Gradient Furniture Series

A multi-material robotic 3D printing approach using biodegradable thermoplastics

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This paper explores the innovative potential of Multi-Material Additive Manufacturing (MMAM) in the realm of bio-composite thermoplastics, which combine the beneficial traits of biological materials and conventional plastics. By harnessing robotic 3D printing technology, MMAM allows for the integration of multiple materials within a single printed object, facilitating the creation of functionally graded components that enhance design flexibility and structural performance. Traditional additive manufacturing focuses on homogeneous materials, whereas MMAM enables diverse material compositions and the formation of complex geometries. This study specifically investigates the application of bio-composite thermoplastics, derived from renewable biomass and capable of being up to 100% bio-based. Initial case studies on three prototypes demonstrate how these versatile materials can yield robust and aesthetically appealing furniture designs. The research probes the challenges of implementing effective mixing and material transitions while ensuring quality and consistency. Furthermore, the paper discusses the technical aspects of achieving seamless gradients in material properties, such as stiffness and density, which improve stress distribution and structural integrity. The findings underscore the significant potential of MMAM to revolutionize manufacturing practices across various industries by promoting sustainability through resource optimization, providing design innovations that respond to environmental changes, and ultimately contributing to a rethinking of material use in design and construction.

Keywords: *Digital Fabrication, Multi-Material Additive Manufacturing, Gradient, Bioplastic Materials, 3D Printing, Robotic*

INTRODUCTION

Additive manufacturing enables precision and freedom in continuous material deposition while minimizing waste and expanding the possibilities of material experimentation. It offers the ability to explore varied material compositions and innovative processes, addressing resource challenges and ecological impacts in a resource-constrained world (Roudavski, 2009; Grigoriadis and Lee, 2024). This approach not only supports the use of eco-friendly resources but also facilitates the creation of complex, free-form designs (Toshev et al., 2024) that were previously unattainable through conventional manufacturing methods (Jones, 2017; Bledzki and Gassan, 1999). The rise of large-scale robotic 3D printing in architecture, design, and construction underscores the growing importance of sustainable materials and environmentally conscious strategies (Jimenez and Retsin, 2025).

Despite its potential, research in this area remains nascent (Klemmt et al., 2022; Kretzer and Mostafavi 2020).

Multi-Material Additive Manufacturing (MMAM) is a groundbreaking fabrication process that integrates diverse materials within a single printed object, enabling variations in material properties and performance. Unlike traditional additive manufacturing, which typically focuses on homogeneous materials, MMAM combines distinct materials or properties to create functionally graded components. This technology enhances design flexibility, improves stress distribution, and minimizes assembly requirements, leading to more elegant and efficient solutions (Schumacher, 2016; Oxman, 2010). MMAM also presents the potential to revolutionize architectural and design practices through adaptive structures that respond to environmental changes. This capability offers significant prospects for transforming manufacturing practices across numerous industries while promoting sustainability through resource optimization. However, challenges persist in ensuring effective mixing and material transitions, as well as maintaining quality and consistency in the final products (Pajonk et al., 2022).

While this paper specifically examines robotic MMAM with bio-composite thermoplastics, which balance the qualities of biological materials and conventional plastics, the principles of MMAM and biodegradable thermoplastics hold significant promise for architectural elements, offering potential solutions for sustainable construction practices. These "drop-in" bioplastics, derived from biomass, are capable of mimicking oil-based plastics and may consist of up to 100% renewable materials. The versatility of bio-composite thermoplastics fosters the development of robust, sustainable solutions applicable across various domains. This study investigates several prototypes developed from this material family, utilizing robotic 3D printing to create complex geometries, bespoke designs, and multi-material gradients. These materials are crafted to combine mechanical strength with diverse surface articulation, offering both functional and aesthetic benefits. Improved stress distribution is crucial not only for stable furniture but also for optimized load-bearing columns or complex roof structures.

