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Bench – A Design Process to Make a Digitally Manufactured Furniture System Using the Spirit of Japanese Joinery

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Abstract

This capstone identifies and implements the spirit of Japanese joinery into a contemporary design process to develop a component based piece of furniture through means of digital manufacturing, namely CNC (Computerized Numerical Control) machining. Through the aesthetic, functional, and structural results of this design process, the impact of applying the spirit of Japanese joinery as a guide for the development of the tectonic language of an object are revealed. The structure of this project will discuss an overview of the design process of an object which was designed in the spirit of Japanese joinery, and an assessment of the success and challenges of the object's utilization of Sashimono wood connections, a contemporary production process, and the structural results juxtaposed with material efficiency.

Capstone Question

What creative opportunities arise as a result of applying the spirit of Japanese joinery to the design process of a furniture object using contemporary production methods, i.e. CNC?

Introduction

Japanese joinery is an art form which originated over 1,000 years ago. As a result of its age and proliferation across Japan, there exists a rich history of joinery typologies, applications, and surviving historical examples of Japanese joinery methods, their uses, and capabilities. What makes Japanese wooden constructions unique, are their exclusive use of wood-to-wood connections. The traditional Japanese carpenter did not have access to adhesives or other fasteners such as glue, nails, or screws. Rather, Japanese joinery relied on friction and geometry to make structurally sound connections, connections which would not come apart unintentionally or degrade overtime. The methodology behind Japanese joinery often lacked any permanent or irreversible processes, and consequently, many Japanese joints are readily disassembled, allowing for the replacement of components without need for destruction.

This capstone investigates the spirit of Japanese joinery, and the result of applying this tectonic methodology to a contemporary design of an object. The spirit of Japanese joinery is briefly described as the methods and attitudes by which traditional Japanese joinery is executed, and a criterion of parameters that frame these methods. These criteria are encapsulated by the Japanese word *Sashimono*, which describes a family of wood to wood connections that feature

no usage of glue, and no usage of mechanical fasteners. In lieu of these, the geometry of the joint, friction, and the strength properties of the wood are used to create durable, yet reversible connections.

In this capstone, the designed object is a bench, assembled by CNC-cut Baltic Birch plywood, at ¾” thick. The components interlock in a series of reversible operations to form a stable structure, which does not rely on glue or fasteners. This application of a construction process which enables endless assembly and disassembly facilitates compatibility with a modular system of substitutable components, allowing for differing capability. It was essential throughout the design process to consider that the reversibility of Sashimono connections leads to a necessary precision in the manufacture of the individual components in order to produce a strong and stable connection. As a result of this necessity, and the need for repeatable and precise components, a workflow of production utilizing a CNC machine to cut the pieces was identified as essential. This workflow provides a method by which the production of precise, and rapidly cut pieces were possible without compromising adherence to the principles of Sashimono woodworking and the spirit of Japanese joinery.

The form of a bench was quickly identified as an ideal medium of experimentation. It is practical in scale for production in the shop, yet in form is similar to a bridge or structural system of columns and beams. It does not require significant extrapolation to envision the potential relationship with my findings on the scale of furniture to that of architecture at scale. In addition, there is precedent for the usage of Sashimono techniques in furniture making as in architecture.

CNC Machining fosters an opportunity within carpentry to create extremely precise and rapidly produced components. The reversible nature of Sashimono woodworking, in tandem with the ability to mass produce precise components, allows for modularity and customization. In the case of this Capstone, a design process considering the spirit of Japanese joinery has enabled the synthesis of this combination of opportunities.

Background

The Evolutionary History of Japanese Joinery

There is no single correct definition of Japanese joinery. It is a system of connecting wooden parts in architecture and furniture, and evolved out of necessity over the passage of time. It could also be understood as a disciplinary set of principles, craftsmanship, and technical skill. It can be as specific as exact joints and executions, or as loose as any wood to wood connection using geometry and friction in lieu of glue or fasteners. To fully appreciate Japanese joinery and the spirit of Japanese joinery, the history of the craft and the discipline of the traditional Japanese craftsperson must be understood. This will enable not only an understanding of Japanese joinery as a technical skill and tectonic method, but also as a craft and as artistic expression.

The island of Japan is 68.5% covered in forest. The historical figure was even higher during the time when Japanese woodworking resulting from the use of metal tools proliferated. There was plentiful wood on the island for the creation of structures and objects leading carpentry to become a highly respected and important discipline in Japanese society. Historically, the Japanese carpenter, or *Daiku,* was equal parts architect and engineer, as well as craftsperson and woodworker. They played a monumental role in shaping Japanese society through their work, practically and culturally speaking (Seike).

The birth of Japanese joinery accompanied the proliferation of iron tools and Chinese influence. Iron tools were first used in the Yayoi period, 200BC-250AD, which unlocked a revolution in wood manipulation to a degree not before seen. Metals were historically very scarce on the island of Japan, so the usage of metal fasteners like Europeans were using at this time rarely occurred; there simply was not enough metal to go around. Rather, the relative preciousness of metals led to their reservation for uses in things like tools, weaponry, armor, and décor for the wealthy. It was the usage of metal tools that truly sparked the birth and subsequent evolution of Japanese joinery, and in turn, Japanese architecture. Skilled craftspeople had the ability to manipulate their material and execute the degree of control necessary to create precise joinery. Methodologies, including both their creation and execution, emerged as closely guarded family secrets, as family guilds of carpenters competed for prominence across Japan through innovation and refinement of their skill and craft. The competitive nature of these exclusive carpenter's guilds accelerated the development of joinery methods, while maintaining the status of craftspeople in Japanese society. (Seike).

Finally, there is an appreciation for the process in the philosophy surrounding traditional Japanese joinery. The Japanese craftsperson understands the process of creating to be equally as important as the final product itself. This appreciation for the process of creating is one way in which the Japanese craftsperson achieves such a degree of precision and strength in their work. When the process is equally as important as the end product, the desire to compromise in quality is limited. This desire to achieve such precision is beneficial not only for the aesthetic quality of a

joint, but also for its structural capability. Tight tolerances prevent natural movements and shifts of load from damaging a structure. This has remained particularly true in the more culturally and aesthetically sensitive role Japanese joinery exists in today, both in the context of architecture and fine woodworking for furniture (Russel).

The story of Japanese joinery is inseparable from the story of the Japanese craftsperson. Alongside technological advancements, Chinese influence, and cultural revolutions, the status, roles, and capabilities of the traditional craftsperson in Japan also evolved. It was the appreciation for the process of creating which the Japanese craftsperson possessed that also played a defining role in the development of Japanese joinery into the remarkable and highly respected craft visible today. Alongside the discipline and skill of the craftsperson, the catalogue of joinery methods, their diversifying applications, and structural capabilities grew to fascinating complexity- all the while keeping one thing consistent: the wood to wood connection.

Tectonics

Complex wood-to-wood connections prevailed in Japan after the Yayoi period. While the effectiveness was known, the potential longevity could not have been known to people thousands of years ago. It was initially by chance that a scarcity of workable metals in Japan meant metal fasteners like the nail or early screws could not feasibly be used for construction, even if desired. The conservative usage of metal products was taken so seriously that they even became the subject of control by imperial law, and it was not until the development of fine woodworking tools that Japanese joinery methods were developed. These tools possessed the durability and sharpness required to enable the production of the joints. Upon their introduction, the development of complex wood-to-wood connections began. As Japanese architecture became more sophisticated, progressively more physically demanding and specialized structural applications emerged. Where need arose, an entirely unique joinery method emerged for these applications. Given the remarkable complexity of Japanese structures, particularly that of later Buddhist temples, it becomes clear how so many varying methodologies arose (Gowland).

The four hundred-plus joinery methods can be categorized into two fundamental groups. The first is *Tsugite*, or the end-joints, where two components are joined end to end in alignment, such as extending a beam along its length. The other is *Shiguchi*, the angled or connecting joints. In *Shiguchi*, perpendicular or otherwise angled connections are made. The hundreds of joinery methods can each be classified as one of these two categories, independent of their application of compression, tension, torsion, shearing, or bending. Naturally, joints were not made, then given an application. Rather, they were developed for the increasingly efficient satisfaction of a potential application. Their remarkable strength is a result of this process of identification and gradual refinement (Sato). There are a handful of essential applications for joining wood members: compression, tension, torsion, shearing, and bending. While these are the five primary applications as a consequence of physics, there are countless Japanese joinery typologies for

any conceivable structural, and sometimes purely aesthetic, application. In this sense, Japanese joinery and its production, are equal parts an artform as they are a practical means to an end. They are applied in varying degrees within Buddhist temples, Shinto Shrines, and residential architecture. Because Japanese joinery methods are usually highly specialized in their exigence, few joinery typologies are found in all three applications (Seike).

Fastener corrosion is a critical concern for modern day joints between structural members. As the joint often relies entirely on the strength of a metal fastener, sheath, clamp, or bracket for their strength, many failure points are introduced, and fastener corrosion is one effect by which a failure can occur. Fastener corrosion is a consequence of moisture introduction in wood to metal connections, and if improperly treated, will inevitably result in the failure of a structural member to varying degrees of severity (Zelinka). It is for this reason that it is fortunate that the Japanese craftsman did not have access to nails, as corrosion of these elements would likely have served as a catalyst for the decomposition and subsequent destruction of the longstanding wood structures Japan and many other East Asian countries are known for today. Due to their usage of wood-to-wood connections, Japanese structures do not face the same corrosion concerns as more modern structures.

It can be difficult for many to imagine wood as being a stronger building material than modern options such as concrete or steel, but comparing them directly is only half the analysis. When one considers strength by volume-weight, even a weaker wood species such as white cedar possesses a tensile strength four times greater than steel, and a compression resistance six times greater than concrete. While outright weaker than modern materials when comparing components of the same size, wood's relative lack of weight for its strength can proves more durable, as seen in purely wooden Japanese constructions (Seike).

Such structures have survived countless earthquakes of varying magnitudes as well. Laying directly on the ring of fire, Japan sees around1,500 earthquakes a year, accounting for 20% of the world's earthquakes of a magnitude 6.0 or higher. With such great frequency, it is remarkable that so many wooden towers survived for hundreds of years. This durability is attributed to the load-dampening wood structure of pagodas. It is thought that the central mast or *Shinbashira* helps to absorb horizontal loads. Storms generating high winds have failed to fell the towers as they bend like the trees in the wind from which they are constructed without breaking. Due to the structural form enabled by Japanese joinery, such resistances are possible even in such a seismically volatile region. The evolutionary development process of Japanese joinery as a driver of tectonic language has enabled such resilience (Hanazato).

Early Japanese constructions rarely suffered fire damage as a result of woods' resilience as well. It was not until gas stoves and fireplaces entered a more densely packed urbanized fabric of wooden buildings that fires became a serious issue for wooden structures (Seike). Fire is not necessarily the danger to wooden constructions and the lives of inhabitants as commonly assumed. While it may seem counterintuitive, wood constructions are fairly fire resistant and able to remain structurally sound even after burning. Wood degrades when exposed to high

temperatures, even before combustion. Because wood is such a poor conductor of heat, however, it is possible for the surface of a wooden beam to burn and char into non-combustible carbon while the core remains at a stable temperature. This allows a wooden member to remain structurally sound for an extended period of time, meaning, the recoverability of burned wooden structures is possible and destruction is not inevitable (Ross).

As increasingly specific and demanding structural requirements were placed upon these connections, increasingly more specialized and refined methods arose, therefore driving Japanese joinery to continuously evolve. To understand the source of the remarkable quantity of Japanese joints, it is important to recognize this evolutionary process by which the joinery methods diverged into various niches. Despite hazardous environmental factors, homogenous wood buildings constructed using Japanese joinery have stood for hundreds of years, rivaling the durability of modern structures. It's remarkable resilience may explain why Japanese joinery is so popular in furniture. Throughout history, it is evident that a design process implementing Japanese joinery has not been a structural disadvantage, but instead an example of structural and formal capability.

Historical Use Cases

As an artform, Japanese joinery has evolved and become refined over hundreds of years into the historic discipline appreciated today, and it has allowed for the construction of remarkably resilient wood structures. Many Japanese wood structures have stood for hundreds of years, some even aging well over a thousand. The oldest wooden structure in the world is constructed using Japanese joinery. Even with modern technology and materials, such a feat in an area prone to earthquakes, flooding, and storms is a daunting task yet has been achieved in multiple examples throughout Japan using traditional joinery methods.

Figure 1: Horyu-Ji Temple, Kondou and Tou. Ikoma District, Nara, Japan. Image by Saigen Jiro, 2019.

Horyu-Ji is a site in Japan containing several Buddhist monuments considered the oldest surviving Japanese temples. The area was reconstructed over 1,300 years ago after being damaged by fire and has survived in its current form to this day. Horyu-Ji temple is considered the world's oldest wooden building, and the site includes a five-story pagoda made entirely of timber joined with wooden connections. The age of this structure speaks for itself, and it represents one of the most profound structural and aesthetic achievements enabled by Japanese joinery. As discussed in the Tectonics section, extreme structural demands have failed to destroy the structure. The ability for Horyu-Ji to have stood for so long despite numerous earthquakes, storm exposure, and fire damage is again attributed to the resilience of Japanese joinery in its wooden construction. (UNESCO).

Figure 2: Horyu-Ji Temple, Roof Detail. Ikoma District, Nara, Japan. Image by Z. Tanuki, 2013.

The exquisite detail of the remarkably complex wooden framing system at Horyu-Ji temple is visible in the above image. Penetrating the columns are beams, which stabilize the columns to support the lattice ceiling structure above. By seating each wooden component within the other, the result is a stout, but not excessively rigid structural system for supporting the roof. There is no shortage of depth, texturing, and detail in form in the system.

During the Yayoi period, Shinto shrine construction began. *The Ise Grand Shrine* is considered Shintoism's most sacred shrine. It dates back to the third century and has been ceremoniously deconstructed and reconstructed every 20 years by Shinto monks, taking breaks only in times of civil war. It has been since the year 690 that the Grand Shrine at Ise has been rebuilt in this fashion. As such, the joinery techniques used are very old, as the 20-year periodic reconstructions are quite faithful to the original as constructed in the third century (Bock). It is in the ceremonial disassembly and reassembly of the Ise Grand Shrine that a key aspect of Japanese joinery can be found. Because no irreversible, nor destructive chemical or physical processes are used to assemble the Shinto shrines, they are easily disassembled and reassembled time and again (Akima).

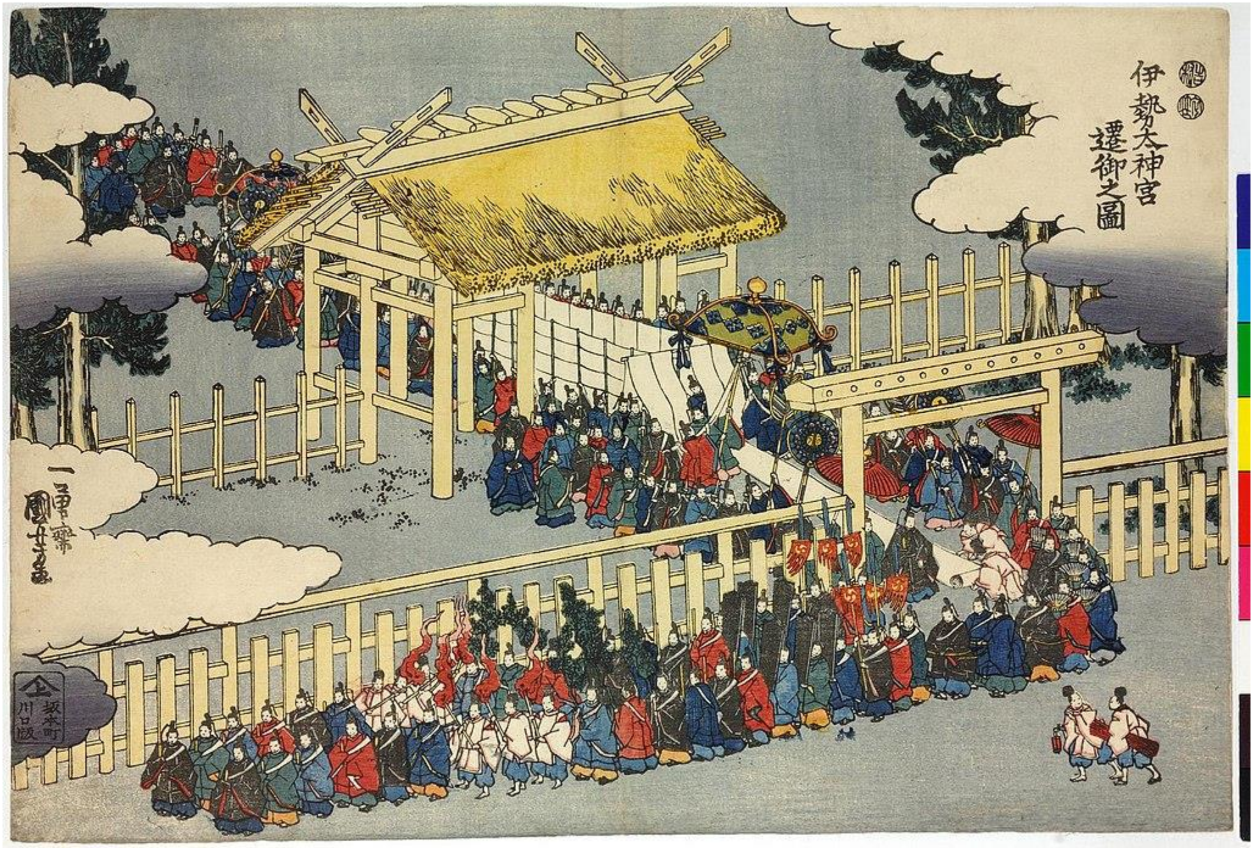


Figure 3: Deconstruction and Relocation Ceremony of Ise, 1849. Ukiyo-e depiction by Utagawa Hiroshige, 1849.

