

Modular Furniture Design for Small Living Spaces: A Development Study Using CAD and Rapid Prototyping

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ABSTRACT

This study presents the design and development of a modular furniture system optimized for small living spaces through the use of CAD-based design and rapid prototyping methods. The project addresses common challenges in compact urban homes, where traditional furniture is often rigid, oversized, and poorly adapted to limited spatial layouts. An iterative design-thinking framework was adopted, supported by user surveys, concept screening, and a House of Quality (HOQ) analysis to translate user requirements into functional design specifications. A scaled prototype was fabricated using 3D printing to evaluate functional mechanisms and validate the design's adaptability, modularity, and usability. Structural simulations demonstrated strong performance, with a maximum deformation of 0.094 mm and stress values well below the material yield limit, confirming the robustness of the design under expected loads. A comparative assessment also highlighted the benefits of digital design and prototyping in reducing material waste and enabling higher customization compared to conventional manufacturing. The findings demonstrate that modular furniture systems developed through CAD methodologies can significantly enhance space efficiency and user adaptability in small living environments, offering valuable insights for future urban furniture innovation.

Keywords: Modular Furniture Design; Small Living Spaces; Space-Efficient Design; CAD-Based Development; Rapid Prototyping; House of Quality.

INTRODUCTION

The modular furniture system project addresses the challenges faced by individuals living in compact spaces, such as apartments or tiny houses. Finding furniture that is both functional and space-saving is often difficult in such environments. This project aims to create a modular furniture system that is adaptable and customizable, using 3D printing and CAD technologies for efficient and cost-effective production (Lundgren, 2021; Neyses, 2015). Traditional furniture can be bulky and hard to reconfigure, making it unsuitable for small spaces. Custom furniture is typically expensive and time-consuming to produce using conventional methods like woodworking and injection molding (Neyses, 2015). In contrast, 3D printing and CAD technologies allow for the creation of complex, customized designs with minimal setup and tooling costs, improving both economy and efficiency (Lundgren, 2021). However, these technologies come with challenges, such as size limitations and the need for specific design approaches to accommodate 3D printing.

Compact living environments such as small apartments and student units continue to pose challenges related to space efficiency, flexibility, and storage management. Although modular furniture has been widely explored in various domains, existing studies often focus on general multifunctionality without addressing the specific ergonomic and spatial constraints of micro-living environments. Prior research (e.g., Wang, 2022; Ler & Sidek, 2023) has demonstrated the importance of adaptable systems, yet few studies integrate structured design methods

such as concept screening and House of Quality (HOQ) to translate user needs directly into technical specifications. This gap highlights the need for a systematic design-driven approach to developing modular furniture tailored for small living spaces.

The project will follow an iterative design methodology, known as the design thinking process, to develop a modular furniture concept based on stakeholder requirements and manufacturing constraints. This process will also involve a co-design approach to understand user needs.

The study analyzes small living spaces, explore existing furniture solutions, and identify user needs. It will include a literature review on modular furniture systems, 3D printing, and CAD integration. The design process will be detailed, focusing on adaptability, customization, and space efficiency. The use of CAD tools and 3D printing technologies will be highlighted, with a focus on selecting suitable materials. The report will cover the prototyping phase, outlining 3D printing fabrication and testing methodologies.

Traditional fabrication routes (e.g., woodworking and injection molding) can be time-consuming and tooling-intensive, limiting customization at small batch sizes. In contrast, digital design workflows and rapid prototyping accelerate iteration cycles and enable form–function exploration at low cost. However, scaling from prototypes to full-size production requires careful attention to materials, joinery, and load-bearing performance.

The objectives of this work are to: (i) elicit user requirements for small living spaces; (ii) generate and down-select concepts using structured decision tools; (iii) map customer needs to engineering characteristics using a House of Quality; (iv) validate structural performance using simulation; and (v) demonstrate key mechanisms via a scaled prototype. Full-scale manufacturing is intentionally left technology-agnostic to accommodate wood-based and hybrid construction suitable for long-term use.

This study addresses that gap by applying CAD-based development and rapid prototyping to create a user-centered modular solution. By grounding the design in empirical user data and structured evaluation methods, the work advances beyond prior art that emphasized general modularity but lacked evidence-based design justification.