"Gradients" refer to gradual changes in material composition or properties within an object, playing a crucial role in the aesthetic and functional dimensions of innovative structures. By facilitating transitions in color, shape, texture, or material properties, functionally graded materials enhance stress distribution, structural integrity, and the reduction of failure risks at material interfaces. These gradients are realized through additive manufacturing processes that blend materials during printing, effectuating seamless rather than abrupt transitions. Despite their advantages, implementing these gradients poses technical challenges, such as preserving material transition integrity during printing and ensuring adequate mixing (Pajonk et al., 2022; Aduatz, 2021). Maintaining consistent material transitions is critical. In architectural applications, this is paramount for ensuring weather-tight facades or structurally sound connections between building components.

AIMS, RESEARCH QUESTIONS

This project aims to investigate the capabilities of robotic MMAM using biodegradable thermoplastics to create material gradients in furniture. While these furniture prototypes demonstrate the feasibility of MMAM, architectural-scale implementation presents challenges related to material volume, printing time, structural certification, and regulatory compliance. The study is guided by the following key research questions, focusing on specific aspects of design, fabrication, materials, and gradient implementation:

- Design optimization: how can design methods and criteria, particularly the use of computational tools like Rhino 3D and Grasshopper, be optimized to create furniture that balances aesthetic appeal with functional requirements, such as comfort and usability?

- Fabrication process efficiency: what fabrication methods and criteria, including procedural growing curves and robotic control of print paths, can be employed to enhance the efficiency and quality of 3D-printed furniture, while minimizing post-processing needs and ensuring suitability for diverse applications (e.g., outdoor use)?
- Material selection and performance: how can material methods and criteria, such as the selection of specific bioplastic blends (e.g., UPM Formi, ARBOBLEND, NaKu), be strategically employed to maximize the advantages of multi-material 3D printing, ensuring optimal mechanical properties and adherence to sustainability principles?
- Gradient implementation effectiveness: how do gradient methods and criteria, including considerations of line, surface, and volume, influence the seamless integration of multi-material gradients in furniture design, ensuring both visual appeal and structural integrity?

Figure 1
The Quadrifoglio Gradient Furniture Series

DESIGN METHODS AND CRITERIA

The Quadrifoglio Gradient Furniture Series, a collection of domestic objects and integrated fixtures, was showcased at the Isola Design Festival during Milan Design Week from 15 to 21 April 2024, draws inspiration from the Italian four-leaf clover, symbolizing good fortune. The design emphasizes renewable resources and non-toxic finishes to achieve a tactile and warm aesthetic, leveraging digital design and robotic technologies to enhance visual appeal and align with sustainable practices. The collection features three stool variations: a small stool functioning as a footrest/side table, a medium-sized chair with a symmetrical non-planar top, and a large barstool with an ergonomic footrest and contoured top. The largest stool (47x47x90 cm, 8.2 kg) has a five-hour print time and a 636.5-meter print path, with a bottom curve transitioning from 1.8 to 7.57 meters at the top for improved ergonomics. The medium stool (50x50x50 cm, 7 kg) has a 3.5-hour print time and a 616-meter print path, transitioning from a 1.73 to 7.08-meter curve. The small stool (40x40x25 cm, 3 kg) has a 2.5-hour print time and a 295-meter print path, transitioning from a 1.53 to 5.29-meter bottom curve.

Designed using Rhino 3D and Grasshopper, the non-planar surfaces were created by projecting curves onto the geometry and refining intermediate curves through lofting, trimming, and smoothing. The final geometry underwent rigorous self-intersection checks to ensure structural integrity and printability, resulting in a cohesive and functional furniture line.

The multi-material gradient primarily enhances the stools' aesthetic appeal. Rendering simulations and small-scale material tests were conducted to predict the gradual material transitions, informing the final design and fabrication by providing insights into visual and textural variations.