The joinery methods seen at Ise could be described as *Sashimono*, a Japanese term derived from the word *Monosashi*, a traditional woodworking ruler used to carefully measure timber. The idea of precision is baked directly into the term for these joinery methods. Sashimono woodworking is based upon a handful of principles. A Sashimono connection utilizes no glue or mechanical fasteners, rather geometry and friction are applied and an order of assembly to achieve strength. Because no glue is used, the connections are reversible. And because no mechanical fasteners are used (just the geometry of the members), the connections are theoretically far more durable and able to be endlessly assembled and disassembled without breaking down the components (Tokyo Metropolitan Government). Sashimono woodworking principles lend themselves well to be translated into guidelines for the development of tectonic language for a structure.

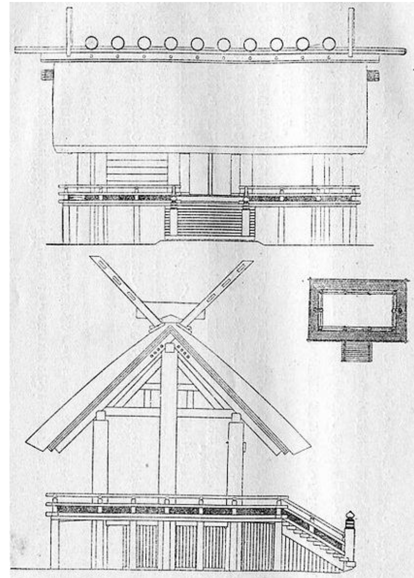


Figure 4 (left): Honden at the Ise Shrine, Mie Prefecture, Japan. Image by Chi King, 2006.

Figure 5 (right): Front and Side View of the Honden at the Ise Shrine. Image by Katsukichi Hattori, History of the Japanese Architecture, 1933.

Ise is arguably the finest example of the capabilities and execution of Sashimono architecture. German Architect Bruno Taut placed the shrine at Ise alongside the Parthenon in terms of architectural achievement, remarking that it was "Japan's greatest and completely original creation in general world Architecture" – Bruno Taut (Reynolds). Both Ise and Horyu-Ji are perhaps the two most exemplary cases in which Japanese joinery was the driver of tectonic language. Whether by necessity or otherwise, time has revealed the remarkable physical properties of joinery methods in these hundreds-of-years-old structures.

Project Parameters

Japanese Joinery Justified

Japanese hand craftsmanship is known for precision and quality across many sectors. From the manufacture of household objects like teapots or cutlery, to wood joinery on the scale of furniture and pagodas, the extreme degree of precision and attention to detail associated with Japanese hand craftsmanship is rivaled by few. Japanese joinery is no exception to this, and its applications in architecture and furniture alike are known for their quality of craft, durability, and aesthetic properties.

Today, consumers frequently face a dilemma between the cost of a product and its quality. The market often offers a spectrum of choices, each offering a slightly different ratio of cost to quality, and each compromising to some degree in one area over the other. The cost of furniture is heavily influenced by its material and its and quality of construction. Wooden furniture pieces constructed using Japanese joinery are revered for their durability and elegance, making them among the most expensive pieces. The required time and skill to produce Japanese joints are arguably their principal disadvantage. To bridge the gap between the bespoke constructions of traditional craftspeople and the accessibly produced furniture markets would be a compelling case for the potential of Japanese joinery in modern production.

Object Type

The form of a bench was quickly identified as an ideal medium of experimentation for the project. It is practical in scale for production in the shop, yet in form and structure it is very similar to a bridge, in that it consists of two bases and a span. It also resembles, in two dimensions, a structural system of columns and beams in a building. In addition, there is precedent for the usage of Sashimono techniques in furniture making, just as in architecture. Moreso than a table, shelf, or chair, a bench is exposed to the dynamic loads of multiple human bodies of various sizes individually or at once.

Defining the Spirit of Japanese Joinery

In the Background section, the term *Sashimono* was defined and explored. While many specific joinery techniques can qualify as being Sashimono, particular Sashimono techniques will not be specified by name. Rather, the common properties among Sashimono joints will be applied as a tectonic language for the construction of the bench. It is necessary to make this shift from specific Japanese joinery terms to the spirit of Japanese joinery, since Japanese joints are often so specialized that it can actually become ingenuine to change their context as approached in this project via the CNC production process, and differing material usage. It is important to specify that the term “spirit of Japanese joinery” is merely my interpretation of the thought

behind Sashimono woodworking methods, used in order to distill the countless possible interpretations and specifications behind Japanese joinery. The primary Sashimono woodworking principles to which the tectonic language of the designed piece will adhere are listed below.

Sashimono Woodworking Principles:

- *No usage of glue*
- *No usage of mechanical fasteners*
- *Wood to wood connections*
- *Geometry and friction*
- *Reversibility of connections*
- *Order of operations*

The spirit of Japanese joinery, then, can be defined as the application of Sashimono wood joining principles in the process of construction, manufacture, and assembly of wooden components of a designed structure or object. For purposes of this project this means that in applying the spirit of Japanese joinery to the design process of the bench, no glue or mechanical fasteners will be used for assembly. Wood to wood connections joined by geometry and friction will be exclusively applied and made structurally sound by the order in which they are assembled. Last, the assembly process will also be entirely reversible.

Modularity

Sashimono joinery achieves its strength by taking advantage of friction, via the redirection of forces. By exclusively using geometry and friction to join structural members, the assembly process is theoretically reversible without breaking down the components or reducing strength.

In addition to disassembly at the end of a product's lifecycle, an endlessly reversible connection readily enables the implementation of a system of modular components. Given the opportunity to utilize various modules, a designed object obtains the ability to satisfy differing structural and functional demands. For example, a standard bench could include arm rests and back rests as optional additions that may or may not be appropriate in certain situations. As the spirit of Japanese joinery naturally enables this functionality, the bench will be designed to take advantage of the option as well. To increase optionality, additional modules and configurations will also be designed for the bench.

It is from the necessity for laboriously repeated precision, that the benefits of a production process involving a Computerized Numerical Control (CNC) machine is recognized. A CNC machine can execute cuts within a fraction of a fraction of an inch's precision. It does so while operating in the background without human intervention. If fed regular amounts of material and electricity, the desired operations will be performed rapidly and accurately. To make great quantities of identical components and coordinating modules, utilizing a CNC in the production process of this project will be essential. The project should be designed within the capabilities of

the machine, but not around the limitations of the machine; meaning that the design should be made with this specific production process in mind, but it should not be hindered or compromised by the limitations of the CNC. Achieving this balance will be essential to the project's success.

The Role of Technology

Sashimono woodworking techniques are heralded for their strength and longevity. Understanding their remarkable capability, it is curious why this method is not more commonplace. The principal drawback to these joinery methods is the high degree of skill and precision required. Those skills in turn, are limited by the number of experienced craftspeople available for bespoke constructions. As discussed in the Background section, the technology available to the craftsperson has been a leading limiting factor in the ability to create sophisticated joinery. The greatest available technology for wood manipulation to the traditional Japanese craftsperson was their pull saws, chisels, planes, and other hand tools. During the time of the development of Japanese joinery, the available time for skilled workers was a critical dependency in their usage and is the primary reason for the lack of examples of Japanese joinery methods in any mass production context.

The capability of the CNC to make precise, but rapid and repeated operations, addresses this challenge. By recontextualizing Sashimono woodworking principles, and applying them to a CNC workflow, the structural and aesthetic characteristics of these joints are retained without the typical need for a time consuming and labor intensive production process.

A drawback to the usage of a CNC machine is that it is only capable of doing exactly as instructed by design. Unlike a craftsperson, a CNC is unable to improvise when inconsistencies in wood, such as knots, voids, or cracks are present. For this reason, a material that is durable, consistent, and somewhat homogenous is also necessary for this workflow. ¾" Baltic Birch plywood is not completely homogenous, but its relatively high ply count, alongside its remarkable strength, consistency, and pleasant appearance makes it a suitable material for purposes of the project. No such material as plywood was available to the traditional Japanese craftsperson, but this does not mean it is unsuitable for this context. The traditional Japanese craftsperson utilized the most optimal cypress lumber they could acquire, working around its imperfections and inconsistencies. This idea will be similarly applied in this capstone where the most optimal material will be selected, and the design and production process will take advantage of its shortcomings while utilizing its strengths.

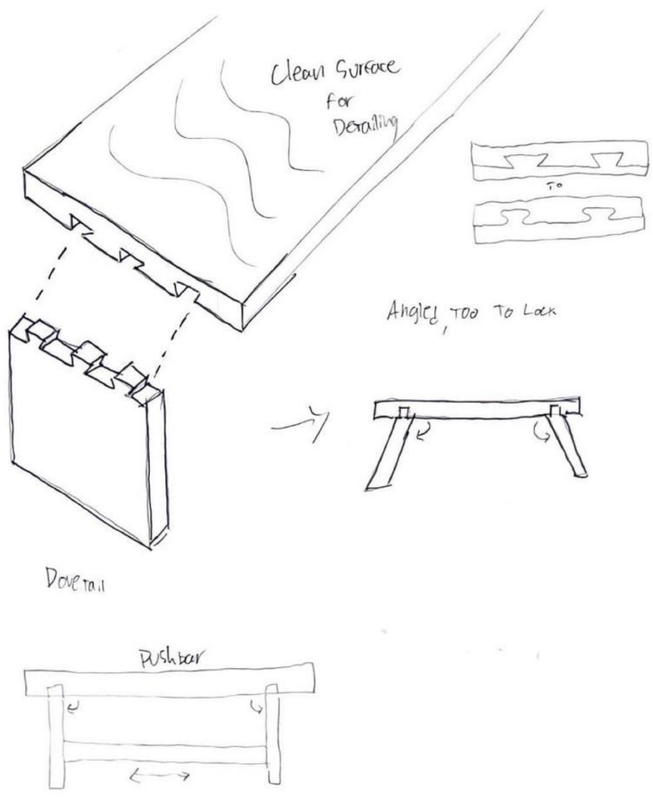
This project embarks on the challenge to integrate integrating the spirit of Japanese joinery into a modern design and production process. By embracing the ability of Sashimono joinery to be disassembled; and including the capabilities of the CNC along with the available materials of modern times, a bench will be designed with modular capability, mass production, and ease of assembly and disassembly in mind.

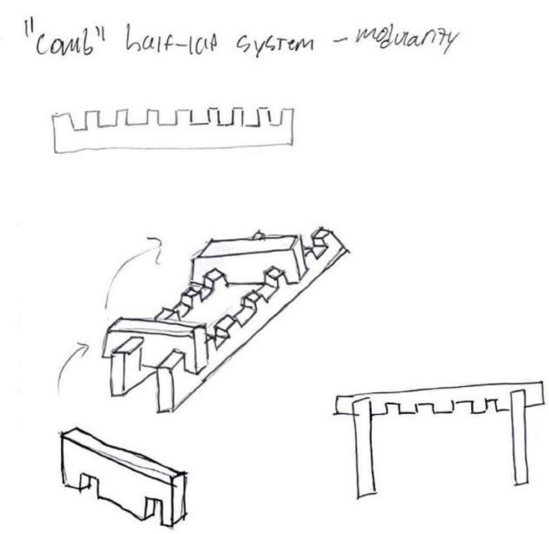
Method

Design Process – 50 Sketches

The design process began with the production of 50 sketches. These are included in their entirety in the Image Index. These sketches largely sought to address the preconceived problem that, due to the expansive and contractive properties of wood, marring of parts under load, and other such inconsistency challenges, making a joint via CNC that would remain tight and stable over the course of months to years would be extremely difficult. If parts were able to work themselves loose by one mechanism or another, the design in terms of its implementation of Japanese joinery made by CNC would be unsuccessful. To resolve this issue, many of the sketches loosely recorded methods by which the splaying or pinning of legs outward could serve to maintain the tightness of joints as the pieces settle over time.

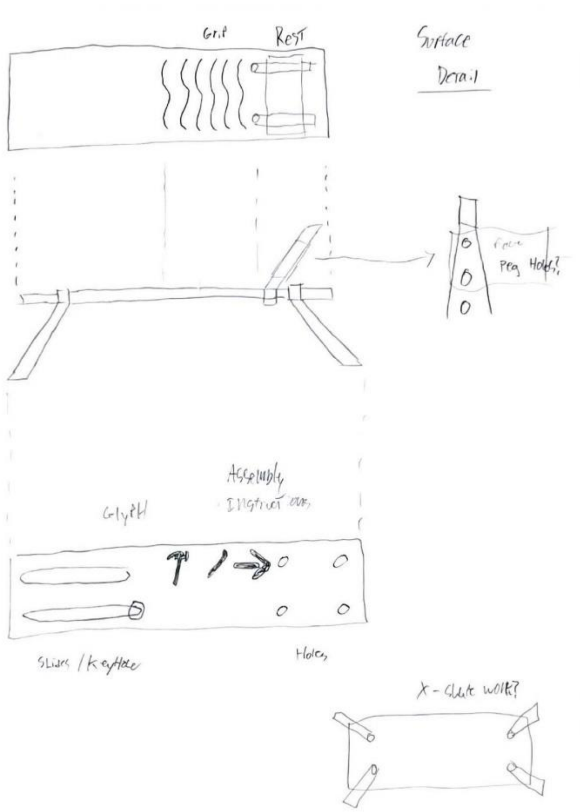
Many methods by which the splaying outward of legs, affixed to a solid planar top, perforated with attachment points were explored. Twist-in legs, and frames which looped around the top and bit down were explored. This idea of the rotation of parts would prove to return at a much later phase in the design process. Perhaps the most important of these sketches is pictured below, in which a frame of interlocking half-lapped comb pieces assemble into a frame. From here, this design concept was taken into Rhino 6 3D design software.

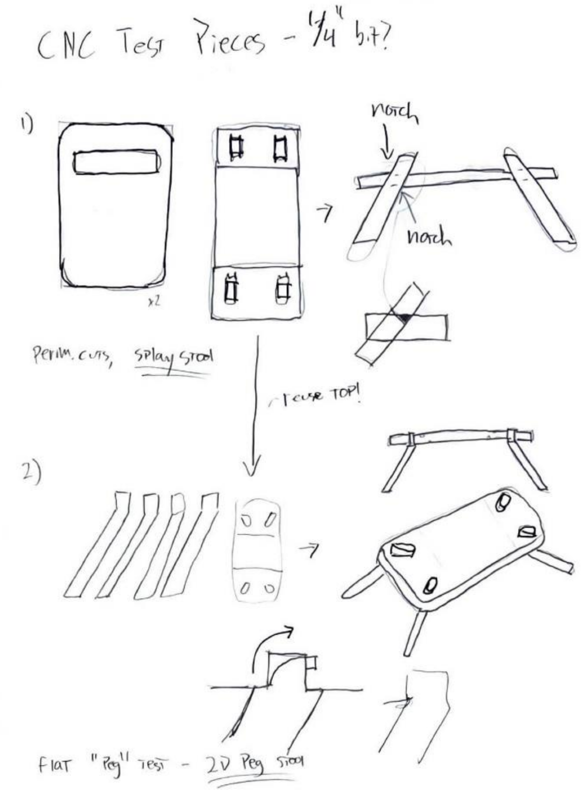




Twist, slot-in components

"Comb" Frame





"Peg Legs"

Wrap-around frame, rotate-in legs

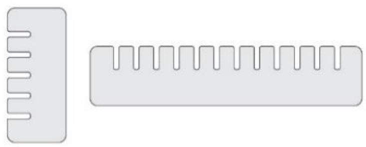
Design Process – CAD Development & Modeling

In order to realize these basic design concepts more fully, namely the Comb Frame and Peg Legs, these designs were taken into Rhino to be drawn precisely, and laser cut as 1/6th scale plywood study models. The wrap-around frame idea, and the rotate-in legs were designed as one unit, to be compatible with one another. These are imaged below.

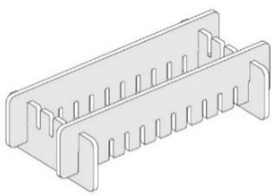
Immediately upon their physical realization, significant challenges regarding lateral stability with the legs was identified, while difficulties with assembly were identified across both concepts. It became apparent that the Comb Frame may prove to be a more successful area for further development.

