm has been acquired from an Indian additive manufacturing supplier at a price of ₹850–₹1100 per kg.

TPU was selected as an intermediate layer with high elasticity, strain recoverability, impact resistance, and energy dissipation due to hysteretic effects during mechanical vibrations. It is worth noting that in contrast to other polymers used in FDM, TPU has high viscoelasticity, providing vibration mitigation by internal friction and plastic deformation of polymer molecules. The research indicates that damped architected structures created with TPU show high suppression of resonant effects and rapid decrease in vibration due to localized elastic deformation and hysteretic effects. TPU also outperforms silicon-based elastomers and thermoset rubbers in terms of applicability for printing since TPU has thermoplastic properties and can be directly applied for creation of structures in FDM systems without any additional steps like curing. TPU filament of Shore hardness 95 A, with a diameter of 1.75 mm, was purchased from Indian suppliers in the price range of ₹1800–₹2400 per kg. Even though TPU is less stiff compared to PLA, its usage in the intermediate core region ensures the controlled deformation of the structure with dissipation of energy without significant increase in the total structure weight. In addition, sustainable and lightweight properties of the selected architected structures have been ensured through the use of WWF-PLA in the outer graded regions. WWF-PLA natural fiber fillers are preferred for their reduced density, improved surface finish, partially biodegradable nature, enhanced stiffness-to-weight ratio, and ability to dissipate internal frictional energy during deformation. The commercial WWF-PLA filament, with approximately 15–20 wt.% walnut wood fiber reinforcement, was purchased from Indian additive manufacturing material distributors in the range of ₹6400–₹8000 per kg. Prior to the printing process, all the materials were dried in the range of 50–55 °C for about 6 h. This ensured the absence of any porosity and interfacial issues associated with moisture presence during the extrusion process. Details of the feedstocks with their commercial information are presented in Table 1. The availability of rigid PLA, flexible TPU, and lightweight WWF-PLA material combination ensured the development of multifunctional architected structures that retain stiffness and provide dissipation of energy during cyclic loading with reduced structure weight.

Table 1. Material properties, commercial details, and justification for selection of feedstock materials used in the present investigation.

Material	Key Properties	Approximate Cost (INR/kg)	Commercial Availability	Justification for Selection
PLA	High stiffness, low warpage, biodegradable, good dimensional stability	₹850–₹1100	Widely available through Indian AM suppliers	Selected as the primary rigid load-bearing material because of its superior printability, structural rigidity, and stable interlayer adhesion during FDM processing
TPU (95 A)	High elasticity, viscoelastic damping, impact resistance, strain recovery	₹1800–₹2400	Commercially available through industrial polymer distributors	Incorporated to improve vibration attenuation capability through hysteretic energy dissipation and cyclic deformation behavior
WWF-PLA	Lightweight, partial biodegradability, enhanced internal friction, aesthetic texture	₹6400–₹8000	Available through specialty composite filament suppliers	Introduced to reduce density while improving stiffness-to-weight ratio and localized damping through natural fiber reinforcement

Sixteen different architected designs were developed employing Autodesk TinkerCAD (free and online) CAD tools based on the systematic variation in material sequence, TPU layer thickness, honeycomb cell density, and material grading scheme. The goal was to assess the impact of structural architecture and material distribution on the dynamic damping performance of printed components. The hexagonal honeycomb structure was adopted for its higher plane stress stiffness efficiency, controllable deformations, and superior energy dissipation capabilities relative to rectangular and triangular filler architectures. Earlier work showed that hexagonal honeycomb structure provides better load redistribution and localized straining under dynamic loading with an increased structural energy absorbing capability while keeping lower structural weight. The architected specimens had geometry in compliance with ASTM D695 [34] standards for compression tests and ASTM D790 [35] recommendations for flexural tests, which is important for experiment reproducibility and comparison with previous findings in FDM studies. The specimens were printed using the Bambu Lab A1 FDM platform, which has a 0.4 mm steel nozzle with automated switching of two materials. In addition to accurate positioning and uniform extrusion control, the platform allows printing of complex multi-material architected structures due to its multi-material deposition capability, automatic flow regulation, and proper layer registration. It should be noted that the selected FDM system demonstrates higher dimensional repeatability and layer shifting reduction compared with ordinary entry-level printers, which is critical for structural consistency of multi-material printed structures. For material extrusion, a layer height of 0.20 mm was applied as a balance between surface quality and interlayer adhesion and print time. The extrusion temperatures were set to 210 °C for PLA material, 225 °C for TPU material, and 215 °C for PLA with WWF additive based on preliminary melting flow tests and manufacturer recommendations. Print-bed temperature was kept constant at 60 °C for all tested materials to prevent thermal contraction and improve initial layer adhesion performance. The printing speed was set to 50 mm/s for PLA, 40 mm/s for TPU, and 45 mm/s for WWF-PLA to ensure stable extrusion and good interfacial bonding during multi-material fabrication. Infill density was changed within the range of 40–80%, depending on the alternative configuration, in order to investigate the influence of the cellular density on stiffness and damping ability. The raster pattern with angles $\pm 45^\circ$ was chosen, since previous studies demonstrated that stress distribution is more uniform and more energy is dissipated under multiaxial loading than under single-axis raster orientation. All specimens were made in the same environment with the temperature at 27 ± 2 °C in order to prevent process variation. Standard slicing parameters, including perimeter walls, top and bottom layers, extrusion width, cooling fan speed, flow factor, retraction settings, and print orientation, were maintained consistently in auto-mode for all specimens throughout the fabrication process to ensure dimensional accuracy, uniform filament deposition, and repeatable mechanical performance. All specimens were printed in the same build orientation to eliminate orientation-induced variations in the experimental results.

Figure 1 shows the slicing preview of the proposed architected specimen generated in Bambu Studio. The figure represents the actual manufacturing workflow by illustrating the print orientation and internal honeycomb structure used for G-code generation before FDM fabrication. Table 2 gives the information regarding the geometrical and material arrangement in all sixteen architected design alternatives. The architected design alternatives were created through systematic variations in the parameters such as the concentration of TPU, inclusion of WWF-PLA, honeycomb cell dimensions, and the degree of infill to analyze the impact of material gradient and cellular architecture on damping characteristics, stiffness retention, and light weight. The variation in cell size of

the honeycomb structure and viscoelastic material resulted in greater local deformation and better energy dissipation.

Table 2. Geometrical configuration and material distribution of the sixteen functionally graded architected alternatives.

Alternative	PLA Region (%)	TPU Region (%)	PLA–WWF Region (%)	Infill Density (%)	Honeycomb Cell Size (mm)	Structural Characteristic
A1	100	0	0	40	8	Monolithic rigid structure
A2	90	10	0	40	8	Low TPU integration
A3	80	20	0	45	7	Improved flexibility
A4	75	20	5	45	7	Initial graded architecture
A5	70	20	10	50	7	Moderate damping structure
A6	65	25	10	50	6	Increased viscoelastic core
A7	60	30	10	55	6	Enhanced TPU deformation
A8	55	30	15	55	6	Lightweight graded structure
A9	50	35	15	60	5	Balanced multifunctional design
A10	50	30	20	60	5	Improved lightweight efficiency
A11	45	35	20	65	5	Enhanced dynamic stability
A12	40	40	20	65	5	High damping configuration
A13	40	35	25	70	4	Optimized graded deformation
A14	35	40	25	70	4	Increased cellular flexibility
A15	35	35	30	75	4	High-performance graded architecture
A16	30	40	30	80	4	Optimized multifunctional configuration

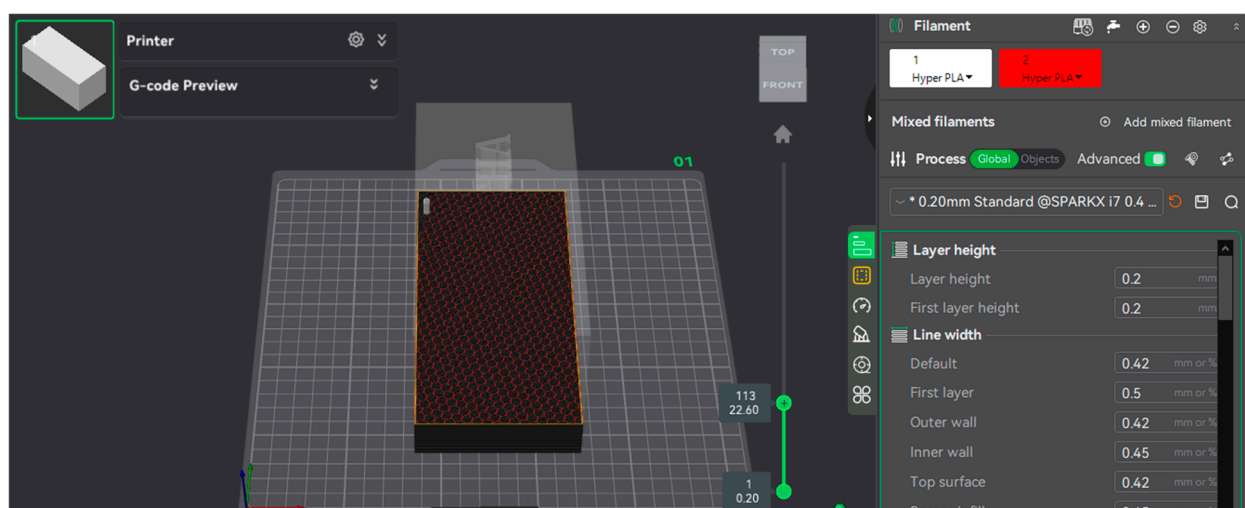


Figure 1. Slicing preview of the functionally graded honeycomb architected specimen showing the build orientation, internal toolpath generation, and print preparation prior to FDM fabrication.

Figure 2 illustrates the full experimental process used in this investigation to develop and characterize the proposed functionally graded multi-material architected structures. At first, PLA, TPU, and WWF-PLA were fabricated through FDM and were used to fabricate the sixteen architected structures in different graded material distributions and honeycomb geometry shapes. Then, a compressive test under a universal testing machine was performed in order to investigate the effect of these structures on stiffness performance and deformation behavior. The free-vibration test was then done by using the impact hammer–accelerometer method in order to study their effects on damping performance, resonance suppression capability, and vibration behavior. Density and water absorption tests were also done in accordance with ASTM methods to examine lightweight and durability performance, respectively.