Application Of Modular Furniture Design

Modular furniture design is highly flexible and versatile, making it suitable for various environments, including homes, offices, educational institutions, retail spaces, and healthcare facilities. This type of furniture is composed of functional, decorative, and part-level modules with standardized interfaces, allowing for easy adaptation to changing user needs (Wang, 2015).

In residential settings, modular furniture is particularly effective for small living spaces due to its multifunctionality. It can be used for storage, seating, and sleeping, making it an adaptable solution for compact areas (Ler & Sidek, 2023). In office environments, modular workstations and desks can be easily rearranged to meet the dynamic needs of modern workplaces, promoting collaboration and flexibility.

Educational institutions benefit from the versatility of modular furniture, which can be quickly rearranged to support different teaching methods, collaborative projects, and various learning environments. This adaptability allows educators to modify physical spaces to meet individual learning needs, creating a dynamic and flexible learning atmosphere .

In the retail sector, modular furniture enhances both aesthetics and functionality, allowing for creative product displays and periodic rearrangements. The visual appeal of a retail space significantly influences customer experience and purchasing decisions. By integrating art into modular furniture design, retailers can create visually engaging environments that attract and retain customers (Shilin, 2022).

Healthcare facilities require adaptable solutions to accommodate fluctuating patient loads, evolving care models, and technological advancements. Modular furniture provides the flexibility needed to quickly adjust to these changing needs, whether by expanding capacity, rearranging spaces, or incorporating new technologies

(Merilampi, 2020).

Public venues and events also benefit from modular furniture, as it allows for quick and easy reconfiguration of seating and display arrangements. This adaptability helps venues respond to varying demands, such as hosting different types of events or adjusting to changes in audience size (Altehenger, 2022).

Overall, modular furniture design proves to be a crucial element in modern design across various industries due to its ability to adapt, rearrange, and customize spaces. This adaptability makes modular furniture an essential component of contemporary and practical environments (Shilin, 2022).

Space-Efficient and Multifunctional Design

Space-efficient design strategies maximize functional density through multifunctional elements (e.g., storage-integrated tables) and foldable or sliding mechanisms. Recent work emphasizes tool-free assembly, disassembly, and material choices that support reuse and circularity. These principles inform the present study's focus on compactness, multifunctionality, and ease of assembly as primary customer requirements.

Space-friendly design focuses on maximizing the use of available space through efficient layouts, furniture, and settings. This concept is increasingly important as more people move into smaller homes and apartments, requiring thoughtful and effective design solutions, as shown in Figure 2.1.



Figure 0.1 : Apartment Floor Plan (Ollár et al., 2022)

Researcher had explores the role of multifunctional furniture during the pandemic, highlighting its ability to enhance productivity and comfort in work This study underscores the potential for furniture to adapt to changing situations. (Wang, 2022) further emphasizes reimagining multipurpose furniture by considering its entire life cycle and proposing sustainable design approaches that incorporate sustainability concepts.

Additionally, there is a focus on the development of modular furniture systems made from wood (Śmietańska & Mielczarek). Suandi, (2022) highlight the use of standardized connectors and rectangular wooden boards to create various furniture forms that can be easily assembled and disassembled without tools.

The analysis of space-efficient design compares traditional furniture with modular systems, showing how each influences suitability for different environments (Suandi, 2022).

METHODOLOGY

User Survey

A structured survey (n = 50) targeted occupants of small residential units (apartments, flats, and hostels) to identify pain points and priority zones within homes. Respondents indicated kitchens as the most constrained areas due to limited counter space, storage scarcity, and workflow congestion. These insights set the design focus on a modular kitchen rack–table concept with sliding and rotational mechanisms to increase usable surface and storage volume.

A detailed survey was conducted to collect data on furniture-related issues in small households. The study aimed to gather perspectives from people living in compact spaces, focusing on their experiences, preferences, and challenges with furniture use. The survey included both quantitative and qualitative questions to provide a comprehensive understanding of the issues.

Participants were asked about space limitations, difficult furniture styles, and preferences for modular or multipurpose solutions. The survey targeted various demographics to ensure a representative sample, considering factors like location, household size, and cultural influences.

The collected data provides valuable insights into the challenges faced in small living environments. These insights guide the next stages of the project, influencing the design and prototyping processes to effectively address the identified issues. The survey method is crucial for understanding customer needs and creating furniture solutions that enhance the efficiency and comfort of small living spaces.

