Geometric Ornamentation for Self-Assembly Guidance in Planar Interlocking Joint System

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ABSTRACT

The ongoing trend of residing in compact living spaces has led to an increased popularity of interlocking joints as a viable solution for both structural design and aesthetic appeal. However, frequent assembly and disassembly can cause wear and tear, leading to an in-depth investigation aimed at overcoming obstacles to self-assembly. To tackle this challenge, a design principle inspired by a three-dimensional interlocking joint has been developed to improve the portability of furniture panels. Since non-professionals may be responsible for joint assembly, a user-friendly design is crucial.

This study presents a novel planar interlocking joint system (PIJS) for furniture panels, which utilizes geometric ornamentation. The integration of geometric ornamentation in complex joint assembly presents an opportunity to reinstate the popularity of ornamentation in contemporary times while also preserving its historical and aesthetic significance.

We have developed five prototypes by integrating the mortise and tenon joint with an interlocking joint and incorporating a geometric ornamentation guide. These prototypes employ two distinct geometrical shapes: Quadrangular shapes, including Prototypes A without geometrical ornamentation, and A_1 and A_2 with three-dimensional and two-dimensional geometrical ornamentation, respectively, and a Triangular shape, including Prototypes B without geometrical ornamentation and B_1 with geometrical ornamentation. To test the effectiveness of geometric ornamentation

guidance in the self-assembly of PIJS prototypes, we conducted five experimental sessions at Iwate University involving 30 graduate students aged 18-35.

There were two types of experiments: (Case 1) using video recording and (Case 2) using a brain activity sensor. In Case 1, experiments 1, 2, and 3, participants were asked to create certain quadrangular shapes using Prototypes A, A_1, and A_2. During the process of assembly, the video was recorded to identify the assembly difficulties in quadrangular PIJS prototypes. The purpose of Case 1 was to investigate the number of errors, instances of disassembly, and the overall assembly time of the prototypes.

In Case 2, experiments 4 and 5 used Prototypes B and B_2. To achieve this, the participants were asked to assemble the prototypes freely and without restrictions. During the assembly process, each participant wore a brain activity sensor to identify the most challenging joint part of the PIJS prototype. The data collected from the brain activity sensor was used to analyze the assembly process.

Following the assembly process of each case, one-on-one interviews and questionnaire sessions were conducted with participants to validate the data collected from the video recording and brain activity sensor. The participants were asked to provide feedback on their experience after the assembly process, including any difficulties they faced while assembling the prototypes.

The experiment's results were analyzed using the Paired Samples T-Test method to compare the prototypes with and without geometrical ornamentation. The aim was to determine the effectiveness of the geometrical ornamentation in improving the assembly process. The analysis was carried out using statistical software to ensure accurate results.

Overall, the experiment provided valuable insights into the assembly process of the prototypes and how the process could be improved. The data collected from the brain activity sensor and the feedback provided by the participants during the interviews and questionnaire sessions helped to provide a comprehensive understanding of the assembly process.

The findings of the study suggest that the incorporation of ornamentation into a planar interlocking joint system can facilitate the identification of concealed holes and notches. Additionally, the study highlights the notion that ornamentation can serve not only as an element of aesthetic appeal but also as a useful prompt for self-assembly in the context of complex joint designs. The Planar Interlocking Joint System (PIJS) has been demonstrated to be advantageous in various domains, with particular relevance to the assembly of furniture. The present research provides valuable insights into the design of planar interlocking joint systems and its potential applications across a broad range of domains.

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CHAPTER 1

INTRODUCTION

1.1 Research Background and Objectives

Adequate living spaces are a crucial element of living standards. In many congested nations, living circumstances are regarded as symptomatic of housing deprivation [1]. Over the years, overpopulation has changed modern furniture design in overcrowded cities such as Hong Kong, Tokyo, and London. In these cities, cramped lifestyles are most common among young adults and young families [2]. For decades, Western research has linked a lack of living spaces to negative psychological repercussions [3].

It is important to note that living conditions vary across regions. The Mongolian ger, called the ger, has been used by nomadic people for more than five thousand years because of its seasonal suitability. Until now, the Mongolian people have utilized Mongolian yurts instead of rental apartments. Living in a ger is much more affordable and convenient for young adults who are not financially stable. The ger has long been known for its assembled structural design. A ger is beneficial for seasonal changes because of its portability and lightweight [4]. The size of the yurt can be changed using its panels. In Mongolia, it is common for people to use a ger made of four panels, covering an area of 19 square meters. This space is equivalent in size to a small studio apartment in Japan.

Small living space which is also called cramped space are not comfortable for the young adults who works at home. The limited space can reduce the productivity of individual. However, the overpopulated cities can only accommodate a tiny space for per person to live in.

1.2 Sustainable Design

Sustainable design is an approach to create more environmentally friendly products to enhance the products lifecycle. A product with a low impact on environment and longer lifespan is becoming more popular in worldwide. The environmental pollution requires change in product design.

Furthermore, furniture production and disposal is a factor that significantly impacts our environment and can enable us to tackle the issue of limited living spaces. As the human population increases and societies become more developed, furniture consumption has increased. Overpopulation and industrialization have changed the direction of furniture criteria from aesthetic and traditional to environmentally friendly [5]. The book Sustainable Practices for Landfill Design and Operation mentions that hazardous particles from waste can affect human health [6], and the recycling and reuse of furniture results in positive economic and environmental outcomes [7]. Multifunctional furniture has the potential to enhance living standards by allowing for better space utilization [8].

1.3 Furniture and Structural Joint

The furniture and construction industries aim to reduce the use of adhesives and fasteners in joints. Joints play an essential role in furniture and structures. The effectiveness of joints is tested using various quality criteria, including load capacity and stiffness, based on the strength of the joint design [9]. The type of glue and thickness of the guidelines are essential for the strength of joints [10]. In recent years, manufacturers and consumers have preferred to use sustainable products and replace hazardous components with wood composites to satisfy environmental requirements [11]. Replacing adhesives and fasteners with sustainable adhesives and interlocking joints facilitates recycling.

On the other hand, the furniture industry prefers to use interlocking joints instead of adhesives because they do not encourage disassembly or re-assembly. An interlocking joint is usually called a complex joint because of its overlapping set of small parts, where the parts are assembled and sealed by the last part and can be repeated [12]. Many ready-to-assemble (RTA) pieces of furniture have been created using the interlocking joint method instead of adhesives. Today, customers prefer to purch [5]ase ready-to-assemble (RTA) and multifunctional products, indicating that products with multiple uses are becoming more popular [13]. Assembling RTA products can be challenging for consumers. Moreover, incorrect assembly can cause significant damage to product parts, thereby reducing long-term sustainability. Frequent disassembly can often lead to damage. A series of studies have investigated cube puzzle joints to improve assembly efficiency. However, the current study specifically focuses on thin-structured interlocking joints that can create multiple forms. The modular elements of interlocking joints can create various functions in the structure and furniture fields. Owing to their similar shapes and components, assembling these joints may confuse users more than furniture and structure that utilizes fasteners and adhesives. Repeatedly assembling and disassembling furniture joints can cause them to deteriorate; hence, this study strives to pinpoint and remediate any challenges in self-assembly. This research establishes a design principle centered around a thin-structured interlocking joint that enhances the mobility of furniture panels. The purpose is to provide a more user-friendly joint assembly method for self-assembly. In contrast to existing interlocking joint techniques, we present a planar interlocking joint that can be utilized in furniture panel components. To achieve this goal, the joint must ensure reliable and secure assembly and simultaneously allow users to customize their furniture designs.

1.4 Modular Furniture and Portable Design

Portable furniture designs are becoming increasingly popular as people look for ways to optimize space in their homes. With the limited area available in spaces such as studio apartments and offices, multifunctional areas are preferred over separate rooms. As a result, the separation of individual spaces has become an essential factor in house design. To cater to this need, many furniture designs have been created with modular functions that save space and allow for the separation of one-room apartments into individual activity spaces.

In addition, the issue of overpopulation has led to changes in the size of rooms, which has affected the comfortability of consumers. Modular furniture and portable designs have become more popular as they provide flexibility and versatility. Young adults, in particular, are the main consumers of such furniture. The designs are not only functional but also stylish and trendy, making them a popular choice for those who want to optimize their living spaces while maintaining a modern look.

Portable furniture has the advantage of being easy to transport when users move to a new location. Rather than discarding the furniture, they can simply disassemble it and reassemble it in their new home. There are various design options available for this type of furniture, such as folding and assembling. Many companies aim to improve compact living in the modern era through modular furniture design, including IKEA (Sweden), Nitori (Japan), and Muji (Japan).

Figure 1: IKEA's GURSKEN chest of drawers.

IKEA

IKEA is a renowned furniture company that is known for producing furniture that is both affordable and comfortable. The company's primary goal is to offer its products at low prices without compromising on quality. However, high transportation costs and damage rates have been a constant challenge for the company. The flatpack and self-assembly furniture proved to be solution to these problems.

IKEA's primary focus is on creating sustainable, functional, and aesthetically pleasing products. This led to the development of five dimensions in the design of IKEA products: price, quality, form, function, and sustainability. The company believes that when all five dimensions are in balance, the product is considered democratic. This means that the product is accessible to everyone, regardless of their budget, and offers the best possible quality.

The concept of Democratic Design was officially launched at the Milan Furniture Fair in 1995. Since then, it has been a crucial tool in developing and evaluating IKEA products. The company ensures that its products are not only affordable but also stylish, functional, and sustainable. This approach has made IKEA a global leader in the furniture industry, with millions of customers worldwide [14]. The IKEA assemblable drawers GURSKEN product is shown in Figure 2.

Figure 2: NITORI’s storage furniture and items.

NITORI

Founded by Akio Nitori in Sapporo back in 1967, Nitori has become a leading furniture and furnishing company in Japan with a mission to cater to the needs of its customers. The company's approach to achieving this goal was to make its products affordable without compromising on quality. This strategy allowed Nitori to compete effectively with other companies in the market and improve the quality of its products over time.

Nitori specializes in providing home furnishings that meet the needs of both individuals and businesses. Their primary focus is on families who seek affordable, easily transportable furniture due to their frequent moves. This demographic tends to replace their furnishings more frequently than their higher-income counterparts. The operational approach of Nitori and IKEA is quite similar as both began as small furniture stores utilizing the SPA (Specialty store retailer of Private label Apparel) method, prioritizing low-cost furnishings and employment. The most attractive attribute of both Nitori and IKEA are their competitive pricing and cost-effectiveness [15]. The Nitori’s storage product is shown as an example in Figure 3.

Figure 3: MUJI's Rattan Stackable Basket Lid

MUJI

MUJI was established in 1980 with the objective of creating simple, good-quality products at a low cost by reexamining the manufacturing process through three lenses: material selection, inspection process, and packaging simplification. MUJI's packaging is light beige in color, which results in products that are remarkably pure and fresh [16].

MUJI's products are simple and empty, yet not in the minimalist style. They embrace the feelings and thoughts of all people with their rational manufacturing process. MUJI’s Rattan Stackable Basket Lid is shown as an example in Figure 3.

1.5 Summary

This section covered the usage of portable furniture and its popularity in modern times. The study reviewed the information of a series of furniture design companies that are in high demand among young adults. The reasons these furniture designs are popular are portability, low cost, sustainability, and multi-functionality in a single furniture design. Therefore, this study aims to focus on a design that can contain all of these aspects.

1.6 Thesis Overview

CHAPTER 1: Introduction

This introductory chapter aims to provide a comprehensive overview of contemporary furniture design approaches and the latest designs. The purpose of this exposition is to establish a solid foundation for the research and to offer insights into the current state of furniture design.

CHAPTER 2: Literature Review

The literature review provides an extensive overview of various methods and approaches for joint design. Drawing on this foundation, the current review emphasizes three critical aspects related to complex joint assembly and usage. Firstly, concerning the types of joints, the review focuses on their utilization and examines previous research conducted on them to identify their strengths and limitations. Secondly, it discusses the ease-to-assemble methods and approaches that have been previously studied for the self-assembly of complex joints. This aspect highlights the significance of developing user-friendly and efficient joint assembly methods and their impact on reducing production costs and increasing overall efficiency. Lastly, the review delves into the intricate details of ornamentation in architectural design, shedding light on its differences and usage in design. This aspect is crucial as ornamentation plays a significant role in enhancing the aesthetic appeal of architectural designs.

CHAPTER 3: Research Methodology

This chapter expounds upon the scope of work by delineating the principal issues addressed in this dissertation. Moreover, it introduces the creation process of the planar interlocking joint system, informed by insights garnered from an extensive literature review. A total of five experimental prototypes, crafted using quadrangular and triangular-shaped interlocking joints, will be showcased. These prototypes adhere to the requirements of portable and sustainable designs.

CHAPTER 4: Analysis and Results

This chapter is dedicated to providing you with a comprehensive understanding of the experiments conducted on the PIJS prototypes. The PIJS (Parallel Intersecting Joint System) prototypes were created to study the behavior of a modular joint system that can be used to build large-scale structures. The prototypes were designed with two different shapes - quadrangular and triangular.

The first experimental case involved three experiments - 1, 2, and 3 - conducted on the quadrangular PIJS prototypes. The experiments were aimed at analyzing the self-assembly difficulty on complex joints. These experiments used the method of video recording to obtain the number of errors, instances of disassembly, and the overall assembly time of the prototypes.

The second experimental case involved two experiments - 4 and 5 - conducted on the triangular PIJS prototypes. These experiments were conducted to identify the most challenging joint part using a brain activity sensor.

CHAPTER 5: Discussion

This chapter presents a detailed discussion of the methodology, experimental setup, and findings of each experiment. We will provide a comprehensive analysis of the advantages of the geometrical ornamentation approach for self-assembly and the user assembly behavior during the experiments. Additionally, the chapter will elaborate on the assembly errors that occurred during experiments 1, 2, and 3 based on the participants' behavior while assembling PIJS prototypes.

Furthermore, the discussion section provides a thorough explanation of the free-form design of experiments 4 and 5. These experiments involved a more open-ended approach to self-assembly, allowing participants to assemble the prototypes in a more creative and personalized way. We will discuss how this approach influenced the assembly behavior and outcomes of the experiments, while also considering its potential implications for future research.

CHAPTER 6: Conclusion and Future Work

The final chapter of this dissertation concludes the entire work. It summarizes the main contributions by revisiting the initial problems and objectives discussed in Chapter 3. Additionally, it analyzes the limitations of the developed approaches and presents potential future work to be done before drawing final conclusions.

CHAPTER 2

LITERATURE REVIEW

Throughout the years, numerous studies have been conducted to assess the durability and efficacy of furniture and structural joints. Given the demands of contemporary lifestyles, industrialization, and mass production, joint design has undergone significant evolution to accommodate more sustainable product designs. Literature reviews have explored a range of methods and approaches to joint design and their applications in furniture and structural fields. Drawing from these methods, this review will examine three crucial aspects related to furniture and structural joint design, ornamentation approach, and self-assembly of the complex joint.