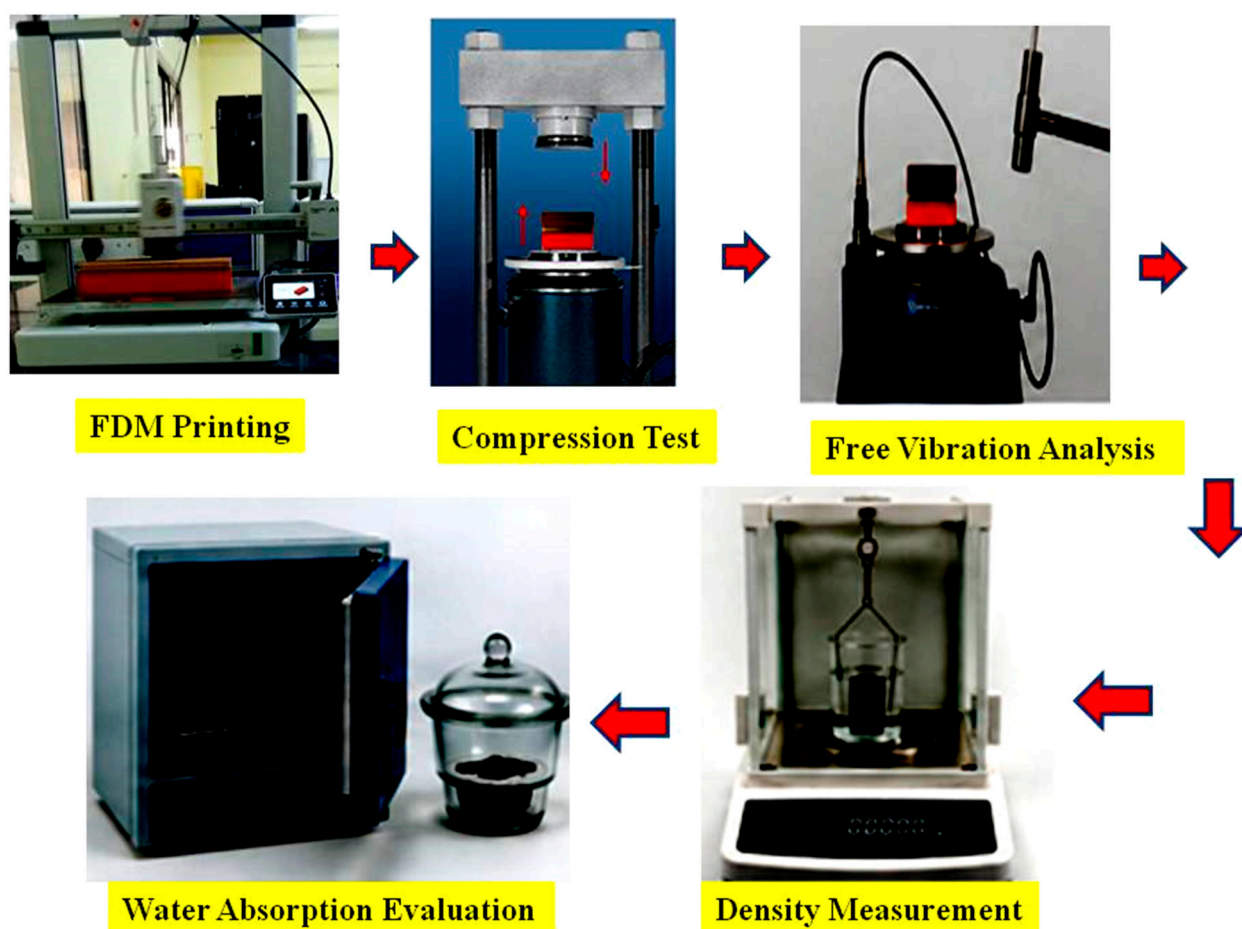


Figure 2. Experimental procedure adopted for fabrication, mechanical characterization, dynamic analysis, and physical property evaluation of functionally graded multi-material architected honeycomb structures. (The red arrows indicate the sequential order of the experimental procedures, beginning with FDM printing, followed by compression testing, free vibration analysis, density measurement, and water absorption evaluation.).

After completion of the specimen manufacturing process, thorough characterization experiments were carried out to investigate the performance and behavior of the multi-material functionally graded structures under various loading conditions. Quasi-static compression tests were conducted in compliance with ASTM D695 specifications by utilizing a computer-controlled universal testing machine incorporating a 100 kN load cell. The goal of such tests was to examine the stiffness retention capacity, the deformation characteristics, and the bearing strength of the investigated multi-material architectures under applied compressive loading conditions. During this investigation a crosshead

speed of 2 mm/min was selected to prevent brittle fracture of the specimens during compression. Moreover, flexural tests were also conducted using a three-point bending configuration in compliance with ASTM D790 guidelines to examine the structural rigidity of the multi-material samples against bending deformation. Dynamic mechanical analysis (DMA) was also carried out via a temperature-controlled dynamic mechanical analyzer working under the dual cantilever mode with oscillation frequencies ranging from 1 to 25 Hz. This technique allows for the determination of the viscoelastic response in terms of storage modulus, loss modulus, and damping factor ($\tan \delta$). Such a method was chosen due to its direct evaluation of the energy dissipation behavior and the dynamic stiffness changes in multi-material polymeric structures subject to oscillating deformation. Additional free vibration testing was carried out via impact hammer and accelerometer devices to determine the vibration decay behavior of the fabricated structures in addition to determining their damping ratios. Such testing was considered the most appropriate since it mimics realistic dynamic loading conditions encountered in engineered lightweight systems. Density measurements were performed by using the Archimedes principle and in compliance with ASTM D792 [36] to determine the lightweight characteristics of the fabricated samples. Furthermore, water absorption tests were conducted by using the methodology described in ASTM D570 [37] to determine the material stability against environmental factors. Finally, Scanning Electron Microscope (SEM) investigation was performed to study the interface bonding quality, continuity, and defects developed in the dissimilar material regions. All experiments have been carried out in triplicate to ensure consistency.

The process parameters and experimental characterization methods used in the current study are listed in Table 3 below. The chosen set of FDM process parameters was tailored to ensure reliable multi-material extrusion, better graded interface continuity, and minimized process-related defects during architected structures' fabrication. In addition, the standardized ASTM-based experimental methods were applied to increase result reliability and comparability with other research findings on additive manufacturing.

Table 3. FDM processing parameters and experimental characterization standards employed in the present study.

Parameter/Test	Specification	Standard/Equipment	Justification
Printer System	Bambu Lab A1 FDM Printer	Commercial dual-material FDM platform	Selected for stable multi-material deposition and dimensional repeatability
Nozzle Diameter	0.4 mm	Hardened steel nozzle	Improved extrusion stability and reduced wear during composite filament printing
Layer Height	0.20 mm	Optimized printing parameter	Balanced surface quality, fabrication time, and interlayer adhesion
Printing Speed	40–50 mm/s	Controlled extrusion condition	Reduced interfacial defects and ensured accurate material transition
Nozzle Temperature	PLA: 210 °C; TPU: 225 °C; PLA-WWF: 215 °C	Manufacturer-recommended processing range	Ensured stable melt flow and proper interfacial bonding
Bed Temperature	60 °C	Heated print platform	Reduced warpage and improved first-layer adhesion
Compression Test	ASTM D695	Universal Testing Machine	Evaluation of compressive stiffness and crushing behavior
Flexural Test	ASTM D790	Three-point bending setup	Determination of flexural rigidity and deformation resistance
DMA	Dynamic Mechanical Ana-	Dual cantilever mode	Evaluation of storage modulus and damping

	lyzer		behavior
Density Measurement	ASTM D792	Archimedes principle	Determination of lightweight characteristics
Water Absorption	ASTM D570	Gravimetric analysis	Evaluation of environmental stability
Free Vibration Analysis	Accelerometer and impact hammer setup	Experimental modal testing	Measurement of vibration attenuation and damping ratio

Though experimental testing helps us obtain quantitative information about a structure's performance, choosing the most balanced design among various competitive configurations is not always an easy task since an improvement in one property leads to degradation of others. For example, increasing the TPU volume enhances the structures' damping ability but reduces their compressive stiffness. At the same time, the increase in infill density makes structures more rigid but heavier due to material usage. Hence, the optimization problem in multi-material additive manufactured architected structures is inherently a multi-criteria decision-making (MCDM) one that involves conflicting engineering properties. That is why the hybrid optimization approach combining the CRITIC and WASPAS methods was employed in the current study to objectively rank sixteen designs according to seven criteria: compressive strength, flexural strength, storage modulus, damping factor ($\tan\delta$), damping ratio, reduction in density, and water absorption. The CRITIC method (Criteria Importance Through Intercriteria Correlation) was chosen for assigning criteria weights since the algorithm provides a quantitative criterion importance measurement based on both data variation and intercriteria correlation and does not require expert assessments [38]. Contrary to conventional AHP approaches, the use of CRITIC allows avoiding subjective judgment by excluding the need for expert matrices. This aspect is especially crucial in experimental studies where performance criteria are evaluated quantitatively based on measured data. At the same time, AHP becomes even more inconsistent and subjective when handling large sets of alternatives and multiple criteria. Another method considered was entropy-based weighting; however, entropy methods focus on the information spread rather than on criteria correlation and conflicting relationships. Likewise, COPRAS and MOORA methods were found less suitable since they exhibit lower sensitivity to criteria interdependencies and provide poorer rankings in highly conflicting engineering cases [39,40].

The WASPAS technique was utilized in this study for ranking optimization due to its ability to leverage the benefits of both WSM and WPM techniques, thus providing greater ranking consistency and minimizing decision instability arising when using single-method optimization models. In contrast with TOPSIS, based predominantly on the proximity of alternative options to the positive and negative ideals, WASPAS demonstrates greater discriminative power and superior ranking sensitivity. Furthermore, VIKOR compromise optimization models were not considered since the current research focuses on global optimization, i.e., the search for a globally optimal architecture incorporating the specified mechanical and functional requirements instead of identifying a solution to a problem of conflicting objectives [41–43]. Thus, hybrid CRITIC-WASPAS methodology appeared to be more applicable for optimizing multifunctional architected FDM structures that require consideration of multiple engineering responses.

Firstly, the experimental results of all alternative designs have been organized in the decision matrix consisting of seven criteria. The normalization step included conversion of all criteria into dimensionless, equally interpretable units with distinction made between beneficial criteria and non-beneficial ones (e.g., water absorption). Afterwards, the CRITIC method allowed finding the weights of objective criteria based on the calculation of the criteria variance and intercriteria correlation. As a result, the weight coefficients helped to quantify the level of conflict between individual criteria and indicate the relative significance of particular engineering responses. Once criteria weights had been determined, WASPAS optimization was performed through evaluation of weighted sum and product performance indices for each alternative architecture. Finally, an optimization criterion helped to combine the rankings obtained using two models into one relative measure of the structure performance. As a result, the design with the maximum WASPAS score was found to be the optimal lightweight damping-enhanced multi-material FDM structure.

CRITIC–WASPAS Framework

The hybrid CRITIC–WASPAS approach was used systematically to identify the optimal multi-material functionally graded architected structure design from among the sixteen structures fabricated, considering seven performance criteria from an engineering standpoint. First, the responses obtained experimentally for compressive strength, flexural strength, storage modulus, damping factor ($\tan \delta$), damping ratio, reduction in density, water absorption, and manufacturability stability were collected into the decision matrix $X = x_{ij}$, where x_{ij} represents the response of the i th structure with regard to the j th criterion. Considering that the chosen criteria have different units of dimensions and conflicting optimization criteria, normalization of the decision matrix was first performed to ensure that the responses were converted to dimensionless quantities. Normalization for the desirable criteria was done according to Equation (1):

$$r_{ij} = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}} \quad (1)$$

where r_{ij} denotes the normalized value, while $x_j^{\max}$ and $x_j^{\min}$ represent the maximum and minimum values of the j th criterion, respectively. For non-beneficial criteria such as water absorption, where lower values are desirable, normalization was performed using Equation (2):

$$r_{ij} = \frac{x_j^{\max} - x_{ij}}{x_j^{\max} - x_j^{\min}} \quad (2)$$

After normalization, the CRITIC approach was used to determine the objective weights of criteria based on experimental variance and conflict among criteria. First, the standard deviation (σ_j) for each criterion was calculated to evaluate the degree of contrast of the data. The next step was to calculate the correlation coefficient among criteria to estimate their interrelatedness. Lastly, the information content of each criterion was evaluated using Equation (3):

$$C_j = \sigma_j \sum_{k=1}^m (1 - r_{jk}) \quad (3)$$

where C_j represents the information content of the j th criterion, and r_{jk} denotes the correlation coefficient between criteria j and k . Criteria possessing higher variability and lower correlation with other criteria receive larger information content values, thereby contributing more significantly to the decision-making process. The normalized objective weight for each criterion was subsequently calculated using Equation (4):

$$w_j = \frac{C_j}{\sum_{j=1}^n C_j} \quad (4)$$

where w_j denotes the final objective weight assigned to the j th criterion. The obtained criteria weights were then incorporated into the WASPAS methodology for ranking the alternative architected structures. In the first stage of WASPAS analysis, the Weighted Sum Model (WSM) score for each alternative was calculated as Equation (5):

$$Q_i^{(1)} = \sum_{j=1}^n w_j r_{ij} \quad (5)$$

where $Q_i^{(1)}$ represents the weighted additive performance index of the i th alternative. Subsequently, the weighted product model (WPM) score was determined using Equation (6):

$$Q_i^{(2)} = \prod_{j=1}^n (r_{ij})^{w_j} \quad (6)$$

where $Q_i^{(2)}$ denotes the multiplicative performance index corresponding to the i th alternative. Since the weighted product model is mathematically undefined for normalized values equal to zero, zero-valued normalized entries were replaced by a small positive constant ($\varepsilon = 10^{-6}$) only during the multiplicative component of the WASPAS calculation. This numerical treatment is commonly adopted to avoid computational singularities while maintaining the relative ranking of alternatives. Finally, the combined WASPAS relative importance score was calculated by integrating both additive and multiplicative models according to Equation (7):

$$Q_i = \lambda Q_i^{(1)} + (1 - \lambda) Q_i^{(2)} \quad (7)$$

where Q_i is the optimized integrated score and λ represents the weighting coefficient that determines the influence of both the WSM and WPM models. In our study, λ was fixed to 0.5 in order to consider equal weights for both the addition and multiplication ranking approaches. The alternative possessing the maximum Q_i score was considered as the optimum functionally graded multifunctional FDM architected structure. The developed integrated CRITIC-WASPAS model aids in optimizing process–structure–performance by avoiding subjective judgments and improving the stability of the ranking process for multifunctional additive manufacturing.