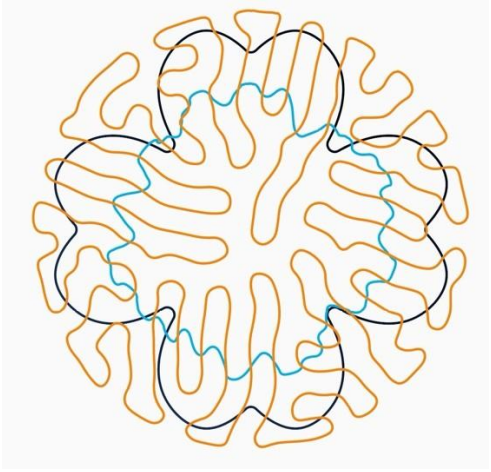

Figure 2
The medium size stool was printed in 250 layers with a total length of 61.6-m print paths: top layer in orange = 7.08 m length, mid layer in blue = 1.26 m length, bottom layer in black = 1.73 m length.

FABRICATION METHODS AND CRITERIA

Balancing functionality with sculptural aesthetics presented significant challenges, particularly in maintaining usability and comfort on the top surface while adhering to a single-curve design suitable for 3D printing. Printing travel moves, especially with larger nozzle diameters, can result in undesirable seams and stringing, necessitating extensive manual post-processing. To mitigate these issues, a procedural growing curve was employed for the top pattern, allowing precise control over print path spacing. This algorithm dynamically adjusts the curve's growth while adhering to specified distances between control points and conforming to a defined perimeter boundary.

The open pattern also enhances functionality by improving aeration and facilitating effective drainage, making the stools suitable for outdoor use. Industrial robotics and additive manufacturing were utilized to achieve intricate geometries and continuous multi-material gradients. A combination of PLA blends was selected to achieve the desired light green hue. Material selection was carefully considered to maximize the advantages of multi-material 3D printing, given a processing temperature between 160°C and 190°C for all materials. For the smallest stool, the material arrangement was inverted, placing a stiffer, less elastic polymer on the top surface to withstand loads, while retaining flexibility in the base. Conversely, the seating stools feature a harder material at the base for structural support, paired with a softer, more elastic material on the top surface for enhanced comfort. For large-scale architectural elements, blending from opaque materials to transparent PLA expands the range of applications.

Additionally, several plant pots and 1:1 interior panel with integrated fixtures were designed and prototyped to test the scalability of the material properties from the stools to other parts of an interior setting.

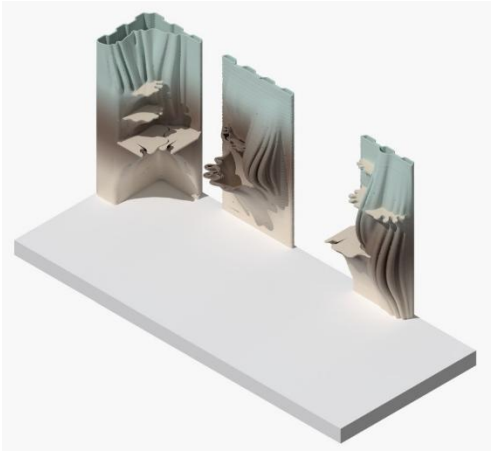

Figure 3
Large scale panels for architectural applications

MATERIAL METHODS AND CRITERIA

The used bioplastics closely mimic oil-based plastics and can be composed of up to 100% renewable resources (Ashby, 2020).

These materials incorporate biopolymers such as polyhydroxyalkanoates (PHA), polylactic acid (PLA), polycaprolactone (PCL), bio-polyolefins (bio-PE), bio-polyamides (bio-PA), and bio-PET, along with additional components like lignin, cellulose, natural resins, oils, waxes, fatty acids, organic additives, and reinforcing fibers. This thoughtful material selection maximizes the advantages of multi-material 3D printing, ensuring optimal performance while adhering to sustainability principles.

Due to the unavailability or incomparability of certain material properties, testing was conducted at the LAB for Fast-Growing Materials at the Institute of Engineering Design and Materials Science at the University of Innsbruck. Each test sample was printed with a layer height of 2 mm and an expected layer width of 5 mm. The robotic fabrication setup consisted of a single Herz/Dohle Exon 10 Pellet Extruder Head mounted on the ABB IRB 2600-20/1.65 industrial robot. The pelletized materials were dried for four hours at 65°C in preparation for printing.