Concept Generation, Screening and Scoring

Five concepts were generated and evaluated against criteria derived from the survey: compactness, multifunctionality, storage capacity, customizability, and aesthetics. An initial screening using symbolic ratings (+, 0, -) shortlisted three concepts. A weighted scoring model then ranked the finalists; the top concept balanced performance across criteria and advanced to detailed design.

Concept Screening and Scoring is a pivotal stage in the design process, systematically guiding the selection of the most viable and promising design concepts. This method involves establishing specific criteria aligned with project goals and user needs, assigning weights to reflect the relative importance of each criterion, and creating a scoring system for evaluation.

Each design concept is then rigorously assessed against these criteria, and the scores are aggregated based on their assigned weights as in Table 3-1 . The outcome is a quantitative representation of how well each concept aligns with the project's objectives. The subsequent ranking of concepts allows for the identification of top-performing designs.

Table 0-1 : Concept Screening and Scoring

Criteria	References	Design 1	Design 2	Design 3
Cost	0	+	+	-
Aesthetics	0	-	-	+
Sturdy	0	-	+	-
Sum +				
Sum -				
Sum 0				
Net				
Decision				

This process not only streamlines decision-making but also provides a transparent and objective basis for selecting concepts that show the most potential. The feedback loop, involving stakeholder and user input, ensures that the final selection aligns closely with the project's goals and can be further refined through iterations if necessary.

Overall, Concept Screening and Scoring serve as a robust framework for making informed decisions in the design phase, setting the groundwork for the subsequent development and implementation stages.

House Of Quality (HOQ)

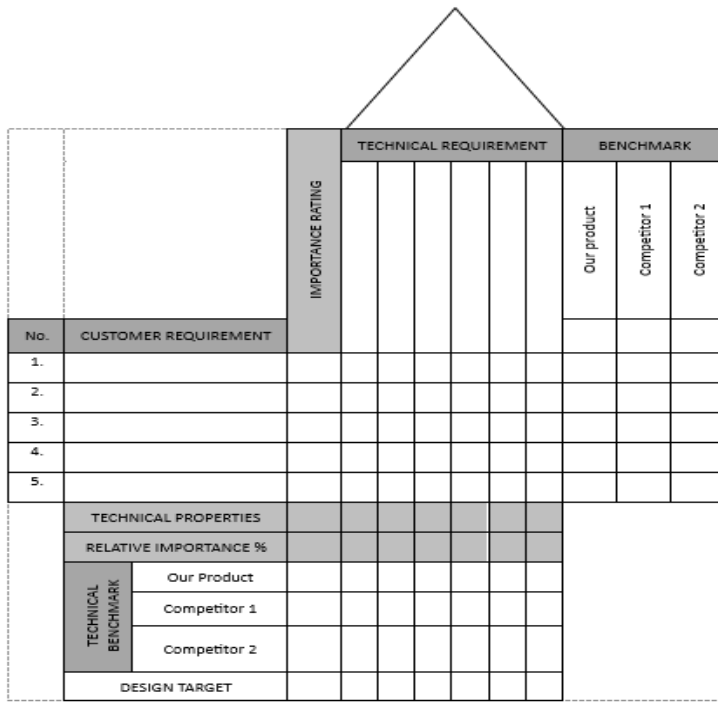


Figure 0.2 : House of Quality

The HOQ translated customer attributes: compactness, versatility, storage, customizability, and ease of assembly, into technical targets including modular architecture, hinge flexibility, efficient volume utilization, and interchangeable components. Competitive benchmarking indicated opportunities to differentiate on storage capacity and customizability, while aesthetics remained a priority for future iterations.

The House of Quality (HOQ) is a crucial tool in product design and development, helping to understand and prioritize customer needs systematically. This framework connects customer requirements with technical specifications, ensuring that products meet consumer expectations.

Customer requirements include compactness, multifunctionality, storage capacity, customizability, and aesthetics. On the technical side, specifications involve modular design, flexible hinges, efficient space utilization, interchangeable parts, and ease of assembly. These technical details are essential for turning customer needs into actual product features.

Importance ratings, usually on a scale of 1 to 5, help designers prioritize their efforts and allocate resources effectively. Technical benchmarking compares the product against competitors, identifying areas for improvement and innovation.