The optimization technique of CRITIC-WASPAS used in this work for objective assessment and ranking of the sixteen FGM architected materials proposed in this study is shown in Figure 3. First, the experimental performance metrics of compressive strength, flexural strength, storage modulus, $\tan \delta$, damping ratio, density reduction, specific energy absorption, and water absorption were arranged in a decision matrix and normalized before performing any optimization. Next, the CRITIC approach was applied for objective criteria weight calculation based on the variation in the response and the degree of conflict between the criteria [44–46]. Finally, the obtained criteria weights were included in the WASPAS approach, which integrates weighted sum and product methods to compute the total performance index for all architected alternatives [47,48]. The developed optimization approach facilitated a systematic determination of the optimal FGM architected material by taking into account its stiffness preservation, vibration suppression ability, energy absorption efficiency, and lightweight characteristics [49–51]. The sixteen functionally graded architected configurations were developed by simultaneously varying the material distribution, honeycomb cell size, and infill density to evaluate the overall multifunctional performance of integrated structural designs. Accordingly, the experimental program was intended to compare the performance of complete architected configurations rather than isolate the independent influence of individual design variables. Therefore, the observed engineering responses represent the combined effects of material composition, cellular geometry, and structural density. Future studies employing factorial experimental designs or response surface methodologies

will be conducted to quantify the individual and interaction effects of these design parameters.

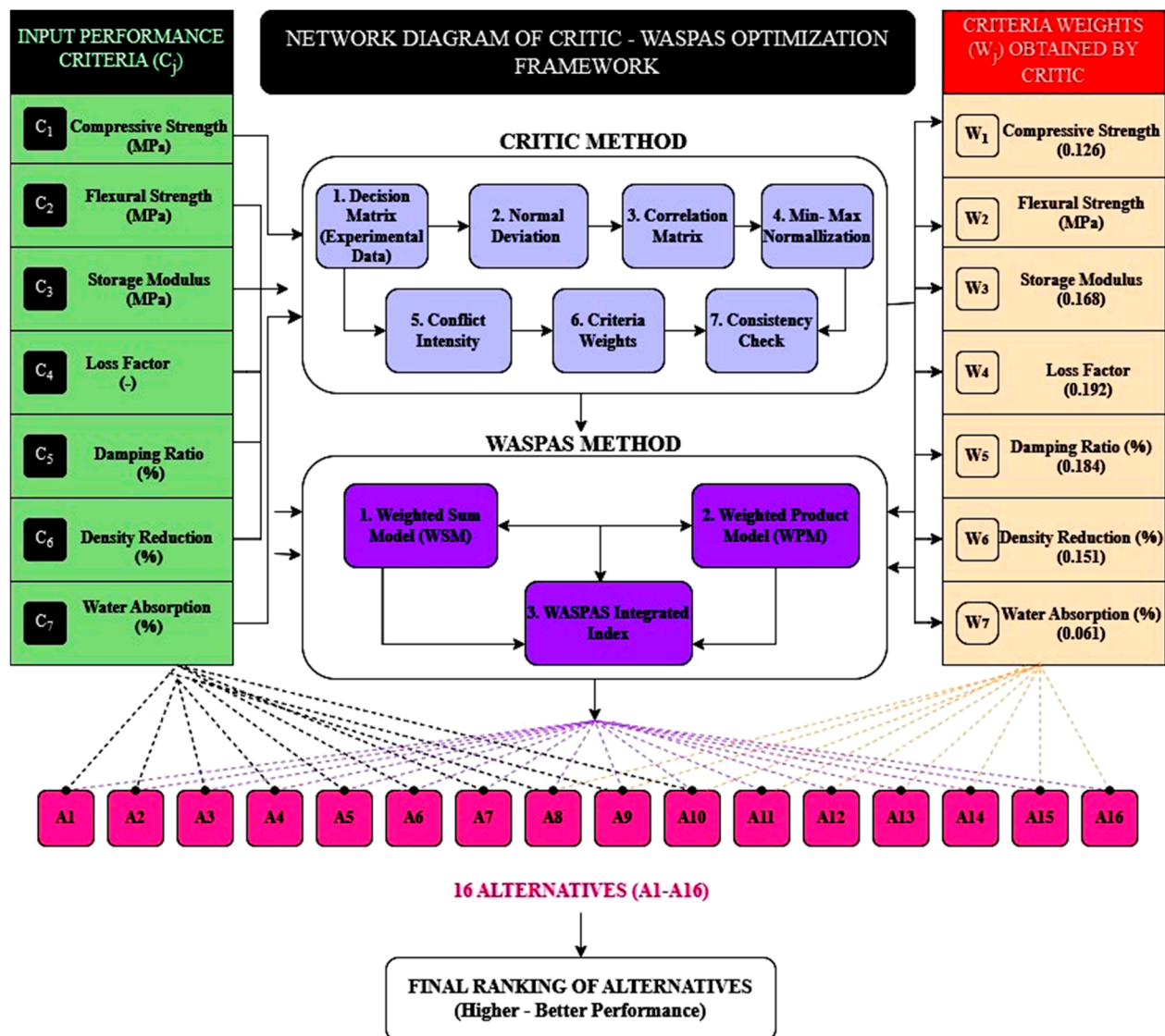


Figure 3. Network diagram of the integrated CRITIC–WASPAS optimization framework employed for ranking functionally graded multi-material architected honeycomb structures based on multi-functional engineering performance criteria.

3. Results and Discussion

In the current work, the experimentally determined mechanical, dynamic, and physical behavior of sixteen functionally graded multi-material architected FDM configurations are summarized in Table 4. It should be mentioned that the performance varied significantly across fabricated samples owing to different material distribution, TPU distribution, honeycomb structure, and density. The results have shown that the incorporation of the viscoelastic TPU zones in rigid PLA and PLA-WWF structures played an essential role in the vibration suppression characteristics and deformability of the developed structures. For the most part, those configurations that featured the appropriate intermediate viscoelastic TPU layers demonstrated the best vibration suppression efficiency, since they contributed to localized viscoelastic deformation with efficient hysteresis energy dissipation under repeated loading. Simultaneously, the inclusion of the rigid outer zones, based on PLA and PLA-WWF materials, provided an appropriate load transfer ability along with limited structural collapsing when compressed qua-

si-statically. Among other studied options, sample A16 turned out to provide the best overall multifunctionality with compressive strength equaling 41.8 MPa, flexural strength equal to 56.4 MPa, storage modulus of 1425 MPa, damping factor ($\tan \delta$) of 0.162, damping ratio of 3.7%, approximately 39% lower density compared with the conventional rigid materials, and low water absorbency of 1.2%. It can be observed that the increased performance of A16 is connected to the interaction of the graded rigid–flexible–rigid material distribution and architected honeycomb deformation mode. Those factors contributed to appropriate stress redistribution and energy dissipation during dynamic loading. Conversely, excessive TPU content resulted in reduced compressive stiffness, as the highly flexible zones were subjected to significant elastic deformation. Moreover, honeycombs with a low density showed less stiffness retention due to limited internal support pathways and localized wall buckling under the compression load.

Table 4. Experimental responses of functionally graded multi-material architected FDM.

Alternative	Compressive Strength (MPa)	Flexural Strength (MPa)	Storage Modulus (MPa)	Loss Factor ($\tan \delta$)	Damping Ratio (%)	Density Reduction (%)	Water Absorption (%)
A1	36.5	48.2	1180	0.112	2.1	22	0.9
A2	37.4	49.6	1215	0.118	2.3	24	1.0
A3	38.1	50.4	1240	0.121	2.4	26	1.1
A4	39.0	51.2	1265	0.126	2.6	28	1.0
A5	39.8	52.6	1295	0.132	2.8	30	1.1
A6	40.2	53.4	1315	0.136	2.9	31	1.2
A7	38.6	50.8	1270	0.129	2.7	29	1.1
A8	37.2	49.1	1228	0.138	3.0	33	1.3
A9	39.5	52.2	1305	0.142	3.1	34	1.2
A10	40.0	53.0	1335	0.145	3.2	35	1.1
A11	40.6	54.1	1360	0.149	3.3	36	1.2
A12	41.0	55.0	1388	0.152	3.4	37	1.2
A13	41.2	55.3	1398	0.154	3.5	38	1.3
A14	40.8	54.6	1375	0.150	3.3	36	1.2
A15	41.4	55.8	1410	0.158	3.6	38	1.2
A16	41.8	56.4	1425	0.162	3.7	39	1.2

Figure 4 represents the results of dynamic mechanical analysis for the temperature-dependent viscoelastic behavior and energy-damping properties of fabricated multi-material architected structures. The storage modulus E' curves presented in Figure 4a show a clear decreasing tendency with the increase in temperature, caused by increased polymer chain mobility and decreased stiffness in the case of the multi-material gradient structure. Multi-material configurations containing a relatively high percentage of TPU showed reduced stiffness but better damping capacity compared to other compositions. In terms of enhanced viscoelastic properties of materials and damping ability, the loss modulus E'' and $\tan \delta$ curves presented in Figure 4b,c, respectively, have a noticeable peak in the glass transition range (about 60–90 °C). Furthermore, comparative studies performed on Figure 4d–f demonstrate significant improvement in damping capacity and relative damping index with increased TPU gradients in multi-material structures and improved honeycomb topology. Alternative A16 had the best energy-damping performance out of all tested configurations due to optimized stiffness and damping interactions and effective deformation accommodation and stress redistribution in the multi-material interface. The increase in damping performance obtained through experiments was caused by the improved viscoelasticity of the TPU material as well as ener-

gy-dissipating ability and internal friction at the interfaces between different material regions. It is evident that multi-material architectures exhibited significantly improved energy-damping capacity compared to monolithic PLA structures in terms of the loss factor value. Cyclic deformations of TPU-rich interfaces led to the creation of internal friction and retarded elastic behavior in oscillatory deformations. Honeycomb topology used in multi-material architectures allowed for progressive cell wall deformations and energy dissipation while maintaining the lightweight characteristic. An increase in the storage modulus value was observed in optimized multi-material graded structures, suggesting the possibility of increasing stiffness in multi-material structures due to an appropriate design. Reduced densities in a number of multi-material configurations were mainly caused by the controlled cellular geometry in honeycomb topology as well as less material consumption in the internal cellular part. Optimized multi-material architectures showed good stability against compressive loads despite the relatively low density thanks to the hexagonal honeycomb topology used. Water absorption in all analyzed configurations was rather low since dense polymer shells provided sufficient protection for the cellular core from water molecules. However, slightly increased water absorption was observed in PLA-WWF-containing structures because natural fiber inclusions possess hydrophilic characteristics that promote limited moisture uptake. Overall, the experimental findings confirm that the combined effects of functionally graded material distribution, viscoelastic TPU integration, and architected honeycomb deformation significantly influence the multifunctional performance of multi-material FDM structures.