To evaluate the mechanical properties of the selected materials, a three-point bending test was performed, utilizing test specimens measuring 15 mm in width, 5 mm in thickness, and with a support spacing of 80 mm. The materials tested included NaKu R, TECNARO Arboblend V3NF15, UPM Formi 3D20, and transparent PLA 3D850. Three test specimens for each material were utilized to provide reliable results.

Key parameters assessed include:

- Average Modulus of Elasticity (GPa): this parameter is defined by the relationship between stress and strain within the elastic deformation range of the material. Higher values indicate greater resistance to deformation. The Modulus of Elasticity was calculated in the linear elastically deforming range of the lower 0.05%–0.25% of the material strain.
- Average Maximum Force (N): this metric indicates the maximum force the material can withstand before failure.
- Average Maximum Stress (MPa): this value measures the highest stress the material can endure before breaking.

Among the tested materials, PLA 3D850 Transparent exhibited the highest modulus of elasticity at 2.80 GPa, indicating it is the stiffest option. In contrast, NaKu R displayed an extremely low modulus of 0.13 GA, making it the most flexible material tested. TECNARO Arboblend V3NF15 (2.10 GPa) and UPM Formi 3D20 (1.96 GPa) fell between these extremes, indicating moderate stiffness. PLA 3D850 Transparent demonstrated the greatest strength, with a maximum force of 238.88 N and a maximum stress of 87.93 MPa. TECNARO Arboblend V3NF15 followed with maximum values of 156.24 N and 47.92 MPa. UPM Formi 3D20 exhibited significantly lower performance metrics at 78.83 N and 26.90 MPa, while NaKu R was the weakest, with a maximum force of 18.88 N and stress of 5.84 MPa.

Table 1
Three-point bending tests (ISO 178) were performed on 3D printed specimens (15 mm width × 5 mm gross layer thickness) with an 80 mm support span.

Material	Modulus Elasticity (GPa)	Maximum Force (N)	Maximum Stress (MPa)
NaKu R	0,13	18,86	5,84
TECNARO Arboblend V3NF15	2,10	156,24	47,92
UPM Formi 3D20	1,96	78,83	26,90
PLA 3D850 Transp.	2,80	238,88	87,93

GRADIENT METHODS AND CRITERIA

The implementation of multi-material gradients in the Quadrifoglio Gradient Furniture Series relies on three primary geometric factors: line, surface, and volume. Each element plays a critical role in defining the overall gradient, ensuring seamless integration and functionality.

- Line: the print path length per layer is vital for determining material deposition. As material deposition occurs linearly, careful calibration of the cumulative print path length across the stool is essential to achieve the desired gradient effect. This calibration requires precise calculations to align local material additions with the intended global surface characteristics.
- Surface: gradient effects are predominantly surface-based, necessitating a focus on the double-curved geometry of the stools. The curvature must be optimized to facilitate smooth transitions in material properties. By manipulating surface contours, the design can accommodate varying densities and stiffness, enhancing comfort and aesthetic appeal. This surface optimization directly influences the visual manifestation of the gradient and its interaction with light.
- Volume: the volumetric design integrates surface and line considerations, as the overall gradient depends on the interaction of these geometric elements within the three-dimensional space of the stool. Adjustments to material deposition must maintain visual appeal while ensuring structural integrity and ergonomic functionality. The volumetric design should support gradient transitions, allowing for diverse material properties throughout the stool to enhance comfort and utility.

Once the number of subdivision steps is set, the print path curves are grouped in the z-direction to match the number of batches. The path lengths within each group and the total length are calculated to determine the proportional weight of each batch based on the final geometry's overall weight. This is crucial as weight per layer can vary significantly; for example, in the Quadrifoglio Gradient Furniture Series, the top curves are longer than the base, shifting the center of gravity upward, which is accounted for in the calculations.

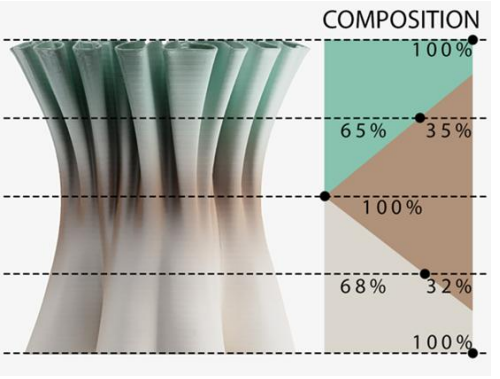

Figure 4
The chart (right) depicts the mixing ratio (material composition) along the x-direction as a function of z-height, with linear gradient interpolation applied.