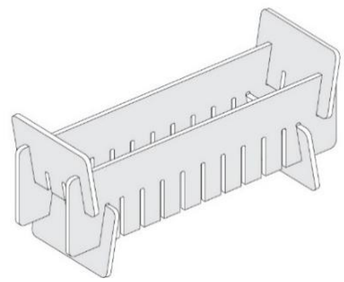
The Comb Frame consisted of four pieces, two long and two short. They would form a frame of two legs and two spans, which could support a top piece. The regular slots were identified as potential attachment points for modular components

Iteration 1

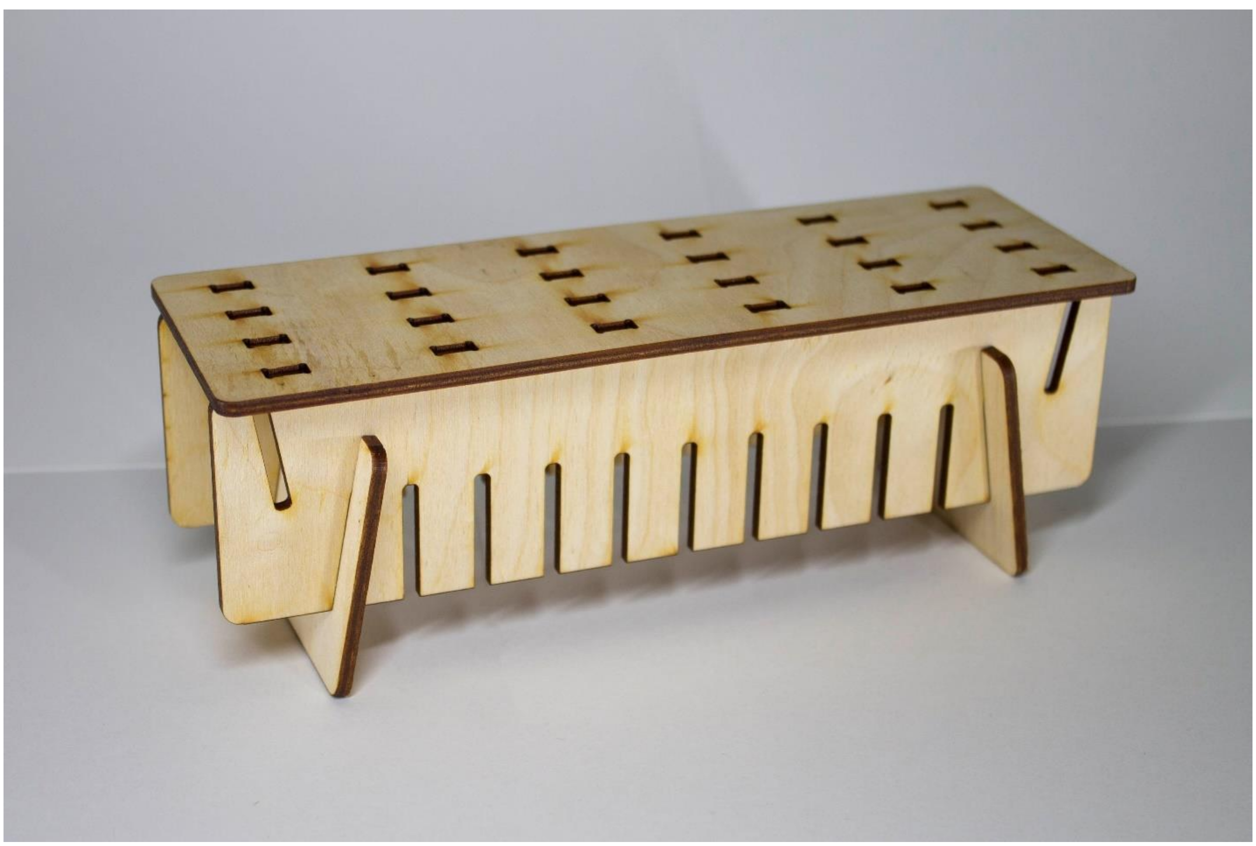


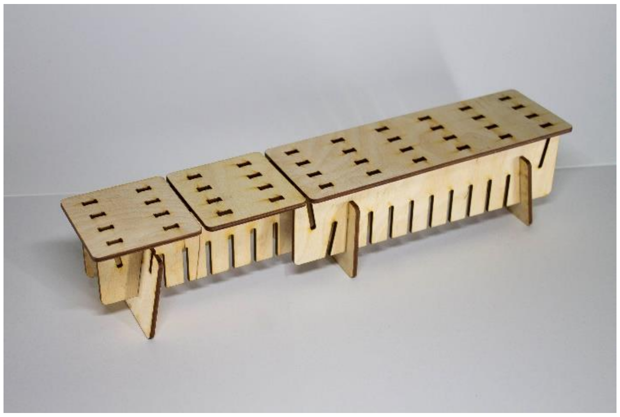
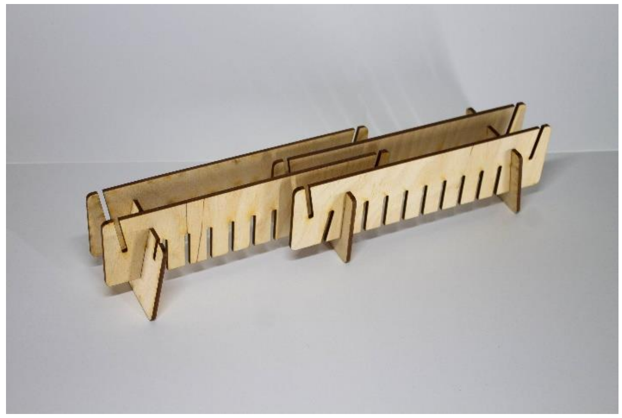
Iteration 2



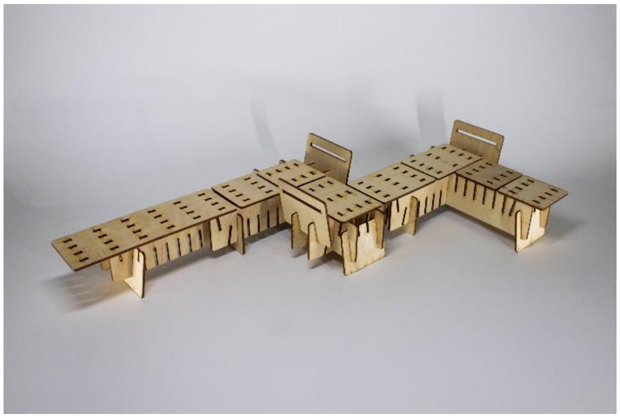
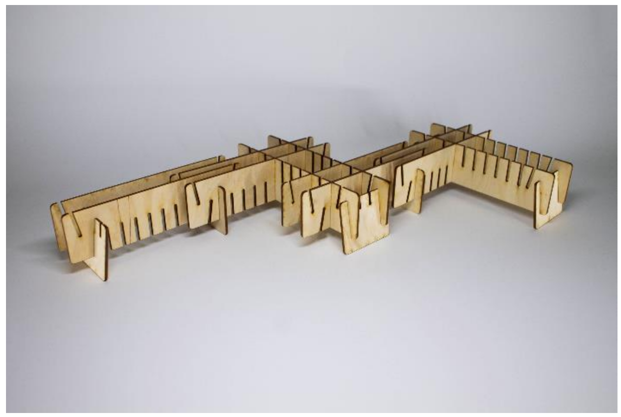


Iteration 1 of the Comb Frame (left) would contend with issues of racking, so a quick second iteration featuring slanted slots for the legs, and arm rests on the other side was created. The simplest bench configuration is pictured below, as a 1/6th scale model. All component sizes from this stage onward are based on divisions of a 4'x8' sheet of plywood. This division limited the bench span at 4 feet.

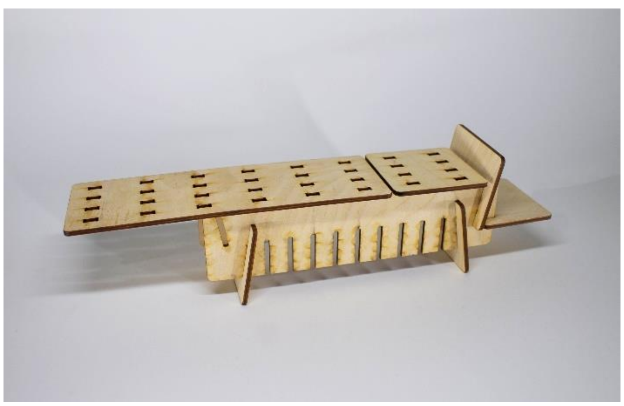


Extensions of the bench system could be achieved by staggering the span components through the four available slots within a leg component.

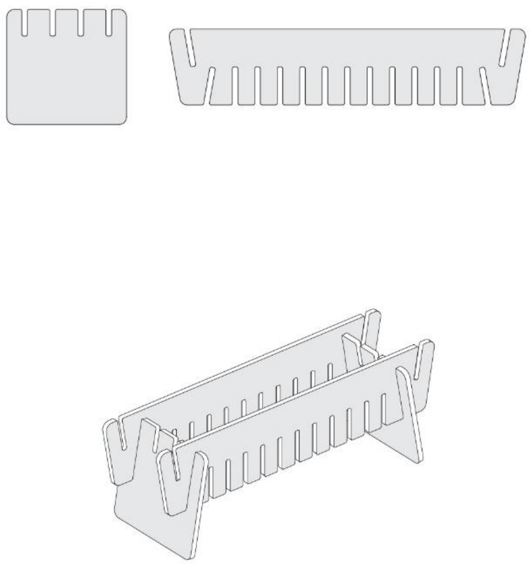



By flipping a span piece over, it could be slotted through the grooves of another span piece, to change direction. This could be compounded with extensions to make complex bench “chains”.

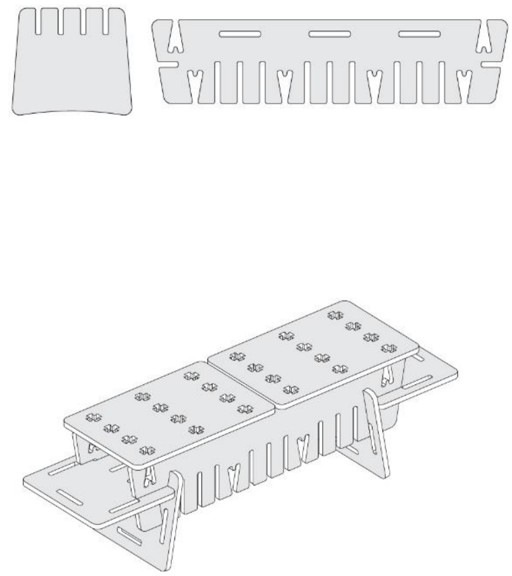



Lastly, armrests, backrests, and cantilevers were identified as desired capabilities, but ones which the current design system did not effectively accommodate. In addition, significant and wasteful overhangs existed when changing direction and extending the bench. The final significant challenge identified by this physical experimentation was the challenge of affixing the seat panels down.

Iteration 3

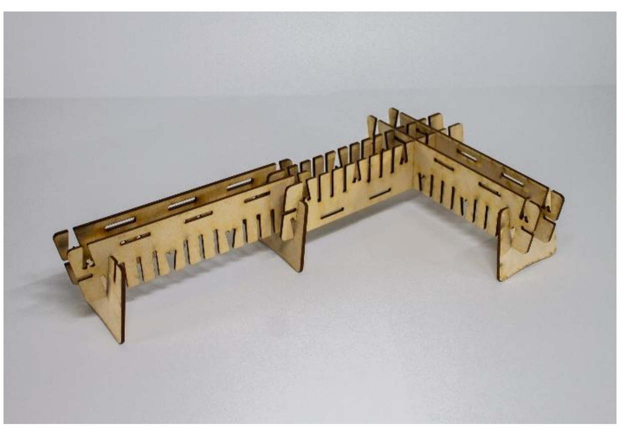


Iteration 4



A third and fourth iteration of the frames were made in order to address a number of challenges with the initial iteration. Iteration three (left) lifted the frames much higher off of the ground for a more elegant and desirable appearance. The profile became more angular, for the aesthetic and functional purpose of reducing overhangs. Iteration four (right) introduced slots for a side table, as well as periodic modified slots, shaped like hearts. This iteration was laser cut and can be seen in the following images.

The addition of these periodic heart-shaped slots was a major functional achievement at this stage. They were a compromise between the requirement to maintain the deep, straight grooves necessary for direction changes, and this desire to accommodate periodic leg attachment points which would facilitate the extension functionality. This compromise became necessary as it was desired to lift the body of the bench higher off of the ground, in order to achieve a more refined and desirable lightweight profile.



The modification of these slots created a new challenge of its own, however. It was necessary that the legs remained able to splay outward in opposing directions in order to prevent racking. Because of this, a leg placed at the connection point of two extending beams needed a groove which accommodated a switch in direction, as the outward splay from the perspective of one

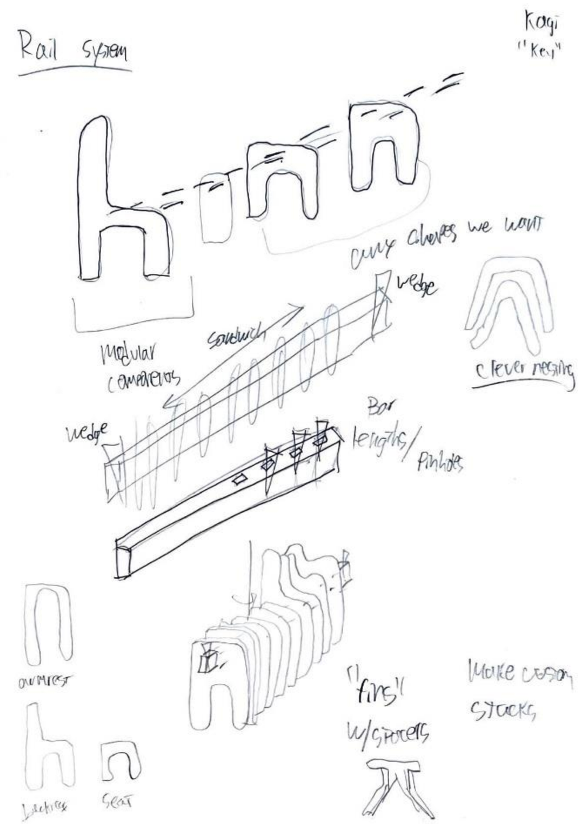
beam, would be an inward splay from the perspective of another. As a result, these heart shaped grooves emerged as a solution which allowed the legs to be positioned at either of the two possible angles. The situation of a leg piece being splayed outward with respect to one leg, but inward to another can be seen in more detail below.

In the case of a direction change, beam pieces would be flipped upside down to interlock flush with one another. Because the beams may have been upside down, these heart shaped grooves were also included in the top to account for this situation

It was at this stage that, while the direction changes and extensions were fun to experiment with, the challenge of fastening down the seat panels could no longer be ignored. No methods by which these panels could be affixed to the frames could be identified, which did not go against the spirit of Japanese joinery. It seemed the only solution possible was to use pseudo fasteners. The limited aesthetic quality of this system was also an issue, as the pieces had become so complex and formally compromised in order to accommodate so many potential modular configurations. This compounded by the imperfect execution of the direction change and extension meant that a new approach was necessary.

Design Process – Return to Sketching

This new shift in the design process required a return to a sketching phase. Sketching led to a new solution, in which the seat panels were instead replaced by a series of seat slats (left). From here, the concept of dropping these seat slats down to the floor, and making them the entire body of the bench was reached. The challenge of this design became one of finding a stable way in which to connect these panels in series.



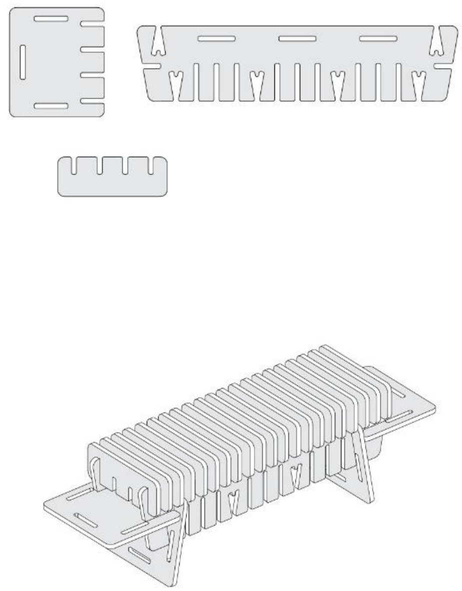
Initially, ideas such as squeezing them together with wedges were looked at. The tectonic challenge seemed great, but the modular promise of being able to switch out components like seats, backrests, and arm rests proved to be interesting enough to warrant further development.

After this period of sketching, a return to Rhino modeling would see the realization of the “Pinch” bench system, in which a spacer resembling a jigsaw blade spaced out the seat components, as it pinched into a notch at the leg and seat junction. These jigsaw pieces, in turn, would be held inward by seat slat pieces, which would reach around and hold them together such that the legs would remain spaced evenly.

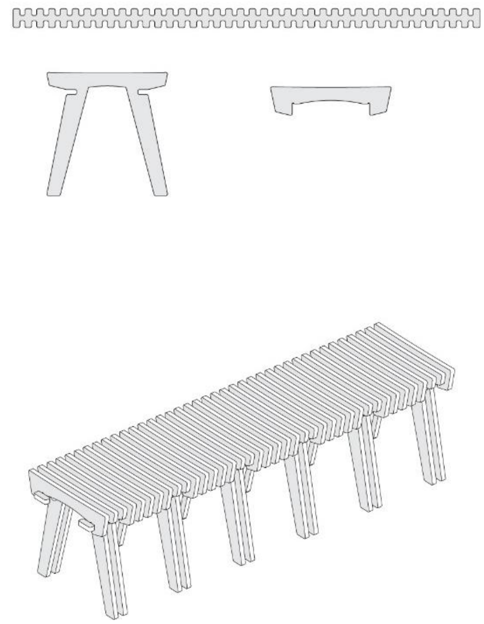
The following diagrams depict this shift between the Comb Frame, and the new Pinch concept.