The relationship matrix in the HOQ shows the connections between customer needs and technical requirements, helping designers focus on key priorities. This understanding ensures that the final product aligns with consumer preferences.

RESULTS AND DISCUSSION

User Needs and Design Focus

Survey results reinforced the kitchen as the most space-critical zone, justifying a modular rack–table concept. The proposed solution integrates a sliding work surface and a rotatable table element to expand functional area on demand while maintaining a minimal footprint when stowed.

Consist of finding 50 respondents to answer the survey questions containing 3 sections. The first section focuses on knowing the respondents conditions and what type of houses their currently live in. The main types of house was Flat, Apartments, Student’s Apartments (Hostel) and Terrace. Based on the result below, in order to focus on small living spaces the respondents mostly living in apartments. While the student’s apartment (hostel) was the lowest due to lack of sections in the living spaces.

Types of houses currently living Jenis rumah semasa
 50 jawapan

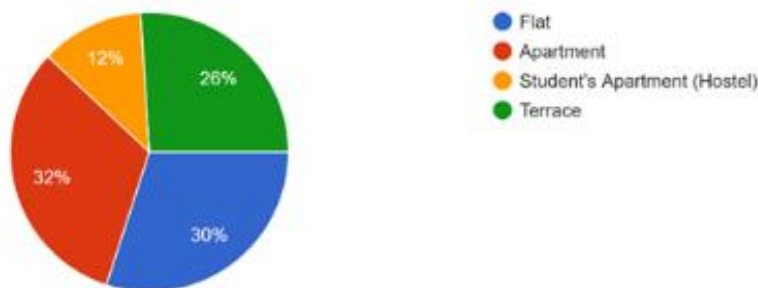


Figure 0.1 : Pie Chart

In order to focus on which sections in houses that required the critical solution saving on small living spaces. In the survey, the questions narrowing down on which part such as foyer, living room, kitchen, bathroom or bedroom required the solution.

Which room(s) in your living space require the most space-saving solutions? Bilik manakah yang anda rasa memerlukan penyelesaian yang paling menjimatkan ruang?
 50 jawapan

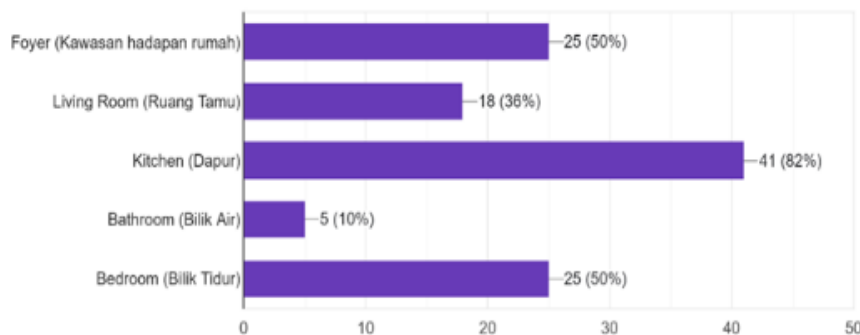


Figure 0.2 : Graph Bar

The results shows that the respondent need the space-saving solutions on kitchen space, which are the highest data. From this data, the design requirement will be focus on how to design space-saving solutions using modular furniture system that specializes in kitchen.