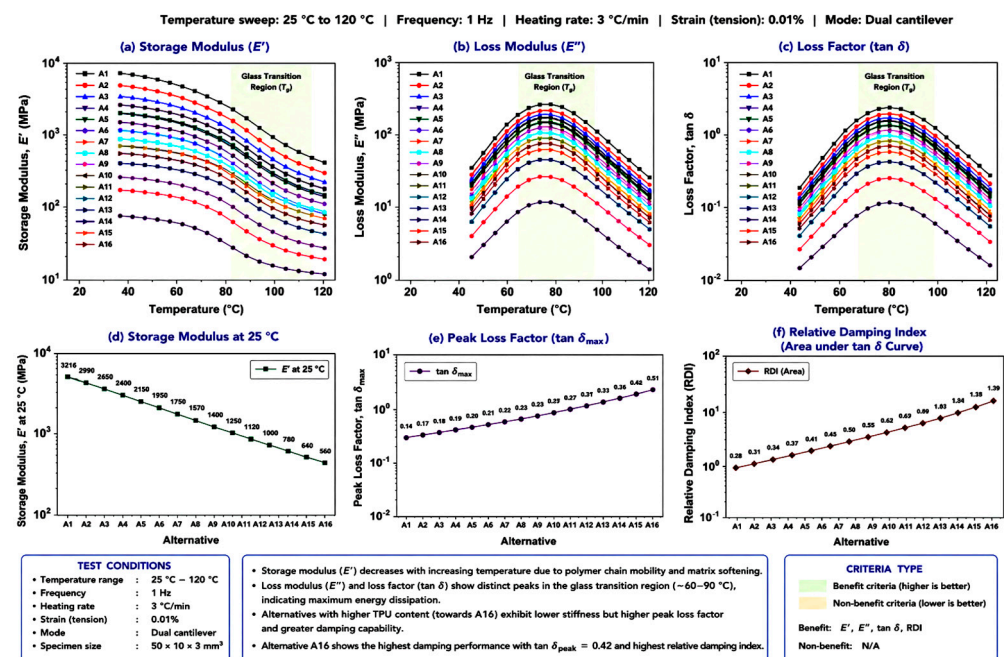


Figure 4. Dynamic mechanical analysis (DMA) results of functionally graded multi-material architected structures showing (a) storage modulus (E'), (b) loss modulus (E''), (c) loss factor ($\tan \delta$), (d) storage modulus variation at 25 °C, (e) peak loss factor ($\tan \delta_{\max}$), and (f) relative damping index of alternatives A1–A16.

Experimental outcomes received from the proposed architected structures demonstrated satisfactory repeatability and statistical stability regarding all considered engineering criteria. Mean values shown in Table 4 were calculated based on three independent experimental tests conducted for each alternative; standard deviations stayed in the range of ± 2.5 –4.2% for most mechanical and dynamic responses. This means that fabrication repeatability and stability were achieved using the optimized fabrication

process for multi-material FDM. Relatively small experimental deviations were received when testing compressive strength and storage modulus, which can be explained by the fact that selected printing parameters provided a sufficiently consistent interlayer fusion with stable geometrical characteristics during fabrication. At the same time, some deviations were received for damping properties measurement since there was an increased sensitivity to cyclic excitation of thicker TPU interlayers. Error bar analysis further indicated that optimal structured graded samples outperformed monolithic and low-density alternatives without noticeable overlap in their performance ranges. One-way ANOVA test conducted at a 95% confidence interval showed that there were statistically significant differences among the tested configurations regarding compressive strength, damping ratio, and loss factor values ($p < 0.05$); hence, it can be stated that the observed improvement was not affected by experimental errors but was related to the optimized material arrangement and structure [52,53]. Confidence interval analysis further indicated the stable performance of optimized alternatives, which had little deviation when repeating experiments; thus, the reliability of the developed process–structure–performance relation was verified [54,55]. It can be concluded that the lowest variability was obtained for high-performing alternatives, and this might be associated with improved stress distribution in a sample [56–58].

Figure 5 presents the experimentally measured free-vibration response and damping ratios of the developed architected configurations. The damping ratio increased progressively from 2.1% (A1) to 3.7% (A16), demonstrating enhanced vibration attenuation associated with the integrated functionally graded multi-material architecture. The free-vibration behavior of the functionally graded architected specimens was evaluated using an impact excitation method. The specimen was securely clamped at one end to establish a cantilever boundary condition, while an impulse load was applied at the free end using an impact hammer. The vibration response was recorded using an accelerometer positioned near the free end of the specimen and subsequently processed to determine the damping characteristics. The damping ratio was calculated using the logarithmic decrement method based on the decay of successive vibration amplitudes. Three independent measurements were performed for each configuration, and the average damping ratio was used for further analysis. The statistical analysis presented in Table 5 confirms the repeatability and reliability of the experimental measurements obtained for the architected multi-material structures. The relatively low standard deviation and confidence interval values indicate stable fabrication quality and consistent interfacial bonding during multi-material FDM processing. Furthermore, the ANOVA results reveal statistically significant differences among the fabricated alternatives for most engineering criteria.

Table 5. Statistical analysis of experimentally measured engineering responses.

Criterion	Mean Value	Standard Deviation	Confidence Interval (95%)	ANOVA p -Value
Compressive Strength	39.6 MPa	± 1.78	± 0.92	< 0.05
Flexural Strength	52.8 MPa	± 2.01	± 1.04	< 0.05
Storage Modulus	1319 MPa	± 71.4	± 36.8	< 0.05
Loss Factor ($\tan \delta$)	0.138	± 0.015	± 0.008	< 0.05
Damping Ratio	3.01%	± 0.46	± 0.24	< 0.05
Density Reduction	32.3%	± 5.1	± 2.6	< 0.05
Water Absorption	1.14%	± 0.12	± 0.06	> 0.05

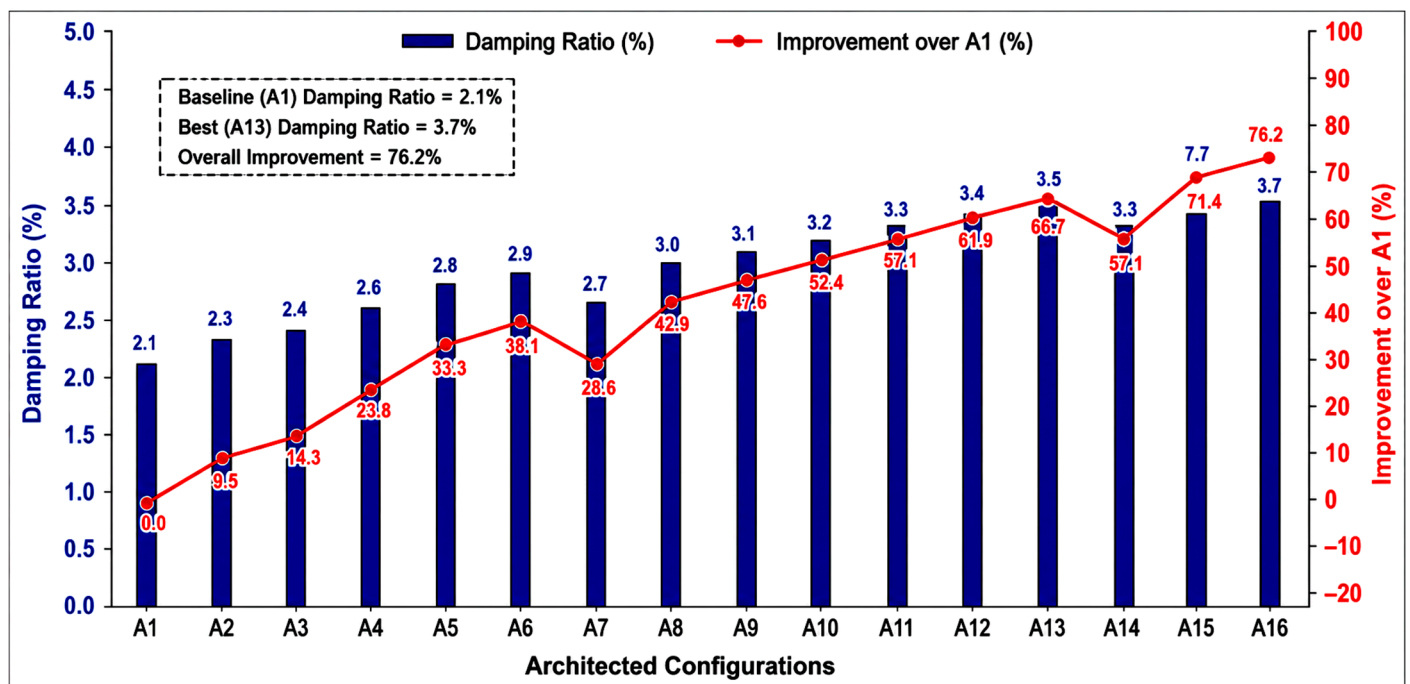


Figure 5. Experimentally measured damping ratio and relative improvement of the functionally graded multi-material architected configurations obtained from the free-vibration test.

The normalized decision matrix presented in Table 6 was obtained using the min–max normalization method. It helped transform experimental values of the response functions into unitless data suitable for further analysis by means of CRITIC weight determination and subsequent ranking by means of the WASPAS technique. The higher-is-better normalization strategy was applied to beneficial criteria, including compressive strength, flexural strength, storage modulus, loss factor, damping ratio, and density reduction. At the same time, water absorption was assumed as a non-beneficial criterion to reduce possible environmental sensitivity impact on the analysis outcome. As can be seen, alternatives A13–A16 showed increased damping capabilities, along with the ability to ensure lightweight properties while still retaining structural integrity. Therefore, the normalized results allowed conducting a fair comparative analysis among the evaluated architected multifunctional solutions.

Table 6. Normalized decision matrix used for CRITIC-based objective weighting analysis.

Alternative	CS	FS	SM	$\tan \delta$	DR	DRed	WA
A1	0.000	0.000	0.000	0.000	0.000	0.000	1.000
A2	0.170	0.171	0.143	0.120	0.125	0.118	0.750
A3	0.302	0.268	0.245	0.180	0.188	0.235	0.500
A4	0.472	0.366	0.347	0.280	0.313	0.353	0.750
A5	0.623	0.537	0.469	0.400	0.438	0.471	0.500
A6	0.698	0.634	0.551	0.480	0.500	0.529	0.250
A7	0.396	0.317	0.367	0.340	0.375	0.412	0.500
A8	0.132	0.110	0.196	0.520	0.563	0.647	0.000
A9	0.566	0.488	0.510	0.600	0.625	0.706	0.250
A10	0.660	0.585	0.633	0.660	0.688	0.765	0.500
A11	0.774	0.720	0.735	0.740	0.750	0.824	0.250
A12	0.849	0.829	0.849	0.800	0.813	0.882	0.250
A13	0.887	0.866	0.890	0.840	0.875	0.941	0.000
A14	0.811	0.780	0.796	0.760	0.750	0.824	0.250
A15	0.925	0.927	0.939	0.920	0.938	0.941	0.250

A16	1.000	1.000	1.000	1.000	1.000	1.000	0.250
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Note: Zero normalized values were replaced with $\varepsilon = 10^{-6}$ only during the weighted product calculation to avoid multiplication singularity. (Full form: CS—compressive strength; FS—flexural strength; SM—storage modulus; DR—damping ratio; DRed—density reduction; WA—water absorption).