The literature review consists of three sections that explore different aspects of joint assembly and ornamentation design in furniture and structures. The first section, 2.1, delves into the context of various types of joints, highlighting their advantages, disadvantages, and common usage. This section aims to collect information that can be used to create new types of joints that are more efficient and environmentally friendly.

Section 2.2 focuses on ornamentation design for furniture and structures from an aesthetic and historical standpoint. It examines how ornamentation has been used in the past and how it can be used in modern-day design to enhance the overall look and feel of a structure or piece of furniture. This section also explores the potential benefits of using ornamentation in modern lifestyles.

The final section, 2.3, investigates the approaches of previous studies on self-assembly in complex interlocking joint assembly. The goal of this section is to develop a convenient method for self-assembly that can be applied to joint assembly in furniture and structures. By reviewing previous studies, this section aims to identify the most effective methods for self-assembly and to develop an approach that is reliable.

Overall, the literature review provides a comprehensive overview of joint assembly and ornamentation design in furniture and structures. It highlights the importance of choosing the right type of joint for a particular application and the benefits of using ornamentation in modern-day design. Additionally, it identifies the most effective methods for self-assembly in complex interlocking joint assembly, providing a convenient approach for this study.

2.1 Types of joint

The wooden joint is usually used in carpentry to create structures and furniture. Each joint design has different purposes: it can be aesthetically pleasing, stronger, complex, or simple [17]. Joints are essential elements that hold two or more pieces of material together. They play a significant role in both furniture and structural fields. When constructing anything, the strength and durability of the final product depend on the type of joint used.

In furniture making, joints are used to connect different parts of a piece of furniture such as legs, arms, and backrests. There are several types of joints used in furniture making, including butt joints, mortise and tenon joints, dovetail joints, and biscuit joints. Each of these joints has its unique characteristics and is suitable for different furniture-making applications.

In the structural field, joints are used to connect beams, columns, and other elements in a building or structure. The type of joint used determines the load-bearing capacity, stability, and durability of the structure. Common types of joints (see Figure 4 and Table 1) used in the structural field include bolted joints, welded joints, riveted joints, and adhesive joints.

In conclusion, understanding the different types of joints used in furniture and structural fields is critical for successful construction and design. This section discusses common joint types used in furniture and structural fields, offering an overview of their characteristics and applications.

Table 1: Types of Wood Joint

	Types	Complexity		Common Uses
1	**Butt Joint**	Low	Low	Building framing
2	**Mitered Butt Joint**	Low	Medium	Trim work, furniture
3	**Dowel Joint**	Medium	Medium	Picture and mirror frames, chairs, tables
4	**Biscuit Joint**	High	Medium	Tabletops, cabinetry
5	**Dado Joint**	Medium	Medium	Shelving, cabinetry, drawer dividers
6	**Rabbet Joint**	Medium	Medium	Shelving, cabinetry
7	**Mortise-and-Tenon Joint**	High	High	Building framing, tables, beds
8	**Finger Joint**	High	High	Boxes, drawers, picture frames
9	**Dovetail Joint**	High	High	Boxes, drawers, tables
10	**Half-Blind Dovetail Joint**	High	High	Boxes, drawers
11	**Sliding Dovetail**	High	Medium	Drawer dividers, cabinetry, shelving
12	**Half-Lap Joint**	Low	Low	Tables, building framing
13	**Bridle Joint**	Medium	Medium	Tables, desks, benches
14	**Tongue-and-Groove Joint**	Medium	Medium	Flooring, tables, wood paneling
15	**Pocket Joint**	Low	Medium	Cabinet faces, tables, chairs

2.1.1 Butt Joint

Butt Joint is a simple joint that usually has two members that are connected together at the ends. It is known as the most accessible woodworking joint but is not very strong. V. Caccese mentioned that butt joints with dogbone-shaped test articles are a common configuration for fatigue studies of welded joints. Butt joints are frequently used to connect plate materials oriented in the same plane, especially in piping [18]. The butt joint is a relatively weak and not very visually appealing woodwork joint, which is only suitable for basic projects. However, its strength can be significantly improved by incorporating a rectangular or triangular block of wood in the corner. This increases the surface area where adhesives are applied, resulting in a more robust joint.

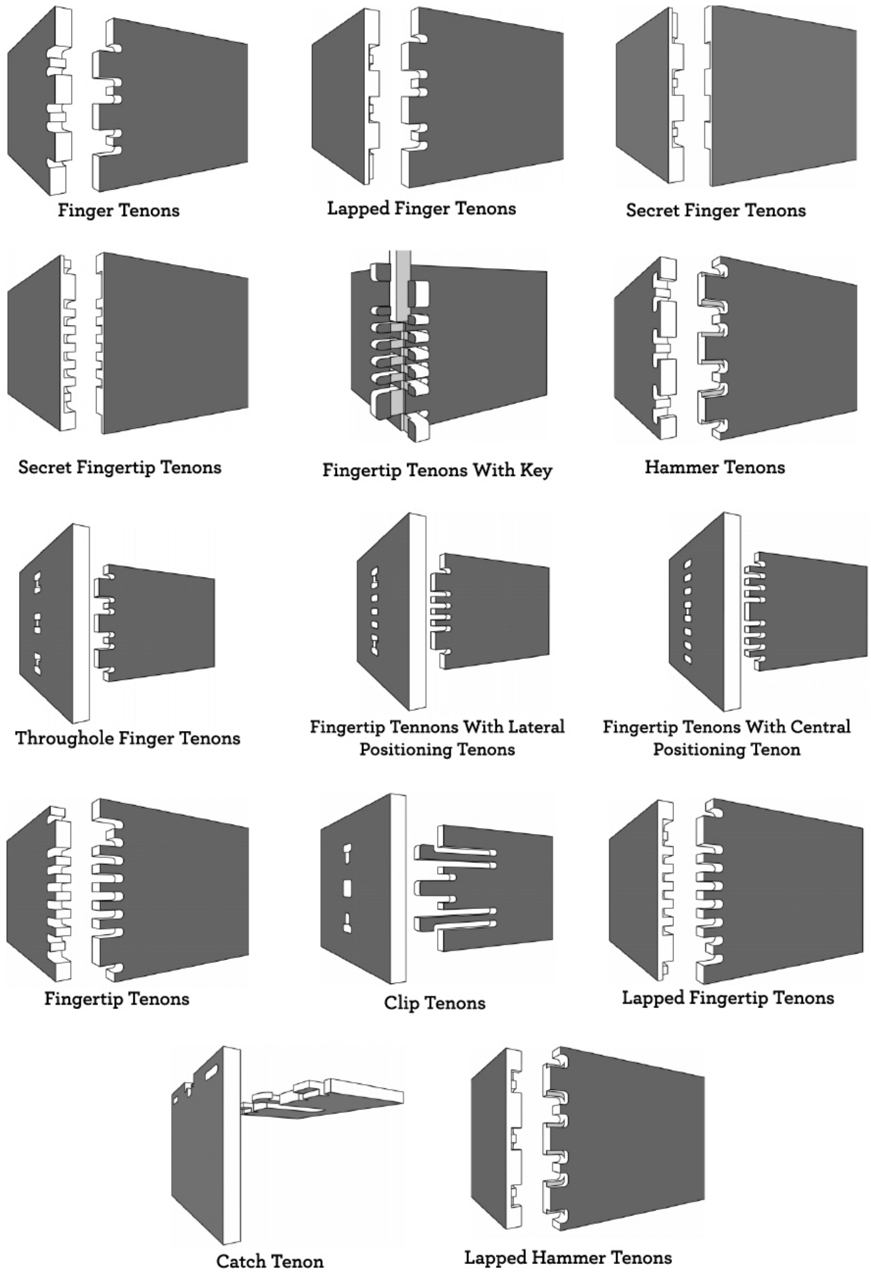


Figure 4: Sample picture of Wood Joint

2.1.2 Mitered Butt Joint

A miter joint is formed when two pieces of material meet at a corner, on a line that bisects the right angle. This type of joint is essentially a butt joint that has been cut at a 45-degree angle. It can be used on angles that are greater or less than 90 degrees. Miter joints are commonly used in various applications such as door and window making, cabinet making, box making, and joining of architraves, picture frames, and all sorts of mouldings.

The primary advantage of a miter joint is that it shows only a line at the angle, and the end wood is concealed. However, this type of joint is not suitable for wide pieces used flatways because the wood will expand and contract, causing issues. Shrinking in width will cause a tapering crack from the inner corner while swelling will cause it from the outer corner [19].

2.1.3 Dowel Joint

Craftsmen have long favored the dowel joint for its simplicity and effectiveness. This joint is particularly useful for reinforcing butt joints, which connect the end or edge of one board to the face of another. To create a dowel joint, two pieces of wood are drilled with holes that are then filled with small round wooden pins, called dowels, and glued together. Carl Eckelman conducted a series of strength-testing studies of dowel joints, in which he tested the effect of different lengths and diameters on dowel joint strength. His findings indicated that increasing the length and diameter can enhance the joint's strength [20]. Owing to their exceptional strength, dowel joints are widely employed in various applications, including furniture fabrication, shelf construction, reinforcing butt joints, and toy manufacturing.

2.1.4 Biscuit Joint

Wood biscuit joints are a popular method of joining particleboard and medium-density fibreboard (MDF) panels. They involve inserting an oval-shaped wooden piece, known as a biscuit, into a crescent-shaped slot cut into the edges of two workpieces. The biscuit is then glued in place, creating a strong and durable joint.

A study conducted by R M Morsi Hussein aimed to determine the mechanical characteristics of biscuit joints, focusing on their bending stiffness and moment of resistance. The study measured the strength of biscuit joints under different conditions, such as varying the gluing of the face and butt members. The results showed that the strength of the joint was significantly affected by the gluing of the face and butt members [21]. In particular, joints where both the face and butt members were glued had the highest strength.

2.1.5 Dado Joint

Dado joints are a type of woodworking joint that is commonly used to connect two objects. They are designed as a channel that can hold a piece of wood firmly, providing additional support for the weight or load that the final product is intended to bear. Dado joints are popular because of their simplicity, ease of implementation, and strength.

These types of joints are widely used in household applications and can be found in various supportive structures. Some of the most common uses for dado joints include bookshelves, cabinet shelves, drawer dividers, partitions, and sideboards. The purpose of dado joints is to provide additional support and improve the weight-bearing capacity of the structure they are used in [22].

2.1.6 Rabbet Joint

The rabbet joint is a type of woodworking joint that is often used for creating strong and durable corners in furniture and other wooden structures. It is a popular choice for constructing cabinets, drawers, and other box-like structures due to its ability to provide a secure and stable connection between the wooden pieces.

To create a rabbet joint, a groove is cut into the edge of one of the wooden pieces, while the other piece is cut to fit into the groove. This groove is typically cut along the length of the board, although it can also be cut across the width of the board.

The rabbet joint uses a similar technique to the dado joint, which involves cutting a groove into the side or end of a wooden plank or panel. However, the rabbet joint features a channel with an extrusion, known as the tongue, and one vertical side, rather than two vertical sides like the dado joint [23].

2.1.7 Mortise and Tenon Joint

The mortise and tenon joint used to connect two pieces together. Many woodworkets uses this technique because it uses glue or locking method to join together. It is consist of two elements: a mortise hole and a tenon tongue.

Hongmin Li conducted a study on the mortise and tenon joint, which uses wood screws for load-bearing. However, the wood screw method often damages the timber joint. To solve this issue, Li used a detachable and replaceable non-destructive flat-steel jacket reinforcement method. This method involves placing horizontal flat steel in the center of the joint and extending the bolt to the outside of the timber beam.

Afterward, Li compared the joint without strengthening to the one retrofitted with carbon fiber-reinforced plastic (CFRP). The comparison was based on the failure modes, initial stiffness, ultimate bearing capacity, and moment-rotation relationship curves. The study's results indicated that the mortise and tenon joint reinforced with flat-steel jackets maintained the original semi-rigid properties of the unreinforced mortise and tenon joints. Additionally, this reinforcement method was effective in preventing the tenon from pulling out [24].

2.1.8 Finger Joint

The finger joint method is commonly used to join short pieces of wood together, creating longer pieces. This method employs structural adhesives to hold the two pieces together. Jian Hou conducted research on the performance characteristics of finger joints by evaluating the strength of finger-jointed laminations using E.nitens. In total, 237 specimens were tested, including bending, tensile, shear, and bearing tests. The study showed that bending strength was highly correlated to the modulus of elasticity value, while tensile and bearing strength were correlated to density. The research obtained promising results on finger-jointed boards made from fiber-managed E.nitens, suggesting that they could be suitable for structural purposes [25].

2.1.9 Dovetail Joint

Dovetail joints are considered one of the strongest types of joints in carpentry. These joints are created by fitting two pieces of wood together in a way that resembles two puzzle pieces coming together. One end of the wood fits perfectly into the other, resulting in an interlocking corner that is both strong and visually appealing.

Wengang Hu conducted a study on the mechanical strength of a dovetail joint with the aim of improving it. The study utilized a dowel-reinforced dovetail joint (DRDJ) method and the results showed that this method is an efficient approach to improve the crack initiation load, critical fracture load, and elastic stiffness, and also to delay crack propagation [26].

2.1.10 Half-Blind Dovetail Joint

The half-blind dovetail is a joint technique used by woodworkers to conceal the joint from the front end. In this technique, the tails are housed in sockets that are located at the ends of the board that will form the front of the item. This way, the ends of the tails are not visible. Half-blind dovetails are commonly used to fasten drawer fronts to drawer sides. Another type of dovetail joint is the sliding dovetail.

The half-blind dovetail joint is primarily used in drawer construction because it resists outward pressure that results from pulling on the drawer box. Its benefits are primarily structural, rather than aesthetic [27].

2.1.11 Sliding Dovetail Joint

The sliding dovetail is a woodworking technique that creates a strong joint by connecting two wooden boards at a right angle, where the intersection is located inside one of the boards, rather than at the end. This method offers comparable interlocking strength to that of a traditional dovetail joint. The assembly process involves sliding the tail into the socket.

A.B.M.A. Kaish utilized a sliding dovetail joint to develop a prefabricated Ferrocement Jacket for Semi-Automated Strengthening of RC Column. This technique helps to accelerate the installation process, as the ferrocement jacket is casted in a controlled environment, reducing the labor effort required for ferrocement construction [28].

2.1.12 Half-Lap Joint

A half-lap joint is a type of carpentry and woodworking joint created by removing half of the thickness from two pieces of wood and then fitting them together. This creates a joint with a uniform thickness with the rest of the boards.

Minjuan He conducted a study to determine the impact of half-lap spliced joints on the mechanical properties of large-span glulam grid shell structures. The study involved testing a series of full-scale glulam components that were either intact or spliced. The test results showed that the moment capacity and initial rotational stiffness of the roller-supported spliced components were only 43.0% and 55.6%, respectively, of the intact components. However, the axial reaction force provided by the hinge support prevented cracks from forming in the tension zones of the spliced components, allowing them to fail in a more flexible manner than the roller-supported spliced components [29].

