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Design and Development of Topology Optimized Three-Dimensional Printed Furniture Joint

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ABSTRACT

This study focuses on the design and development of a three-dimensional (3D) printed furniture joint that is versatile and applicable across various furniture designs and styles, addressing the inherent limitations of traditional furniture joints. Conventional methods often rely on custom-made joints, which are not only time-intensive but also costly to produce, modify, or repair. To overcome these challenges, this research aims to create a furniture joint optimized for both strength and functionality through the application of topology optimization analysis. A comprehensive methodology was employed, beginning with a questionnaire survey to identify user needs and establish product design specifications. Following this, the design concept was developed and evaluated to finalize the joint design. Based on the selected design, a topology optimization analysis was performed to enhance its structural efficiency. The analysis revealed a 45.6% reduction in mass compared to the original joint design. While the structural analysis indicated that the optimized joint experienced slightly higher stress levels than the original design, the maximum stress values remained well below the yield strength of ABS material. This finding confirms the optimized joint's structural integrity and low likelihood of functional failure. The optimized furniture joint, manufactured using 3D printing, demonstrated excellent compatibility and fit with furniture components, including tabletops and legs. This adaptability enables the production of a wide range of furniture designs, including coffee tables, side tables, bookshelves, shoe racks, and honeycomb bookshelves. Furthermore, integrating 3D printing and topology optimization offers several advantages, including reduced material waste, shorter production times, and a more environmentally sustainable approach to furniture manufacturing.

Keywords: Furniture joint, Three-dimensional printing, Topology optimization, Finite element analysis, Design, Modelling, Acrylonitrile butadiene styrene.

1. INTRODUCTION

Furniture joints are fundamental components in woodworking and furniture manufacturing, serving as the connection points between two or more pieces of wood. These joints are critical for ensuring the strength, stability, and functionality of furniture. The design and quality of furniture joints directly influence the structural integrity of the final product [1], as joints often represent the weakest points in furniture construction [2]. Even if the individual components of furniture are robust, joint failure can compromise the entire structure, leading to reduced

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*Corresponding author: ikman@unimap.edu.my durability and functionality [3, 4]. Therefore, designing secure and reliable joints is essential to ensure that furniture can withstand loads and stresses from frequent use.

Traditional furniture joints, such as dowel joints and mortise-and-tenon joints, have been widely used in furniture construction [5]. However, these joints come with inherent limitations. For instance, dowel joints require precise alignment during drilling and measurement, which can be challenging without advanced tools. Additionally, dowel joints may not be suitable for heavy-duty furniture due to their limited load-bearing capacity [6]. Similarly, permanent joints, which rely on screws or nails for assembly, offer stability and ease of construction but pose challenges during repair and maintenance [7, 8]. Damaged permanent joints often require specialized tools and advanced woodworking skills for repair, increasing costs and time. Environmental factors, structural stress, and wood movement can further compromise the strength and durability of these joints over time [9, 10].

In recent years, advancements in 3D printing technology have introduced innovative solutions for furniture joint design and manufacturing [11]. 3D printing enables the creation of complex, highly functional joints with intricate shapes and features, offering significant advantages over traditional manufacturing methods. These advantages include flexible design capabilities, reduced material waste, and rapid prototyping, enabling the production of parts within hours [12]. One notable innovation is the development of modular furniture joints, which simplify assembly, reduce manufacturing time, and improve structural strength. Modular joints enable versatile furniture designs by connecting wooden components for easy assembly and disassembly without tools. However, existing 3D-printed joint designs face limitations in accommodating diverse furniture styles, particularly due to constraints in cross-sectional shapes and technical design features [12-14].

To address these challenges, this study proposes the design and development of a universal 3D-printed furniture joint. The universal joint aims to be adaptable across various furniture designs and styles, significantly reducing production time and cost while enhancing functionality and durability. By leveraging topology optimization, the joint is optimized for strength and lightweight construction, ensuring it can withstand the expected loads of furniture use while minimizing material waste and production costs. Topology optimization involves identifying and removing unnecessary material from the design to achieve an ideal structure without compromising functionality [15, 16].

This study focuses on the application of 3D printing to create a universal joint specifically designed for light-use furniture, such as coffee tables, bookshelves, and side tables. The joint prioritizes ease of assembly and disassembly, as well as adaptability to various furniture styles. Usability testing is conducted to ensure the joint meets the functional and aesthetic requirements of modern furniture design. By utilizing a universal joint, manufacturers can streamline the production process, reduce costs, and facilitate easier modifications and repairs, ultimately contributing to a more efficient and sustainable furniture industry.

The proposed universal 3D-printed furniture joint represents a significant advancement in furniture design and manufacturing. By addressing the limitations of traditional and existing 3D-printed joints, this study aims to develop a highly functional, cost-effective, and environmentally sustainable solution that meets the diverse needs of modern furniture production.

2. MATERIAL AND METHODS

2.1 Identification of User Needs

Identifying user needs is an essential step prior to developing design concepts for furniture joints. To accomplish this, a survey or questionnaire was employed as the primary method. The survey was conducted online and targeted a specific group comprising furniture manufacturers, workers, and users. This method was chosen to gather comprehensive insights into the characteristics and processes associated with furniture production, with a particular focus on the application and functionality of furniture joints.

A total of 46 respondents participated in the survey, all of whom were actively involved in daily furniture manufacturing or were regular furniture users. The survey began with collecting background details from participants, such as age, gender, and occupation, followed by questions assessing their knowledge of furniture joints. Additionally, participants were encouraged to suggest improvements to existing joint designs to gather innovative ideas for further development. The survey covered various topics, including the durability of traditional furniture joints, current joint designs, different furniture configuration styles, factors influencing furniture selection, methods for repairing damaged furniture, the benefits of furniture joints, and recommendations for enhancing the design of existing joints.

The findings indicated that dovetail joints were considered the most secure and durable, with 60.9% of respondents favoring them, followed by nails and screws (23.9%), mortise-and-tenon joints (8.7%), and dowel joints (6.5%). Regarding familiarity with existing furniture joint designs, the dovetail joint emerged as the most recognized, with nearly half of the respondents (47.8%) being familiar with it. This popularity can be attributed to its widespread use in the furniture industry, where it is valued for its durability, adaptability, and ease of use. In contrast, the Jonction-P connector had the lowest familiarity rate at 4.3%, suggesting it is less well known or used in the market.

When it comes to furniture configuration styles, most respondents (47.8%) preferred ready-assembled furniture, while flat-pack furniture was the second most popular choice at 30.4%. Second-hand and modular furniture were the least favored, with each receiving 10.9% of the responses. In terms of factors influencing furniture selection, durability was identified as the most important criterion, with 76.1% of respondents prioritizing it. Style ranked second, valued by 63% of participants, followed by ease of use at 56.5%. Price was considered the least significant factor, with only 50% of respondents listing it as a priority when purchasing furniture.