Concept Evaluation Outcome

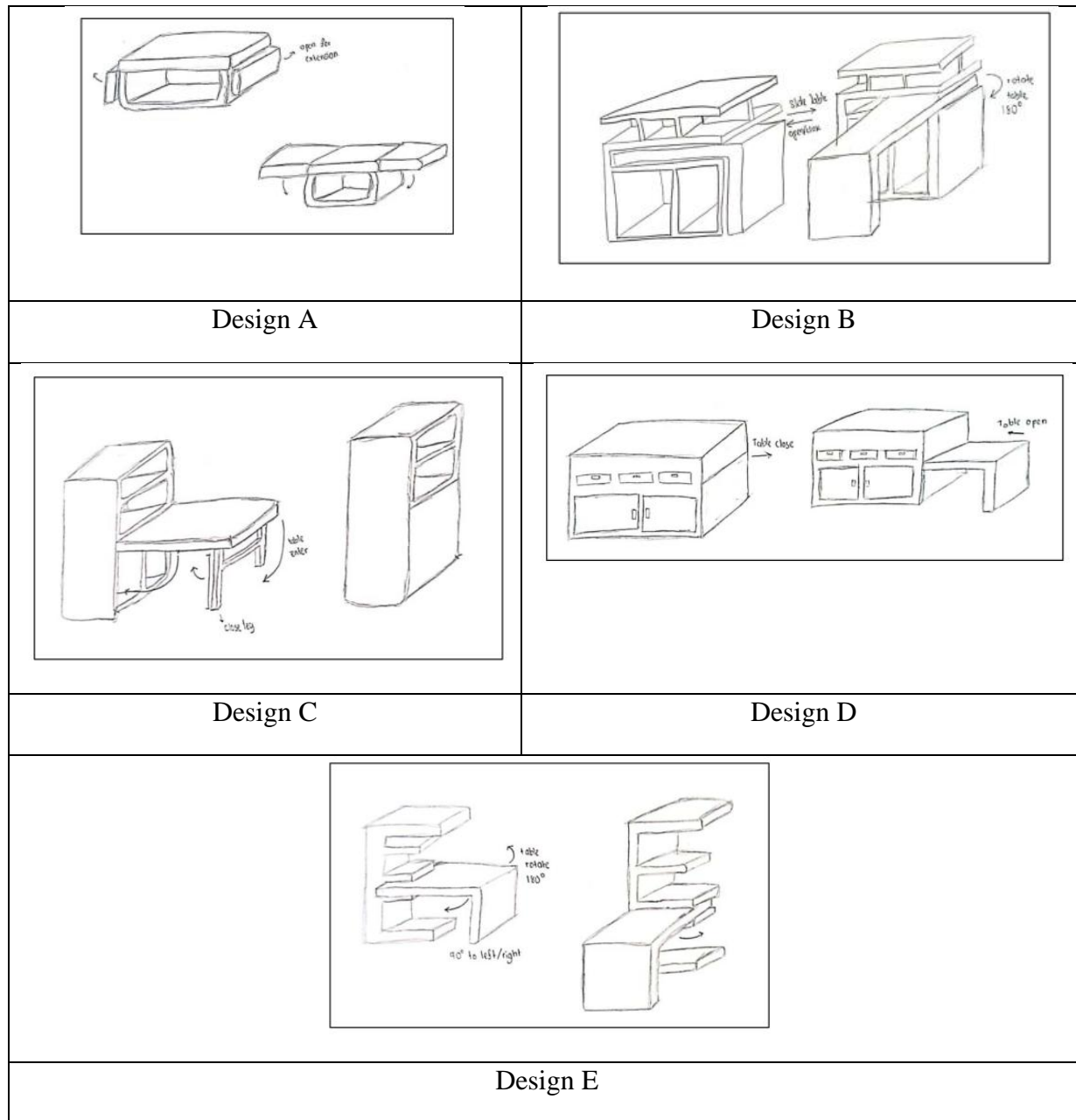


Figure 4.3 : The conceptual designs.

Table 0-1 : Screening

Selection Criteria	Design A	Design B	Design C	Design D	Design E
Compact Size	+	0	0	-	0
Multifunctionality	+	++	++	+	+
Storage Capacity	-	++	+	++	+
Customizability	+	+	++	+	+
Aesthetics	0	+	+	+	++
Sum of +	3	6	6	5	5
Sum of 0	1	1	1	-	1
Sum of -	1	-	-	1	0
NET SCORE	2	6	6	4	5
RANK	4	1	1	3	2
CONTINUE?	NO	YES	YES	NO	YES

Selection Criteria	Weight %	Concepts					
		Design B		Design C		Design E	
		Rating	Weight Score	Rating	Weight Score	Rating	Weight Score
Compact Size	21.28	5	1.06	5	1.06	4	0.85
Multifunctionality	23.40	4	0.94	4	0.94	4	0.94
Storage Capacity	26.24	5	1.31	5	1.31	5	1.31
Customizability	18.44	4	0.74	4	0.74	3	0.55
Aesthetic	10.64	4	0.43	3	0.32	5	0.53
TOTAL	100%	4.48		4.37		4.18	
	RANK	1		2		3	
	CONTINUE	YES		NO		NO	

Table 0-2 : Scoring

The structured down-selection identified the chosen concept as the best compromise across compactness, multifunctionality, storage, customizability, and aesthetics. The process ensured transparency and alignment with user priorities before committing to detailed design.