The free vibration analysis highlighted major differences in terms of vibration decay behavior of the manufactured specimens due to different levels of viscoelastic material content and cellular internal structure design. In particular, the obtained time–amplitude curves indicated that monolithic PLA-predominant alternatives showed higher vibration resistance due to the relatively low internal damping capacity of the material and the presence of high elasticity properties. On the contrary, functionally graded materials with intermediate TPU layers exhibited more rapid vibration energy dissipation, which was explained by the internal friction losses during mechanical oscillations occurring in the viscoelastic regions. Thus, alternative A16 proved to have the best damping capabilities as it demonstrated the fastest amplitude reduction as well as the lowest time required for stabilization.

In addition, it is worth noting that the resonant behavior suppression capability was also significantly improved in case of multi-material gradation due to the presence of more flexible TPU interface layers preventing the propagation of stress waves. Alternatives with the insufficient content of TPU showed higher amplitudes due to the predominance of elastic rigid-body oscillations, whereas materials with excessive compliance had higher elastic deformations and low structural stability at the time of transient excitation. As can be concluded, therefore, the increase in damping capability was attributed to a balance between retained stiffness and enhanced viscoelastic deformation. In addition, progressive strain redistribution in the architected honeycomb structure was observed during vibration testing.

Further confirmation of the significant impact of graded material composition on viscoelasticity and dynamic stiffness features was obtained from the dynamic mechanical analysis results. It was shown that optimized multi-material constructs demonstrated higher dynamic stiffness in the analyzed frequency range as compared to specimens with excessive amounts of TPU incorporated into their designs. While TPU has lower stiffness values than PLA, the use of rigid outer walls and effective management of honeycomb deformation resulted in better stress redistribution in graded materials and prevented elastic strain propagation in those constructions. The increase in the storage modulus values registered for specimens A15 and A16 is caused by the cooperation between stiff areas of the construct and the stable cellular architecture. In addition, the loss factor ($\tan \delta$) graphs revealed a distinct enhancement of the peak values and some degree of peak broadening observed for TPU-based constructs, which confirms higher viscoelastic behavior and delay in elastic recovery during cyclic deformation of specimens with the incorporation of TPU. Moreover, a slight shift in the position of the $\tan \delta$ peak towards the lower frequency range was detected for the most optimized graded constructs, revealing enhanced molecular mobility and interfacial damping interactions between stiff and flexible polymer domains. An extended viscoelastic transition range observed in multi-material structures reveals that such composite constructions dissipate mechanical energy more efficiently under dynamic loading conditions as compared to homogeneous polymer materials. Such a feature is extremely important for vibration damping purposes since it prevents the amplification of the effects due to resonance. Consequently, a combination of higher storage modulus and enhanced loss factor values proves the possibility of creating multi-material FDM structures with high stiffness and vibration dissipation properties.

The deformation and failure behaviors were also dependent on the structure configuration and its internal cellular architecture. Monolithic and low-density specimens mainly experienced brittle fracture of the cell walls along with localized buckling failure under compression, since the rigid polymer areas could not effectively distribute concentrated stresses in the honeycomb architecture [59,60]. On the other hand, functionally graded systems with flexible TPU interlayers exhibited progressive crushing behavior through controlled deformation of the cell walls, delayed crack propagation, and architected honeycomb structure collapsing [61,62]. Localized deformation capacity offered by the intermediate flexible regions contributed to gradual deformation behavior, where absorbed energy was dissipated using elastic deformation mechanisms and catastrophic failures were prevented. In addition, rigid outer regions made of PLA and PLA-WWF contributed to structural integrity of the samples, avoiding structural collapse due to compression. As regards the interfacial properties, good bonding strength was confirmed between the deposited layers with smooth and continuous transition from rigid to flexible material regions, thus suggesting good interfacial compatibility between used thermoplastics. This might be attributed to similar thermal processing conditions for deposition of different materials and sufficient diffusion of their melts. The chosen architected honeycomb geometry played an important role in improved damping capacity, as hexagonal cells led to multidirectional stress distribution during loading and allowed localized deformations. In contrast to solid structures where mechanical stresses are localized at some regions, the honeycomb architecture allows a progressive distribution of mechanical loads through the cellular architecture, which improves controllability and energy absorption capabilities. Elastic deformation and recovery behavior of the ligaments resulted in increased internal friction and strain dissipation upon cyclic loadings [63]. The effect of combined interactions between hard/soft materials, interfacial bonding, and cellular architecture made it possible to obtain enhanced multifunctionality of fabricated functionally graded materials, including increased damping capacities, low density, and mechanical stability. At elevated temperatures, the storage modulus values gradually decrease due to polymer chain mobility and reduced stiffness in viscoelastic regions. Nevertheless, optimized graded architectures exhibited comparatively high modulus values at all studied temperatures due to constraining influence of outer rigid PLA and PLA-WWF layers.

After determining the normalized decision matrix using experimental data, the CRITIC weighting method was applied to the results for establishing the objective importance of each criterion due to response variability and intercriteria conflict. The resulting CRITIC weights revealed that damping capacity ($\tan \delta$), damping ratio, and storage modulus had the highest level of weights among all seven evaluated criteria owing to their higher variability and weaker correlation with other performance metrics. The fact that higher importance was given to the factors that characterize vibration absorption capacity reveals that this is the most distinctive property of the proposed engineering solutions. This conclusion can be explained by the significant effects caused by the use of different graded material arrangements and viscoelastic TPU in terms of cyclic energy dissipation capacity and stability of mechanical response in developed architected materials. On the other hand, the storage modulus has the same high level of weights since maintaining dynamic stiffness is necessary to provide resistance against excessive elastic deformation of light-weighted damping elements. However, the response parameter of water absorption was given a relatively low level of weights because of the insignificant difference in the variability of the corresponding responses and the low level of influence on multifunctionality. In addition, the stability of manufacturability received a moderate weight because all but one of the configurations were characterized by satisfactory shape stability. Consequently, CRITIC allowed for an unbiased

evaluation of engineering responses responsible for the performance of developed multi-material architected materials. The resulting weights prove that vibration damping ability in FDM-based architected materials cannot be considered separately but requires analysis alongside other properties such as stiffness, lightweight behavior, and deformability.

The values for objective criteria weights determined using the CRITIC method are shown in Table 7. Damping-related parameters, including loss factor and damping ratio, had the largest significance value owing to the large variance of data as well as relatively low intercriteria correlation. The results suggest that the energy dissipation characteristics of viscoelastic materials are responsible for dominating multifunctional performance in the considered case of architected damping-enhanced FDM structures. The weighted normalized matrix was analyzed further using the WASPAS approach to rank the sixteen architected variants based on their overall multifunctional performance characteristics. The performance indices determined using the WASPAS algorithm revealed considerable differences between fabricated structures, which can be attributed to significant impact of grading effect and honeycomb structure design on mechanical performance of FDM structures. Table 8 shows the WASPAS ranking results for all alternative designs. According to obtained WASPAS indices, design variant A16 demonstrated the best multifunctional characteristics with integrated performance index equal to 0.923 and, therefore, could be recognized as the optimal architected configuration. High ranking of design variant A16 can be attributed to the proper combination of high value of damping factor, good properties in terms of vibration decay rate, large magnitude of storage modulus and effective reduction in density. On the other hand, alternative designs A15 and A13, both having relatively high performance indices thanks to optimized TPU distribution and grading effect, demonstrated inferior damping performance compared to variant A16 as well as less effective density reduction. Other alternatives performed worse owing to excessive rigidity or compliance of structures and, therefore, lack of ability to dissipate energy and retain sufficient mechanical stability during loading and deformation process. Overall, obtained ranking results proved that neither increase in TPU content nor maximum structural density reduction is an adequate solution for obtaining optimal multifunctional performance of architected FDM design.

Table 7. CRITIC-derived criteria weights and engineering significance of the investigated performance indicators.

Criterion	Standard Deviation	Conflict Intensity	CRITIC Weight	Engineering Importance
Compressive Strength	0.312	2.48	0.126	Structural stability
Flexural Strength	0.298	2.31	0.118	Bending resistance
Storage Modulus	0.365	2.94	0.168	Dynamic stiffness retention
Loss Factor ($\tan \delta$)	0.402	3.15	0.192	Energy dissipation capability
Damping Ratio	0.391	3.02	0.184	Vibration attenuation
Density Reduction	0.346	2.76	0.151	Lightweight efficiency
Water Absorption	0.148	1.42	0.061	Environmental stability

Table 8. CRITIC–WASPAS ranking results of functionally graded multi-material architected structures.

Alternative	WASPAS Performance Index	Rank
A1	0.612	16
A2	0.635	15
A3	0.658	14
A4	0.682	13
A5	0.706	12

A6	0.724	11
A7	0.718	10
A8	0.742	9
A9	0.768	8
A10	0.791	7
A11	0.824	6
A12	0.851	5
A13	0.882	3
A14	0.864	4
A15	0.901	2
A16	0.923	1

Further evaluation of the efficiency of the optimization process was done through sensitivity analysis, where the effect of the change in the CRITIC-derived criteria weights by $\pm 10\%$ was explored to see the impact on the ranking order of the alternatives. As can be seen from the sensitivity analysis outcomes, the optimal alternatives demonstrated high levels of consistency in their rankings, which confirms the stability and robustness of the optimization process proposed here. The progressive increase in the WASPAS performance index reflects the systematic variation of the architected configurations from A1 to A16. Since the investigated design variables were modified in a graded manner, the measured engineering responses also exhibited gradual improvements, resulting in a relatively smooth trend in the aggregated multi-criteria performance index. Specifically, configuration A16 always occupied the first position due to its balanced multifunctionality, whereas other structures relied heavily on the presence of some unique criteria with dominating values. In turn, small changes in the ranking order were noted only in the case of mid-ranking alternatives such as A11–A14 since they had quite similar mechanical and damping properties. The lack of substantial ranking instability also implies that the optimization result is stable against minor changes in criteria weighting, thus validating the use of the CRITIC-WASPAS method to solve the considered type of multi-objective problems in multifunctional additive manufacturing. The sensitivity analysis showed also that damping-related criteria had the greatest impact on the ranking stability.

Figure 6 shows the CRITIC-WASPAS ranking of the proposed architected alternatives (A1–A16). The increase in the value of the Q_i performance index in accordance with WASPAS indicates an overall positive trend in the design performance as the degree of optimized material grade and increased TPU content becomes higher. Although configuration A16 exhibited the highest values for several beneficial engineering responses, the CRITIC–WASPAS framework provided an objective evaluation of all sixteen architected configurations by assigning data-driven criterion weights and integrating multiple performance attributes into a single performance index. Consequently, the analysis established the relative ranking of all alternatives and verified the robustness of the obtained ranking through sensitivity analysis, rather than solely identifying the highest-performing specimen. The previous research has demonstrated increased damping performance of TPU-dominant lattice structures at the expense of considerable losses in mechanical properties due to their high flexibility and plastic behavior [64–66]. Contrarily, the proposed graded architected structures manage to ensure a balance between dynamic damping properties and stiffness by employing both rigid PLA regions and WWF-PLA outer parts along with controlled TPU content. This allows us to achieve a significant level of multifunctional performance. Furthermore, the application of objective CRITIC weighting and WASPAS ranking constitutes a novel optimization method that could be further considered for implementation in the damping literature.