Repairing broken furniture was another concern, with 63% of respondents preferring to repair the damage themselves. Purchasing new furniture was the second most common option, chosen by 50% of participants. Seeking professional assistance for repairs was the least preferred choice, highlighting a general tendency to either fix damaged furniture independently or replace it altogether.

As for the advantages of furniture joints, most respondents identified “ease of use” as the primary benefit, followed by “durability”. This suggests that universal furniture joints are highly valued for constructing long-lasting furniture, as they are perceived to be both user-friendly and robust. Recommendations for improvement included developing furniture joints with clear, straightforward installation instructions. Additionally, respondents suggested that the joints should allow for quick and easy assembly, requiring minimal tools and specialized skills to use.

2.2 Product Design Specifications

Based on the analysis of the survey data, the proposed furniture joint design should adhere to the following specifications. First, it should feature a simple mechanism for attaching furniture components, allowing for easy assembly and disassembly. Second, the material used should be lightweight yet high-strength, reducing overall furniture weight for easier handling. Third, the joint should have a functional shape or design, enabling it to accommodate various furniture configurations effectively. Fourth, safety features must be incorporated, such as smooth edges to minimize the risk of injuries. Fifth, the overall dimensions of the joint should be appropriate for one-handed operation, ensuring it is neither excessively large nor too small. Lastly, the joint should operate using a manual system, which not only reduces its weight but also ensures straightforward and user-friendly functionality.

The criteria were later utilized in a functional analysis using a morphological chart. This chart details various functions corresponding to the product specifications, which were further explored during a brainstorming session. From this process, five functional groups were identified for the proposed design: body shape, assembly mechanism, flexibility features, assembly complexity, and connecting joint. Each functional group was elaborated into at least three specific ideas to generate a range of potential solutions. By combining these ideas in different ways, four distinct design concepts were developed. These design concepts for the furniture joint are presented in sketch form in Figure 1.

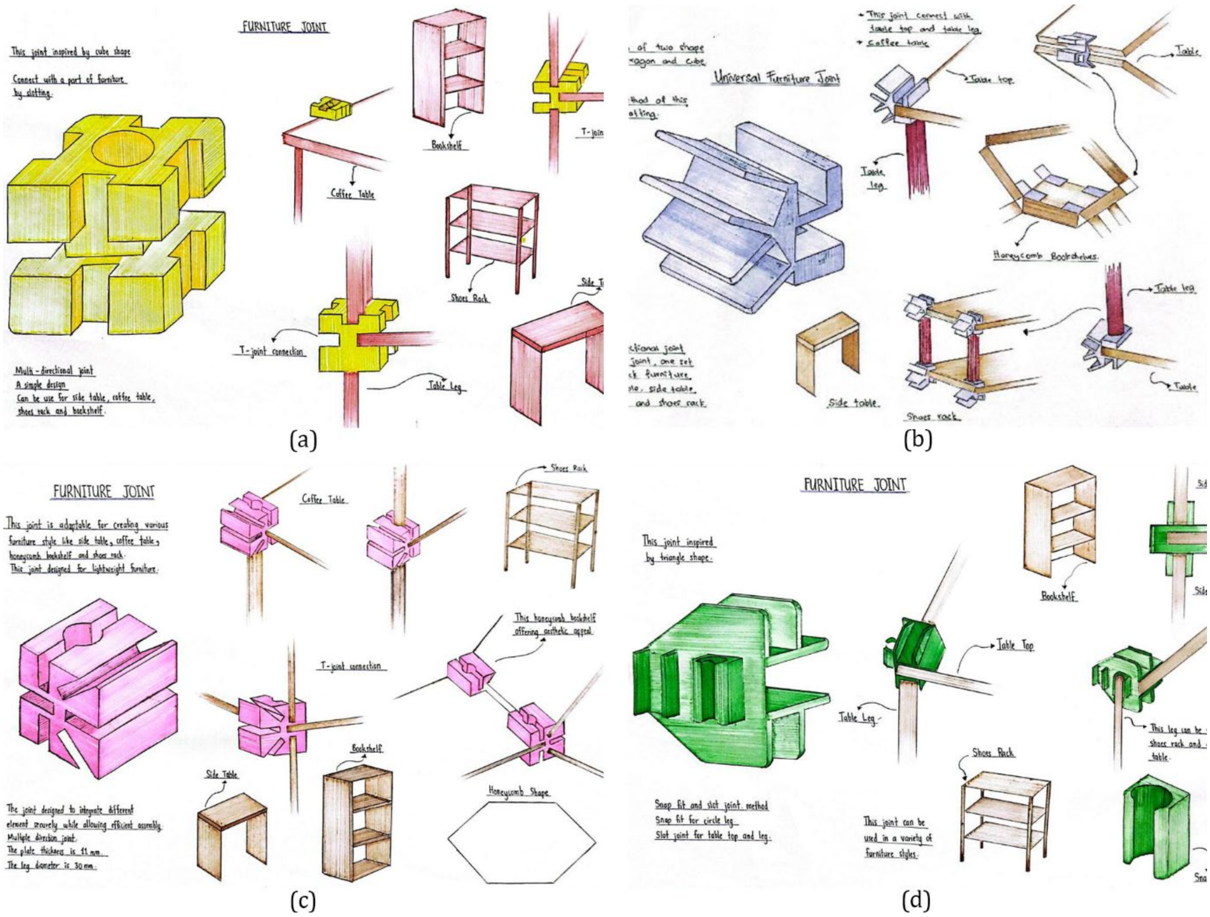

Figure 1: Four distinct design concepts for the proposed furniture joint: (a) Concept A; (b) Concept B; (c) Concept C; (d) Concept D.