2.1.13 Bridle Joint

The bridle joint is a type of joint that resembles the mortise-and-tenon joint. In this joint, the tenon is cut on the end of one of the members, and the mortise is cut into the other member so that they fit together perfectly. This joint is commonly used in furniture frames because of its strength, which makes the furniture long-lasting.

Santosh K Sahu utilized a bridle joint to enhance the quality of the weld in the slotted edge. His study aimed to investigate the characteristics of axial force and weld quality. Through micro-hardness variation analysis and energy dispersive spectroscopy, it was found that the weld joint interface was the weakest zone rather than the weld stirred zone due to the presence of carbon-rich phases [30].

2.1.14 Tongue and Groove Joint

Tongue and groove is a popular technique used to assemble similar objects like wooden panels or flooring. This method involves joining the edges of two flat pieces of wood to create a strong and seamless surface. Tongue and groove boards were commonly used before the advent of plywood for sheathing buildings and constructing concrete formwork.

According to Robert W. Messler Jr., the tongue and groove joint uses a push motion for assembly. This method makes the joint resistant to out-of-plane shear forces but does not resist shear parallel to the joint or tension in the opposite direction from the engagement. The strength and resistance of these joints can be improved using adhesives or various mechanical fasteners to prevent movement in directions not constrained by the joint's geometry [31].

2.1.15 Poket Joint

Pocket hole joinery is a woodworking technique used to create strong and concealed joints between two pieces of wood. It involves drilling a hole at a 15-degree angle into one of the pieces, using a pocket hole jig. A specially designed screw is inserted into the hole, creating a robust and secure joint without glue

Reza Hassanli tested a precast concrete frame reinforced with glass fiber-reinforced polymer (GFRP) bars under lateral cyclic loading. Four-pocket connections were tested to speed up construction using epoxy resin instead of grout. While epoxy resin accelerated and simplified construction, its thickness and low modulus of elasticity affected the pocket joint's performance [32].

2.1.16 New Joint Approaches

A series of joint design studies have been conducted in the architectural field, such as finding freeform structures using joint assembly. Most of these studies focused on the aesthetics of the joints and external visuals. Mortise and Tenon joints have been used in timber structures for over 7000 years [33]. The architecture and furniture fields use mortise and tenon joints because of their mechanical performance. However, the funicular shell design in architecture has become more popular because of its curved freeform and joints. J. Harding constructed free-form faceted thin-shell structures in his research on low-cost materials [34]. O. Tessmann used the topological interlocking of solid modules to create a force-locked system within an architectural framework [35]. M. Rippmann researched the form-finding approach in complex funicular shell design. The form-finding approach helped reduce the surface area, affecting construction and assembly times [36].

In Asian countries, the interlocking joint is an essential architectural function, similar to that of a portable ger in Mongolia. X. Liu stated that Mongolian yurts changed with respect to the living heritage approach and were transformed into solid structures instead of portable ones [37]. In addition, G. Altangerel mentioned that current pollution has become a negative image of ger and a loss of value [38]. According to C. Evans, yurts represent a contemporary form of housing in Ulaanbaatar [39].

2.2 Complex Joint

With the rise of unique lifestyles and preferences, there has been a growing trend towards Do-It-Yourself (DIY) furniture. These days, people are looking for ways to personalize their living spaces and express their creativity through furniture design. Many furniture manufacturers have responded to this trend by offering self-assembly options for their products.

Self-assembly furniture is designed for the buyer to put together easily without the need for professional help. It is typically shipped in a flat-pack form, with all the necessary parts and instructions included. These instructions may include diagrams, written instructions, or both.

Additionally, construction design has become an important aspect of DIY furniture. This involves designing and building furniture from scratch using materials such as wood, metal, or plastic. With the right tools and skills, people can create unique pieces that perfectly fit their needs and style.

Overall, the popularity of DIY furniture is driven by a desire for uniqueness, personalization, and affordability. Self-assembly and construction design are two methods that allow people to achieve these goals in a fun and creative way.

There are various methods of assembly that are used in the design of assembleable furniture.In their research on new furniture joints, M. Podskarbi mentioned that furniture joints must be easy to assemble and disassemble, have a minimum number of components, meet aesthetic requirements, and be externally invisible [40]. This study focused on the structure and furniture fields to enhance the quality of joint assembly in complex joints. Numerous research studies have been conducted to explore the assembly method of furniture joints. The following section aims to provide insight into a former study conducted on the self-assembly of complex joints.

2.2.1 Wooden joint assembly

Lei Han's research investigated adhesive- and metal-free assembly techniques for wood products to overcome the challenges associated with poor recyclability and reusability. To achieve this, he examined alternative methods such as using wood dowels, rotary dowel welding, wooden nails, and dovetail joining. Lei also highlighted the importance of studying various manufacturing parameters, including dowel species, spacing, diameter, insertion angle, and shape, to improve the stiffness of the assembled wood products [41]. Such assembly methods can be complex for designing a joint that is easy to use. Tai Alan Song-Ching studied the computational process of generating and constructing interlocking frames. The outcome of his study delivers a software that can create a three dimensional interlocking pattern, analyzes the intersecting conditions between members, and provides instruction of its assembly sequence [42].

2.2.2 Easy-to-Assemble Methods

In complex joint assembly, proper instruction plays a crucial role. Over the years, a series of studies have been conducted to delve into the ease of assembly in an interlocking joint, specifically a cubic joint. These studies aimed to identify the factors that affect the efficiency of joint assembly and to develop techniques to improve the process.

Extensive research has been conducted on the assembly performance of complex interlocking joints. In a study conducted by W. Thongthai [43], it was proven that notches and holes are effective in assembling the joint. The study found that the use of notches and holes can improve the stability and strength of the joint, making it more reliable.

Y. Wang's research has shown that the shape and labeling of parts can significantly improve the disassembly efficiency of cubic joints [44]. The study found that labeling parts with clear and readable labels can reduce the time required for disassembling the joint. Additionally, the use of unique shapes for different parts can allow the players to recognize the parts easily, making the disassembly process much smoother.

Furthermore, P. Jiang's research has shown that the use of shapes and curves can enhance the players' recognition of complex assemblies [45]. The study found that the use of curves and shapes can make the assembly process more intuitive, reducing the need for instructions or guidance. The players can identify the parts easily and assemble them correctly, resulting in a more efficient and streamlined assembly process.

It's worth noting that this sequence of joint research did not mention any visual aspects. However, studies have shown that the use of notches, holes, shapes, and labeling can significantly improve the performance of complex interlocking joints.

2.3 Ornamentation

Ornamentation and architecture are closely related. Architecture and art have been decorated with ornamentation for many decades. Ornamentation existed long before the advent of advanced geometrical science. Patterns are multiplied and arranged in an orderly sequence in the designed device. Ornamentation can convey tradition, social significance, paternity, rank, or societal vacancy through its unique pattern work [46]. Geometrical architectural designs create pleasing rhythmic effects compared to complex types [47]. Different pattern design versions, such as geometric constructions and decorative art, can be found in European churches and museums. However, pattern design also applies to architectural structures or product designs for decorative purposes.

2.3.1 Types of Ornament

Ornament in architecture is categorized into three types [48]: mimetic ornament (having specific definite meanings or symbolic significance), applied ornament (adding beauty to structure), and organic ornament (being inherent in a building's material or function).

Mimetic ornament.

Mimetic ornament is the most common ornament in primitive cultures. The most common building types in antiquity, such as tombs, pyramids, temples, and towers, began as imitations of primeval house and shrine forms.

Applied ornament.

By the 5^{th} century BCE in Greece, the detail of the order and symbolic meaning or structural significance has primarily lost. They simply became the decorative elements. For example, the Doric frieze's origin remained evident: it is treated as a decorative sheath without referencing the actual structure.

Organic Ornament.

In the mid-20th century, the concept of architectural ornament, which has been called organic ornament, was formulated. The essential principle of this ornament in architecture is that it should derive directly from and function as a function of the nature of the building and the materials used.

2.3.2 Geometrical Elements and Motives

Geometrical ornament is the primordial or oldest element of decoration. In Franz Sales Meyer's book, the majority of geometrical ornament is divided into three groups [49]: continuous and ribbon-like (bands), enclosed spaces (panels), or unlimited flat patterns.

Band motives.

The system of subsidiary lines required in geometrical patterns, e.g., parquets, mosaics, and window glazing, are termed nets. The most frequent are quadrangular and triangular reticulations, combined of single squires or equilateral triangles. A unique network resembling the plait of a cane chair is required for some Moorish patterns.

Diaper patterns.

Almost all construction may be referred to as quadrangular or triangular net. The designs used to be used as patterns for parquet flooring, window glazing, and similar work without further enrichment. They are also available as construction lines for the further development of richer patterns for mural and glass painting, carpets, tapestry, and ceilings.

Unlimited flat patterns.

Geometric shapes with equal sides and angles are frequently used in design. These shapes can be divided into compartments in various ways to create ceilings, floors, and other objects (see Figure 5). The simplicity of each shape determines how it can be subdivided. In most cases, a large central compartment is kept in this pattern.

2.3.3 Usage of Ornamentation

Ornamentation is a form of art and decoration that serves to enhance the aesthetic qualities of objects and buildings. The term is defined differently across various dictionaries [50]. The Oxford Dictionary defines ornament as an object or embellishment that is primarily used to enhance the visual appeal of something, without serving any practical purpose. Examples of ornamentation include buildings, objects, character traits, and music. The Cambridge Dictionary defines ornamentation as a formal decoration that is added to increase the beauty of something, or an object that is beautiful but serves no practical purpose. Examples include buildings, objects, and

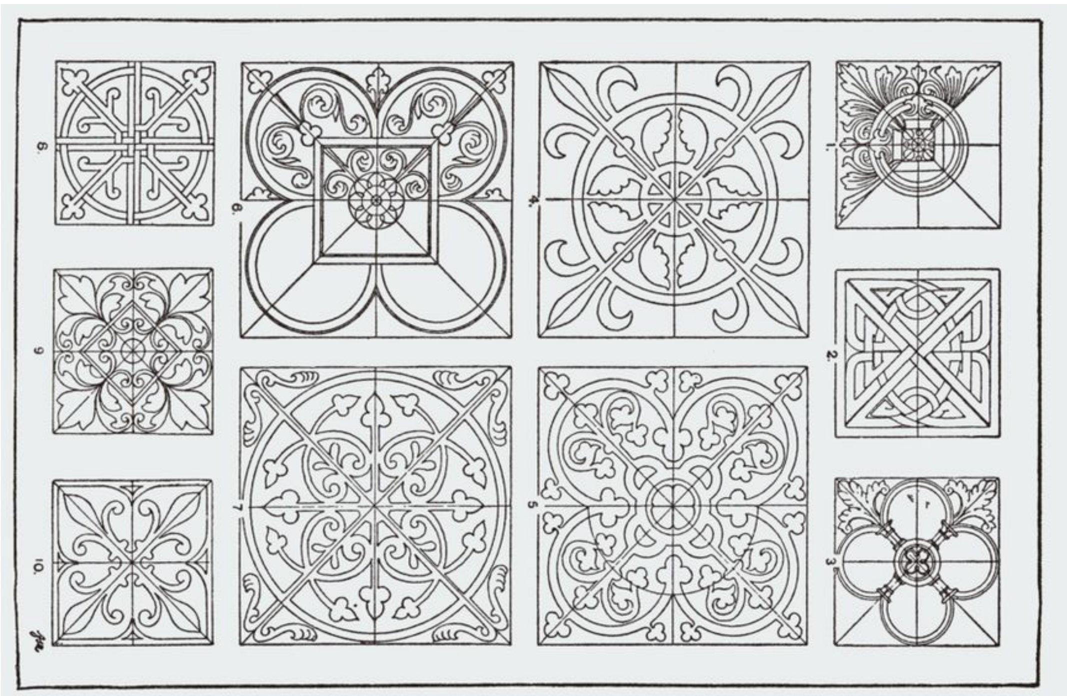


Figure 5: Meyer's Ornament-Defined flat Ornament.

urban design. The Merriam-Webster Dictionary defines ornamentation as something that adds grace or beauty to an object, a quality that beautifies, or an embellishing note that does not belong to the essential harmony or melody.

It is evident that ornamentation is primarily created for decorative purposes or to add cultural value to an object. Ornamentation has been used in architecture, art, and design throughout history to add visual interest and convey cultural or symbolic meanings. Ornamentation is often used in combination with design elements such as patterns, shapes, and colors to create a cohesive visual aesthetic. The use of ornamentation has evolved over time, with different styles and techniques emerging in different historical periods and cultures. The study of ornamentation is an important aspect of art history, design theory, and cultural studies, as it sheds light on the visual language and cultural values of different societies and periods.

2.4 Summary

It is proven that the joint in furniture and structural design should be sustainable and long-lasting. The overview on types of joints mentioned that the stiffness of wooden joints is a crucial element for long-lasting. On the other hand, in the overview of complex joints, the important factor was to be visually aesthetic with minimum parts and easy to assemble. After reviewing the types of joints, the most suitable joint design for planar joints could be mortise and tenon joints because of their structural strength and visually invisible joint design.

There are a series of ease-of-self-assembly studies made on cubic joints or interlocking joints to decrease unsuccessful assembly and wear and tear in cubic joints.

However, this study is made for planar joint design. Therefore, the ease of assembly in planar joint design is still lacking in this field. After considering the existing method for ease of assembly, this study opted to use video recording to acquire data on assembly mistakes, disassembly, and total assembly time.

In our analysis of ornamentation, we discovered that its use and significance have diminished in contemporary society. Ornaments now primarily serve a symbolic or decorative purpose. As a result, this paper aims to explore how ornamentation can be utilized in joint design to achieve a new purpose and provide direction.

CHAPTER 3

RESEARCH METHODOLOGY

This study aims to develop an innovative and straightforward approach for creating a planar interlocking joint system that can be easily assembled. The proposed method incorporates geometrical ornamentation into the design, making the joint system more aesthetically pleasing and improving its functionality. The study introduces a novel joint system design, which is referred to as Planar Interlocking Joint System (PIJS). This system combines geometrical ornamentation with interlocking mechanisms to create an efficient joint system. The study employs various approaches to achieve the research objectives, including a comprehensive literature review, analysis of the new PIJS, and experimentation with geometrical ornamentation assembly guidance. The study also evaluates the performance of the PIJS design, considering the ease of assembly factor. Overall, the study aims to provide a better understanding of planar interlocking joint systems and to develop a practical design that can be used in various applications.

3.1 Scope of work

The objective of this research endeavor is to fabricate a thin-structured interlocking joint that can be deployed in both the furniture and structural domains. The proposed joint design is intended to increase the ease of assembly in complex joint designs. By developing this innovative joint, the study aims to contribute to the advancement of interlocking joint technology and its practical applications in the construction industry.