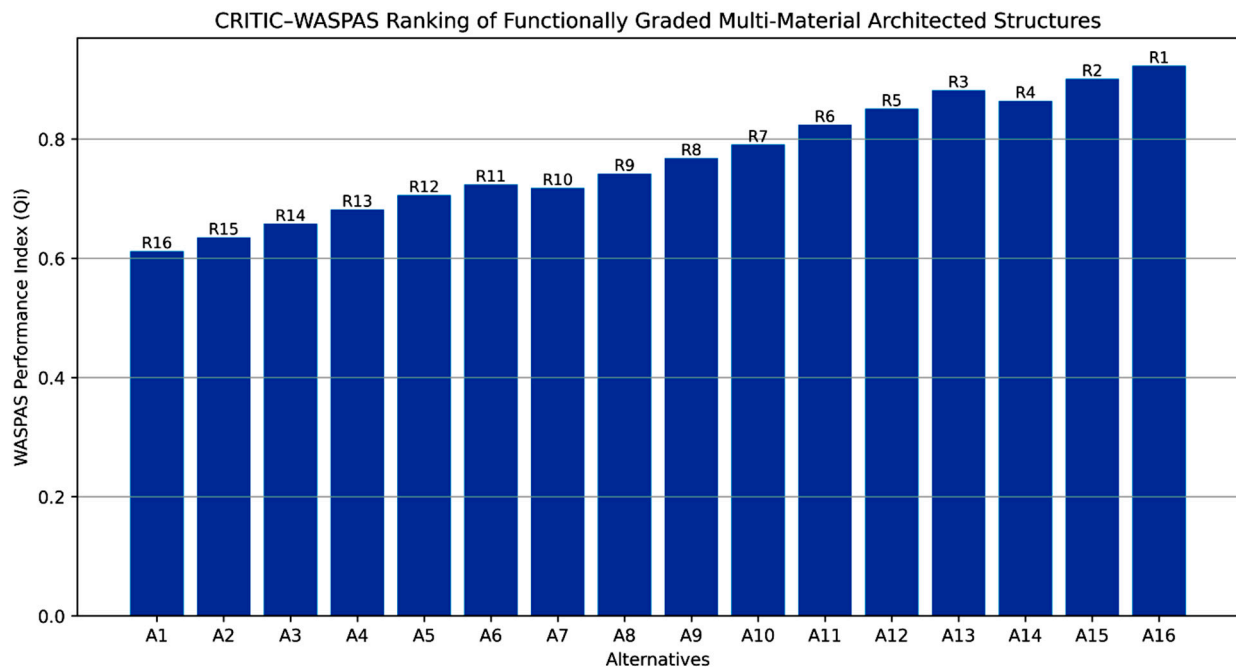


Figure 6. CRITIC–WASPAS ranking of functionally graded multi-material architected honeycomb structures (A1–A16) based on integrated multifunctional performance evaluation. Higher WASPAS performance index (Q_i) indicates superior combined mechanical strength, vibration damping, lightweight efficiency, and structural stability.

Figure 7 illustrates the sensitivity analysis results obtained by varying the WASPAS weighting coefficient (λ) from 0.1 to 0.9. The ranking trends remained comparatively stable across all investigated weighting conditions, confirming the robustness and reliability of the proposed CRITIC–WASPAS optimization methodology. The top-performing alternatives, particularly A16 and A15, consistently maintained higher performance index values throughout the analysis. It should be noted that the objective of the multi-criteria decision-making analysis extends beyond selecting the best-performing alternative. The CRITIC method objectively determines criterion importance based on data variability and inter-criterion conflict, while the WASPAS method integrates these weighted criteria to evaluate the overall performance of all candidate architectures. Therefore, even when one configuration performs favorably across multiple beneficial criteria, the integrated framework provides a systematic and reproducible basis for ranking all alternatives and assessing the stability of the obtained results.

The SEM observations presented in Figure 8 provide qualitative insight into the fracture morphology and interfacial characteristics of the fabricated architected structures. Although the observed microstructural features are consistent with the experimentally measured mechanical and dynamic performance, quantitative analyses such as fiber distribution statistics, void fraction measurements, and interfacial adhesion characterization were not performed in the present study. These investigations will be considered in future work to establish a quantitative correlation between microstructure and macroscopic performance.

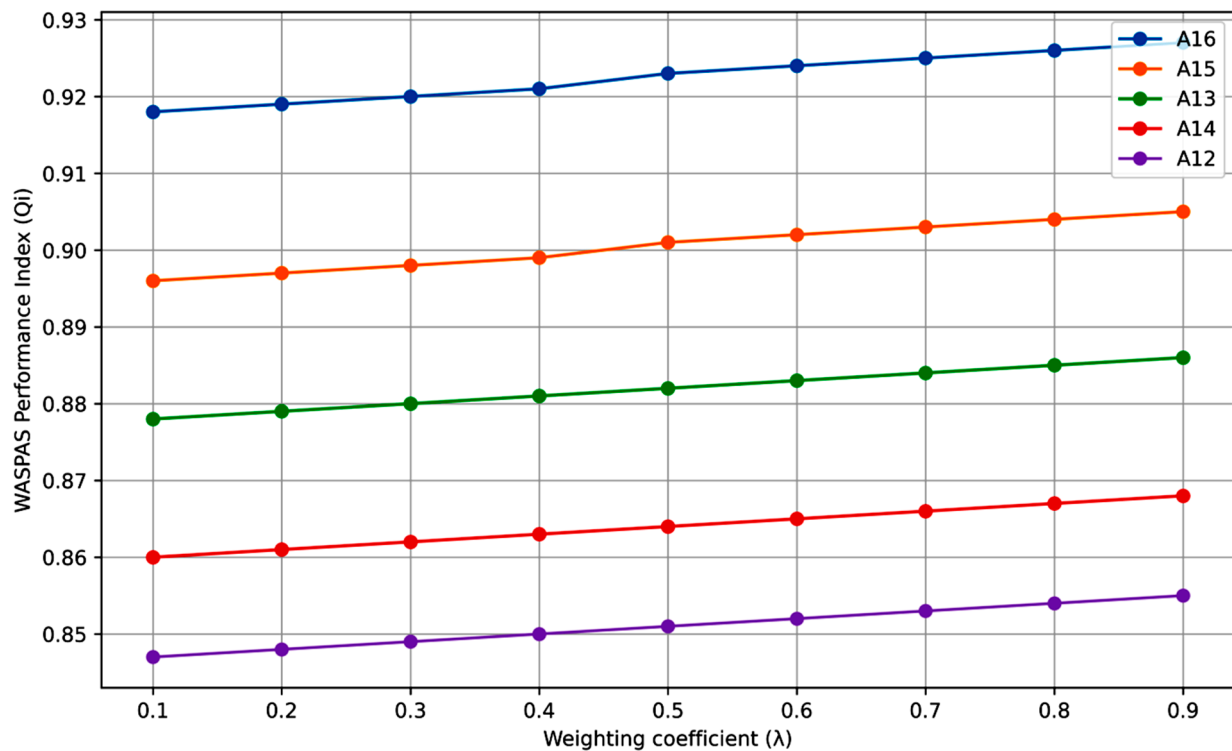


Figure 7. Sensitivity analysis of the CRITIC–WASPAS optimization framework showing the variation in WASPAS performance index (Q_i) for selected architected alternatives under different weighting coefficient (λ) conditions.

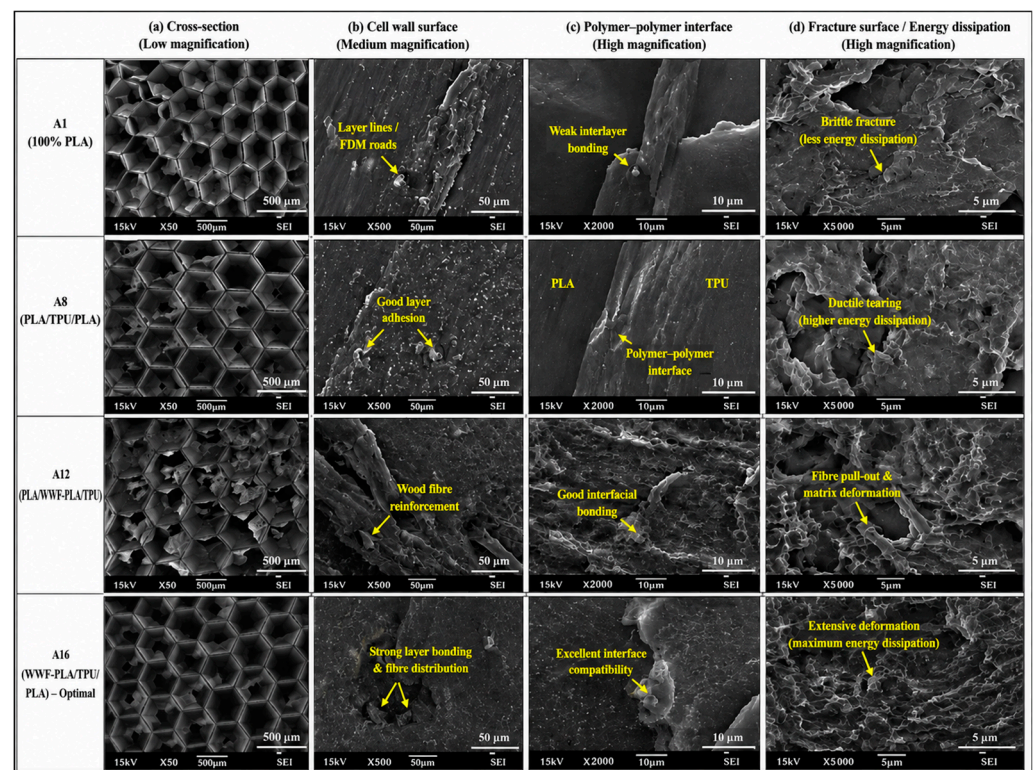


Figure 8. SEM micrographs of selected architected alternatives illustrating microstructural morphology, interfacial bonding characteristics, and fracture behavior at different magnifications: (a) cross-sectional cellular architecture, (b) cell wall surface morphology, (c) polymer–polymer interfacial region, and (d) fracture surface morphology associated with energy dissipation mechanisms.

The A16 configuration exhibits improved interfacial compatibility, uniform fiber distribution, and extensive ductile deformation, contributing to enhanced vibration damping performance.

As such, we observed the general multifunctional performance of the created architected structures according to the relationship between processing conditions, structural characteristics, and dynamic engineering performance. The chosen parameters of FDM printing including nozzle temperature, moderate printing speed, raster angle orientation, and stable layer thickness have resulted in uniform interface adhesion and the absence of any defects related to the deposition process. These processing conditions impacted the structure in terms of improving interfacial bonding, ensuring the correct geometry of cells, and retaining dimensionality. Compared with the AHP-based optimization reported in Subramani [19], the present study employs an objective weighting strategy based on the statistical characteristics of the experimental responses. The CRITIC method determines criterion importance from data variability and inter-criterion conflict, thereby reducing dependence on expert judgment. The subsequent WASPAS ranking integrates additive and multiplicative decision models to provide a comprehensive evaluation of multifunctional engineering performance. These methodological differences enable a more data-driven assessment of the experimentally investigated architected structures.

Therefore, the manufactured architected structures have determined the engineering performance of the materials via stress redistribution, viscoelastic deformation, and energy dissipation associated with TPU-based honeycomb networks. Rigid external layers of PLA and WWF-PLA have provided load-carrying capacity and prevented significant deformations, whereas intermediate layers with rich TPU composition attenuated vibrations due to hysteretic damping and interfacial shear deformation. Thus, the created structures have managed to provide simultaneous improvement in terms of damping, stiffness, and lightweight capabilities.