Concept A features a straightforward cube-shaped design that prioritizes both stability and simplicity. Constructed from acrylonitrile butadiene styrene (ABS), it measures 75 mm high, 60 mm wide, and 60 mm long. This design is specifically modelled for a slotting assembly technique, enabling secure connections between various furniture components. The assembly method offers versatility and facilitates quick, hassle-free construction, making it suitable for furniture applications such as coffee tables, side tables, and bookshelves. Concept B draws inspiration from a hexagonal shape, offering both enhanced structural stability and an appealing aesthetic. Like Concept A, it is made from ABS material, but with slightly different dimensions of 70 mm in height, 60 mm in width, and 60 mm in length. Its compact size ensures compatibility with light-use furniture, while the slotting mechanism allows for secure connections between furniture components. The design's versatility enables quick, multi-directional assembly, making it ideal for applications such as coffee tables, side tables, and bookshelves. Additionally, the hexagonal design enables the creation of honeycomb-shaped bookshelves, providing modular and visually striking storage solutions that combine functionality with aesthetic appeal. Concept C draws inspiration from the geometric forms of a cube and a hexagon, resulting in a design that combines structural stability with aesthetic appeal. Constructed from ABS, it measures 85 mm in height, width, and length. Unlike Concept B, Concept C differs significantly in both functionality and form. The design incorporates a slotting mechanism, enabling a flexible assembly process and facilitating rapid, multi-directional connections. Moreover, the joint design, influenced by its hexagonal concept, allows for the creation of a honeycomb-shaped bookshelf, similar to the design approach seen in Concept B. Concept D is based on a simple triangular shape, enabling the formation of L-joints for various applications. It is manufactured from ABS and measures 60 mm in height, 50 mm in width, and 50 mm in length. The design is tailored for slotting and snap-fit mechanisms. However, the snap-fit method is limited to circular shapes, which may limit both the aesthetic appeal and the functional versatility of the furniture. Furthermore, the snap-fit assembly is prone to loosening or breaking under repeated use or heavy loads, potentially affecting its durability.

The proposed design concepts were systematically analyzed to address the finalized user requirements. A detailed comparison was conducted using multiple selection criteria to determine the most appropriate design, employing both concept screening and concept scoring techniques. For the concept screening phase, a selection matrix was created based on the identified user needs, with an existing product serving as a benchmark for comparison. Each concept was evaluated against the criteria using the symbols "+," "–," and "0," which indicated performance levels that were superior, inferior, or equivalent to the benchmark, respectively. The ranking of the concepts was determined by calculating the net score, which is the total number of "+" symbols. The concept with the highest net score was ranked first, while the one with the lowest was placed last. Further evaluations were conducted to identify specific areas for improvement across all concepts. Table 1 summarizes the evaluation results from the concept screening process, indicating that Concept A and Concept D were excluded from further consideration due to their performance.

During the concept scoring phase, Concept B and Concept C underwent a detailed evaluation to determine their superiority over the existing design. A rating scale was employed for each selection criterion to indicate its level of importance or relevance. This scale ranged from 1 to 5, with 1 signifying "Poor," 2 indicating "Ok," 3 representing "Fair," 4 denoting "Good," and 5 signifying "Excellent." Each criterion was assigned a specific weight (%) to reflect its relative contribution to the product's overall functionality. The concept scoring process for both Concept B and Concept C is summarized in Table 2. Among the two, Concept C achieved the highest overall score, outperforming Concept B, and was subsequently chosen as the final design for further development. To optimize its performance, minor adjustments were made to Concept C to improve specific features.

Table 1: Concept screening for Concept A – Concept D.

No.	Selection Criteria	Concept A	Concept B	Concept C	Concept D	Competitor (Reference)
1	Easy assembly and disassembly	+	+	+	+	0
2	Aesthetic design	-	-	-	0	0
3	Durable	0	0	+	0	0
4	Attachment method	+	+	+	+	0
5	Lightweight	0	+	0	+	0
6	Easy manufacturing	-	-	+	-	0
7	Save time	+	+	+	+	0
	Sum '+'	3	4	5	4	0
	Sum '–'	2	2	1	1	0
	Sum '0'	2	1	1	2	7
	Net Score	1	3	4	2	-7
	Rank	4	2	1	3	0
	Continue?	No	Yes	Yes	No	No

Table 2: Concept scoring data for Concept B and Concept C

No.	Parameter		Concept B		Concept C	
	Selection Criteria	Weightage (%)	Rating	Weightage Scoring	Rating	Weightage Scoring
1	Easy assembly and disassembly	20	4	0.8	5	1
2	Aesthetic design	10	4	0.4	4	0.4
3	Durable	25	3	0.75	4	1
4	Attachment method	15	4	0.6	5	0.75
5	Lightweight	10	3	0.3	2	0.2
6	Easy manufacturing	10	4	0.4	5	0.5
7	Save time	10	4	0.4	4	0.4
	Total Score		3.65		4.25	
	Rank		2		1	
	Develop?		No		Yes	

2.3 Development of a Three-Dimensional Model

The final design was developed as a detailed 3D model in CATIA, a computer-aided design platform. Main modelling operations, such as revolve, extrude, extruded cut, mirror, and shell, were applied to construct the furniture joint model, which was subsequently rendered to obtain an accurate representation of the part. The dimensional decisions of the model were guided by ergonomic benchmarks, drawing on reported furniture joint measurements from the literature to verify compliance with human-factor requirements. The resulting furniture joint model is illustrated in Figure 2. The joint model measures 85 mm in height, 85 mm in width, and 85 mm in length.

The proposed joint adopts a compact, box-like form and incorporates four primary slot types: vertical, horizontal, rounded, and slanted. These slot geometries enable straightforward detachment and reassembly of connected furniture elements. Each slot was dimensioned to match standard furniture components, with particular attention to thickness and, for cylindrical members, diameter, to ensure a precise fit. Two units were provided for each slot type, yielding a total of eight attachment slots. To address user safety, the joint is designed without sharp edges or other hazardous features.

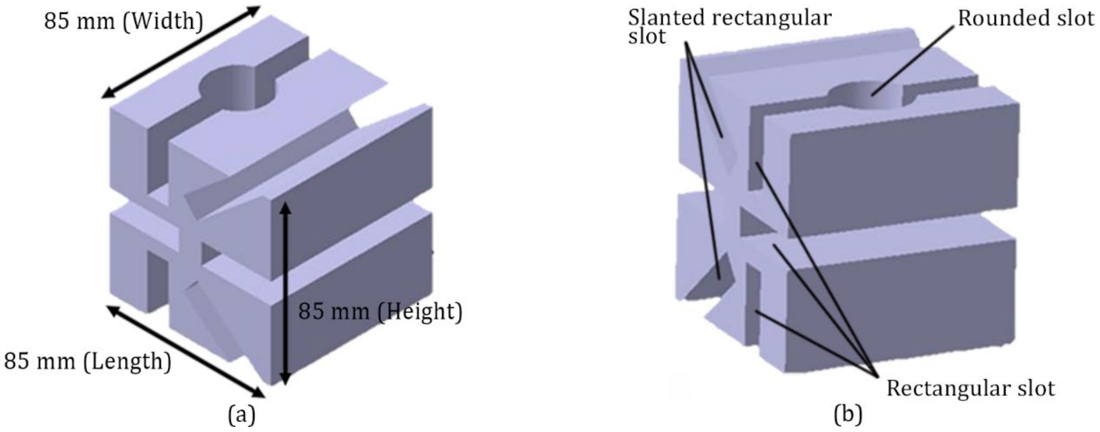

Figure 2: The 3D model of the final design concept of furniture joint from: (a) front; and (b) left views.