3.2 Problem statements

As mentioned in the literature review, assembling the complex interlocking joint can only be challenging with proper guidance, leading to inefficiency and time-consuming efforts. Therefore, the primary issue addressed in this research can be summarized as follows:

- *How does joint design development impact sustainable design?*

The main challenge associated with this issue is the limited availability of environmentally sustainable joint methods. A considerable number of joint designs rely on adhesives and fasteners, which are not conducive to reassembly or assembly, thus hampering the sustainability of the final product. Raw materials such as wood are easily recyclable and reusable, making them an ideal choice for joint materials. However, the joinery techniques applied to these materials can hinder their sustainability. Therefore, the interlocking joint approach, which has existed for several years, is a viable alternative that promotes using raw materials while facilitating product disassembly and assembly. The positive impact of interlocking joints on the environment is significant and can inspire the development of sustainable products.

Throughout history, interlocking joint systems have been a popular and sustainable building construction method. This eco-friendly approach not only extended the lifespan of the structures but also made it easy to recycle or repurpose materials when the building or furniture had reached the end of its lifecycle. The designs were simple to assemble and disassemble, allowing for easy recycling and repeated use of the materials in other furniture. The benefits of this longer lifecycle included reduced deforestation and a decreased need for raw materials.

- *How can the use of interlocking joints be extended into the fields of architecture and furniture design?*

Interlocking joints are an aesthetically pleasing locking system that the inherent weakness of wooden connectors, such as mortise and tenon joints, can compromise. As an alternative, Three-Dimensional joints (3D joints) have been studied to evaluate their assembly and disassembly efficiency and have already been implemented in the furniture and architecture fields. However, there is an opportunity to expand the use of interlocking joints to thin-structured objects like roof and floor members, which currently rely on toothed plates. Manufacturing toothed fasteners is energy-intensive and requires a specific technique to minimize splitting. Moreover, this method is not easily accessible to customers as it necessitates professional workers. An easy-to-use, thin interlocking joint could replace adhesives and assist skilled workers, allowing users to build or maintain their roofs or floors without needing tools.

Interlocking joints are a type of joint that relies on the interlocking of two or more components to create a strong connection. By incorporating thin-structured interlocking joints, planar components such as roofs and flooring can extend their usage, leading to more versatile and durable designs. Additionally, furniture design can benefit from this concept by enhancing portability. Changing the size of planar parts of furniture, including tabletops, makes furniture more easily transportable without compromising its structural integrity.

- *Does Planar interlocking joint design require assembly guidance in Self-Assembly?*

The literature review indicates that the current approach to self-assembly of three-dimensional joints is intricate. Although several studies have explored the self-assembly method to simplify the process, it has been established that the interlocking joint can be challenging. Hence, this study aims to develop a self-assembly planar joint that can be effortlessly assembled without needing any tools. However, since customers often need guidance to complete the joint assembly, there is a risk of assembly errors and component wear and tear.

When working with components that have interlocking joints, the assembly process can be visually challenging. This is because interlocking joints require internal locking to secure the components, making it difficult to ensure proper alignment and fit. Moreover, the intricate nature of these joints further adds to the complexity of the assembly process. It is advisable to provide guidance emphasizing the importance of repetitive elements of the thin-structured components to prevent component breakages. By doing so, the lifecycle of the joint can be sustained and extended with the help of self-assembly guidance.

3.3 Research objectives

In pursuit of the aim of creating sustainable joint design and ease of assembly in the created complex joint system, the following objectives will be addressed in this study:

- Creating and designing a sustainable interlocking joint system that can replace fasteners and adhesives of furniture and structure fields.

- Identify the self-assembly difficulty in PIJS without instruction.

- Using geometrical ornamentation self-assembly approach on designed complex joint.

- Identify the self-assembly difficulty in PIJS with geometrical ornamentation self-assembly guidance.

3.4 Research approach

This research targets structural and furniture joint design and extends typical interlocking joint usages in architecture and furniture design. Extension of joint purposes can be complex with the existing three-dimensional joints. Therefore, it is strongly desirable to create a new interlocking joint design that can extend the usage of interlocking joints in both structure and furniture fields separately. The thinner depth of the three-dimensional joint allows planar objects to assemble and disassemble horizontally and vertically. This newer version of the interlocking joint is called the planar interlocking joint system. The thinner part of the interlocking joint allows the furniture and structure to be portable.

This research aims to create an interlocking joint system that boasts a slender structure while prioritizing two key factors: sustainability and portability. Sustainability is emphasized by developing joint components that are more recyclable, reusable, and built to last longer. Meanwhile, the second criterion aims to enhance the mobility of both furniture and structural objects. Four types of PIJS Prototypes have been developed in this study based on these design criteria.

The PIJS prototypes were developed, investigated, and evaluated over four experimental seasons. The primary focus of the experiments was to evaluate the ease of self-assembly, which included identifying potential difficulties while assembling the PIJS joint. The experiments used a qualitative approach to evaluate the results, ensuring that all data was accurately analyzed and interpreted.

3.5 Design process of PIJS

This section discusses relevant concepts of PIJS design. This study designed four types of PIJS prototypes based on a 3D interlocking joint. The PIJS was created by changing the depth of the 3D joint into a thinner structure. Two design criteria were applied to the PIJS design process.

3.5.1 Design Criteria 1: Sustainable Design

As mentioned in the Introduction section, Sustainable Design is becoming more popular in modern lifestyles due to industrial pollution. This study credits the criteria for easy recycling and reuse. We aim to create a sustainable joint design in this study. Using the Circular and Sustainable Design Model shown in Figure 6.

Figure 6: Circular and Sustainable Design Model

3.5.2 Design Criteria 2: Portable Design

The concept of product portability pertains to a given product's capacity to be effortlessly and securely transported and utilized in diverse scenarios without imposing an undue burden on the user's effort or workload.

Most furniture and structural joints are designed for portability, and certain requirements apply to portable objects. Hwang Dongwook identified 27 heuristics and 8 meta-heuristics for designing portable products, which were applied to Table 2 [51]. The base design of PIJS aims to incorporate these requirements. The most crucial requirements for PIJS within the meta-heuristics would be (1) Shrink in size, (2) Extract, (3) Simplify, and (4) ease of use.

(1) Shrink in size: This requires the PIJS design to be more complex in joint. The design of PIJS is created to divide one big part into tinier pieces of parts. (2) Extract: The tinier pieces should be easier to transport, meaning each object's size should be easy to carry. (3) Simplify: The complex parts should become more accessible, and the number of parts should be reduced in PIJS. (4) ease of use: The utilization of PIJS should be easy for users to understand. However, this requirement needs to be met on PIJS because the new joint system can have a complex design when it comes to user self-assembly.

The study will focus on the (4) requirement as the main subject since PIJS design meets (1),(2), and (3) meta-heuristics.

Table 2: Meta-heuristic and heuristics of Portable product design

Meta-heuristic	Heuristic	Description
Shrink in size	Transform	Transform an object for easy carriage (e.g. fold, roll, transform, etc.)
	Segment	Divide an object into independent parts or make an object sectional
	Use nesting	Place one object inside another
Use advanced materials	Utilize elasticity	Use elastic materials
	Select waterproof materials	Use new materials which are waterproof
	Select flexible materials	Replace customary constructions with flexible material
	Select light materials	Use materials light enough to hold with hand(s)
Add protection	Use rigid outer protection	Provide rigid outer protection to improve portability
	Provide within a container	Store the content inside a container protecting from external stresses
Extract	Utilize what is already portable	Extract parts from an object and integrate them to what is already portable
	Extract essential parts	Extract only essential parts/properties from an object to maintain original functionality
Universalize	Standardize	Standardize products, components and interfaces
	Provide an intermediary or a connector	Provide an intermediary/connector
	Use multiple connectors	Provide ways for interfacing with multiple devices/elements
Provide power supply	Include battery	Store energy in batteries and use them as energy source
	Provide energy through harvesting	Provide energy through harvesting as power source
	Convert energy	Convert energy to generate power
Simplify	Organize/unclutter	Group objects performing related functions
	Combine into one	Combine multiple entities with different functions into one entity
	Reduce unnecessary parts	Reduce unnecessary parts while maintaining original functionality
	Add multiple functions	Add multiple functions to a single object
Provide ease of use	Reduce stress	Reduce stresses on the human body
	Provide grips/handles	Attach grips or handles
	Attach wheels	Attach wheels to an object
	Provide adjustability	Provide adjustability to enhance flexibility
	Use fixture	Fixate not to fall down and get damaged
	Attach to body parts	Design a product to be a wearable

3.5.3 Base Design

The thin-interlocking joint design integrates the mortise and tenon joint via interlocking techniques. This approach differs from existing three-dimensional (3D) joints that employ these methods by introducing a thinner structure, making it ideal for planar components in furniture and structures. The design is based on the primary 3D joint method, based on which we have developed a PIJS by adjusting the depth of the joint (see Figure 7). In order to ensure the durability of the furniture's structure, a locking component is necessary for its thin design. With the ever-increasing threat of industrial pollution to our environment, it is vital to prioritize sustainability in a joint structure. A collaborative approach that emphasizes sustainability can enhance the lifespan and ease of assembly of the furniture design. These factors are crucial for extending the life of furniture. Incorporating geometric ornamentation may be a practical solution to this issue. Offering guidance on patterns can have a significant impact on sustainable design concerns such as energy efficiency, material preservation, and recyclability during self-assembly. These criteria were taken into account when selecting the most appropriate solutions.

PIJS prototypes were created by laser cutting 3.8 mm thick plywood. After the laser cut, 12.3 mm thick Prototype A and 12.3 mm thick Prototype B were created by layering and gluing the cut pieces. As previously mentioned in a Literature Review, a series of studies have been conducted on three-dimensional joint self-assembly. Additional research is required on the self-assembly of joints with thin structures, as

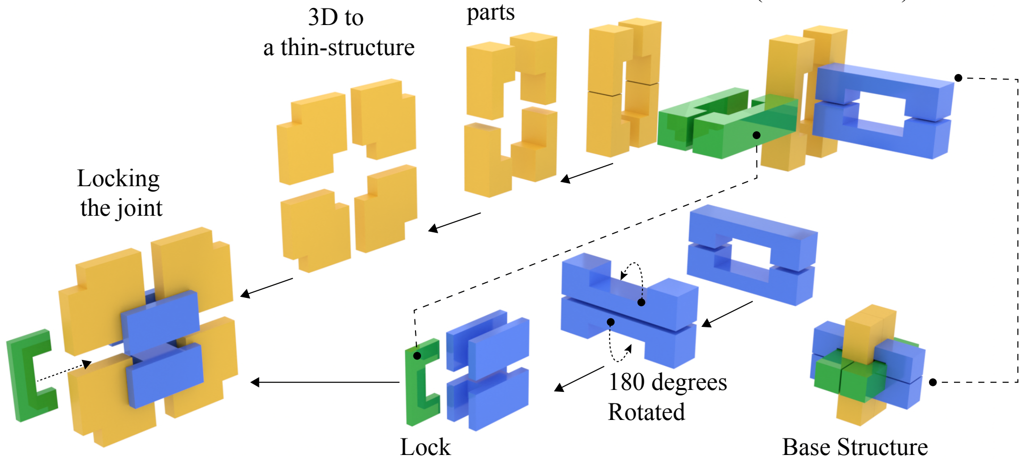


Figure 7: Base Design of PIJS

current joints lack variety. Therefore, we created a PIJS to identify the difficulty level in thin-interlocking joint design. The elements of the PIJS are based on a combination of Mortise and Tenon joints and interlocking joints that are applied on Prototypes A (Quadrangular) and B (Triangular).

3.6 Quadrangular PIJS Prototype Design

Quadrangular PIJS Prototype A was created using Quadro shapes that can create rectangular and quadrangular objects with the help of interlocking joints that consist of 16 modular parts similar to a ger's panels; it can expand its structure quickly. Prototype A parts 1 and 2 were designed to make the hole and notches invisible for aesthetic

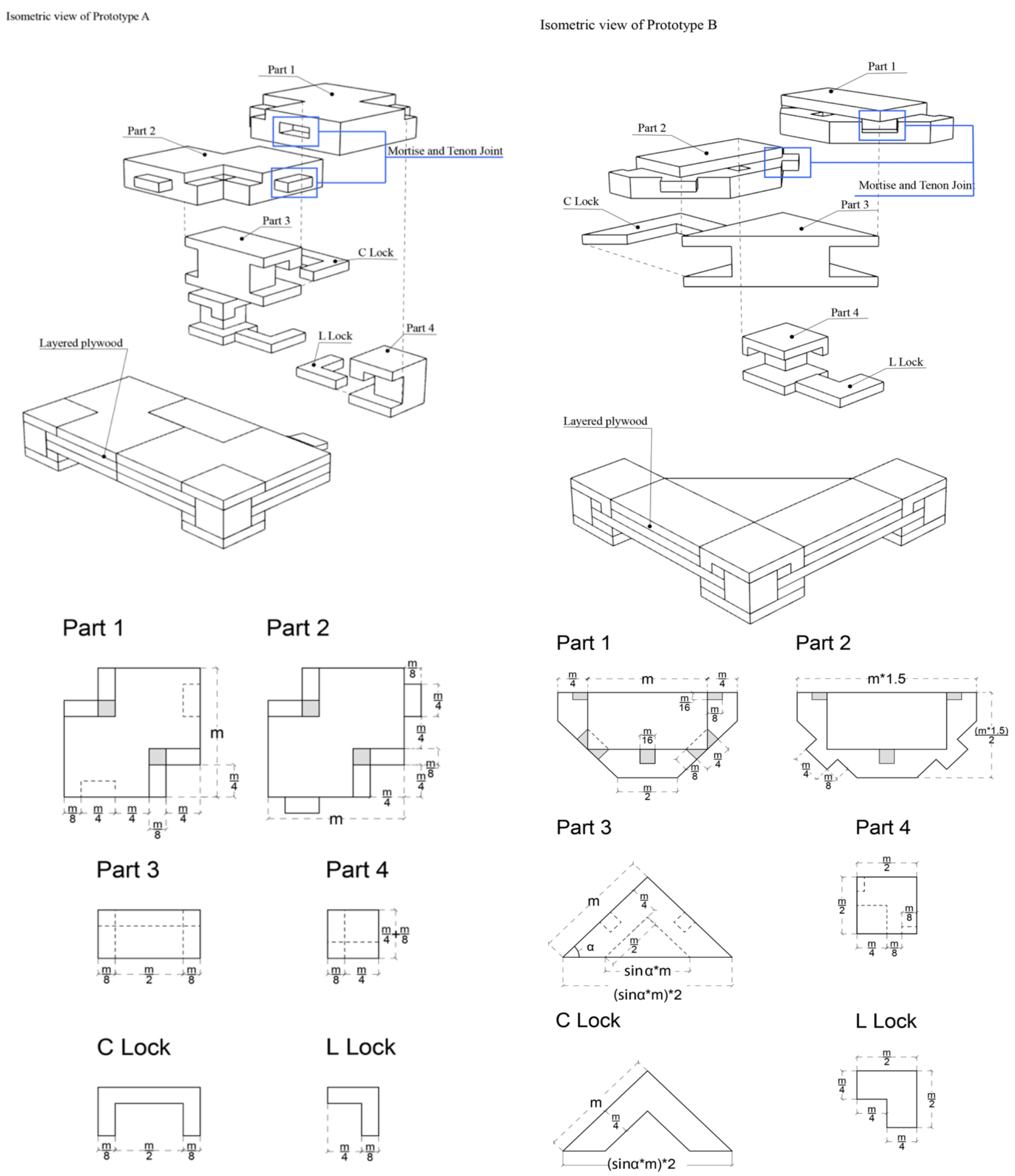


Figure 8: Isometric view of Prototypes A and B

purposes. Figure 8 was created using AutoCAD and SketchUp to describe the dimension and show the Isometric view of each part. Parts 1 and 2 of Prototype A are based on mortise and tenon joint design, and the rest are interlocking joints to lock the whole Prototype A. Prototype A's m is a base unit that can induce the size of parts. The author created Prototype A with a base unit of 400 mm and a depth of 12.3 mm by layering laser-cut plywood [52].