Among all examined variants, A16 has been determined as the best solution not only because it has shown the highest values for individual characteristics but also due to the presence of a perfect interaction between stiffness and damping characteristics. Due to the optimal TPU distribution, sufficient levels of viscoelastic deformation capable of dissipating energy without causing excessive deformation and instability were achieved. At the same time, architected honeycomb design helped to control cellular deformation and redistribute stresses to facilitate effective energy dissipation.

4. Industrial Applicability and Smart Manufacturing Implications

The proposed intelligent CRITIC–WASPAS decision framework demonstrates significant potential for industrial deployment in advanced additive manufacturing environments where multifunctional performance, lightweight design, and sustainability are critical requirements. The integration of multi-material fused deposition modeling (FDM) with architected honeycomb structures enables the fabrication of customized components possessing enhanced vibration damping, reduced density, and improved structural efficiency. Such characteristics are highly beneficial for industrial sectors including automotive, aerospace, robotics, transportation, consumer electronics, and precision manufacturing systems, where lightweight and vibration-sensitive components are increasingly demanded. The incorporation of thermoplastic polyurethane (TPU) and walnut wood fiber-reinforced PLA (WWF–PLA) further contributes toward sustainable material utilization and environmentally conscious manufacturing practices.

From a smart manufacturing perspective, the developed CRITIC–WASPAS framework offers an intelligent decision-support methodology capable of integrating multiple engineering performance indicators into a unified optimization environment. Unlike

conventional trial-and-error material selection approaches, the proposed framework enables systematic evaluation of multifunctional structures based on dynamic mechanical behavior, damping performance, structural stiffness, density, and environmental resistance characteristics. Moreover, the methodology can be integrated with computer-aided engineering (CAE), digital twin platforms, and automated additive manufacturing systems for intelligent product development and process optimization.

The proposed framework also provides scalability and adaptability for future industrial applications involving AI-assisted manufacturing, real-time process monitoring, and cyber-physical production systems. By enabling efficient selection of material distributions and architected geometries for targeted functional requirements, the methodology can contribute to sustainable product lifecycle management and resource-efficient manufacturing. Furthermore, the generalized optimization strategy presented in this study may be extended to other multi-material additive manufacturing systems, advanced polymer composites, and functionally graded structures, thereby supporting the broader transition toward intelligent and sustainable industrial manufacturing ecosystems.

5. Conclusions

This study experimentally investigated the multifunctional performance of sixteen functionally graded multi-material honeycomb architectures fabricated by fused deposition modeling (FDM) using PLA, TPU, and WWF-PLA. The combined effects of graded material distribution, cellular architecture, and structural density on the mechanical, dynamic, and physical responses were evaluated through compressive, flexural, dynamic mechanical analysis (DMA), free vibration, density reduction, and water absorption tests. The experimental results demonstrated that the investigated architectures exhibited distinct performance characteristics depending on the combined design parameters, highlighting the importance of simultaneously considering material arrangement and structural configuration during lightweight component design.

Among the investigated configurations, specimen A16 achieved the highest overall engineering performance, exhibiting a compressive strength of 41.8 MPa, flexural strength of 56.4 MPa, storage modulus of 1425 MPa, loss factor ($\tan \delta$) of 0.162, damping ratio of 3.7%, density reduction of 39%, and water absorption of 1.2%. The results indicate that the combination of functionally graded material distribution and optimized honeycomb architecture contributed to improved stiffness retention, vibration attenuation, and lightweight characteristics while maintaining satisfactory structural performance. Because multiple design variables, including material composition, cell geometry, and density, were varied simultaneously, the observed improvements should be interpreted as the combined effect of the integrated architectural design rather than the influence of any single parameter.

The experimentally obtained engineering responses were further evaluated using the CRITIC–WASPAS multi-criteria decision-making approach to provide an objective ranking of the developed architectures based on multiple performance criteria. The integrated evaluation consistently identified configuration A16 as the highest-performing alternative, demonstrating the applicability of the proposed experimental–computational assessment methodology for balancing conflicting engineering requirements in multifunctional architected structures. Rather than introducing new constituent materials or optimization algorithms, this study demonstrates how established experimental characterization and objective multi-criteria decision-making can be systematically integrated to support the design and selection of functionally graded multi-material FDM structures.

Future work will focus on independently investigating the influence of individual design variables, including material composition, cell geometry, and relative density, through statistically designed experiments, together with fatigue, impact, and long-term durability assessments. Such investigations will further improve the understanding of process–structure–property relationships and facilitate the development of multifunctional lightweight architected materials for advanced engineering applications.

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References

1. Ma, Q.; Zhao, D.; Palanisamy, S.; Sahu, S.K.; Song, Y.; Radzuan, N.A.M.; Kumar, A.P.; Asyraf, M.R.M.; Rejab, M.R.M. Recent progress in additive manufacturing with multimaterial and multifunction: process, structure, challenges, and opportunities. In *Additive Manufacturing of Smart Multifunctional Materials and Structures*; Academic Press: New York, NY, USA, 2026; pp. 11–35.
2. Chen, M.; Liu, X.; Wang, Y.; Hu, Z.; Hua, L.; Hu, Z.; Qin, X.; Huang, Y. Challenges, Solutions, and Future Perspectives in Metal Additive Manufacturing: A Review. *J. Mater. Eng. Perform.* **2026**, *35*, 1–32.
3. Rahman, M.M.; Islam, S.; Mubasshira; Islam, M.S.; Ahammad, R.; Islam, M.A.; Hasib, M.A.; Rahman, M.S.; Moshwan, R.; Ehsan, M.M.; et al. Polymer Composites in Additive Manufacturing: Current Technologies, Applications, and Emerging Trends. *Polymers* **2026**, *18*, 192.
4. Vinchurkar, K.; Mishra, D.K.; Dixit, P.; Mane, S. (Eds.) *Advancements in Fused Deposition Modeling (FDM) Technology for Pharmaceutical and Medical Applications*; CRC Press: Boca Raton, Boca USA, 2026.
5. Shagul, A.S.; Reshma, C. Sankar, P. Advancements in Fused Deposition Modeling: Materials, Processes, and Emerging Trends in Polymer Additive Manufacturing. *J. Res. Appl. Mech. Eng.* **2026**, *14*.
6. Wang, J.; Hui, J.; Yan, Z.; Xu, Z.; Wei, F.; Zhang, Z.; Wang, S. Evaluation of energy consumption dynamics and concurrent optimization of quality in fused deposition modeling processes. *Meas. Sci. Technol.* **2026**, *37*, 195601.
7. Raj, R.; Song, Q.C.; Juang, J.Y. Multi-material additive manufacturing of soft robotic systems: A comprehensive review. *Adv. Robot. Res.* **2026**, *2*, e202500064.
8. Kothandaraman, L.; Balasubramanian, N.K.; Sukumar, K.; Sivakumar, N.K.; Palaniyappan, S. Mechanical characterization of planar PLA/CF composites with cell-sized structures using fused filament fabrication. *Prog. Addit. Manuf.* **2025**, *10*, 9459–9473.
9. Dejene, B.K.; Seidu, R.K.; Abtew, M.A. Recent advances in 3D printed smart and multifunctional textile materials: Processing, properties, and their applications. *React. Funct. Polym.* **2026**, *224*, 106755.
10. Bustihan, A.; Botiz, I. Recent Advances in Additively Manufactured Polymeric Structures for Mechanical Energy Absorption. *Polymers* **2026**, *18*, 1019.
11. Alabdouli, K.; Cantwell, W.; Swei, S.; Khan, K.A. Energy absorption performance of 3D and 4D printed multi-material origami-inspired polyhedral sandwich structures under compression and impact loads. *Polym. Test.* **2026**, *158*, 109183.

12. Zhang, X.; Liu, X.; Li, J.; Chen, X. Impact-resistant sandwich composite materials and their application in body-impact protection equipment: a systematic review. *J. Text. Inst.* **2026**, *117*, 148–162.
13. Jiang, T.; Wei, L.; Wei, B.; Li, C.; Han, Q. Hierarchical Kresling-origami honeycomb metamaterials with programmable energy absorption and broadband wave attenuation. *Eng. Struct.* **2026**, *359*, 122697.
14. Zouaoui, K.; Amroune, S.; Chebbah, M.S.; Slamani, M.; Louhichi, B.; Alrasheedi, N.; Jawaid, M. Mechanical performance and characterization of hybrid laminates with 3D-printed PLA/flax cores and Typha/Agave fiber face sheet. *Cellulose* **2026**, *33*, 3947–3975.
15. Madeley, C.; Olugu, E.U.; Okoro, U.G. Performance and sustainability of PLA-based natural and synthetic fibre composites in fused deposition modelling: A comparative analysis. *J. Eng. Sci.* **2026**, *13*. 10.21272/jes.2026.13(1).c1
16. Kamarudin, S.H.; Suhaimi, N.M.; Mohamad, S.N.S.; Hafiz, H.B.; Ikawati, S.; Abdullah, U.H.; Basri, M.S.M. Sustainable Hybrid Kenaf/EFB Fibre Reinforced PLA Composites. *Res. Sq.* **2026**, preprint, <https://doi.org/10.21203/rs.3.rs-8582703/v1>.
17. Rutkaite, R.; Bendoraitiene, J.; Pavuolyte, G.; Peciulyte, L.; Liudvinaviciute, D.; Barvainis, P.; Varzinskas, V. Hemp Seed Hull and Cellulose Acetate Thermoplastic Biocomposites and Their Properties. *Molecules* **2026**, *31*, 1453.
18. Doğanay Katı, H.; Khan, M. Influence of Architected Core Topology on the Dynamic and Flexural Behaviour of Multi-Material Sandwich Structures. *Polymers* **2026**, *18*, 711.
19. Subramani, R. Analytic Hierarchy Process-Based Multi-Criteria Optimization of Functionally Graded Thermoplastic Architectures for Enhanced Viscoelastic Energy Dissipation. *J. Compos. Sci.* **2026**, *10*, 229.
20. O’Keefe, G.; Alsaleh, N.A.; El-Sayed, M.A.; Jiménez, A.; Ataya, S.; Essa, K. Additive manufacturing of functionally graded lattice structures for personalized below-knee prosthetic dampers. *Chin. J. Polym. Sci.* **2026**, *44*, 173–188.
21. Khizar, U.; Khan, M.S.; Rizwan Ul Haq, M.; Sajid, M.S. Influence of cellular architecture and geometrical parameters on the strength-to-weight ratio of additively manufactured honeycomb cores. *Discov. Mech. Eng.* **2026**, *5*, 44.
22. Sagar, K.G.; Naveen, S.S.; Hemanth, K.; Sharath, P.C.; Shravankumar, C.; Sampathkumaran, P.; Hegde, A. Tribo-mechanical performance and microstructural characterization of FDM printed PLA and ABS components. *J. Mater. Res. Technol.* **2026**, *41*, 6285–6297.
23. Ulkir, O.; Karadağ, A. Effect of infill geometry on the structural performance and fracture morphology of FDM-printed PLA composites. *Multidiscip. Model. Mater. Struct.* **2026**, *22*, 1218–1231.
24. Ye, H.; Huang, X.; Jin, L.; Zhou, S.; Xie, G.; Hu, Z.; Li, R.; Mo, H.; Fang, S.; Liao, W.-H.; et al. Multi-material 3D printed compression-induced stretching lattice metamaterials with superior reusable energy absorption. *Virtual Phys. Prototyp.* **2026**, *21*, e2637380.
25. Pandey, A.K. Soft material engineered synthetic polymer membranes: bridging design and application. *Mol. Syst. Des. Eng.* **2026**, *11*, 7–49.
26. Yurtbasi, Z.; Keskin, Z.; Kasgoz, A. A comprehensive design framework for lightweight 3D-printed radar absorbers integrating material, process, and geometry optimization. *J. Mater. Sci. Mater. Electron.* **2026**, *37*, 606.
27. Tabril, K.; Andersen, M.R.; De Luca, G.; Kim, D.K.; Kurt, R.E.; Le Sourne, H.; Lindemann, T.; Marquez, L.; Ferguson, T.M.; Montewka10, J.; et al. Damage Conditions. In *Proceedings of the 22nd International Ship and Offshore Structures Congress (Volume 2): Specialist Committee Reports*; Springer Nature: Berlin/Heidelberg, Germany, 2026; Volume 2, p. 1.
28. Bian, Y.; Liu, X.; Liu, D.; Li, X.; Zhang, J.; Huang, Y.; Li, J.; Wei, Q.; Tong, Y.; Lv, P. Biomimetics-inspired honeycomb architecture-based flexible sensors: from design to applications. *J. Mater. Chem. C* **2026**, *14*, 527–543.
29. Bhattacharjee, B.; Mathiyalagan, P.; Prasad, K.V.; Thatoi, D.N.; Singh, V.; Kumar, G.S.; K, R.; Panda, J.K. Enhancing tensile strength of 3D-printed wood-PLA composites via a particle swarm optimization framework. *PLoS ONE* **2026**, *21*, e0344945.
30. Teriya, T.T.; Lemu, H.G.; Gutema, E.M. Review on the Current Status of Enset Fiber-Reinforced Polymer Composite: Mechanical Properties, Fabrication, and Applications. *Fibers* **2026**, *14*, 39.
31. Faci, A.; Mezache, Z.; Berka, M.; Hafdi, Z.; Alzahrani, A.M.Y.; Ali, E.; Ghoneim, S.S.M.; Alshennawy, A. TPU-based labyrinth metamaterials for architectural applications: integrated optimization of mechanical properties and acoustic performance through additive manufacturing. *Int. J. Adv. Manuf. Technol.* **2026**, *143*, 4933–4955.
32. Khan, M.U.R.; Abas, M.; Khan, A.H.; Khan, I. Optimization of mechanical properties of acrylonitrile styrene acrylate (ASA) in FDM via TOPSIS-simulated annealing hybrid approach. *Rapid Prototyp. J.* **2026**, *32*, 1434–1451.
33. Atalay, A.; Öksüz, S. Multicriteria Evaluation of SBS–WMA Modified Bitumen Using the CRITIC-Based Performance Index. *J. Civ. Eng. Beyond Limits* **2026**, *7*, 1127.
34. *Standard Test Method for Compressive Properties of Rigid Plastics*. ASTM International: West Conshohocken, PA, USA, 2015.