2.4 Topology Optimization

The furniture joint model underwent topology optimization analysis in ANSYS to improve its structural performance while preserving both strength and functionality. This optimization process was designed to ensure the joint could endure the anticipated loads associated with furniture use while remaining lightweight and efficient [17]. By systematically eliminating excess material, the method aimed to achieve a balance between weight reduction and performance enhancement [18]. As a result, the universal furniture joint was optimized to be strong, lightweight, and material-efficient, meeting the intended design objectives.

Five distinct furniture styles (Figure 3) were modelled in CAD and analyzed using topology optimization: coffee table, side table, standard bookshelf, shoe rack, and honeycomb-style bookshelf. These models consisted of furniture components assembled with the proposed joint design. For each furniture configuration, the design space and constraints were carefully defined to determine the optimal material distribution, identifying areas to retain or remove material. Since each furniture style has unique structural requirements, the design space and constraints were adapted accordingly to ensure accurate and efficient optimization.

The material properties used in the model were assumed to be isotropic, homogeneous, and linearly elastic. The furniture joint was constructed from ABS, while the furniture components were made from pine. The specific material properties applied in the analysis are detailed in Table 3.

The contact between the furniture joint and the wooden furniture components was modelled as bonded to simulate strong and secure attachments. For the boundary conditions, the bottom surfaces of the furniture parts in contact with the ground were treated as fixed supports. A uniformly distributed load of 350 N was applied to the top surface of the furniture to represent the typical weight load expected during use [19]. Besides, a target mass reduction of 50% was set and applied to the furniture joint across all configurations to meet the objectives of the topology optimization process.

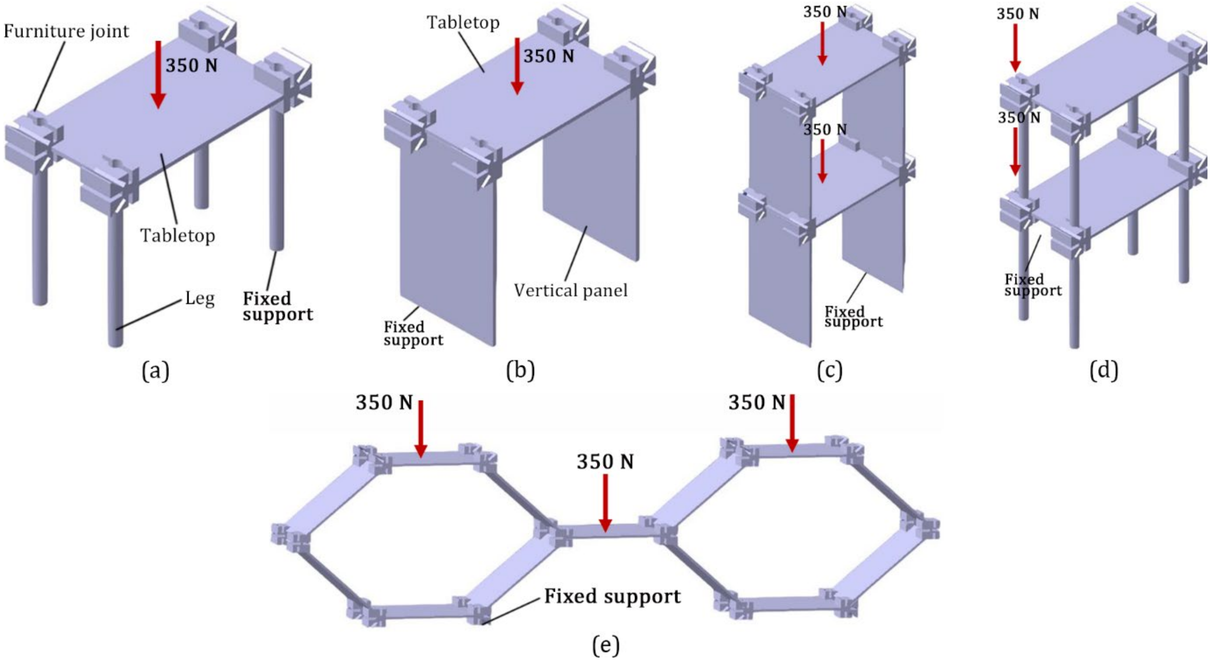

Figure 3: Different furniture configuration styles formed using the furniture joint model: (a) coffee table; (b) side table; (c) bookshelf; (d) shoe rack; (e) bookshelf in honeycomb design

Table 3: Material properties used in the topology optimization analysis

No.	Material	Young's Modulus, *E*	Poisson's Ratio, *v*	Strength	Density
1	ABS	3.2 GPa	0.35	Yield: 48 MPa	1050 kg/m^3
2	Pine wood	9 GPa	0.329	Tensile: 18 MPa	470 kg/m^3

2.5 Fabrication of Prototype and Functional Testing

After completing the topology optimization and confirming the results were satisfactory, the 3D design of the furniture joint was refined and exported in STL format to prepare it for production. To fabricate the optimized joint, the 3D printing method was employed. The finalized model was loaded into the slicing software, where key settings, such as layer thickness, print speed, infill pattern, and density, were carefully configured. The printer setup included selecting suitable material and calibrating the print bed to ensure proper adhesion of the initial layer. The part was fabricated from ABS via fused-filament 3D printing, a lightweight choice that facilitates handling and storage. Once everything was in place, the printing process commenced. Post-production involved a detailed finishing stage that required both specialized tools and skilled handling. This stage included sanding and polishing the printed part, followed by painting to improve the overall surface finish and aesthetic quality.

To determine how well the prototype joint performed in real-world applications, a series of functional tests was conducted. These tests focused on evaluating how effectively the joint could be used to assemble various types of furniture, including a coffee table, a side table, a shoe rack, a standard bookshelf, and a uniquely styled honeycomb bookshelf. The assessment considered the typical dimensions of commercially available furniture components to ensure compatibility. Rather than simply testing mechanical fit, the goal was to confirm that each configuration could be built with minimal difficulty, demonstrating the joint's practicality and adaptability in multiple design contexts.

3. RESULTS AND DISCUSSION

3.1 Topology Optimization

The outcomes of the topology optimization were evaluated through the resulting density distribution. Structural comparisons were conducted between the initial and optimized models to examine performance variations. The optimized configurations were expected to demonstrate mechanical strength equal to or greater than that of the baseline design. The main findings are presented in Figure 4, which illustrates the optimized joints across five furniture categories: coffee table, side table, bookshelf, shoe rack, and honeycomb bookshelf. The optimization process systematically eliminated redundant material, thereby enhancing both structural efficiency and functional performance. High-density areas represent regions subject to greater stress concentrations, where material retention is necessary. Conversely, regions of lower density correspond to areas of minimal structural demand, indicating potential for material removal. Each optimized joint displays distinctive structural features that correspond to the specific loading conditions and support requirements of its respective furniture type.