3.7 Triangular PIJS Prototype Design

Triangular PIJS Prototype B was created using triangular shapes that can form a series of forms based on user creativity. A triangular shape has many advantages because of its universal form; it can create many shapes and functions. Unlike quadrangular PIJS, the holes and notches of parts 1 and 2 are visible to the user, making it easier for our participants to understand. Figure 3 shows the dimensions and Isometric view of each part of Prototype B. In Figure 3, m denotes the base unit, and $\sin\alpha$ is 45°. Prototype B was created with a base unit of m= 400 mm and a depth of 12.3 mm. Like Prototype A, Prototype B's Parts 1 and 2 are based on mortise and tenon joints, and the rest are based on interlocking joint design.

3.8 Appliance of Geometrical Ornamentation

Ornamentation, which is significant to Mongolian culture (see Figure 9), in the design of the ger matches the furniture and parts and every ornament has meaning [53]. All adornments are connected when the ger is fully assembled, creating a unified symbolic meaning. Mongolia has several types of ornamentations. However, the current prototype had a modular design. In this case, a geometric ornament could repeat itself, creating an engaging composition. Therefore, it is necessary to use repetitive patterns in this study.

Figure 9: Ornamentation of Mongolian ger.

The authors used geometrical ornamentation as a guidance tool on a PIJS to prove that parts of Prototype A easily create a free form with the help of a geometrical pattern sequence. Therefore, the prior study applied geometrical ornamentation in Prototype A_1 (Three-dimensional pattern) and Prototype A_2 (Two-dimensional pattern) as self-assembly guidance. The ornamentation was created using a sequence of circles in a square opening [28].

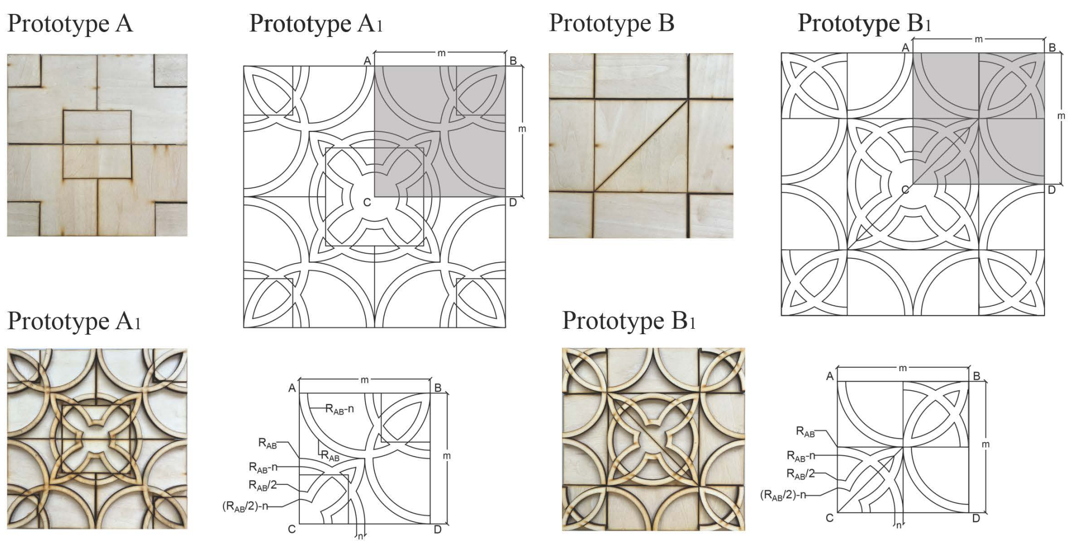


Figure 10: Ornamentation Appliance on the Prototypes

The size (m) in Figure 10 refers to the size of parts 1 and 2 of Prototype A. The radius of the circles is equal to m/2 in the square opening, and (n) designates the depth of ornamentation. Prototypes A_1, A_2, and B_1 were created by applying this geometrical ornamentation to the surfaces of Prototypes A and B.

3.9 Summary

This chapter aimed to develop a detailed and user-friendly planar interlocking joint system (PIJS). The PIJS design takes inspiration from a three-dimensional interlocking joint structure, specifically crafted to meet the criteria of sustainable design principles and offer portable functionality for various applications. Within the scope of this study, two distinct types of PIJS were proposed during the initial phase: Quadrangular (Prototype A) and Triangular (Prototype B). Both prototypes are composed of modular parts and elements designed to be easily assembled and disassembled. However, during the testing phase, it became evident that the parts and elements were challenging for users to understand and assemble accurately. To address this issue, we introduced geometrical ornamentation as a visual and functional assembly solution. The geometric ornamentation serves as a self-assembly guide, aiding users in the correct construction of the system. In the subsequent phase of the study, three refined prototypes were developed: Prototypes A_1, A_2, and B_1. Prototype A_1 is an enhancement of Prototype A, featuring three-dimensional ornamentation. Prototype A_2 is another enhancement of Prototype A, but with two-dimensional ornamentation for easier user comprehension. Meanwhile, Prototype B_1 is an improved version of Prototype B, employing three-dimensional ornamentation to facilitate assembly. This detailed development process aims to ensure that the PIJS not only meets sustainable design criteria but is also accessible and straightforward for users to understand and employ efficiently.

CHAPTER 4

EXPERIMENTS

This study analyzed two main experiments, which involved the use of five PIJS prototypes for user self-assembly. The first experiment was conducted using Prototypes A, A_1, and A_2, while the second experiment utilized Prototypes B and B_1. Each experiment featured a different set of experimental cases, and this section provides an in-depth analysis of the results obtained from each of these experiments.

Participants and Tools

Initially, this study was conducted on 30 graduate students at Iwate University. However, due to the comparison of Experiments 2, 3, 4, and 5, 10 participants were excluded for precise data. The 20 participants were graduate students, 12 from the design course and eight from the media course at Iwate University. They were recruited on the condition of living in a small space aged 18 to 35. The five experiments session used a video camera, Active Brain CLUB, and Active Brain CLUB's Application. Active Brain CLUB is created for training the prefrontal cortex of the brain. The prefrontal cortex is used for short-term memory, attention, thinking, decision-making, and action control in the human brain. This tool is created at Tohoku University to measure and develop human brain activity. The Application of Brain Activity CLUB helps to develop and measure brain activity in real-time. This application can train the brain by upgrading the difficulty levels of each activity. This tool's brain meter can confirm the cognitive function of brain improvement. The brain meter contains four kinds of activities shown in four different colors. These colors change based on the bloodstream in the brain; i) blue - bloodstream, ii) green - high brain activity, iii) yellow - trains the brain, iv) red - maintenance and improvement of cognitive function [54]. In our study, we decided to use Active Brain CLUB to measure the maintenance and improvement of cognitive function in each prototype part to identify the difficulty levels in PIJS.

Experimental Procedure

Five experimental sessions were conducted, applying two qualitative cases on Prototypes A, A_1, A_2, B, and B_1: Case 1: Self-assembly difficulty levels of PIJS; Case 2: Focus element on parts of PIJS using the Active Brain CLUB tool.

Case 1:

The difficulty level of the self-assembly is an essential factor for complex joints. As mentioned in the literature review, a series of studies has been conducted on cube or three-dimensional interlocking joints. However, our study combines architectural thin-structured joints with interlocking joints to create a planar interlocking joint system. Therefore, the assembly difficulty levels of the new joint system were determined in this study. Case 1 used qualitative methods, such as one-on-one interviews and video recordings, during the assembly process of Prototypes A, A_1, and A_2. We asked our participants to create a table shape using Prototypes A, A_1, and A_2. After the assembly process, we asked the participants to answer a questionnaire about their experience with complex joints and the difficulty in the assembly process. The purpose of each study was similar. Experiment 1 is created to identify the effectiveness of pictural guidance in the self-assembly of quadrangular PIJS. Experiments 2 and 3 were created to identify the effectiveness of two and three-dimensional geometrical ornamentation self-assembly guidance.

4.1 Experiment 1 (Case 1, Prototype A, Video Recording)

This experiment is a preliminary experiment created to observe the participant's behavior when using pictural instruction. It was created to identify assembly difficulties in quadrangular PIJS. This experiment employs Prototype A as an experimental subject. It has three steps and two groups of participants. In the first group, a total of ten participants did the following steps:

Firstly, the participants will be introduced to the pictural assembly guidance of Prototype A. After the introduction of assembly guidance, participants can use pictural guidance while assembling Prototype A. For the second time, we instructed the participants to assemble Prototype A without any guidance and to create their own design. Thirdly, we asked the participants to fill out the questionnaire.

In the second group, ten participants completed the following steps: First, they were asked to figure out the assembly method of Prototype A without the instructor's

Figure 11: Prototype A_1 with three-dimensional ornamentation.

help or visual guidance. Second, we gave the participants visual guidance and asked them to use it while creating their own design by assembling prototype A. Third, we asked the participants to answer the questionnaire.

Experiment 1 was the preliminary stage; therefore, the task was conducted with a limited number of participants. This experiment was conducted on a total of 20 participants: 14 design students and six non-design students. The difficulty levels were identified qualitatively by recording the assembly process and conducting one-on-one interviews. In Experiment 1, we aimed to determine the difficulty levels of Prototype A by (1) assembly errors, (2) disassembly, and (3) the sum of assembly time.

4.2 Experiment 2 (Case 1, Prototype A_1, Video Recording)

Experiment 2 aims to identify the effectiveness of a three-dimensional geometrical ornamentation appliance as a self-assembly guidance in quadrangular PIJS. The subjects of the experiment are Prototype A_1 (see Figure 11) with three-dimensional geometrical ornamentation and Prototype A. The experiment has three steps. Firstly, we asked our participants to assemble Prototype A_1 without any guidance or help from

Figure 12: Prototype A_2 with two-dimensional ornamentation.

an instructor. Secondly, participants understood the design of the joint using the geometrical ornamentation in the first step; they asked to assemble

Prototype A was not helped or given guidance right after the assembly of Prototype A_1. Thirdly, we asked the participants to answer the questionnaire based on their experience in the self-assembly of PIJS.

We aimed to make the geometrical ornamentation helpful rather than confusing the participants. In Experiment 2, we planned to address any issues that arose during the observation process for Prototype A. The current experiment was conducted with ten participants: six design and four media graduate students with no prior experience with complex joints. We decided to conduct Experiments 1, 2 and 3 for Case 1. Therefore, Experiment 2 collected the data of Prototype A_1's i) assembly errors, ii) disassemblies, and iii) sum of assembly time.

4. 3 Experiment 3 (Case 1, Prototype A_2, Video Recording)

Experiment 3 identifies the effectiveness of two-dimensional geometrical ornamentation in quadrangular PIJS. Given its proven efficacy in previous research endeavors, the present study employed Prototype A_2 (see Figure 12) with two-dimensional geometrical ornamentation and Prototype A. The experiment has similar steps to Experiment 2. Firstly, our participants were tasked with assembling Prototype A_2 without any help or guidance. Secondly, we asked them to assemble Prototype A without help and guidance right after they assembled Prototype A_2. Thirdly, we asked our participants to answer the questionnaire.

Experiment 3 was conducted to explore the distinction between two-dimensional and three-dimensional patterns. As the primary experimental subject, our primary objective was to analyze the variation in depth of ornamentation, which could be useful for providing guidance in self-assembly. Ten participants were involved in this experiment, including six design and four media graduate students with no prior experience with PIJS prototypes.

Case 2:

Several studies on design thinking and human behavior have been conducted based on human brain activity. Human behavioral research uses electroencephalography (EEG), functional magnetic resonance imaging (fMRI), and magnetoencephalography. Most of these devices require participants to maintain minimum movements [55].

To identify the exact assembly problem in the PIJS, the current experiment used a qualitative method and the Active Brain CLUB tool to record the assembly process and identify the focus element of the PIJS.

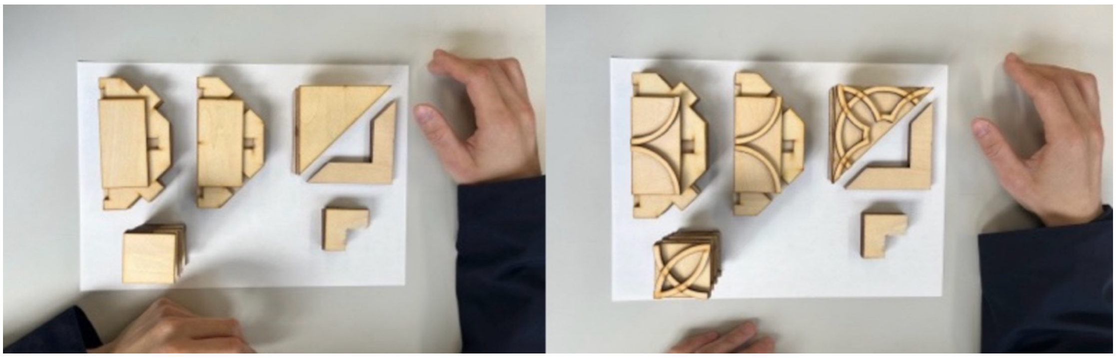


Figure 13: Start of Case 2 (Experiments 4 and 5)

During the assembly process, the colors of the application changed to four colors (blue, green, yellow, and red). To collect data on brain activity, we used these colors to indicate different processes: i) blue - bloodstream, ii) green - high brain activity, iii) yellow - trains the brain, iv) red - maintenance and improvement of cognitive function. In our case, we collected data on red activity, such as maintenance and improvement of cognitive function, in each part of prototypes B and B_1. The selected or focused features of the prototype must be more precise if the screen is red. At the beginning of Experiments 4 and 5, we asked participants to concentrate only on the prototypes to collect specific data on their brain activity. The environment of each participant was the same throughout the study, and the starting position of each part was the same, as shown in Figure 13. The main objective of Experiments 4 and 5 was to create the desired design using Prototypes B and B_1.