The first table, titled "Screening Data", presents the outcomes of a concept screening process for five design alternatives (A, B, C, D, and E) evaluated against five selection criteria: Compact Size, Multifunctionality, Storage Capacity, Customizability, and Aesthetics. Each design is assessed with a "+" if it meets the criterion, "0" if it partially meets the criterion, and "-" if it does not meet the criterion and is a negative factor.

The table also displays the cumulative counts of "+", "0", and "-" for each design, along with a net score and a rank. Notably, Design B and Design C both achieve the highest net score (6), followed by Design E (5), Design D (4), and Design A (2).

The second table, titled "Scoring Data", provides the results of a more detailed concept scoring process for the top three designs (B, C, and E) identified in the initial screening. This table includes:

- i. Selection Criteria: The same five criteria from the initial screening.
- ii. Weight (%): The percentage weight assigned to each criterion (e.g., Compact Size is weighted at 21.28%).
- iii. Design B, Design C, Design E: The scores each design receives for each criterion on a scale of 1 to 5.
- iv. Rating x Weight: The product of the rating and the weight for each criterion (e.g., for Design B, Compact Size is $5 \times 1.06 = 5.3$).
- v. Score: The total sum of the Rating x Weight for each design.
- vi. Rank: The rank of each design based on the overall score.
- vii. CONTINUE?: A column indicating whether to continue scoring concepts, with all three designs marked as "NO".
- viii. Design B emerges with the highest score (4.48), followed by Design C (4.37), and Design E (4.18).

In summary, the tables illustrate a two-stage concept evaluation process for five designs. The initial stage involves screening to identify the top three designs. The subsequent stage entails a detailed scoring process where weights are assigned to different criteria, and each design is rated on a scale of 1 to 5. Based on this comprehensive scoring process, Design B is identified as the top-ranked design.

HOQ Insights

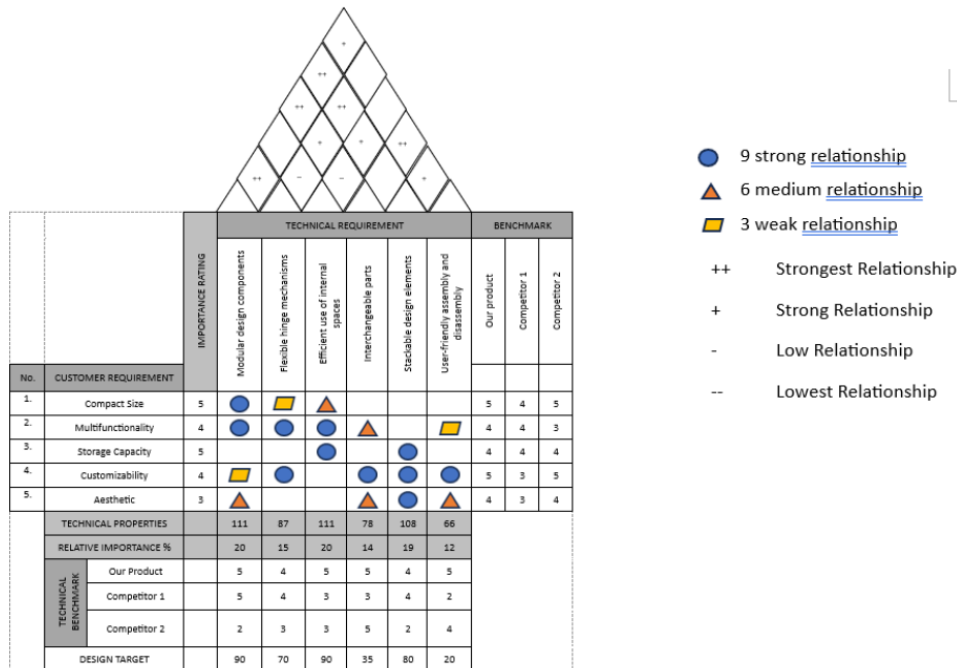


Figure 0.4 : House of Quality Product

The HOQ confirmed strong relationships between customer needs and technical parameters, particularly for storage density and modularity. Benchmarking suggested that while the proposed design leads in adaptability and storage, aesthetic refinement can further enhance perceived value.