Design Process – CAD Development & Modeling of New System

Iteration 5



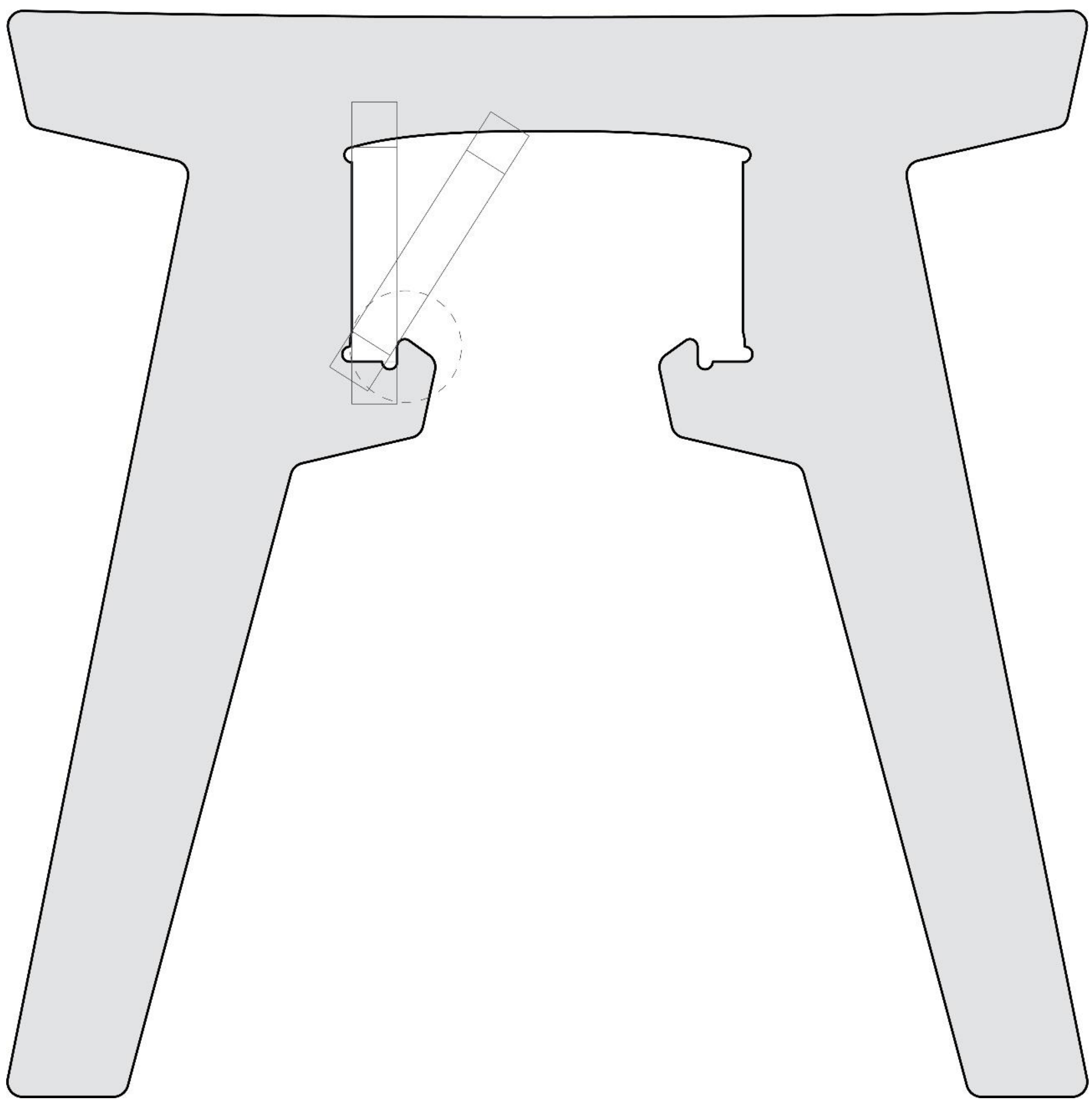
The "Pinch" iteration



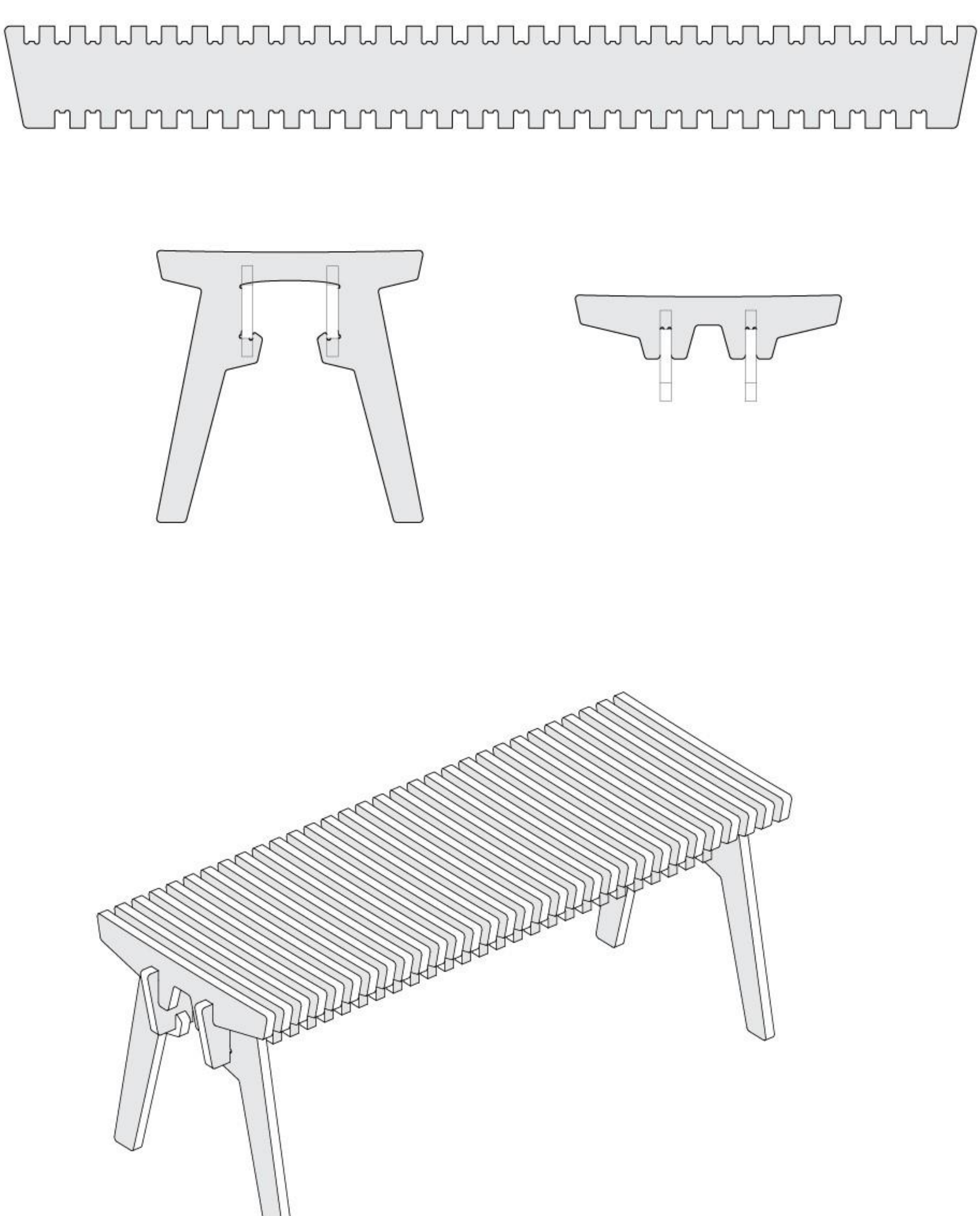
This development saw a complete overhaul in terms of the tectonic system of assembly, the modular capabilities, and the aesthetics of the bench. A new, more elegant and better proportioned profile was achieved, while the ability to add seat backs and arm rests was more readily realized. This phase never advanced beyond CAD, however, as clear structural issues were apparent. The jigsaw spacers were so thin that the bench could not possibly span significant distances. In addition, there was very little lever arm available to prevent the entire structure from racking. The key to solving both of these issues, was to take this jigsaw spacer, turn it on its edge, and increase its thickness.

The process of rethinking the jigsaw spacer as a beam turned on its edge can be visualized by the following grid of drawings, which also depicts the shift of each additional component into their respective role of the "Twist-Lock" system, including the armrest and backrest.

An intermittent stage between the Twist-Lock and its predecessor the Pinch, was a Drop-In style system, in which two beams could be dropped into two slots within the leg frame, upon which seat slats could be rested. Challenges were realized within the Drop-In system quickly, in that it rapidly lost the thin, elegant profile of the Pinch in order to have enough supporting material around the beams. Immediately, a way in which the beams could drop into some kind of shelf or notch on the leg structure was sought. A successful configuration was achieved when the placement of a notch into which the beams could rotate up into was made. From here, these beams could be pinned back apart at the top by the seat slats, to create a stable system. The rotational movement of the beam into its notch can be seen in the diagram below.

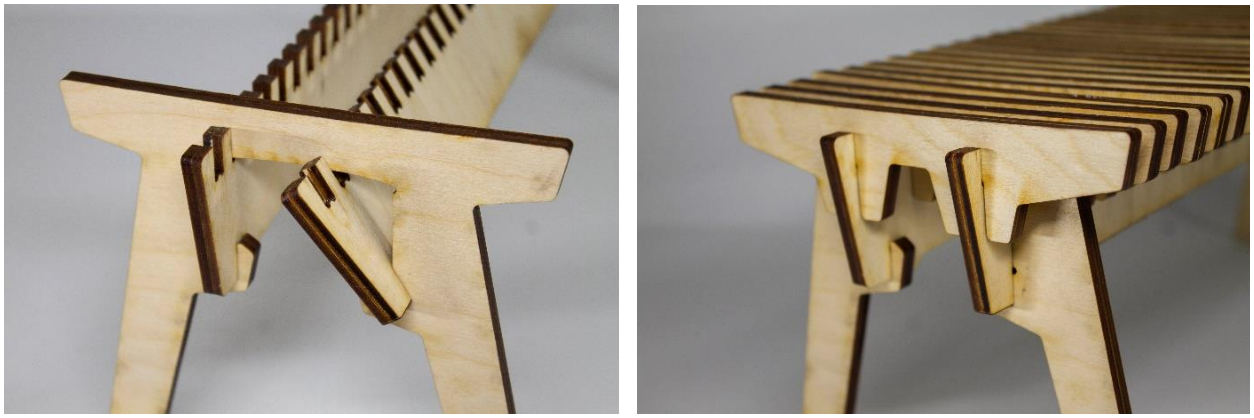


The Twist-lock leg frame



The Twist-lock bench system, version 1

The Twist-Lock assembly mechanism solved many issues. The relatively large area by which it could grab the leg frames prevented racking. Its vertical thickness allowed it to easily span desired distances. The process for assembly was smooth, and the ability to drop in modules in place of seat slats was clearly identified. In order to locate any unforeseen challenges, this system was laser cut at 1/3rd scale, and assembled.

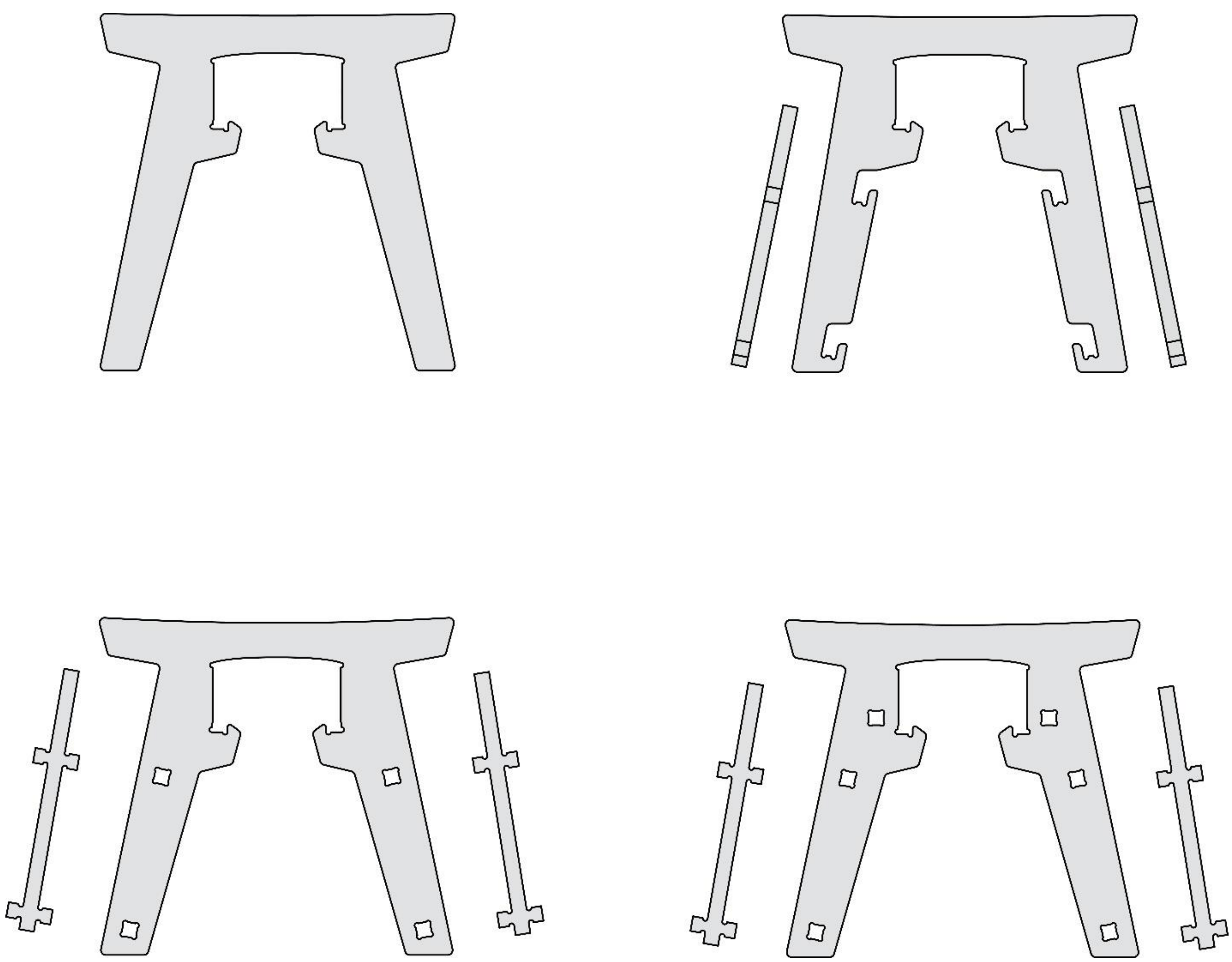


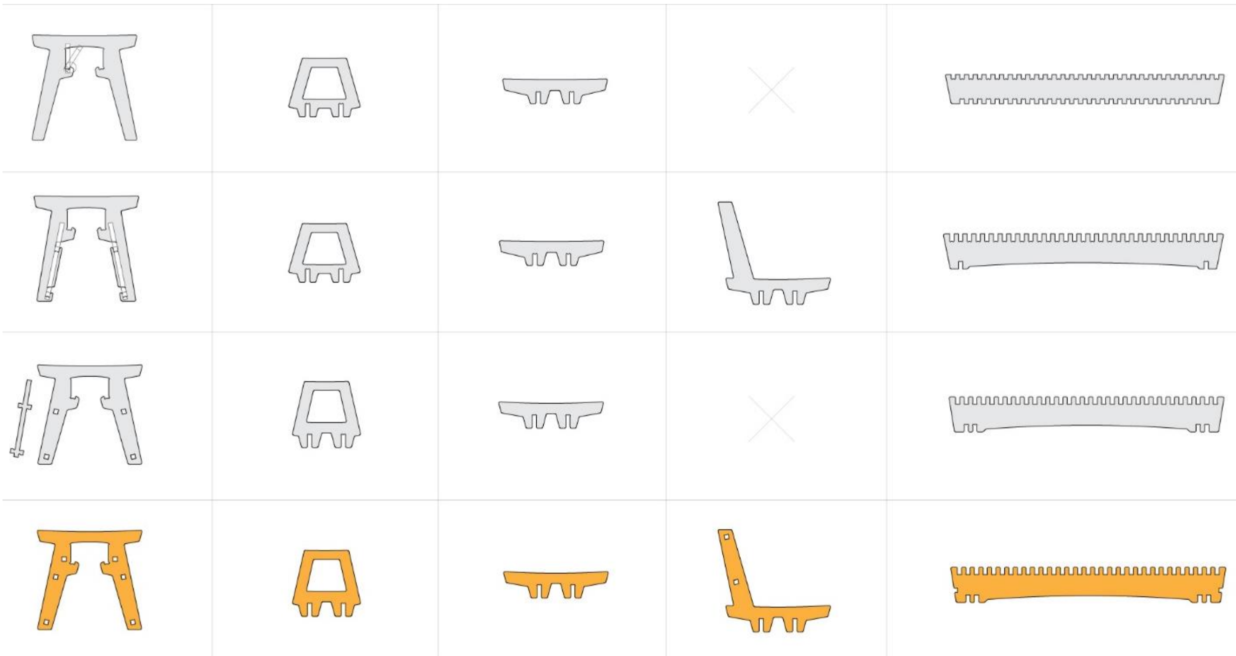
The Twist-Lock, leg frames and beams.

The full bench.

The issues regarding span, aesthetics, and modularity were addressed by this iteration, to varying degrees of success. The final significant structural challenge of this design was that the legs were simply too thin to resist lateral loads without wobbling. In order to prevent this, they needed to be doubled up or braced in some way which did not go against the spirit of Japanese joinery.

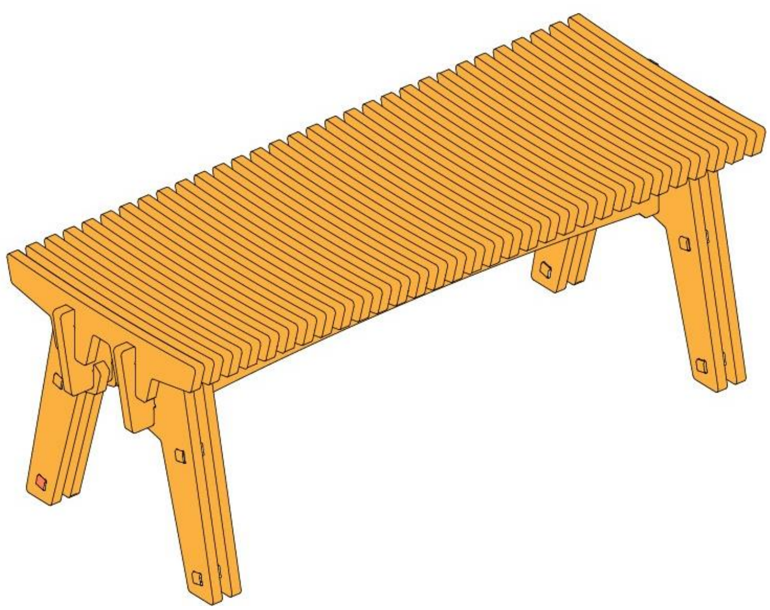
A frame method in which a splint-like brace could slot into notches from the inside was explored. Due to the need for such notches that reduced effective material thickness, this option was not feasible. Instead, a pair of brackets were developed which would become sandwiched between two identical leg frames, preventing them from sliding past one another and bending. These options can be seen below.