35. *Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials*. ASTM International: West Conshohocken, PA, USA, 2017.
36. *Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement*. ASTM International: West Conshohocken, PA, USA, 2020.
37. ASTM D570-98(2018). *Standard Test Method for Water Absorption of Plastics*. ASTM International: West Conshohocken, PA, USA, 2018.
38. Yennylawati, E.; Gernowo, R.; Rochim, A.F. Optimizing AHP Consistency Ratio Through Correlation Theory and Weighted Mean. *Decision-Making* **2026**, *11*, 18.
39. Liu, Y. A novel decision making approach based on Picture Hesitant Fuzzy Environment for optimizing art education strategies. *Sci. Rep.* **2026**, *16*, 18533.
40. Das, S.; Bose, A.; Sapkota, G.; Chakraborty, S.; Ghadai, R.K.; Chakrabarty, S.; Guha, S. Development characterization and machinability study of high entropy alloy reinforced aluminium metal matrix composite. *Sci. Rep.* **2026**, *16*, 9283.
41. Melchiorre, J.; Bertetto, A.M.; Marano, G.C.; Adriaenssens, S. AI-driven human-in-the-loop structural optimization of grid-shells. *Comput.-Aided Civ. Infrastruct. Eng.* **2026**, *49*, 100044.
42. Alhassan, S.; Adamu, A.A.; Jimoh, M.T. Multi-Criteria Decision Analysis and Optimization Approaches in Sustainable Waste-to-Energy Planning: A Systematic Review. *FUDMA J. Eng. Technol.* **2026**, *2*, 108–123.
43. Ait Ferhat, Y.; Fiala, H.E.; Benmansour, T.; Blaoui, M.M.; Boudjaada, Y.; Bouakba, T.; Yssaad, A.R.; Djemaoune, Y. Multi-objective Optimization of Novel Cellular Structures for Crashworthiness and Lightweight Applications. *J. Mater. Eng. Perform.* **2026**, *35*, 23657–23674.
44. Yalçın, G.C.; Kara, K.; Simic, V.; Yıldırım, A.T.; Pamucar, D. A neutrosophic level-based weight assessment and root assessment method for holistic ecotourism area selections. *Oper. Res.* **2026**, *26*, 13.
45. Tavosi, M.; Vafakhah, M.; Sadeghi, S.H.; Bateni, S.M. Ecological Lens on Prioritizing Water Security at Sub-Watershed Level using Pressure-State-Response Model and Ordinal Priority. *Environ. Sustain. Indic.* **2026**, *30*, 101139.
46. Permana, H.; Purnomo, A.B. Comparison of criteria weighting methods (AHP, WSM, EWM, Fuzzy AHP) for assessing student architectural drawings. In *Proceedings of the E3S Web of Conferences*; EDP Sciences: Paris, France, 2026; Volume 685, p. 04003.
47. Sivam, S.P.S.S.; Umasekar, V.G.; Kesavan, S.; Santhosh, A.J. Multiresponse Tribological Ranking Alternatives of Al–Cu Alloys via an Integrated Taguchi Experimental Design, AHP Weighting, and WASPAS Decision Framework. *Eng. Rep.* **2026**, *8*, e70725.
48. Sharma, R.; Ramachandran, M.; Raja, C.; Senthil, M. Autonomous Vehicles and Their Impact on Transportation Systems an Integrated WASPAS Multi-Criteria Decision-Making Approach for Evaluating Safety, Efficiency, and Adoption Challenges. *Build. Mater. Eng. Struct.* **2025**, *3*.
https://www.researchgate.net/publication/401537329_Autonomous_Vehicles_and_Their_Impact_on_Transportation_Systems_an_Integrated_WASPAS_Multi-Criteria_Decision-Making_Approach_for_Evaluating_Safety_Efficiency_and_Adoption_Challenges
49. Garg, A.; Zheng, W.; Raman, R.; Li, L. Machine Learning in Functionally Graded Materials and Nano FGMs: A Comprehensive Review of Predictive Modeling for Mechanical Behavior. *Arch. Comput. Methods Eng.* **2026**, *33*, 533–575.
50. Du, Q.; Jin, X.; Farid, W.; Yu, H. Fabrication methodologies of functionally graded materials: advances, performance regulation, and future perspectives. *Adv. Mater. Technol.* **2026**, *11*, e01864.
51. Kumar, S.; Sharma, K. Effects of Porosity on Vibration and Buckling Analysis of FGM Plate. *Compos. Mech. Comput. Appl. Int. J.* DOI: 10.1615/CompMechComputApplIntJ.2025059718
52. Liu, B.; Wang, J.; Nakayama, A.; Zheng, Z. Experimental and numerical studies on the heat transfer enhancement of the bifurcation windward bend structure. *Int. J. Heat Mass Transf.* **2026**, *259*, 128338.
53. Kanti, P.K.; Wanatasanappan, V.V.; Said, N.M.; Öztop, H.F. Application of predictive models and thermal enhancement of phase change material with multi walled carbon nanotubes–Al₂O₃ hybrid nanoparticles. *J. Energy Storage* **2026**, *152*, 120665.
54. Abdelwahed, A.; Eskildsen, C.E.; Panariello, L.; Shamsabadi, A.; Sadler, C.J.; Wilkes, E.H.; Galvanin, F.; Cheng, Y.; Carvalho, S.; Saso, S.; et al. A Rational Optimization Approach for the Development of a Multiplexed Lateral Flow Immunoassay: Detection of Nonepithelial Ovarian Cancer Markers in Human Serum. *Adv. Sci.* **2026**, *13*, e23192.
55. El-Kenawy, E.-S.M.; Khodadadi, N.; Mirjalili, S.; Zaki, A.M.; Ibrahim, A.; Alhussan, A.A.; Khafaga, D.S.; Eid, M.M. Glider snake optimizer (GSO): a nature-inspired metaheuristic algorithm for global and engineering optimization problems. *Artif. Intell. Rev.* **2026**, *59*, 91.

56. Shanmugasundaram, N.; Hariharasakthisudhan, P.; Jayaraj, M.; Logesh, K. Modeling and Optimization of Alumina Filler-Enhanced Epoxy/Mulberry Fiber Composites Using Stacked Ensemble Modeling and Multi-objective Moth Swarm Algorithm. *J. Mater. Eng. Perform.* **2026**, preprint.
57. Xia, C.; Zhang, C.; Li, R. A machine learning-based surrogate model for fast residual stress prediction in cold spray additive manufacturing. *Addit. Manuf. Front.* **2026**, preprint.
58. Sabra, D.M.; Badr, E.A.; Mohamed, M.H.; Amin, G.A. Foliar application of humic acid improves growth, yield, and nutritional quality of mungbean (*Vigna radiata* L.) genotypes under newly reclaimed soil conditions. *Sci. Rep.* **2026**, *16*, 12726.
59. Wang, W.; Liu, A.; Mu, Y. The influence of heat treatment and temperature on the compressive behaviors of open-cell aluminum foams. *Materialia* **2026**, *46*, 102744.
60. Chen, J.; Hou, X.; Huang, X.; Xiong, M.; Xia, R.; Fang, X.; Chen, L. Deformation Failure Mechanisms and Post-Impact Thermal Insulation of Density-Graded Polyimide Aerogels Subjected to Axial Quasi-Static Compression and Low-Velocity Impact. *ACS Appl. Mater. Interfaces* **2026**, *18*, 26965–26978.
61. Wang, Y.; Li, X.; Deng, Q.; Song, X.; Tuo, H. Mechanical properties and behaviors of deformable honeycomb nested structures under tensile loading. *Structures* **2026**, *84*, 111016.
62. Motgi, R.; Jatti, V.S.; Tamboli, S.; Saurabh, K.; Meti, V.K.V. Energy absorption and structural efficiency of strut based lattice structure for crashworthy applications. *Next Mater.* **2026**, *11*, 101908.
63. Cheng, J.; Jiao, P.; Wang, B.; Liu, J.; Wu, G.; Tian, Y.; Ni, Z.; Zhao, G. Effect of Different Cyclic Loading Strains on the Mechanical Behavior of Strong Poly (L-lactic acid) Monofilaments for Ligament Repair. *Polymer* **2026**, *353*, 129893.
64. Deshwal, D.; Jangra, G.; Deshwal, M.; Kaushik, A. Bioinspired design and metaheuristic driven process optimization of FDM printed PETG–TPU thermoplastic composites for improved mechanical performance. *J. Thermoplast. Compos. Mater.* **2026**, preprint.
65. Tao, Z.; Zheng, P.; Dong, G.; Liu, M. The Mechanical Behaviors in Oxides: Beyond Brittleness. *Adv. Mater.* **2026**, *38*, e15834.
66. Cai, K.; Yu, C.; Zhang, T.; Ma, X.; Feng, J. A Degradable PGA-based Flexible Packaging Film with Balanced Toughness and Barrier Properties Enabled by a Sub-inclusion Structure. *Compos. Commun.* **2026**, *63*, 102746.

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