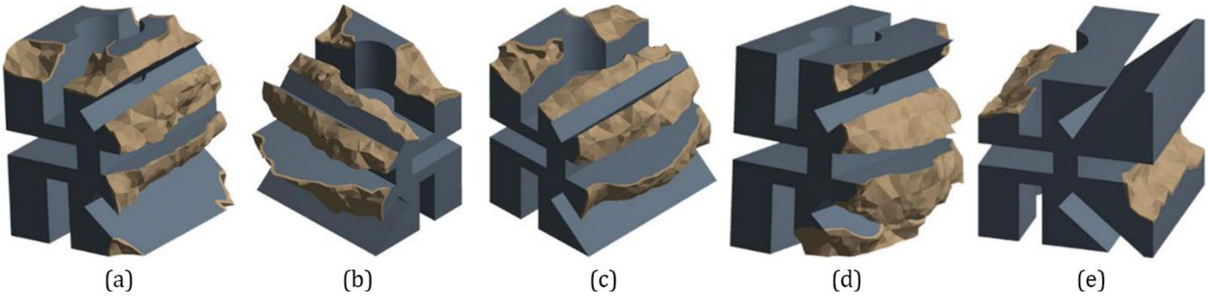

Figure 4: The results of topology optimization of the furniture joint for each furniture style: (a) coffee table; (b) side table; (c) standard bookshelf; (d) shoe rack; (e) honeycomb bookshelf.

The optimization of the side table joint indicates that material should be concentrated at the base, particularly at the point of leg attachment. The inclined section was removed because it made no significant contribution to the table's structural performance. A comparable trend was observed in the coffee table, where material was preserved at the base and along the side supports, reflecting similar functional demands. In the bookshelf, material reduction was achieved in the inner and lateral regions, while adequate reinforcement was maintained to sustain vertical loads from stored books. For the honeycomb bookshelf, optimization emphasizes retaining material along the joints and perimeter of the hexagonal framework, with reductions in less critical regions subjected to lower stresses. Overall, the findings demonstrate that material is strategically concentrated at connection points, vertical members, and edge supports, zones that are essential for carrying loads and maintaining structural stability.

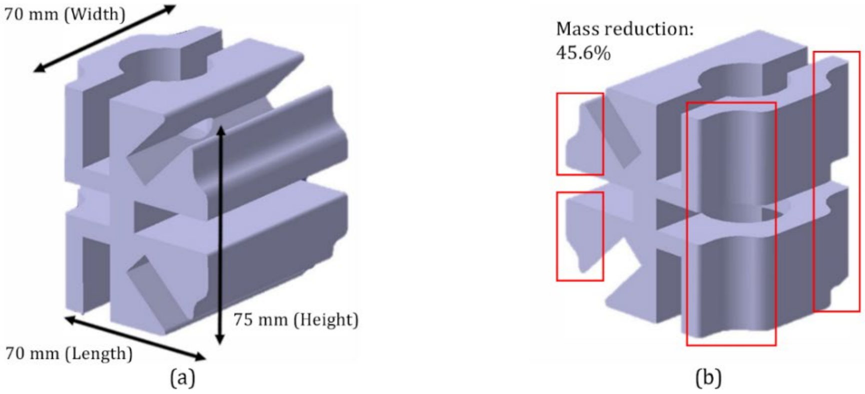

Figure 5: Topologically optimized design of furniture joint: (a) front view; (b) back view.

Figure 5 presents the optimized configuration of the furniture joint, developed in CATIA, based on the outcomes of the topology optimization analysis. The design process incorporated geometric considerations drawn from all the furniture styles examined. Material distribution was refined to reinforce regions subjected to high stress, while redundant material in less critical zones was systematically removed, thereby improving both mechanical performance and functional efficiency. Minor geometric adjustments were introduced relative to the original model. The final joint measures 70 mm in length, 70 mm in width, and 75 mm in height, with a mass of 184 g compared to the original 338 g. This represents a weight reduction of approximately 45.6%. To validate the redesigned joint, a linear static structural analysis was conducted to evaluate its strength through stress behavior.

3.2 Structural Analysis

Figure 6 shows the stress-contour plot for the coffee table design. This configuration incorporates four joints that connect the tabletop to its supporting legs. The analysis revealed that the maximum stresses in the joints ranged between 1.63 MPa at Joint 1 and 2.37 MPa at Joint 3. Among all joints, Joint 3 exhibited the highest stress concentration, located at the interface between the leg and the tabletop. Despite the variations in magnitude, the overall stress patterns were consistent across all joints, with critical stress concentrations observed predominantly in the connection regions where load transfer occurs.

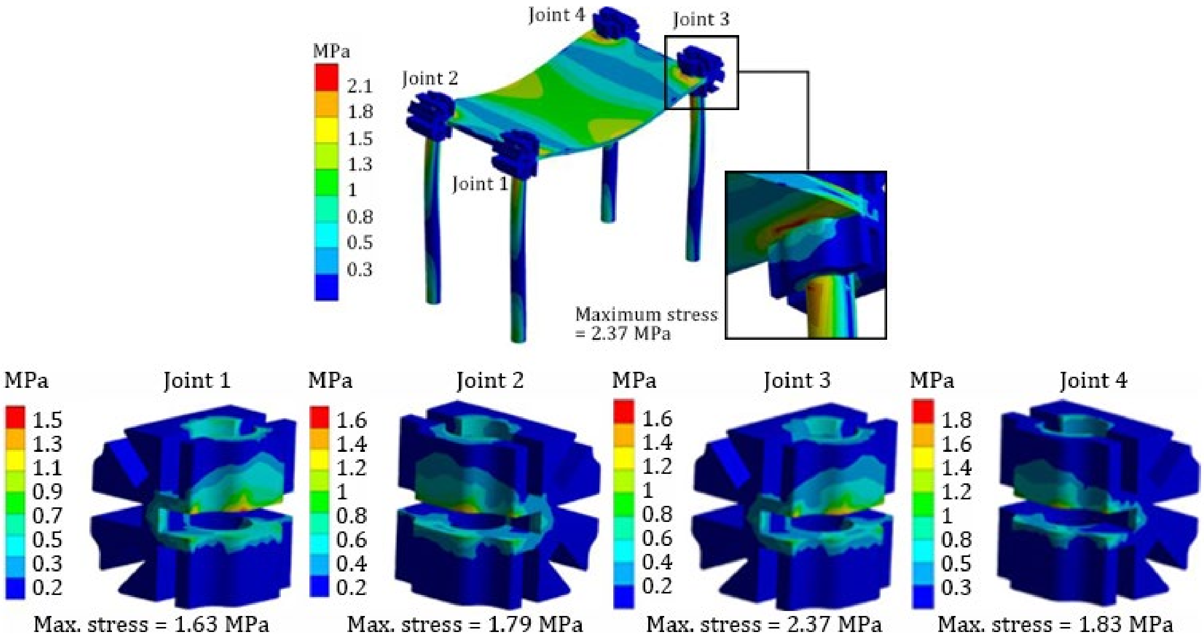

Figure 6: Stress plot within the optimized joints for the coffee table design.