Due to the interconnected nature of the Twist-Lock assembly method, when one component changed in any dimension, each corresponding component or module also had to adjust to accommodate this change. As the four phases of the leg frame were explored, the backrest, beam, seat slat, and arm rest modules, all had to be redrawn and refined to reflect each minor change in profile, size, fit, and so on.

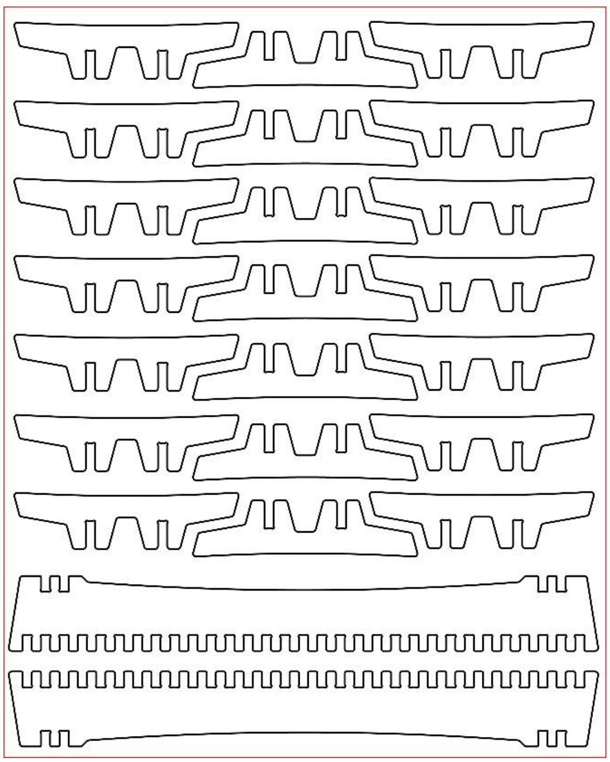
The final iteration of the primary bench components can be seen above, highlighted in orange. Below is an expanded view of the final unmodified bench form.

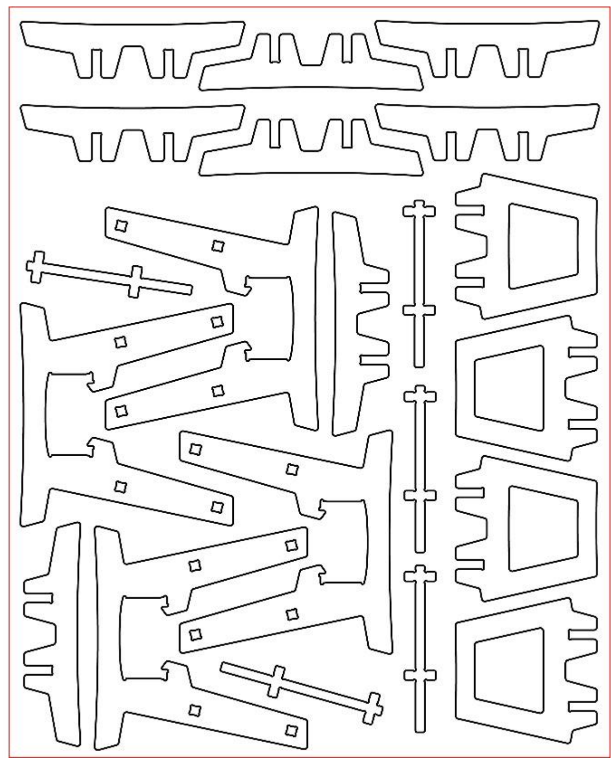


The Twist-Lock bench system, fully realized.

Production Process – CNC & Mass Production

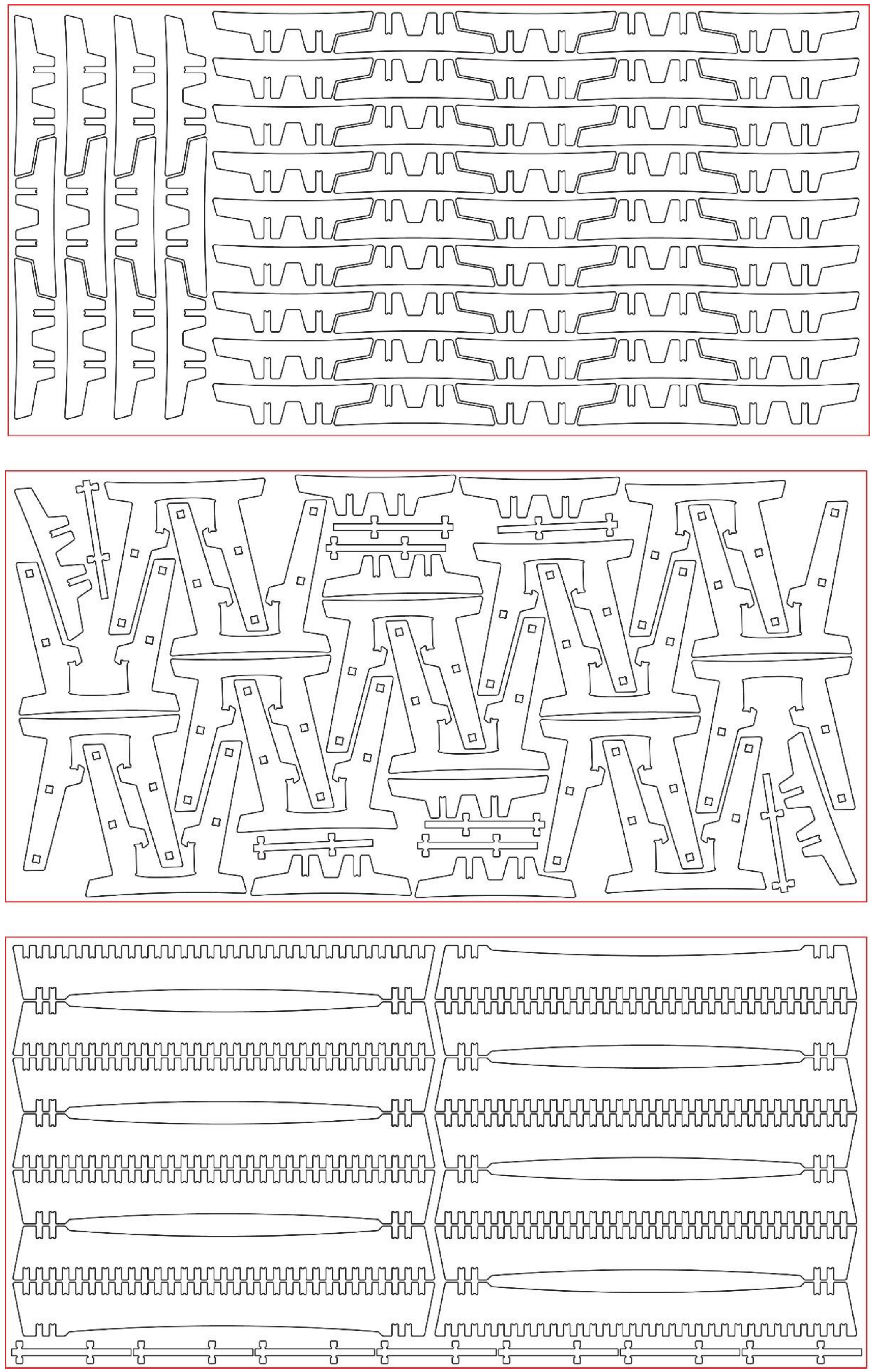
At this point, extremely minor refinements to the capability and form of the bench could have been made, but they were not necessary for the scope of this project. From here, the task became to set up the Rhino files to produce a bench at full scale on the CNC. The first step was to dial in the tolerance of the cuts for CNC production. Because ¾" plywood is just shy of being actually ¾" thick in reality, this roughly 1/32" difference in thickness had to be accounted for. Once this test was completed, the file was adjusted, and layouts for cuts were made.





The material on hand was limited to 4'x5' in size, rather than the standard 4'x8' sheet size that the bench was designed to be mass produced from. Because of this, two sheets had to be used. There was extra room for a few spare pieces, and arm rests in my production case. In a true mass production process, the bench would not be produced in this way.

In a mass production context prioritizing material efficiency, each component of the bench could be much more efficiently produced both in terms of pieces per sheet, and sheets per bench. The following layouts of standard 4'x8' sheets could theoretically produce each part of the standard bench with material waste approaching just 20% of a sheet. If produced at the optimal rates, these plywood layouts would produce one bench per .73% of sheet input.

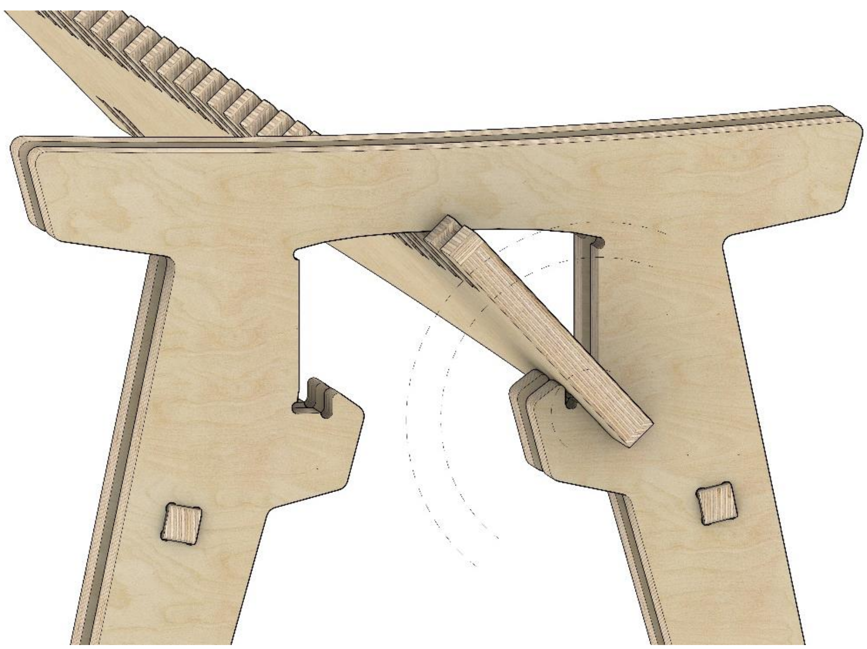


Mass production component layouts

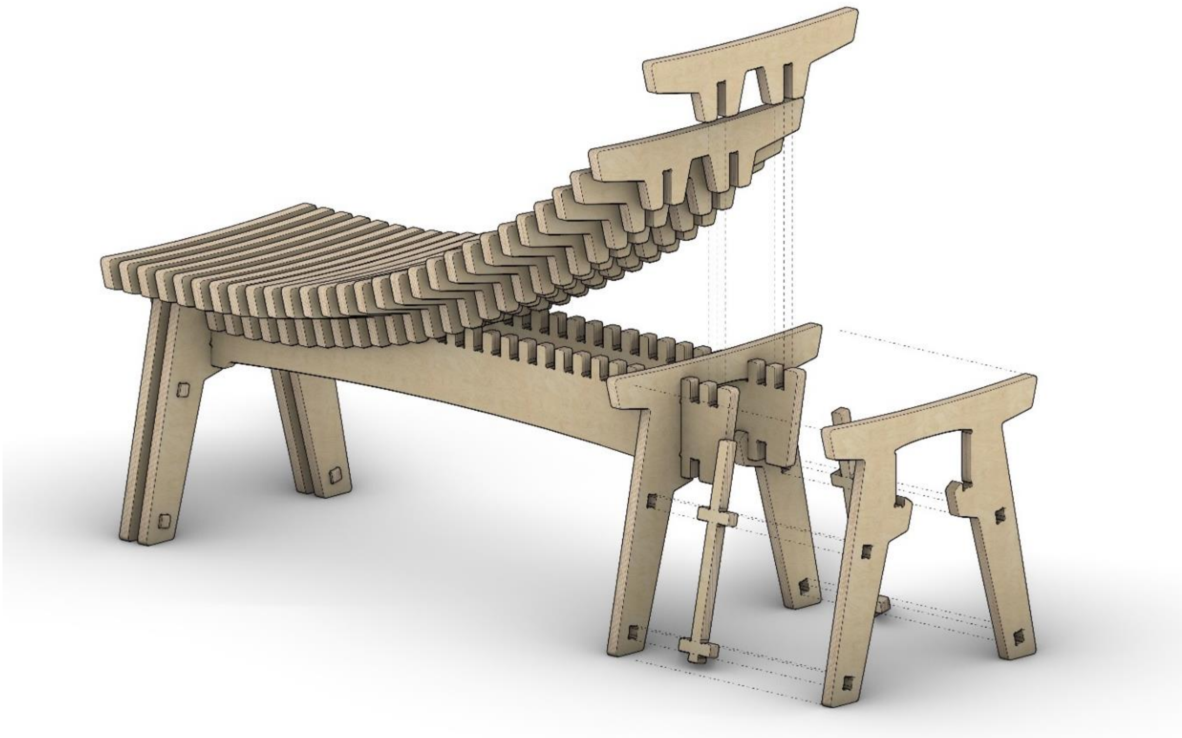
Production Process – Final Visual Representations

Alongside the physical production of the bench, presentation materials for the final design were produced. The series of renderings produced are below. These include exploded diagrams, and various possible configurations of the available modules.