As illustrated in the HOQ table in Figure 4.4, the findings demonstrate that the proposed product excels in meeting most customer requirements, especially in terms of customizability, storage capacity, and ease of assembly, surpassing competitors in these areas. However, it is noteworthy that competitor products receive higher ratings concerning aesthetic appeal.

The technical properties section of the House of Quality (HOQ) underscores the significance of each technical requirement, identifying modular design components, storage capacity, and customizability as the top priorities. The design targets established for these key technical requirements indicate that the design aims to achieve a high level of performance to fulfill customer needs.

Overall, the HOQ results reflect a methodical and data-driven approach to the design and development of the modular furniture system. The clear alignment of customer requirements with technical specifications, supplemented by competitive benchmarking, provides a robust foundation for the product development process. Insights gained from this analysis will facilitate informed decision-making and optimization of the design, resulting in a highly functional and aesthetically appealing product tailored for small living spaces.

Structural Simulation - Engineering Analysis

Finite element analysis of load-bearing components predicted a maximum total deformation of 0.094 mm and a peak von Mises stress of approximately 1.174 MPa, well below the yield strength of the modeled material. These results indicate adequate stiffness and a large safety margin under expected service loads.

The simulation results reveal that the maximum total deformation of the structure is 0.093665 mm (approximately 0.094 mm), while the minimum deformation is 0 mm. The average deformation throughout the structure is 0.034474 mm. This minimal maximum deformation suggests that the structure exhibits substantial rigidity under the applied loads. Zero deformation is likely occurring in proximity to the fixed support, whereas the maximum deformation is observed in the Part2 Part Body component. The deformation pattern, as depicted

in the accompanying image, indicates greater displacement in the upper sections of the structure, which diminishes as it approaches the fixed support regions.

The equivalent (von-Mises) stress analysis indicates a maximum stress of 1.1744 MPa and a minimum stress of 0.000015193 MPa (approximately 0.015 kPa), with an average stress of 0.03008 MPa across the structure. Notably, the maximum stress is considerably lower than the tensile yield strength of the material, ABS high-impact plastic, which is 27.44 MPa. This finding demonstrates that the structure operates well within its safe stress limits, providing a substantial safety margin. The stress distribution, illustrated in the provided image, reveals localized regions of elevated stress near points of applied force or geometric discontinuities, while the majority of the structure experiences relatively low stress levels.

Overall, these findings indicate that the structure performs effectively under the specified loading conditions, with both deformations and stresses remaining within manageable limits. The maximum deformation of less than 0.1 mm indicates good structural stiffness, and the peak stress being significantly below the material's yield strength suggests that the structure is unlikely to undergo plastic deformation or failure under these conditions.

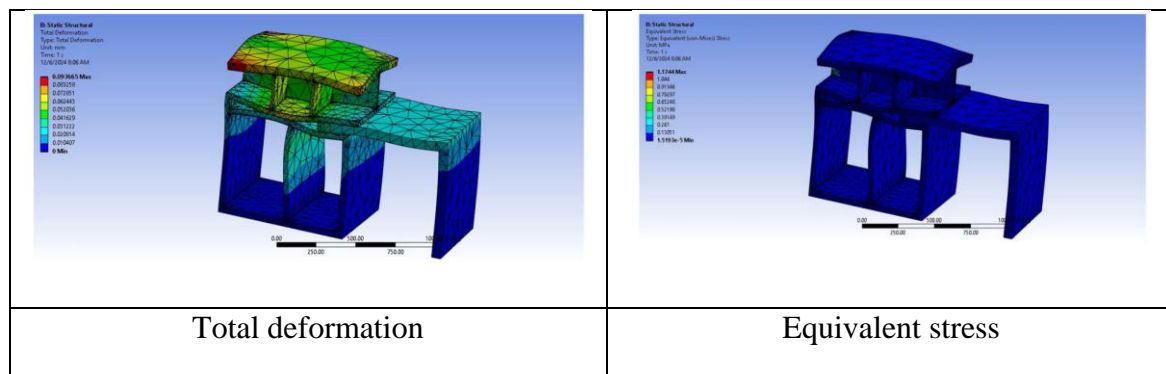


Figure 4-5 : The structural simulation - engineering analysis

The simulation results provide quantifiable evidence supporting the claims made regarding the durability and structural performance of the proposed furniture system. The maximum deformation recorded (0.094 mm) and peak stress (1.174 MPa) remain significantly below material limits, indicating strong structural stability. These results validate that the modular joints and load-bearing members can reliably support operational use.