Figure 7 presents the stress distribution for the side table configuration. The model consists of a single tabletop supported by two vertical side panels, assembled using four joints. The analysis identified the highest stress at Joint 4, with a peak value of 2.88 MPa occurring at the junction between the tabletop and the supporting panel. In contrast, Joint 1 experienced the lowest stress level, measured at 2.03 MPa. Across all joints, stress accumulation was consistently observed at the interfaces where the vertical panels meet the tabletop edges. Among the four joints, Joint 4 demonstrated the most critical stress response, indicating that this connection is the most structurally vulnerable region of the design.

In relation to another furniture configuration, namely the standard bookshelf design, the stress analysis results are presented in Figure 8. This model consists of two horizontal shelves supported by four vertical panels, interconnected through eight joints. The findings indicate that the highest stress concentration, measured at 1.46 MPa, occurred at Joint 8, whereas the lowest stress, 1.05 MPa, was observed at Joint 1. Similar to the side table configuration, the critical region was identified at the junction between the vertical panels and the horizontal tabletop. This elevated stress is primarily attributed to the distributed load acting on each shelf level, which amplifies the force transfer at the panel–tabletop interfaces.

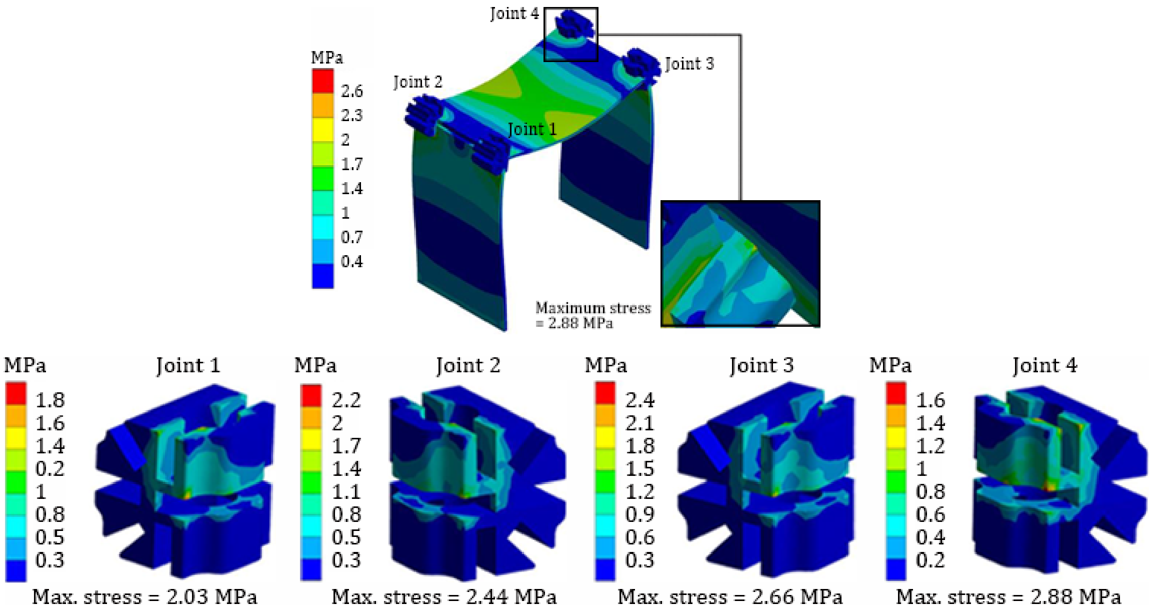

Figure 7: Stress plot within the optimized joints for the side table design.

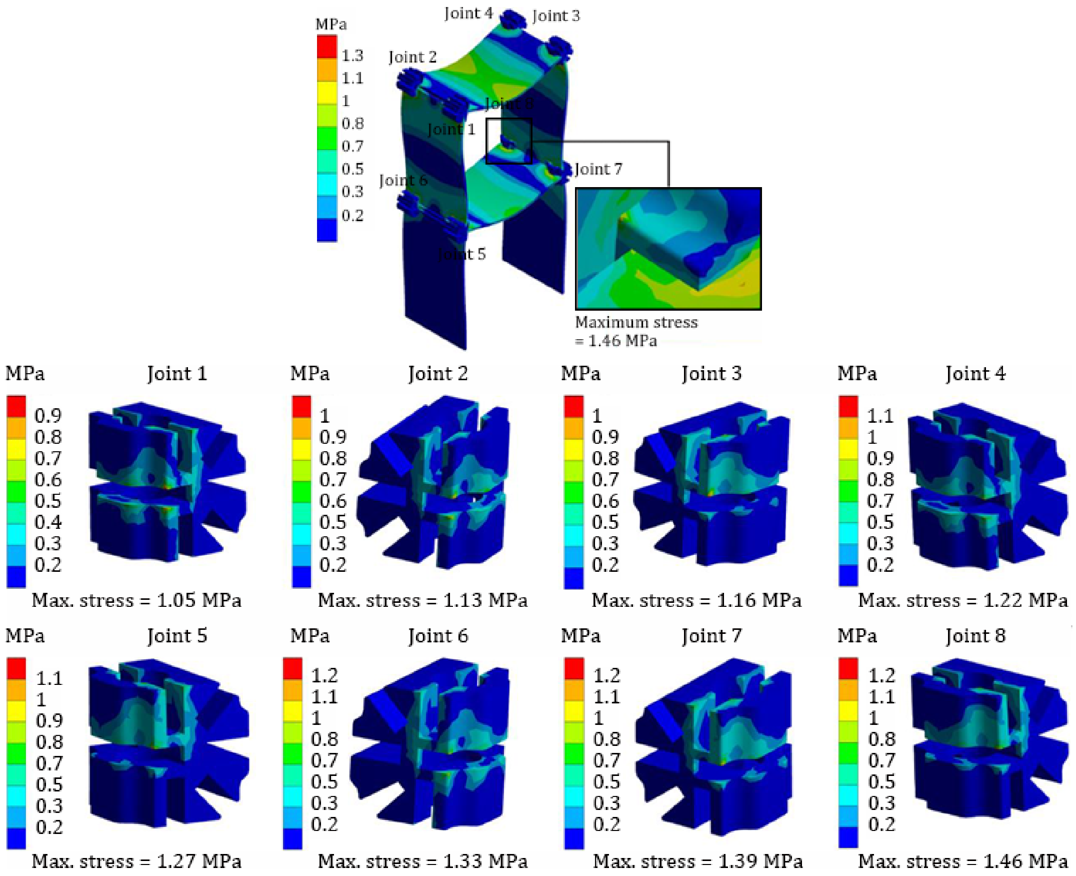

Figure 8: Stress plot within the optimized joints for the standard bookshelf design

For the shoe rack configuration, the design can be regarded as an extended form of the coffee table structure. The modification was achieved by adding a tabletop with four supporting legs, creating two shelf levels for shoe placement. As illustrated in Figure 9, the highest stress value, 1.07 MPa, was observed at Joint 8. In contrast, the lowest stress, 0.86 MPa, was recorded in Joints 1 and 2. The critical stress concentration occurred at the junction where the vertical support leg connects to the horizontal shelf. This localized effect can be attributed to the retention forces developed at the connection, which play a significant role in counteracting the applied loading on the shelf.