4.4 Experiment 4 (Case 2, Prototype B, Brain activity recording)

Experiment 4 aims to identify the focus element of the planar interlocking joint system to support the results of Experiment 2. The triangular Prototype B (PIJS) was used in this experiment as a practical object. However, because of its triangular shape, Prototype B was more complicated than Prototype A for individuals who did not have experience in the design field. Therefore, Experiment 4 was conducted with ten participants from Experiment 2 who had previously completed the assembly task of Prototype A with a six-month gap. Case 2 demonstrates the participants' brain activity; it is said that the design-thinking process can activate the brain more than instructed design [56]. Therefore, the participants were asked to create their desired freeform design using any of the parts of Prototype B. After assembly, the author administered the questionnaire to the participants to identify the difficulty levels of each part of Prototype B.

4.5 Experiment 5 (Case 2, Prototype B_1, Brain activity recording)

This experiment used triangular PIJS Prototype B_1 with a geometrical ornamentation self-assembly approach as the practical object. This experiment was conducted with ten participants from Experiment 3 with a six-month gap. Because of the incompletion of the triangular PIJS in preliminary investigations, we decided to conduct Experiment 5 with Experiment 3's participants with a six-month gap. This experiment aimed to identify the focus element of Prototype B_1 to support the results of Experiment 2. The difference between Prototypes A_1 and B_1 was the separation line of the geometrical ornamentation on each prototype, as shown in Figure 5. For Experiment 5, we utilized the identical case 2 used in Experiment 4.

4.6 Summary

In this section, we conducted five experimental sessions involving two cases. The first case (Case 1) used assembly video recording to quantify errors, disassembling, and total assembly time. Participants were then asked to complete a questionnaire (see Appendix B) after the video recording of the assembly process. Case 1 was utilized in Experiments 1, 2, and 3, with Quadrangular Prototypes A, A_1, and A_2 as experiment subjects. A total of 40 young adults aged between 18 and 35, without any prior experience in PIJS, participated in Experiments 1, 2, and 3, with 20, 10, and 10 participants in each experiment, respectively.

In Case 2, we utilized the assembly video recording process and the Brain Activity tool to validate the findings of the previous experiment. The Brain Activity tool was used to assess the maintenance and enhancement of participants' cognitive function. Afterward, participants completed a questionnaire to confirm the results (see Appendix C). Case 2 was employed in Experiments 4 and 5 with Triangular Prototypes B and B_1, each involving ten young adults aged 18 to 35. Unfortunately, due to the intricate nature of the Triangular prototypes, individuals without prior PIJS experience encountered challenges in completing the assembly task. To ensure the thoroughness of our research, participants from Experiments 2 and 3 were asked to repeat the assembly task, six months apart, demonstrating our dedication to understanding the cognitive function and assembly processes.

CHAPTER 5

RESULTS AND DISCUSSION

This section contains the experimental results of Experiments 1, 2, 4, and 5 using the JASP interface and summarizes the results qualitatively by observing the participants' behavior with each prototype. The results were obtained from 20 graduate students at Iwate University.

5.1 Result of Experiment 1 (Prototype A, pictural guidance)

The aim of experiment 1 was to identify the effectiveness of pictural guidance of PIJS in self-assembly. During experiment 1, we realized that most of our participants did not rely on the pictural guidance due to their interest in assembling the complex joint without any information about the joint assembly. There was a difference in the number of participants in Group 1: design students, and Group 2: non-design students. Therefore, we excluded 8 design students' data from the result to compare the two groups' differences. For a better understanding, we divided the results into two sections: 1. Result of Guidance, 2. Result of non-guidance. In comparing the two groups, we observed that there are certain assembly error frequencies occurred in both groups. However, assembly errors occurred in different parts of Prototype A in Figure 14. Additionally, there was a difference between our participants due to their experience in design; the pictural guidance was easier to understand for the design students than the

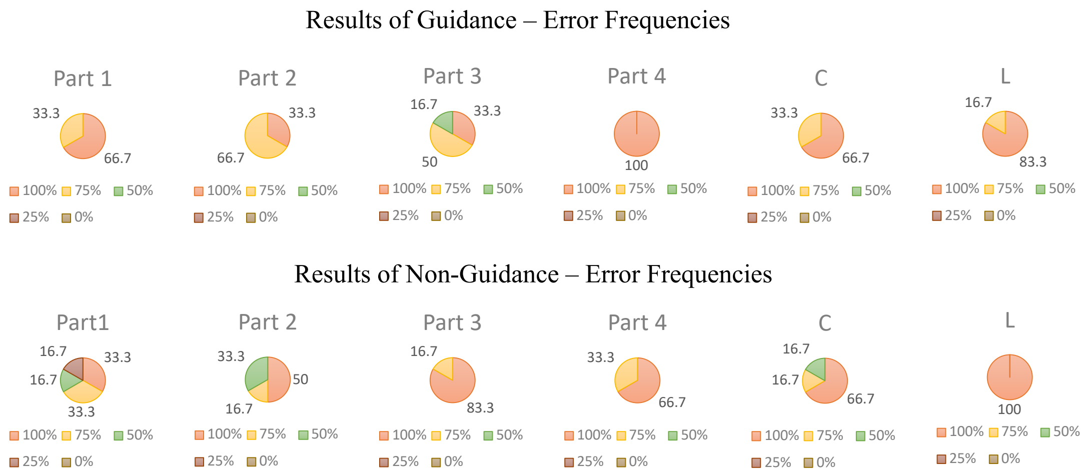


Figure 14: Frequencies of Assembly errors in Prototype A with and without guidance.

non-design students. However, in step 2, design students took more time to create their creative ideas using Prototype A (see Figure 15).

1. Result of Guidance

In the first group's design students, we observed that design students understood the pictural guidance quickly and finished the task within four minutes. On the other hand, the second group of non-design students completed the same task for more than five minutes.

In the second step, we asked the same group of participants to assemble Prototype A without any guidance or help. The design and non-design students finished the assembly in more than three minutes. However, neither of these groups of participants could remember how to assemble the parts. Therefore, several assembly mistakes were made during the assembly process.

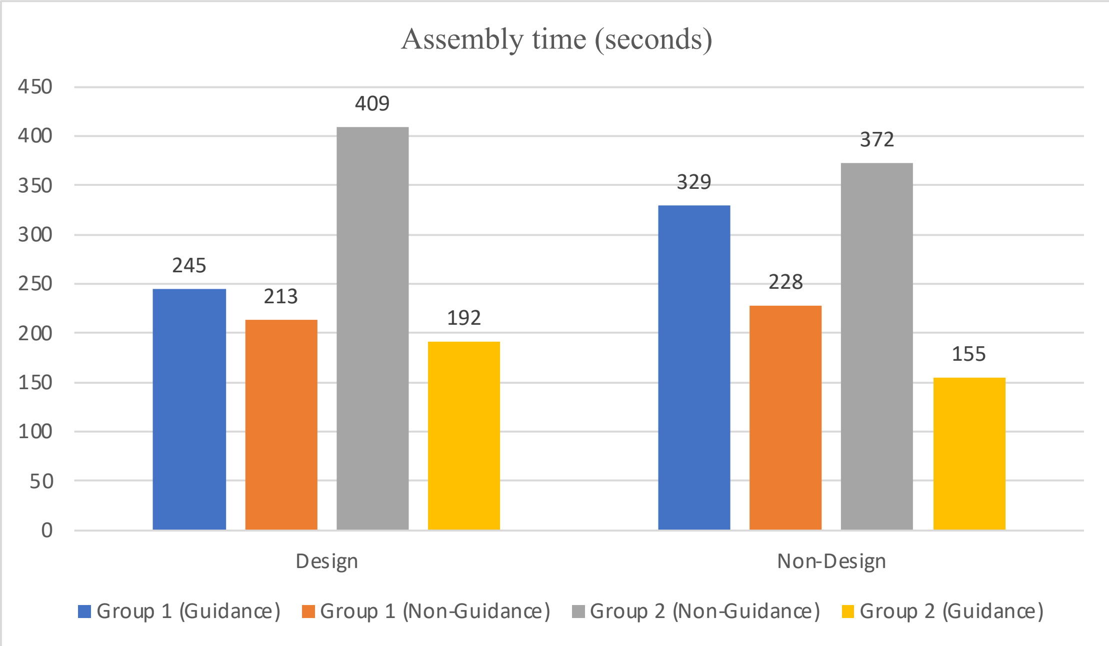


Figure 15: Assembly time of Experiment 1

2. Result of non-guidance

In the second group, design and non-design students struggled to understand and assemble Prototype A without guidance, taking more than six minutes to complete the task. However, after the initial assembly, the instructor provided them with pictural guidance for their second attempt at assembling Prototype A. During their second attempt, the design students were able to assemble the prototype in three minutes with the help of guidance. In contrast, non-design students were able to assemble the prototype in two and a half minutes with the aid of pictural guidance.

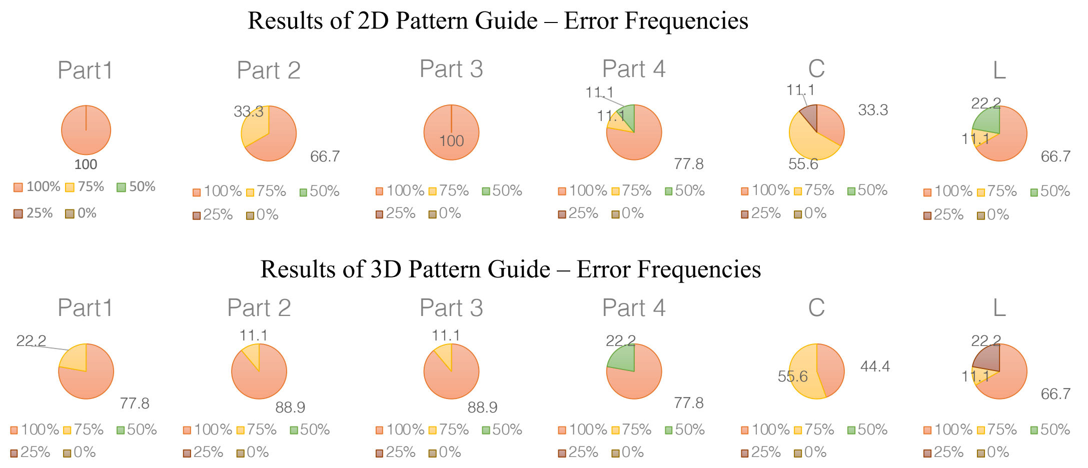


Figure 16: Frequencies of Assembly Errors in Prototype A_1 and A_2 with geometrical ornamentation.

5.2 Result of Experiment 2 (Prototype A_1, three-dimensional pattern)

Experiment 2 aimed to identify the assembly effectiveness of three-dimensional geometric ornamentation design in Prototype A_1. The experiment data were collected from ten participants without prior experience in PIJS. In the first step of experiment 2, the participants assembled Prototype A_1 without any guidance. In the observation of video recording, we discovered that the common mistake in Experiment 1 was eliminated because of the three-dimensional geometrical ornamentation guidance. In the results, four out of ten people could assemble the Prototype A_1 without help. Figure 16 shows the error frequencies of the 3D pattern guide in Prototype A_1. In the second step, we asked the participants to create a table shape using Prototype A without any guidance. Ten out of four people could assemble Prototype A without a problem. However, the rest of the participants could not assemble Prototype A. Most of our participants were confused on the back side of prototypes A and A_1. The locking part of each prototype did not have any geometrical guidance. Because of that, the most confusing parts were C Lock and L Lock in this experiment.

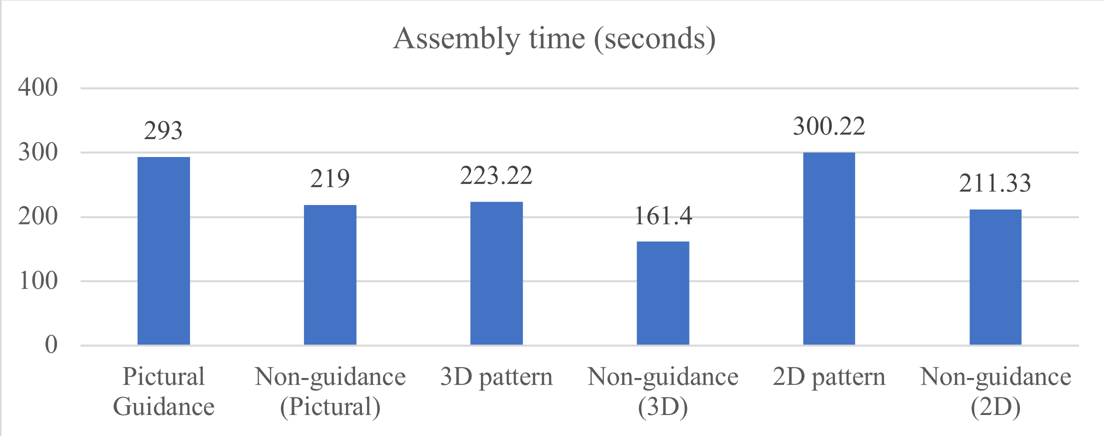


Figure 17: Average assembly time of Experiments 1,2, and 3

5.3 Result of Experiment 3 (Prototype A_2, two-dimensional pattern)

Experiment 3 aimed to identify the assembly effectiveness of two-dimensional geometric ornamentation design in Prototype A_2. The experiment data were collected from ten participants without prior experience in PIJS. The result of error frequencies in the two-dimensional pattern is shown in Figure 16. Due to the same pattern, the results of Experiments 2 and 3 were identical. However, there was only a difference in assembly time (See Figure 17). The thickness of Prototypes A_1 and A_2 affected the ease of assembly, which resulted in Prototype A_1 being more accessible to grab due to its thicker structure than Prototype A_2. Like Experiment 2, the most difficult-to-understand parts were C Lock and L Lock in Experiment 3. Because of the identical data, Experiment 3 is excluded from the rest of the comparison (See Figure 18).

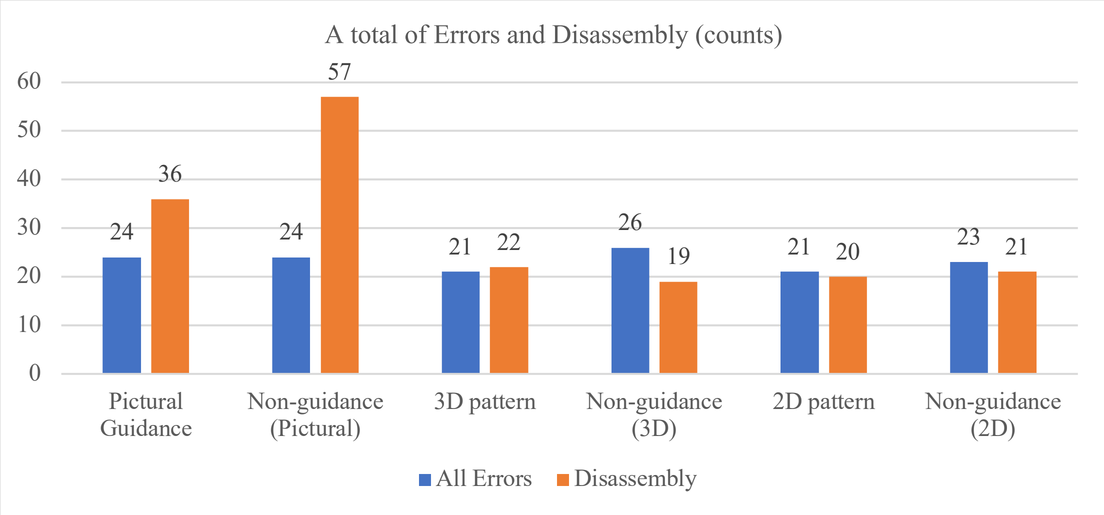


Figure 18: A total of Errors and Disassembly of Experiments 1, 2, and 3

5.3.1 Comparison of Experiments 1 and 2

Experiments 1 and 2 focused on improving the self-assembly of PIJS. Therefore, the author collected data on the errors, disassembly times, and assembly times for Prototypes A and A_1. Table 3 presents the statistical hypothesis test, which tests the alternative hypothesis specifying that Prototype A's assembly process requires more time than that of Prototype A_1.