Prototype Demonstration

A scaled prototype was fabricated via 3D printing to validate mechanism feasibility. The prototype demonstrated smooth sliding and 180° rotational motions, confirming usability and assembly intent. The prototype serves as a communication artifact for stakeholder feedback and informs full-scale material and joinery selection.

After the design was finalized, a scaled-down prototype was printed to demonstrate the product's functions and mechanisms. To ensure high quality, the printing process for the prototype required approximately 24 hours to complete two components: the rack and the table.

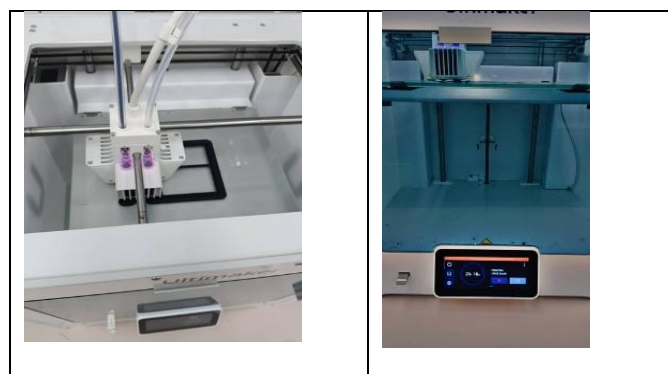


Figure 0.6 : 3D Printing Machine

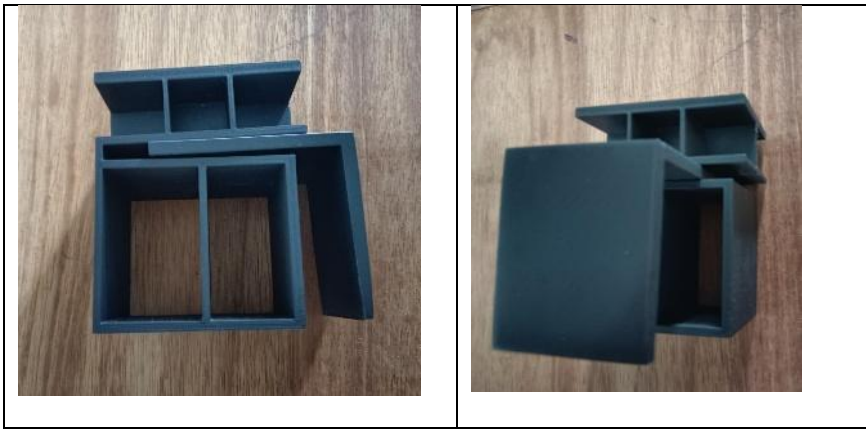


Figure 0.7 : Product Prototyping

After 24 hours, the prototype was completed. The resulting model successfully demonstrated its intended functionality, showcasing the table's ability to slide in and out and rotate 180 degrees both left and right. Furthermore, usability observations from the prototype demonstration, such as smooth sliding and 180° rotational capability, corroborate the design's functional adaptability. This aligns with findings in existing literature showing that movement-based mechanisms enhance user interaction and improve spatial efficiency in constrained environments (Ler & Sidek, 2023; Merilampi et al., 2020). These strengthened findings directly support the conclusion that the final design improves both functionality and convenience in small domestic environments.

Overall, the completion and successful operation of the prototype mark a significant achievement in the development of the modular furniture system. It validates the design concepts and provides a solid foundation for the next steps, which include further testing, refinement, and preparation for full-scale production.

CONCLUSION

This study achieved its objectives by systematically developing a modular furniture system tailored to small living environments. User surveys identified kitchens as the most constrained area, guiding the design toward a modular rack-table solution. Structured decision tools such as concept screening and HOQ ensured alignment between user needs and technical specifications.

Simulation analyses confirmed the structural reliability of the proposed system, while the scaled prototype validated its mechanism performance. These results collectively support the claim that the system enhances space efficiency and functional adaptability.

Future work should include full-scale user testing, sensory evaluation of usability, and long-term durability assessments. These additional studies will further reinforce the system's applicability and readiness for real-world deployment.

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