For the bookshelf with a honeycomb configuration, the structure was assembled using thirteen square wooden panels connected through twenty-four joints. As presented in Figure 10, the maximum stress value recorded was 30.28 MPa, concentrated at the joints linking the panels. In contrast, most regions of the bookshelf exhibited relatively low stress, which may be attributed to the even distribution of forces across the interconnected panels.

Among the furniture configurations examined, the honeycomb-style bookshelf exhibited the highest stress concentration within its joints. To evaluate the likelihood of joint failure under functional loading, the maximum stress values obtained from each configuration were compared with the yield strength of the joint material. Given that the yield strength of ABS is approximately 48 MPa [20], the analysis revealed that the peak stress values in all optimized joint designs remained well below this threshold. This finding suggests that the optimized joints possess a low risk of structural failure under the applied loading conditions.

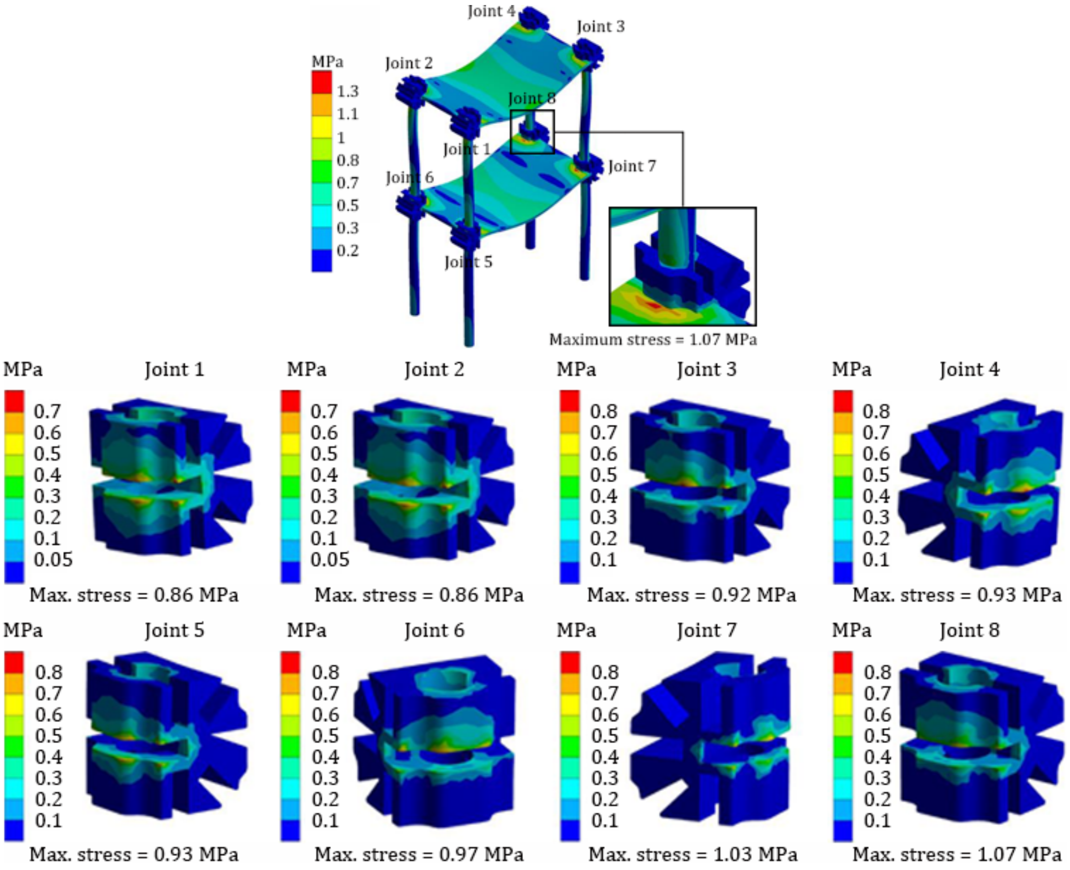

Figure 9: Stress plot within the optimized joints for the shoe rack design.

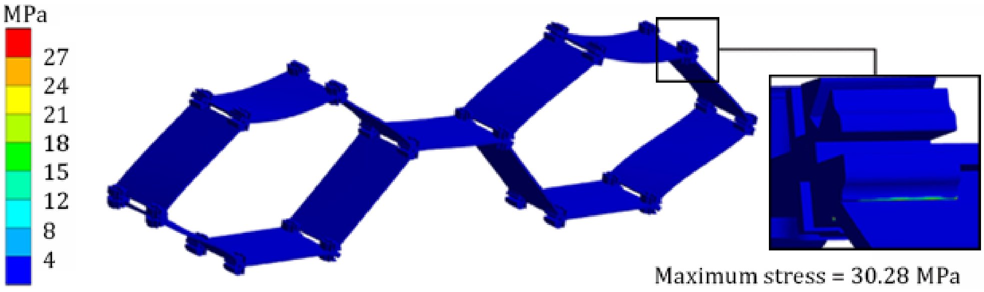

Figure 10: Stress plot within the optimized joints for the honeycomb bookshelf design.

3.3 Prototyping and Usability Testing

A total of eight optimized furniture joint prototypes were fabricated, enabling the assembly of four distinct furniture configurations, as illustrated in Figure 11. The fabrication of these prototypes provided practical insights into integrating joints into complete furniture assemblies. By physically assembling the components, the accuracy of the joint design, its compatibility with adjoining parts, and the ease of installation could be effectively evaluated. Furthermore, the prototype production served as a validation step to bridge the numerical analysis with real-world application, ensuring that the optimized design could be translated into functional furniture structures without compromising structural integrity.