The unmodified bench

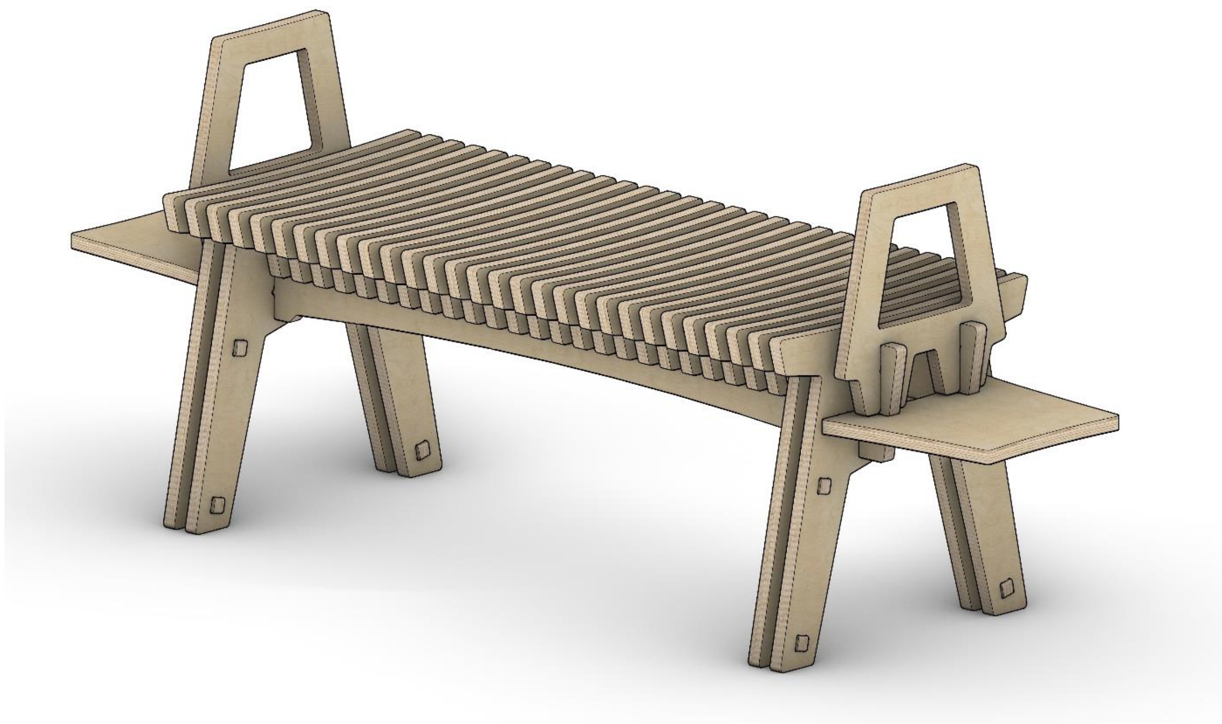


Twist-Lock detail

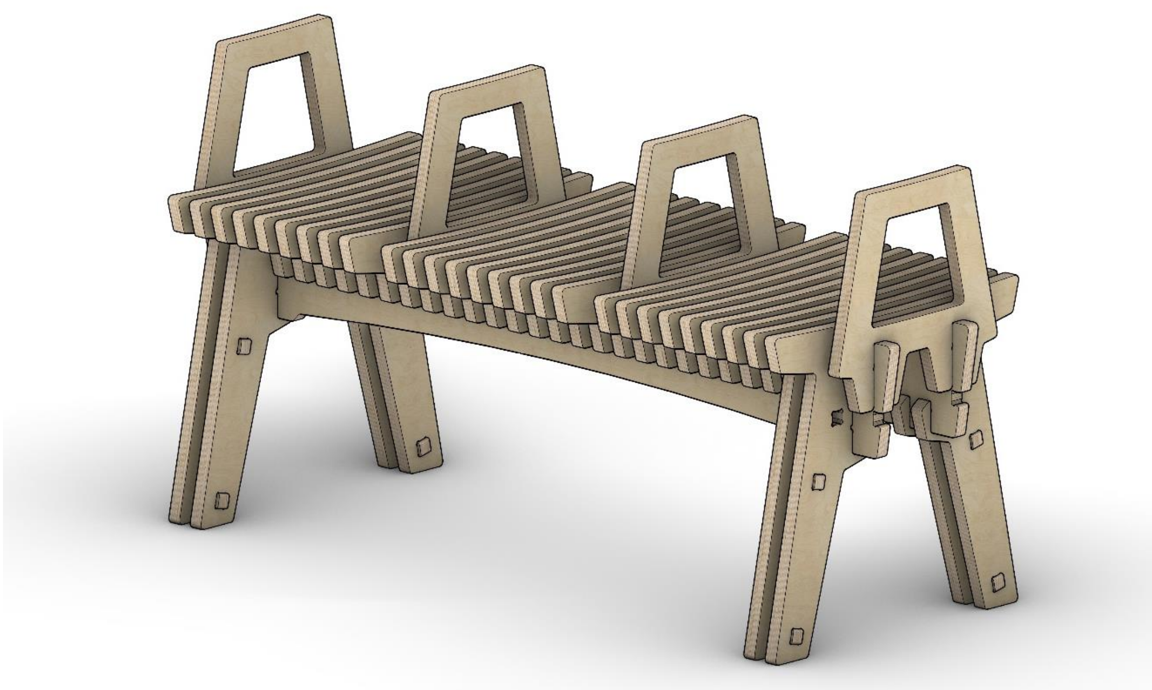


Exploded unmodified bench

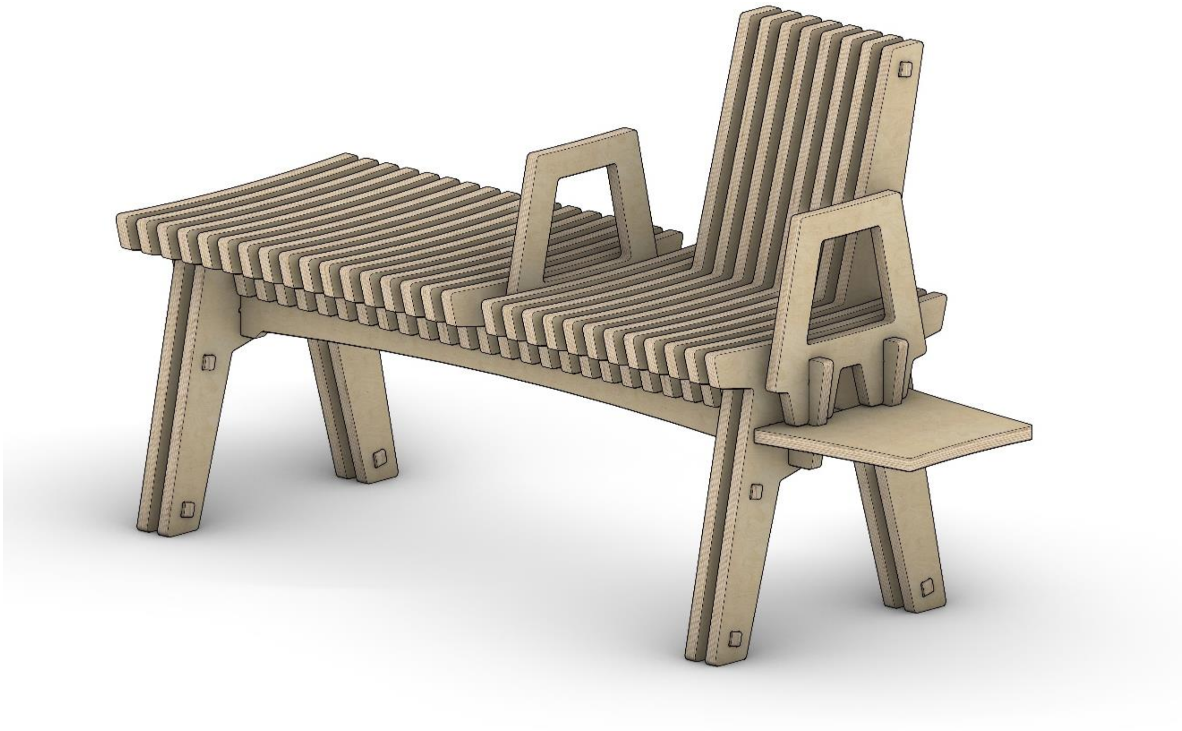
Modular attachments demonstrated, side table and arm rest



Two arm rests, two side table configuration

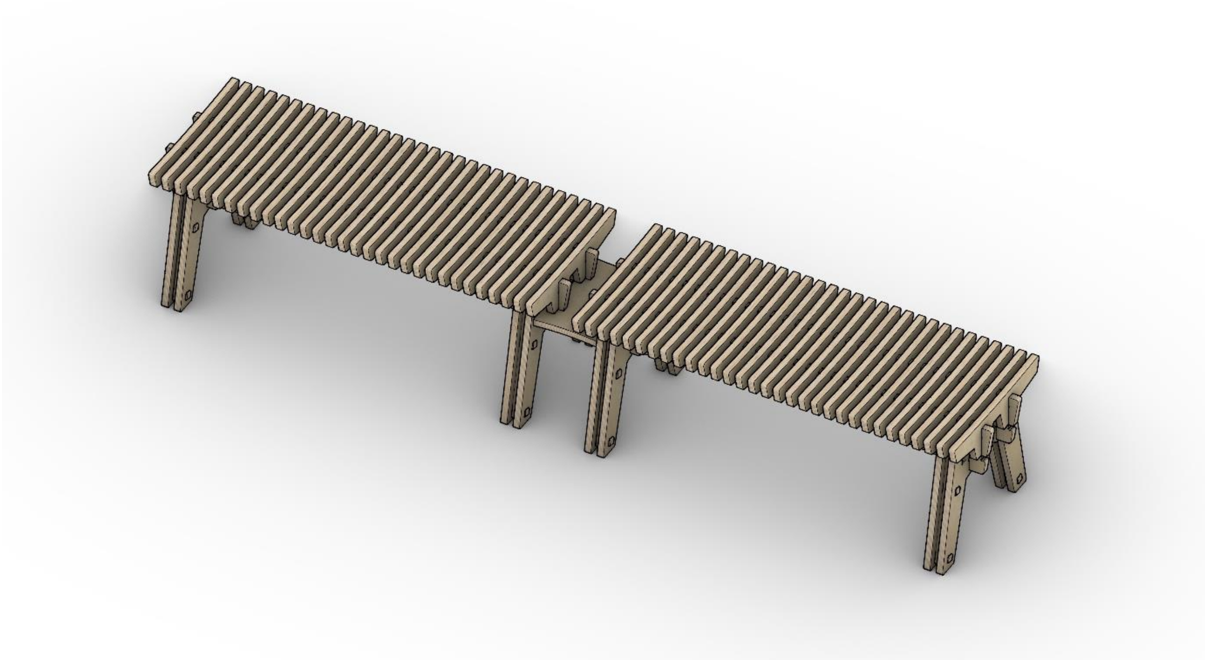


Four arm rest configuration

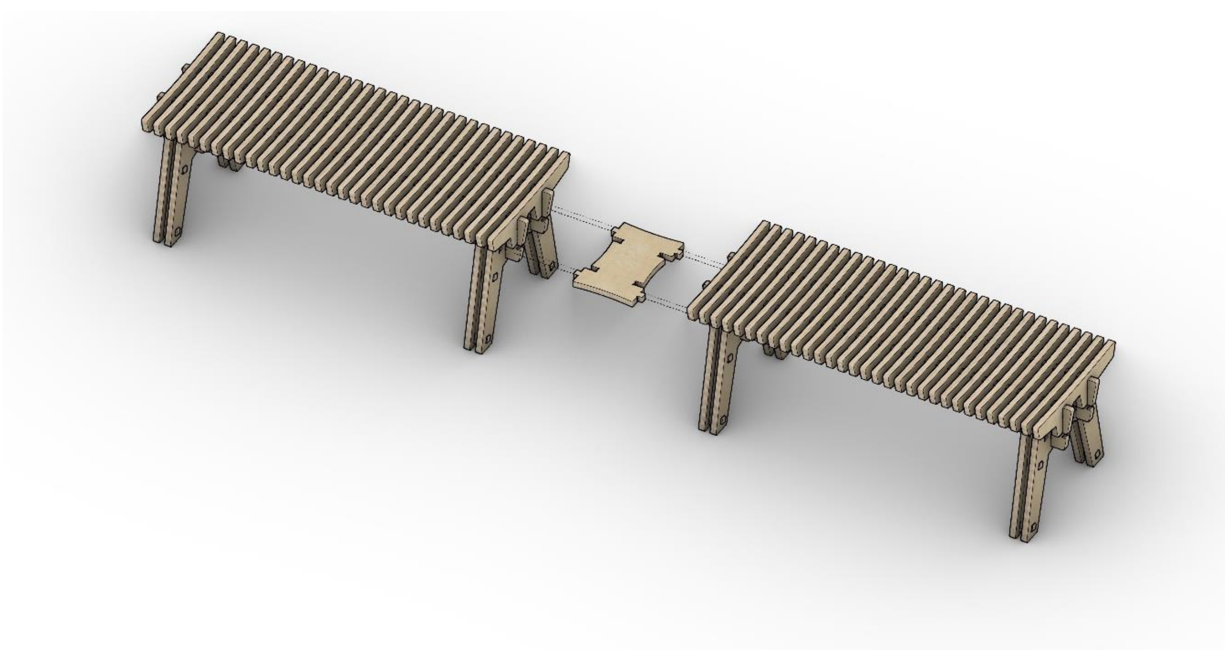


Asymmetrical configuration

Full seat pair configuration



Side table connector bench pair



Connector component demonstrated

Production Process – The Completed Bench Prototype

The finishing process for the bench began with collecting the materials from the CNC and separating them. When the components are separated, the burrs, tabs, and splinters can be sanded down. In addition, a final surface sanding for smoothness was completed. With all of the pieces prepared, the bench could be assembled. Assembly of the bench took fewer than three minutes. The bench, fully constructed, can be seen below.

Conclusion

The intention of this capstone was to learn what creative opportunities arise as a result of applying the spirit of Japanese joinery to a design, and a digitally manufactured furniture piece. The desired outcome was to develop a modular, component-based furniture system capable of being efficiently and mass produced by CNC machining, and to produce a functional prototype based on this system.

Successes

The completed bench design prototype, enabled by the Twist-Lock assembly mechanism, was successful in its application of the spirit of Japanese joinery. The principal influences of this application are the following achievements. The piece is readily assembled and disassembled, without compromising durability. The friction fit components do not rely on fasteners or glue, nor are they broken down as the piece is disassembled. As a consequence of this capability, the piece accepts various modules for additional capability. Additional module components designed for this bench include the seat back the arm rest, and the side table/ connector components, all of which can change the way the bench is interacted with and used.

The bench succeeds aesthetically due to its thoughtful and attractive proportions and its handcrafted feel. Various design sensitivities such as the gentle cambering of the beams from underneath to the subtle convex curve applied to the seat slats contribute to an elegant, refined form. The alignment and consistency of various angles across components, and details such as the protrusion of the pegs of each leg brace convey the deep consideration given to every aspect of each element. These design sensitivities work to define a striking, angular yet timeless form composed a carefully articulated plywood edge.

An additional success of the project was the mass production capability. The primary components of the bench, the beams, seat slats, and leg components, all were designed with intention to tesselate/ nest within one another. This enables a maximum quantity of pieces to be created per sheet of plywood, while reducing the wasted and excess material as much as possible. If mass produced via the mass production plywood layouts at appropriate quantities, the material input cost of the bench is less than the cost of a single sheet of 4’x8’ plywood, at approximately 75% of a sheet input per standard bench produced.

Challenges

The key challenges that arose in the production of the prototype were the CNC tolerances, material thickness discrepancies, and the splintering of the plywood upon machining. Due to a generous tolerance being added during the CNC cutting process, each component has some play at every connection. This is not an issue for the prototype, as the Twist-Lock assembly mechanism’s strength is unaffected. For the purposes of fit and finish, however, this tolerance should be dialed in to a more precise degree. The challenge of material thickness can be addressed by standardizing the material source, while the tolerance of the CNC and the width of

the notches of each part can be adjusted in accordance with the material thickness until an optimal balance of rigidity, but ease of assembly is achieved.

A pivotal challenge in the overall design process was the challenge of reconciling plywood's weakness in its planar form, when load is applied perpendicular to the plane. This challenge was overcome when a shift in thought occurred, that an array of vertical pieces of plywood could interlock to create surface, rather than the more intuitive thought of using the plywood face as surface. This shift sparked an aesthetic overhaul, as the plywood edge was freed to allow for formal refinement. This accompanied a great increase in tectonic capability, as the plywood resisted load exclusively in its most rigid direction.

Lessons Learned

In the design process of this digitally manufactured furniture system, challenges and opportunities as a result of applying the spirit of Japanese joinery to this process were identified. The development of a component based furniture system, capable of mass production, modular configuration, and disassembly was successfully realized. In achieving this, an appreciation for the degree of precision required to properly execute Japanese joinery-style connections was developed.

An appreciation and respect for the value of the iterative and thoughtful design process which was the body of this project is the most paramount takeaway. This project comprises the most thorough understanding and execution of the iterative design process I have experienced in my entire design education. Each phase of the design process from the sketches to the several stages of CAD and model prototyping each served vital roles in developing the project and product into what it became. Without each step in the process, the output would not have been the same, and the results could not have been as successful. Throughout the design process, various interesting and exciting opportunities arose even in the earliest stages, such as the extending and direction-changing bench configurations. Where these systems struggled aesthetically, they still identified these interesting opportunities in their ability to change form and adapt to new contexts, a capability enabled by their implementation of the spirit of Japanese joinery.

Future Research Opportunities

The design methodology which produced this bench prototype could be adjusted and reapplied to other projects in multiple ways. By instead prioritizing the complete elimination of waste over aesthetics, one could seek to create a furniture system whose form and resultant CNC production process results in zero material waste, while still maximizing the number of pieces obtained from any sheet of plywood.

Another way in which this process could be adapted would be in attempting to apply these design criteria to a project involving differing materials which may offer increased structural and aesthetic opportunities, to the potential detriment of the ease of manufacture, material cost, and

so on. To use hardwood, for example, would introduce new challenges pertaining to the expansion and contraction of the material over time, or the presence of inconsistencies such as knots and cracks, would prove to be interesting challenges to overcome, with the potential benefits including increased thickness of components beyond ¾" thick, and the aesthetic qualities of various hardwood species.

Lastly, a change in the scale targeted from that of a bench, to something more intimate and versatile like a chair, or to something much larger in scale such as a pavilion would create an interesting expansion upon the potential impacts of applying the spirit of Japanese joinery to digital design processes across various scales.

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Images

Figure 1: Horyu-Ji Temple, Kondou and Tou. Ikoma District, Nara, Japan. Image by Saigen Jiro, 2019.

https://commons.wikimedia.org/wiki/File:Horyu-ji,_kondou_and_tou.jpg

Figure 2: Horyu-Ji Temple, Roof Detail. Ikoma District, Nara, Japan. Image by Z. Tanuki, 2013.

https://zh.wikipedia.org/wiki/File:Horyuji_temple_,_%E6%B3%95%E9%9A%86%E5%AF%BA_-_panoramio_%2818%29.jpg

Figure 3: Deconstruction and Relocation Ceremony of Ise, 1849. Ukiyo-e depiction by Utagawa Hiroshige, 1849.

https://upload.wikimedia.org/wikipedia/commons/b/b1/Ise_Daijingu_sengyo_no_zu_%E4%BC%8A%E5%8B%A2%E5%A4%AA%E7%A5%9E%E5%AE%AE%E9%81%B7%E5%BE%A1%E4%B9%8B%E5%9B%B3_%28Depiction_of_the_Relocation_of_the_Grand_Shrine_of_Ise%29_%28BM_2008%2C3037.21409%29.jpg

Figure 4: Honden at the Ise Shrine, Mie Prefecture, Japan. Image by Chi King, 2006.

https://commons.wikimedia.org/wiki/File:The_Art_of_Preserving_One%27s_Own_Culture_and_Heritage_XI_(KYOTO-JAPAN-ISE_JINGU-ISE_SHRINE)_(845279379).jpg

Figure 5: Front and Side View of the Honden at the Ise Shrine. Image by Katsukichi Hattori, History of the Japanese Architecture, 1933.