In the case of the examined assembly time data, the independent samples t-test p-value in the fourth column confirmed the alternative hypothesis. The p-value <.05 indicates that Prototype A requires more time to assemble than Prototype A_1. These data prove that applying geometrical ornamentation to Prototype A_1 reduced the self-

Table 3: Comparison of Prototypes A and A_1's Assembly Time

	t	df	p	Mean Difference	SE Difference	Cohen's d	SE Cohen's d
Time	2.661	17.543	0.008	149.2	56.065	1.19	0.52

Note: (t): a test statistic , (df): Degree of Freedom, (P-value): Significance

assembly time in PIJS. The results of the errors and disassembly in Prototypes A and A_1 are listed in Table 4 and Table 5. Welch's t-test was used to prove a significant p-value of <.05, suggesting a violation of the equal variance assumption.

Comparing Prototypes A and A_1, the p-value of error (p=.017) and disassembly (p=.013) in Part 1 indicates that the number of errors and disassembly of Part 1 were higher than those of Prototype A_1. This result led to the assumption that Part 1 confused participants during the assembly process. The main problem in Part 1 was the hidden holes. Experiments 1 and 2 recorded each participant's assembly errors, disassembly times, and assembly times during the assembly procedure. Experiments 1 and 2 used qualitative methods to collect data via video recordings and one-on-one interviews, respectively. Using qualitative case studies, researchers can profoundly understand complex phenomena within a specific context [57].

Table 4: Comparison of Prototypes A and A_1's Errors

	Type	N	M	SD	**t**	df	**P-value**
Part 1	**A**	10	0.9	0.994	**2.424**	10.8	**0.017**
	A_1	10	0.1	0.316			
Part 2	**A**	10	0.6	0.843	**0.976**	14.33	**0.173**
	A_1	10	0.3	0.483			
Part 3	**A**	10	0.2	0.422	**0.6**	16.69	**0.278**
	A_1	10	0.1	0.316			
Part 4	**A**	10	0.3	0.483	**-0.325**	14.33	**0.625**
	A_1	10	0.4	0.843			
C Lock	**A**	10	0.4	0.699	**-0.361**	16.73	**0.639**
	A_1	10	0.5	0.527			
L Lock	**A**	10	0.1	0.316	**-1.467**	9.82	**0.913**
	A_1	10	0.8	1.476			

Note: (t): a test statistic , (df): Degree of Freedom, (P-value): Significance

Table 5: Comparison of Prototypes A and A_1's Disassembles.

	Type	N	M	SD	**t**	df
Part 1	**A**	10	1.6	1.35	**2.49**	13.5
	A_1	10	0.4	0.69		
Part 2	**A**	10	1.1	1.66	**1.08**	10.78
	A_1	10	0.5	0.53		
Part 3	**A**	10	0.8	1.32	**1.37**	10.82
	A_1	10	0.2	0.42		
Part 4	**A**	10	1.5	2.01	**1.59**	12.06
	A_1	10	0.4	0.84		
C Lock	**A**	10	0.3	0.48		**-**
	A_1	10			-	
L Lock	**A**	10	0.5	0.7	**-0.58**	12.92
	A_1	10	0.8	1.47		

Note: (t): a test statistic , (df): Degree of Freedom, (P-value): Significance

5.4 Result of Experiment 4 (Prototype B, without pattern)

Experiment 4 was designed to identify the difficult-to-comprehend part of Prototype B. It was conducted using Case 2 as the experimental method, and the brain activity sensor was used to identify the part. The experiment was carried out in a controlled environment to ensure accurate and reliable results from the ten students who participated.

5.5 Result of Experiment 5 (Prototype B_1, with pattern)

Experiment 5 has been designed to identify the challenging component in Prototype B_1. This experiment utilized the case 2 method of brain activity sensor under controlled conditions, similar to Experiment 4. A total of ten students participated in this experiment.

5.5.1 Comparison of Experiments 4 and 5

In Experiments 4 and 5, data on participants' brain activity were collected using the Brain Activity tool, and the results were evaluated using the JASP interface. Welch's t-test was used to compare Prototypes B and B_1 and investigate the hypothesis that Prototype B_1 is easier to understand than Prototype B. Table 4 shows that Part 3's p-value=.024, confirming that Part 3 of Prototype B_1 needs less effort to understand than Prototype B. This result indicates that the triangular shape is more complex than rectangular or quadrangular shapes. In addition, the maintenance and improvement of cognitive function levels of each participant differed. Therefore, the alternative hypothesis indicates that the triangular shape (Part 3) of Prototype B activated the brain's maintenance and improvement of cognitive function.

Table 6: Comparison of Prototypes B and B_1's maintenance and improvement of cognitive function

	Type	N	M	SD	**t**	df	**P-value**
Part 1	**B**	10	0.8	0.63	**0.67**	17.82	**0.255**
	B_1	10	0.6	0.69			
Part 2	**B**	10	0.7	0.67	**1.33**	18	**0.101**
	B_1	10	0.3	0.67			
Part 3	**B**	10	1.9	0.99	**2.13**	17.81	**0.024**
	B_1	10	0.9	1.1			
Part 4	**B**	10	0.9	0.87	**0.93**	14.58	**0.183**
	B_1	10	0.6	0.52			
C Lock	**B**	10	0.5	0.71	**0.65**	17.96	**0.263**
	B_1	10	0.3	0.68			
L Lock	**B**	10	1	1.05	**2.59**	10.6	**0.013**
	B_1	10	0.1	0.32			

Note: (t): a test statistic , (df): Degree of Freedom, (P-value): Significance

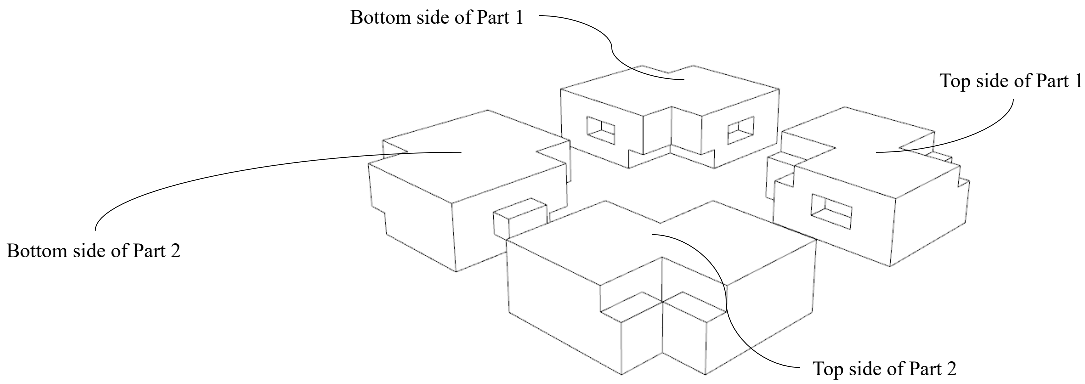


Figure 19: Common assembly mistake in Prototype A

The results of Experiments 4 and 5 were based on a qualitative research method that focused on the participants' focus elements for Prototypes B and B_1. Experiments 4 and 5 were created to support the results of Experiments 1 and 2. This experiment used the Active Brain CLUB tool to identify the participants' assembly difficulties of PIJS by measuring their brain activity. Data from Prototypes A, A_1, B, and B_1 were collected qualitatively.

5.6 Discussion

This section describes the objectives of Experiments 1 and 2's hint-less parts and Experiments 4 and 5's geometrical ornament appliance to reduce confusion in hint-less parts.

The primary objective of this research was to establish guidelines for developing portable furniture components incorporating PIJS. The ultimate aim was to enhance the self-assembly approach for the easier assembly of planar objects, ensuring greater convenience and ease of use. This design principle allows furniture panels to be easily assembled and disassembled, enabling convenient transportation and storage. This approach can revolutionize the furniture industry by providing customers with versatile, efficient, and practical solutions that meet their needs and preferences.

5.6.1 Common Mistakes in Experiment 1

Experiment 1 was created to check the assembly difficulty levels on the Quadrangular joint (Prototype A) design using case 1. In case 1, we recorded the results of i) assembly errors, ii) disassembly, and iii) the sum of assembly time. Afterward, we took a questionnaire to compare it with the data from the video recording (our observation during the participants' assembly). Before the start of Experiment 1, we asked our participants to create a table shape using Prototype A.

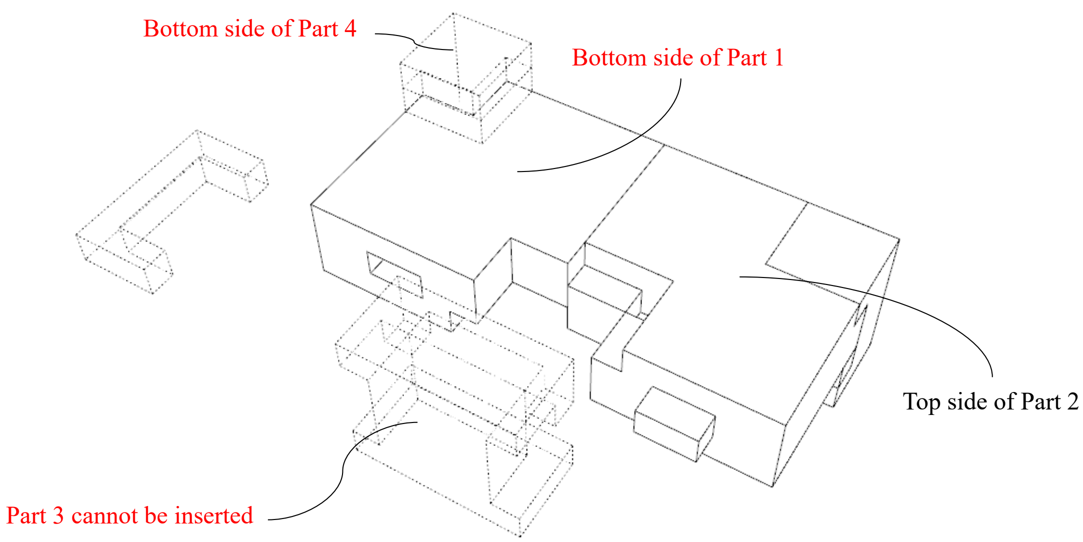


Figure 20: Explanation of common mistakes in Prototype A

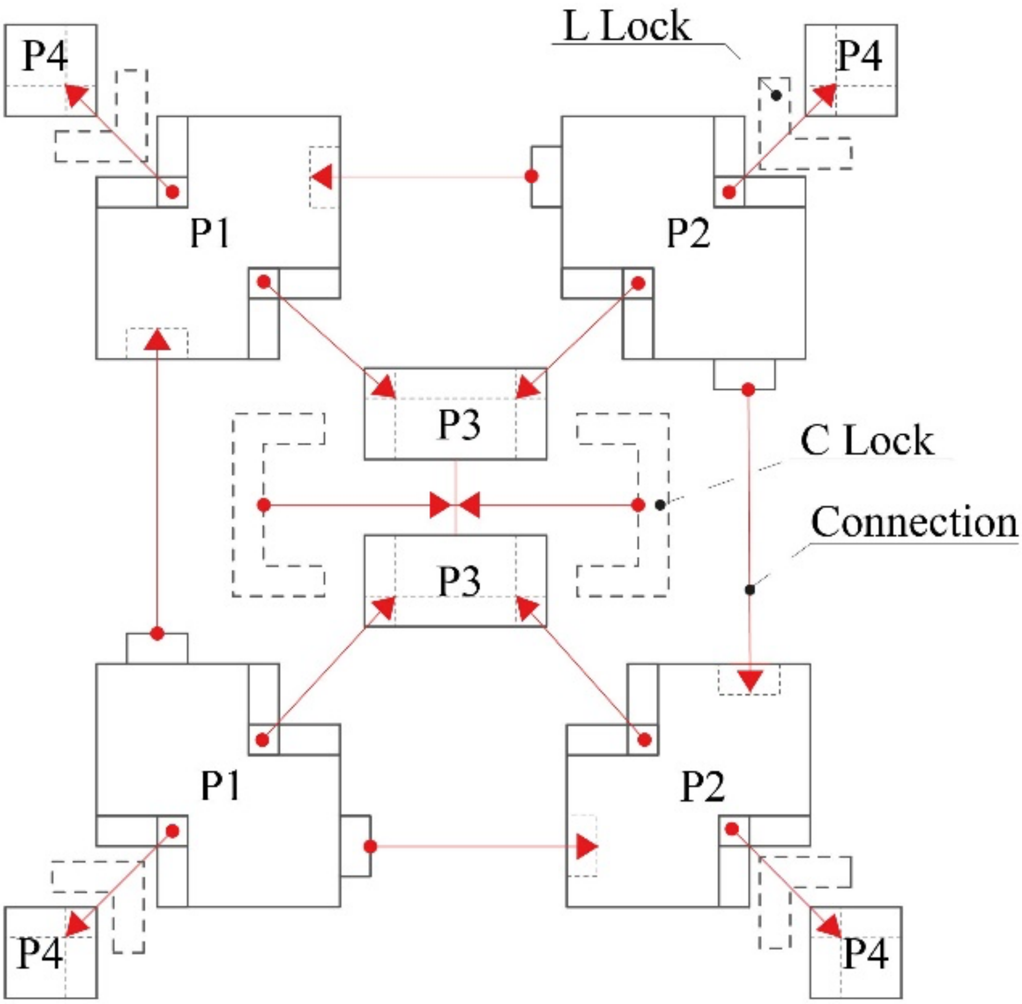


Figure 21: Assembly technique 1 of Prototype A_1 and A_2

Ten participants participated in Experiments 1 and 2 (Prototype A and A_1, respectively), which were designed to identify the assembly difficulty of quadrangular prototypes.During Experiment 1's assembly process, participants made a mistake while assembling Parts 1 and 2 of Prototype A, which led to unsuccessful assembly (see Figure 20).