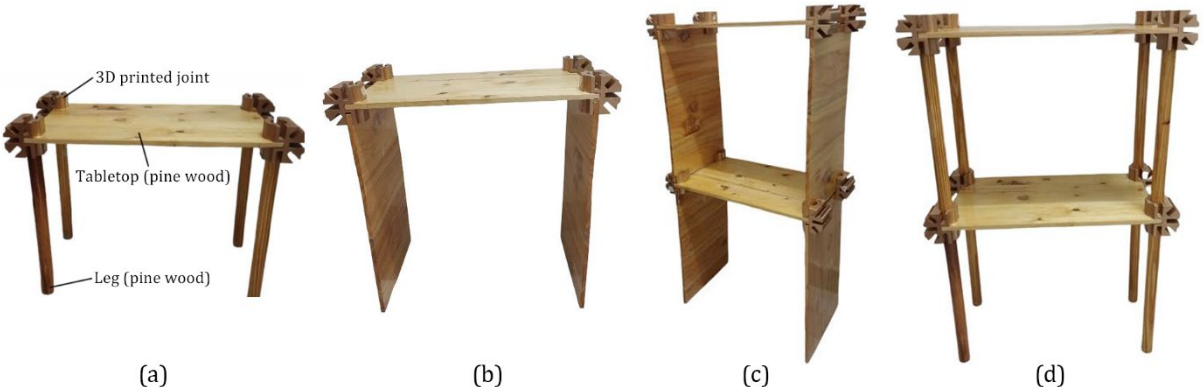

Figure 11: Prototype fitting and assembly of furniture joint for different furniture styles: (a) coffee table; (b) side table; (c) standard bookshelf; (d) shoe rack.

Following the fabrication of the proposed furniture joint prototype, its performance was evaluated by assembling it into flat-pack furniture to verify compatibility with other components. The assembly trials confirmed that the printed joint was able to integrate seamlessly with the furniture parts, demonstrating both its functionality and adaptability across different furniture configurations. These tests served as an important validation step, ensuring that the joint design fulfilled the intended performance requirements and could be reliably implemented in diverse applications.

In addition to assembly testing, dimensional verification of the printed joint was conducted before and after fabrication. The joint was initially designed with nominal dimensions of 75 mm in height, 70 mm in width, and 70 mm in length to guarantee a precise fit with the furniture elements. However, post-printing measurements revealed slight dimensional reductions, with the prototype recording values of approximately 74.5 mm in height, 69.5 mm in width, and 69.7 mm in length. These discrepancies can be attributed to several factors, including material shrinkage during cooling, printer tolerances, and minor warping. Although the deviations were relatively small, they highlight the influence of manufacturing limitations on the accuracy of 3D-printed components. Such findings emphasize the importance of accounting for fabrication tolerances during the design phase to ensure reliable assembly outcomes in practical applications.

The proposed joint design offers several notable advantages over conventional furniture joints currently available on the market. One of its distinctive features is the incorporation of two attachment geometries: a rounded slot and a rectangular slot. The rounded slot facilitates the connection of circular components, such as cylindrical legs, thereby enhancing the stability of the overall structure. In contrast, the rectangular slot is particularly advantageous for accommodating linear elements, including tabletops and side panels, which are commonly used in modular furniture systems. Recent studies have explored various approaches to designing 3D-printed furniture joints. For instance, Petrova and Jivkov (2024) introduced a joint with an L-shaped configuration [11]. While the design demonstrates simplicity and ease of fabrication, its application is limited because it supports only L-shaped attachments, limiting its adaptability to other furniture geometries. In a related work, Nicolau et al. (2022) proposed a joint consisting of three square-shaped slots [21]. This design allows slender structural members to be assembled; however, the dimensional constraints of the slots make it less suitable for bulkier or irregular components. Abdullah et al. (2023) presented an alternative concept through the development of a modular 3D-printed joinery system known as FLUX, which emphasizes an ergo-aesthetic framework [22]. Unlike conventional joints with sharp corners, FLUX uses smooth, curvilinear geometries, allowing thin members to be connected into complete, visually appealing furniture configurations. Such an approach reflects a growing trend towards integrating structural performance with ergonomic and aesthetic considerations. Another noteworthy contribution comes from Hajdarevic et al. (2023), who examined the mechanical performance of 3D-printed connectors in comparison with the traditional mortise-and-tenon joint for chair applications [23]. Their results revealed that although additive manufacturing offers design flexibility, the printed joints require further optimization to withstand standard load conditions reliably. This finding underscores the importance of balancing innovative geometrical designs with sufficient structural robustness when adopting 3D printing technologies in furniture joinery.

In addition to the basic configurations of our joint design mentioned earlier, the joint includes an inclined rectangular slot. This modification enables more versatile assembly arrangements, allowing the development of unconventional and aesthetically appealing designs. For instance, such a configuration can support honeycomb-style bookshelves or other furniture requiring non-standard angular alignments. By accommodating both functional and stylistic demands, the design offers flexibility that is often lacking in traditional joints. Another important consideration is the thickness of the joint. Although it is slightly bulkier than typical designs, its structural performance remains efficient due to the application of topology optimization techniques. These optimization strategies ensure that the material distribution within the joint is both structurally reliable and lightweight. Consequently, the final design achieves a balance between robustness and material efficiency, addressing concerns related to both durability and weight.

Despite the promising outcomes of this study, certain limitations should be acknowledged, particularly with respect to dimensional accuracy and print quality of the fabricated joints. Variations in geometry, especially in complex sections of the design, may influence the precision of fitting and long-term performance. To address this, future work should focus on employing high-resolution 3D printers and refining key process parameters, including layer height, print speed, and temperature control, to minimize deviations from the intended dimensions. Moreover, the current design, while effective, is constrained by fixed dimensions, which may limit its adaptability to furniture parts of varying sizes. Further improvements could therefore explore adjustable or modular joint configurations that enhance universal compatibility across a wider range of furniture styles. Such refinements would not only improve manufacturability but also extend the practicality and scalability of the proposed joint system for industrial applications.

4. CONCLUSION

In conclusion, this study successfully developed and validated a 3D-printed universal furniture joint that is adaptable across various furniture designs while remaining structurally efficient. Through a systematic process involving literature review, customer need surveys, and iterative concept development, a final design was generated and optimized using topology techniques, resulting in a mass reduction of approximately 45.6% compared to the original model. Structural analyses revealed that the critical stress values remained significantly below the yield strength of ABS material, indicating a low probability of failure under typical loading conditions. The fabrication of prototypes further confirmed the practicality of the design, with successful fitting tests demonstrating its compatibility in multiple furniture configurations. Post-processing enhanced both the aesthetic and functional quality of the joint, underscoring its feasibility for real-world applications. Overall, the findings highlight the potential of 3D printing and topology optimization to advance the development of lightweight, reliable, and versatile furniture joints, offering a promising solution for future furniture manufacturing and customization.

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