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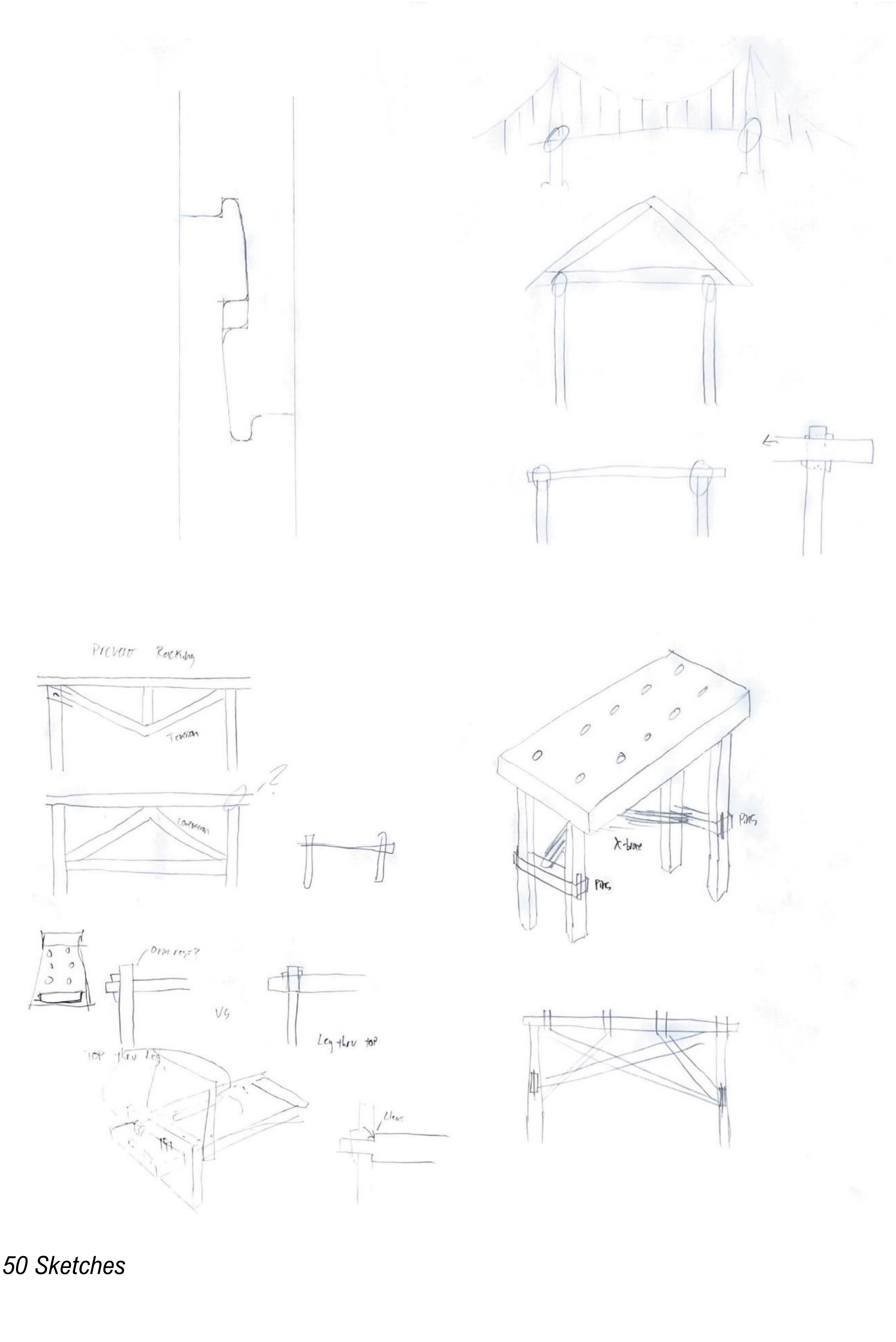
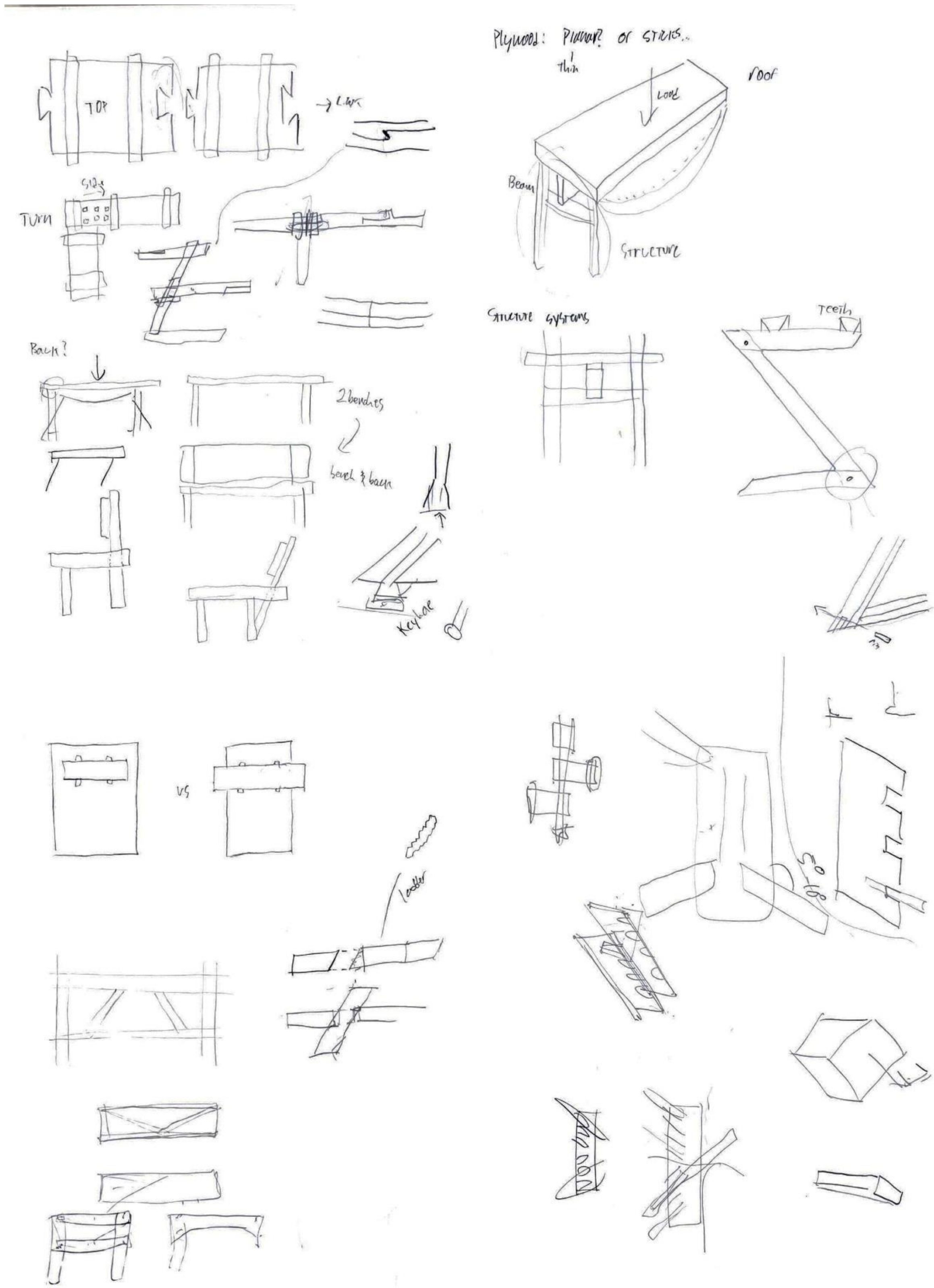
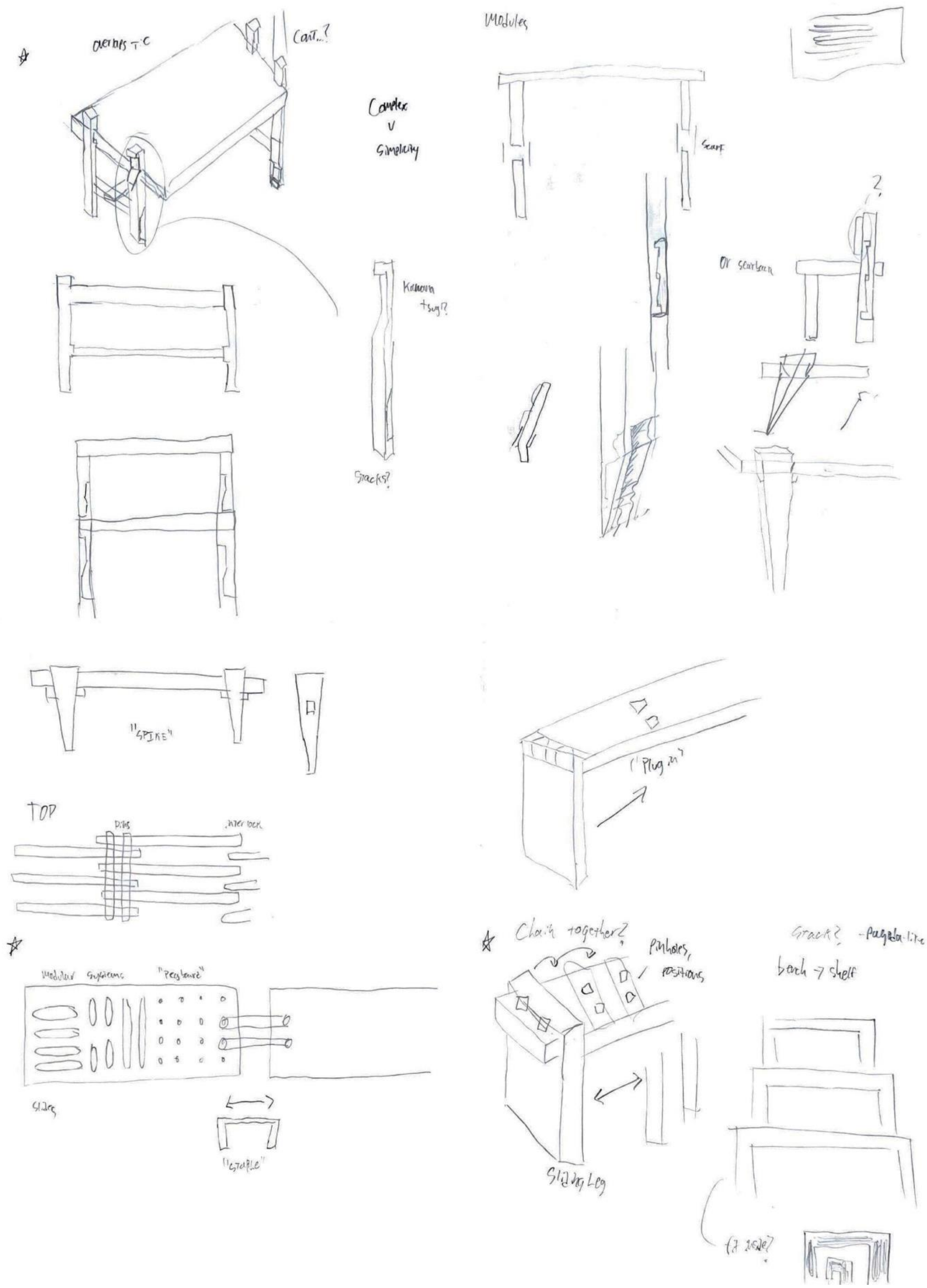
Image Index



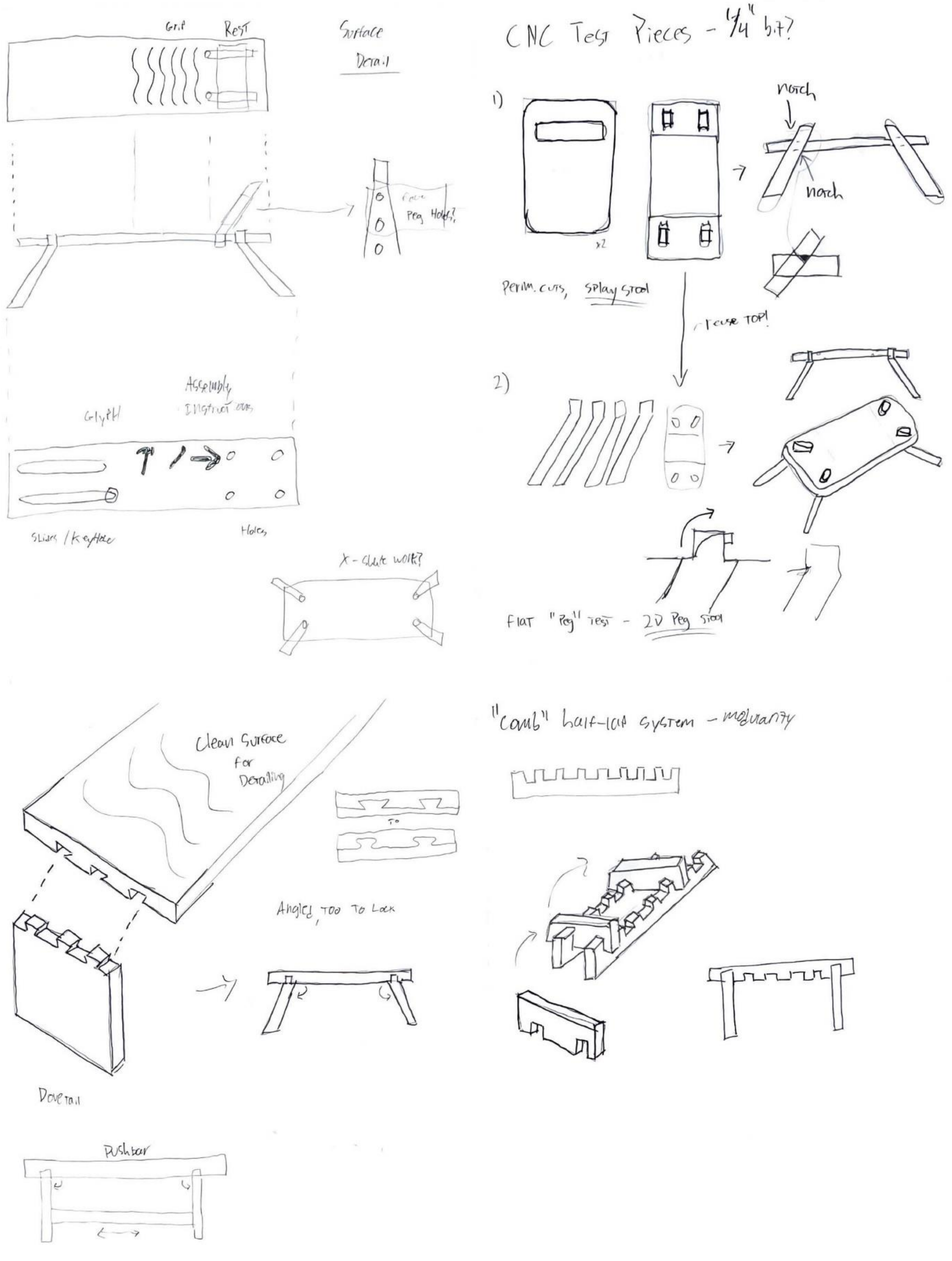
50 Sketches


TOP
Plywood: Planar? or Sticks..
thin
roof
Load
Beam
Structure
Turn
Back?
2 benches
Structure systems
Teeth
vs
ladder

50 Sketches

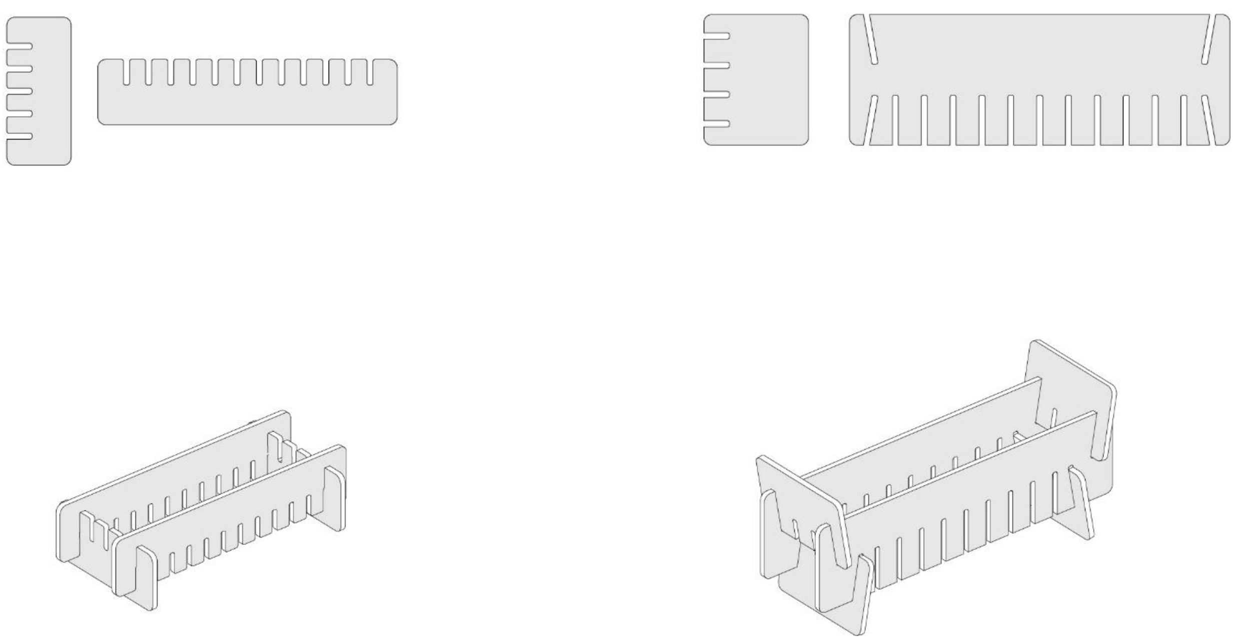

Complex
v
Simplicity
Modules
Scarf
"SPIKE"
TOP
interlock
Modular Systems
"Pegboard"
"Staple"
"Plug in"
Chain together?
Pinholes, positions
bench → shelf
Sliding Leg