RESULTS AND DISCUSSION

In this study, gradients were achieved by subdividing layer lines into weighted batches. The number of batches was determined by the geometry's overall height, weight, layer count, and print path length. Increasing the number of gradient steps resulted in smoother transitions between material mixtures. Given that material weighing and mixing were performed manually, the number of steps was minimized while still achieving a uniform gradient with barely noticeable batch switches.

The pellet extrusion system significantly impacts transition time. A longer heating chamber and extrusion screw prolong the transition between materials, as the material mixes inside the extrusion chamber, requiring complete extrusion before a new color appears. For our setup, an optimal weight of approximately 100g per gradient batch ensured a seamless transition, although this can be adjusted as needed. Automating pellet feeding to the end effector could enable additional steps for an even

smoother optical transition.

Accurate material mixing requires estimating the overall weight of the final print. This can be achieved by calculating weight per length printed, using previous iterations as references. Alternatively, weight can be calculated based on the geometry's surface area or mesh.

In summary, various systems were tested to achieve different material combinations. The simplest approach used a linear mixing ratio for the first material (0 to 1) and the inverse (1−x) for the second, ensuring total factors per batch summed to one. While functional, this method proved inflexible and difficult to adjust.

Recent advancements in mapping RGB gradients to materials have enhanced the flexibility of multi-material 3D printing. This approach enables the use of up to three materials, allowing for precise adjustments to the gradient's start, end, and midpoint using various interpolation techniques. With each RGB channel representing a different material, transitions such as red to blue to green effectively illustrate blending among three materials. Scaling RGB values (0 to 255) to a range between 0 and 1 facilitates the proportional distribution of materials, optimizing batch weight distribution.

REFLECTION, OUTLOOK TOWARDS ARCHITECTURAL APPLICATIONS

The long-term environmental sustainability of biodegradable thermoplastics remains a key area for future research. Accelerated aging tests and rigorous durability assessments are crucial to understanding their real-world performance and longevity in diverse conditions. Beyond material properties, significant engineering and regulatory hurdles must be addressed to effectively adapt MMAM techniques for architectural applications.

The focus must shift to create scalable fabrication systems by means of: the development of larger robotic printing systems capable of processing increased material volumes, material certification and by means of the establishment of robust, application-specific certification and structural engineering standards for bioplastics in building as well as integrated workflow systems and regulatory alignment means of the exploration of strategies for seamlessly integrating MMAM within existing construction practices while meeting all relevant building codes and regulations. Successfully addressing these challenges will unlock the potential to create a new generation of high-performance building components, such as customized partition walls with integrated acoustic dampening, dynamic facade panels optimized for solar shading, or even load-bearing hybrid systems that strategically combine bioplastics with traditional materials for optimal resource efficiency.

For example, this approach could enable interior partitions with seamlessly integrated lighting and storage, or facades that gradually transition from opaque to translucent based on sun exposure, minimizing waste and precisely tailored to building needs. Future research must focus on these interdisciplinary challenges, bridging the gap between material science, engineering, and regulatory frameworks to fully realize the potential of MMAM and biodegradable thermoplastics for a more sustainable built environment.

CONCLUSIONS

In summary, this exploration of MMAM with biodegradable thermoplastics demonstrates a promising approach to sustainable furniture design and fabrication. The manipulation of line, surface, and volume provides significant flexibility. We used the Rhino and Grasshopper to enable creation of complex geometries and precise control of material distribution. We implemented procedural growing curves, careful material selection, and the three-point bending tests to assist in the challenges of balancing aesthetics with functionality. With RGB, we then produced preliminary validation of our designs. Because our method is a refinement of multi-material gradients it has the potential for innovative applications in sustainable design and fabrication.

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