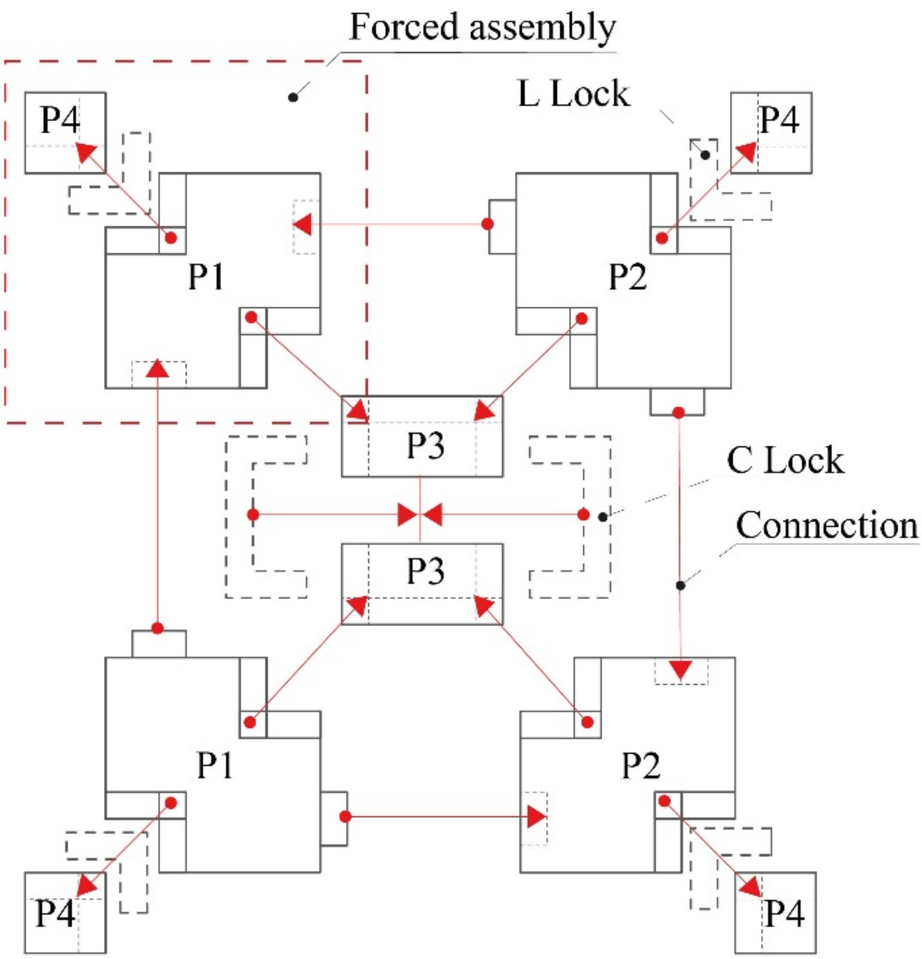


Figure 22: Assembly Technique 2 of Prototypes A_1 and A_2

5.6.2 Solution for Common Mistakes in PIJS (Experiments 2 and 3)

The geometry ornament approach applied to Prototype A_1 helped participants comprehend the bottom and top of the joint. This helped to reduce the assembly errors and disassembles in Prototype B_1, which led to the correct Assembly technique 1 (see Figure 21) of Prototypes A_1 and A_2. Participants persisted in using assembly technique 2 (see Figure 22) for Prototype A_2 despite the potential for it to break easily.

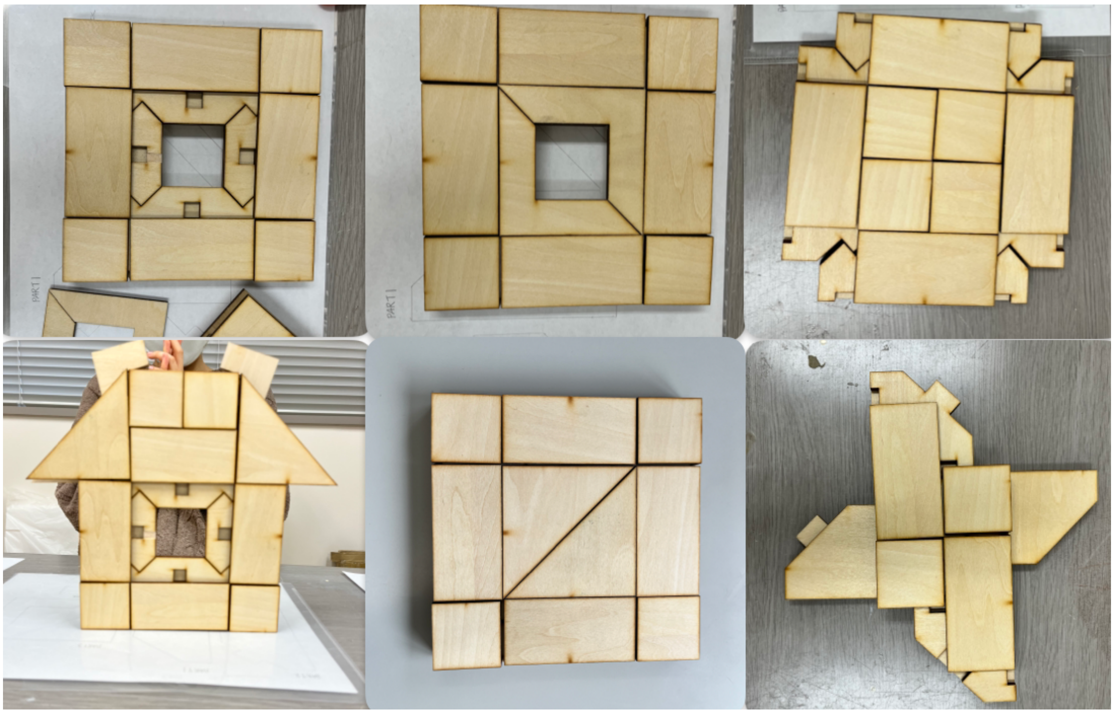


Figure 23: Prototype B enables free and unrestricted design creation, fostering unique and original output.

As mentioned in the Results section, the errors and disassembly of Prototype A's Part 1 were more than those of Prototype A_1's Part 1. Therefore, the problem of externally invisible joint parts (hinting at fewer joint parts) can be resolved with geometrical ornamentation.

5.6.3 Hard-to-understand part in PIJS

Prototypes B and B_1 (Experiments 4 and 5) used triangular prototypes. These experiments were conducted six months apart and involved participants who had previously taken part. The findings revealed that geometric ornamentation can help assist users and make the assembly process less challenging. To obtain qualitative data, we conducted two experiments: video recordings during assembly and interviews with participants afterward. During the interviews, participants were asked about any aspect

Figure 24: Participants utilized Prototype B_1 to create designs without any specific guidelines or limitations.

of the experiment that they found difficult to comprehend. However, as their responses matched those captured in the video recordings, we did not incorporate the interview results into this study.

Part 1 of the quadrangular PIJS and Part 1 of the triangular PIJS assembly steps were identical. However, the visual features of Parts 1 and 2 of Prototypes A and B differed. Part 1 of the quadrangular PIJS has externally invisible holes and notches. Because of the small depth of Part 1, it was difficult for participants to observe the holes and understand the purpose of Part 1. In contrast, the triangular PIJS's Part 1 had externally visible holes and notches. Therefore, unlike Prototype A's Parts 1 and 2, participants' first inclination was to assemble Parts 1 and 2 together.

5.7 Summary

First, we aimed to create a portable joint structure in a planar elemental joint. In each prototype used in the experiment, the adhesive and fastener were replaced with an interlocking joint. Prototypes A and B could create multiple forms based on flexible designs. These design approaches are suitable for achieving portable interlocking joint designs. However, the design creates complex joint systems. In particular, the assembly difficulty level of our prototype is higher than that of other joints. Therefore, we conducted Experiment 1 to identify the difficulty levels and focus elements during the assembly of Prototypes A and B. During Experiment 1, participants had difficulty observing Prototype A Parts 1 and 2. Their thin structures made it challenging to observe the differences between these two parts. Participants of Experiment 4 created various free-form designs, as shown in Figure 23. In Experiment 4, the participants required clarification about Part 3 and excluded Part 3 from their free-form assembly design. However, Prototype B's Part 3 was more complicated than the other parts because of its hidden features.

Second, geometrical guidance for joint assembly is advertised to add traditional patterns to the joint design. Experiment 1 proved that Part 1 is difficult to observe in the results section. Therefore, we added self-assembly guidance to Prototypes A and B to externally change the confusing Parts 1 and 2. Prototype A was created using a quadrangular shape, and its parts were visually similar. Therefore, most participants in Experiment 1 needed clarification on Parts 1 and 2 of Prototype A. On the other hand, Experiment 4 proved that Part 3 was difficult to understand and more confusing than the other parts. However, using geometrical ornamentation, Part 3 of Experiment 5, shown in Figure 24, confirms that geometrical ornament helps to understand Part 3 of Prototype B_1.

Finally, we determined the difficulty levels of the new sustainable joint design using qualitative methods and Brain Activity tools to gather valid data on the PIJS. Experiment 4 indicated that Part 3 of Prototype B should be more precise than the other Parts. Most of our participants spent more time trying to understand the purpose of Part

3 and eventually gave up and excluded Part 3 from their final free-form design. On the other hand, participants used less time to understand Part 3 in Experiment 5 and used Part 3 in their final free-form design.

This study shows that geometrical ornamentation can guide the self-assembly of objects with complex assembly requirements. The portable product meta-heuristics mentioned in the Methodology section are contained in PIJS. Our extensive research project, PIJS, delved into four key aspects: size reduction, extraction, universalization, and simplification. An additional important consideration for us was the product's usability, which we evaluated through a series of experiments that tested the assembly process of each prototype. Additionally, our research identified three or more higher-level heuristics, as outlined in Dongwook Hwang's research [58]. This valuable insight confirms that PIJS boasts a higher-level heuristic approach to designing portable products.

CHAPTER 6

CONCLUSION AND FUTURE WORKS

Several studies have been conducted on interlocking joints to improve joint sustainability. However, because of its thin-structured design, the planar interlocking joint is not as well-known as a three-dimensional cubic interlocking joint. This study aimed to establish a new planar interlocking joint system to develop sustainable joint structures.

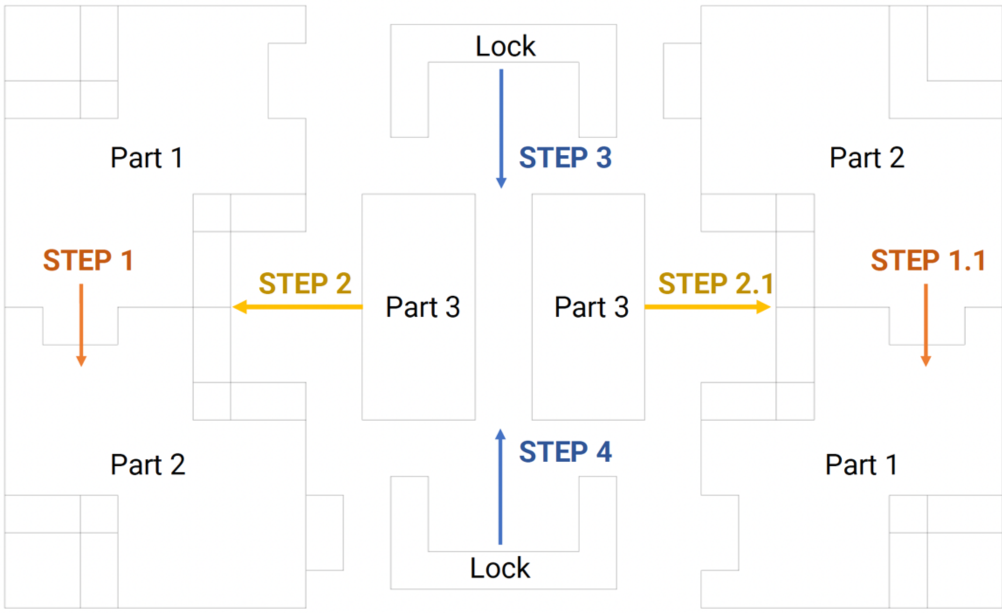
We analyzed the results and found that the difficulty level of the joint system directly correlated with design success. The results showed that a planar interlocking joint system could be used to create portable designs in small spaces. PIJS can be applied to various architectural elements and furniture designs to eliminate the need for adhesives and fasteners. Owing to its thin-structured design, it can also be used in furniture, both horizontally and vertically. This study demonstrates that first-time customers struggle to use PIJS.

Geometrical ornamentation self-guidance can decrease the complexity of the PIJS and reduce the difficulty in using planar interlocking joints. Fixing furniture requires a repair process in the affected area. PIJS is an effective method for furniture panel repair. Moving forward, we plan to incorporate PIJS into architectural design studies, which will expand the usage of interlocking joint design and repair structural damages.

In further studies, we seek a better quality and longer-lasting product that can be achieved using PIJS in furniture design and repair.

APPENDIX A

Pictural Guidance in Experiment 1



APPENDIX B

Questionnaire of Experiments 1, 2 and 3

Guide:

1. Use the Prototype A to create a square shape

2. There should be no visible holes in the final design

Age:

Country:

1. Have you ever assembled flat-pack furniture before?

a. yes b.no

2. How useful was the pattern guide for assembling the joint?

a. Very useful b. Useful c. not useful d. not useful at all

3. Which part was easy to understand?

Part 1:	a. 100%	b. 75%	c. 50%	d. 25%	e. 0%
Part 2:	a. 100%	b. 75%	c. 50%	d. 25%	e. 0%
Part 3:	a. 100%	b. 75%	c. 50%	d. 25%	e. 0%
C Lock:	a. 100%	b. 75%	c. 50%	d. 25%	e. 0%
L Lock:	a. 100%	b. 75%	c. 50%	d. 25%	e. 0%

4. Do you think this assembly method should be improved? (If yes, what parts should be improved?)

a. yes b. no

APPENDIX C

Directory of Experiments 4 and 5

Title: Research on free-form assembly.
This experiment aims to identify the focus elements on the thin interlocking joint using ActiveBRAIN.

Guide:

1. Create your desired design by using the parts (create your own design).
2. No time restriction.

Final Design:

1. The design should be stable and locked.
2. The holes and notches can be visible after the assembly.

After assembly:

- Please explain what kind of design you were planning to do after the assembly.
- Please focus only on the prototypes during the experiment.

Experiment 3

We asked students to complete creative tasks.

Questionnaire of Experiments 4 and 5

Name:
Participant number:
Video number:

This questionnaire aims to identify brain activity on each part to identify difficulty levels on a thin interlocking joint system (TIJS).

1. Please leave a circle mark (◯) on the difficulty levels in each part.

Parts	Very easy	Easy	Medium	Hard	Very Hard
Part 1					
Part 2					
Part 3					
Part 4					
C Lock					
L Lock					

2. Which part was the easiest to assemble (why)?

3. Which part was the most difficult to assemble (why)?

4. Which element in the part you were more focused on (you can choose more than 1 answer)?
    a. Pattern of the parts
    b. Holes and notches of the parts
    c. Size of the parts
    d. Shape of the parts
    e. Depth of the parts

5. Why did you focus on these elements?

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