50 Sketches

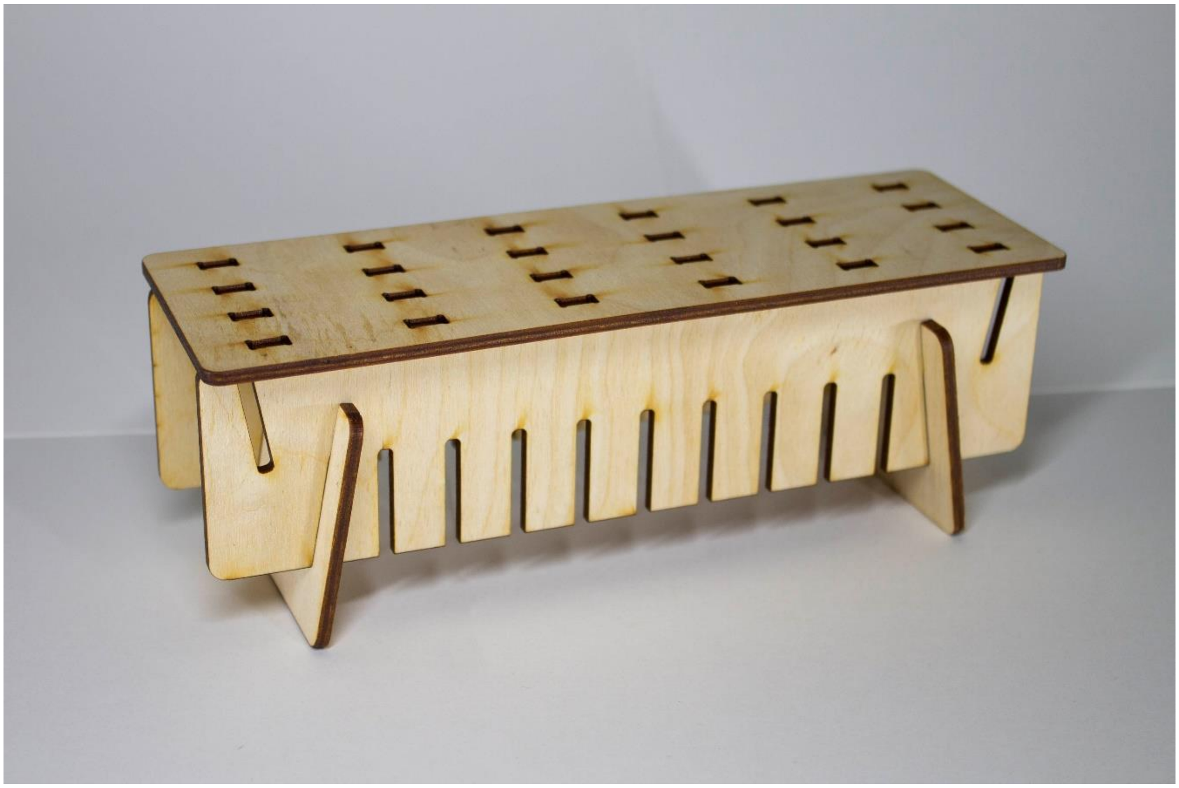

Grip
Rest
Surface Detail
Peg Holes?
Assembly Instructions
Glyph
Slides / Keyhole
Holes
X - would work?
CNC Test Pieces - 1/4" bit?
1)
notch
notch
x2
Perim. cuts, Splay Stool
reuse top!
2)
Flat "Peg" test - 2D Peg Stool
Clean Surface for Detailing
to
Angled, too to Lock
Dovetail
Pushbar
"comb" half-lap system - modularity

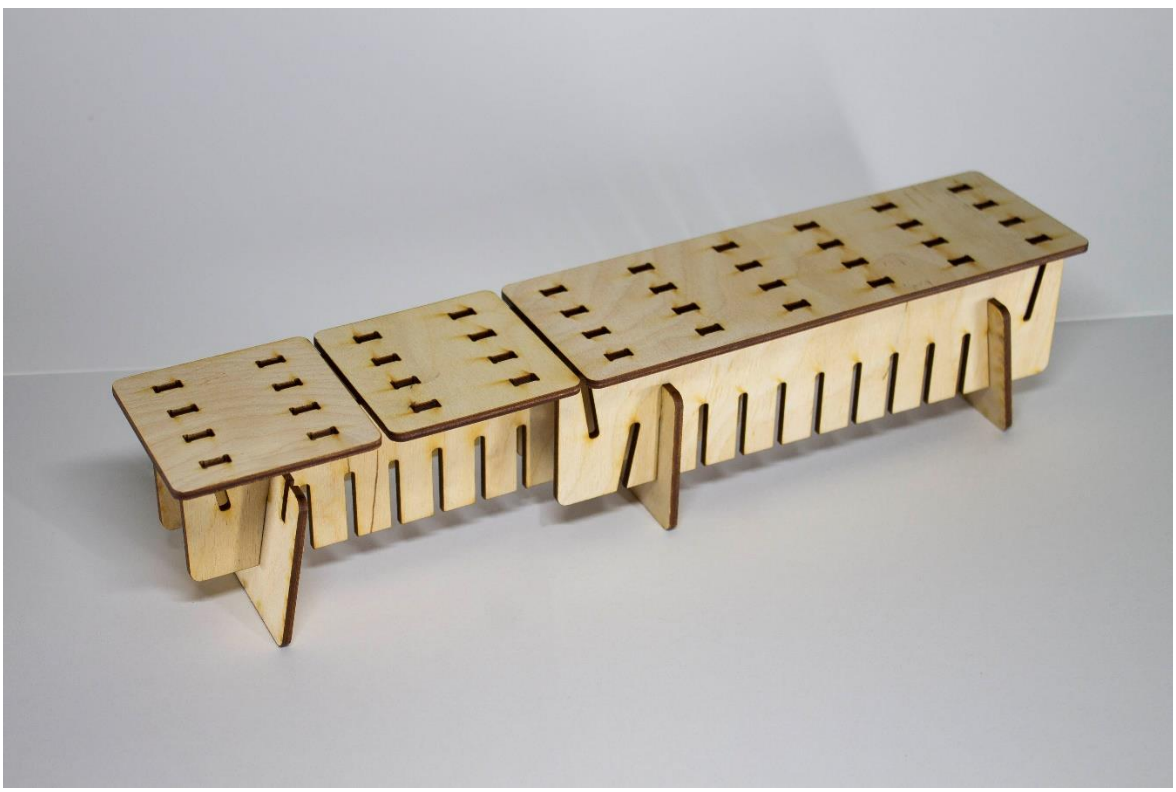
50 Sketches

Rotate-In Leg, Wrap-Around Frame study models

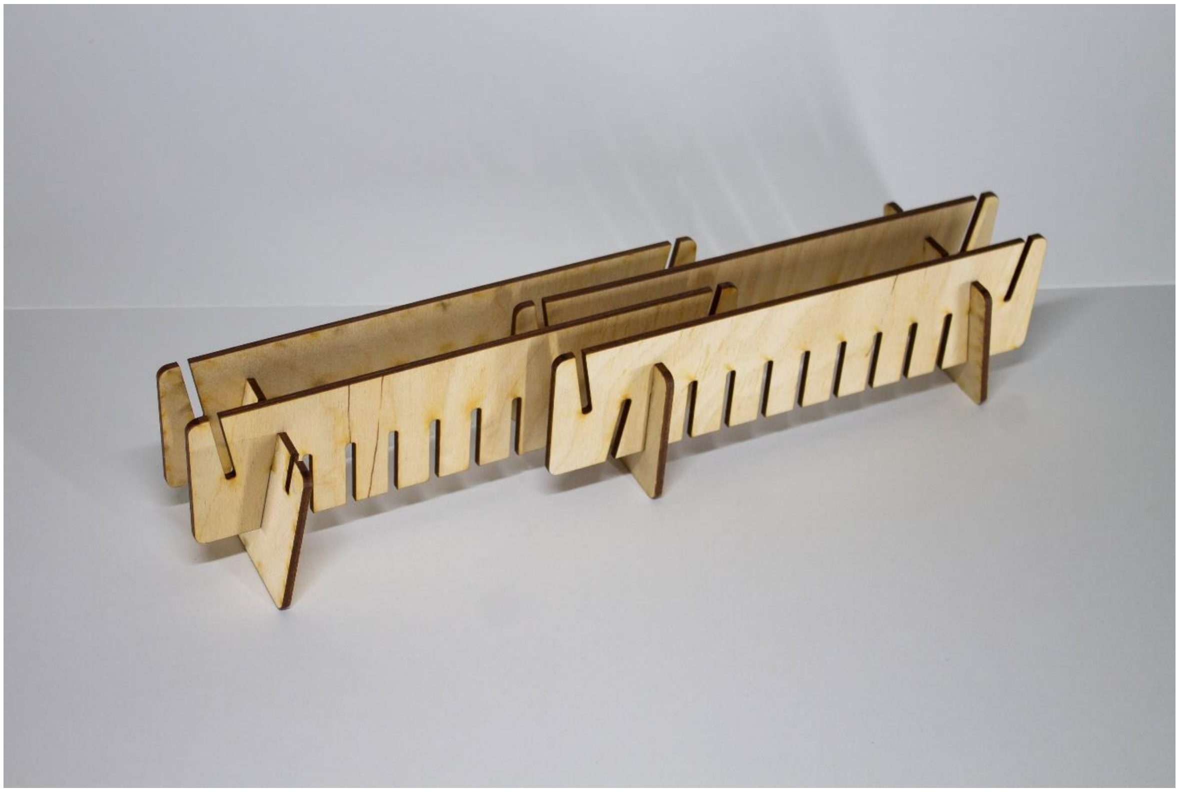


Comb Frame v1 & v2 CAD design diagrams

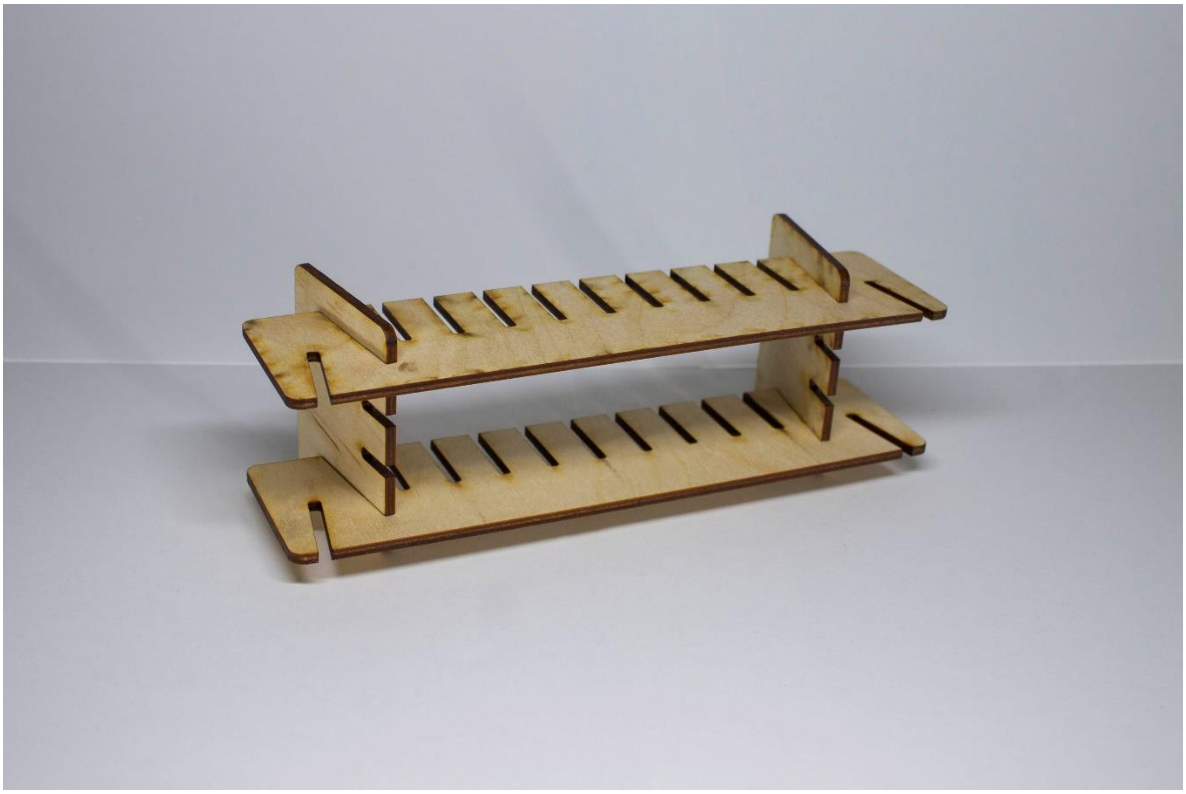


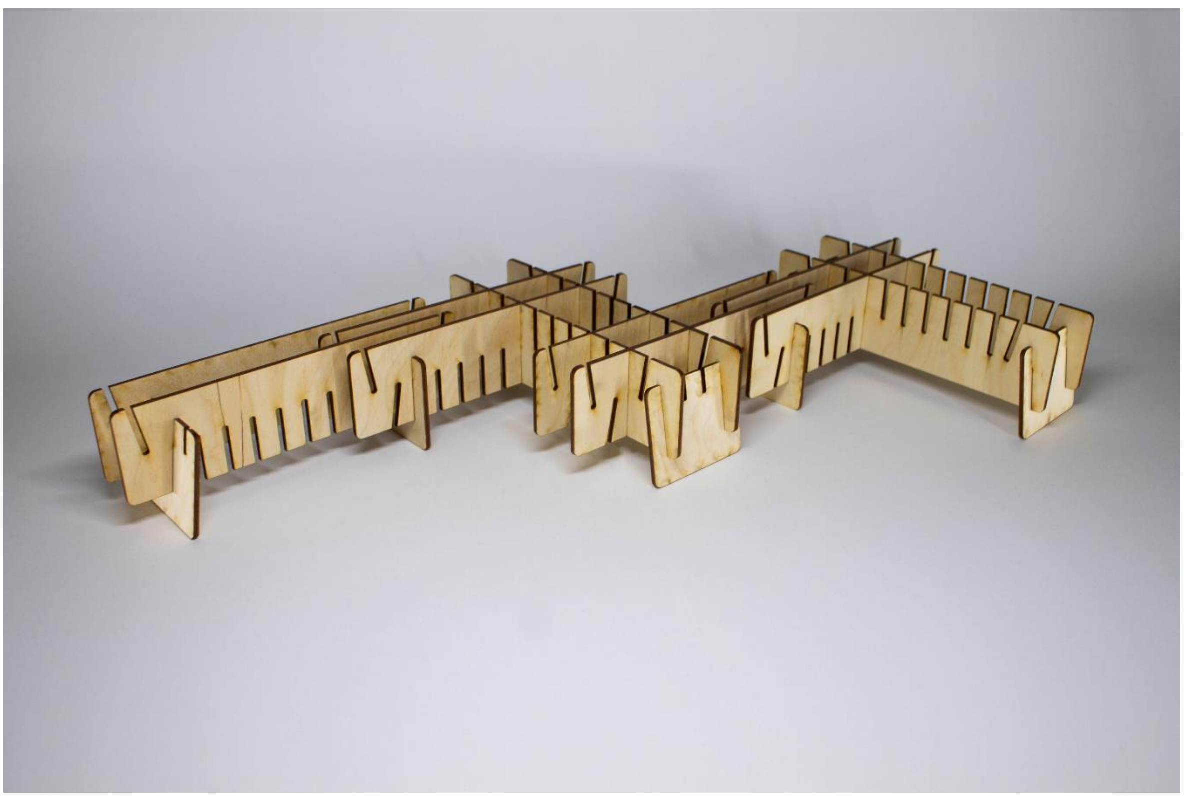


Comb Frame v2 study models

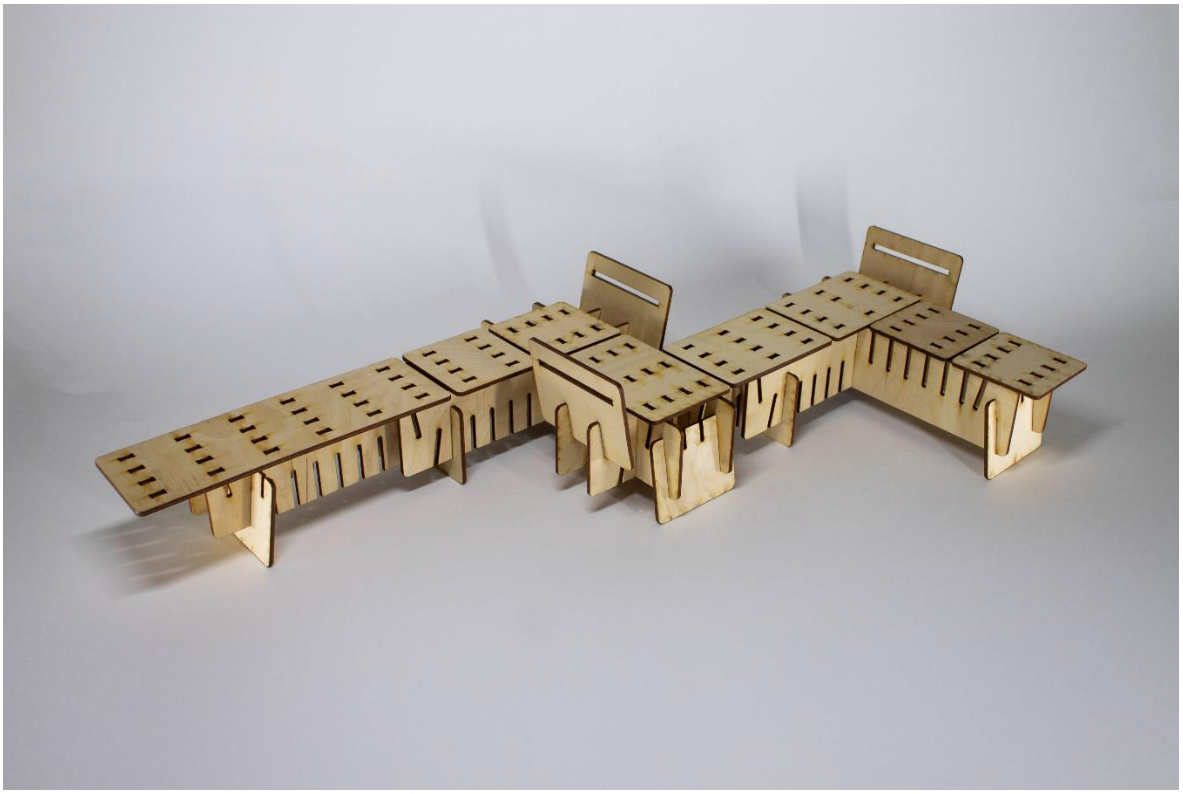


Comb Frame v2 study models





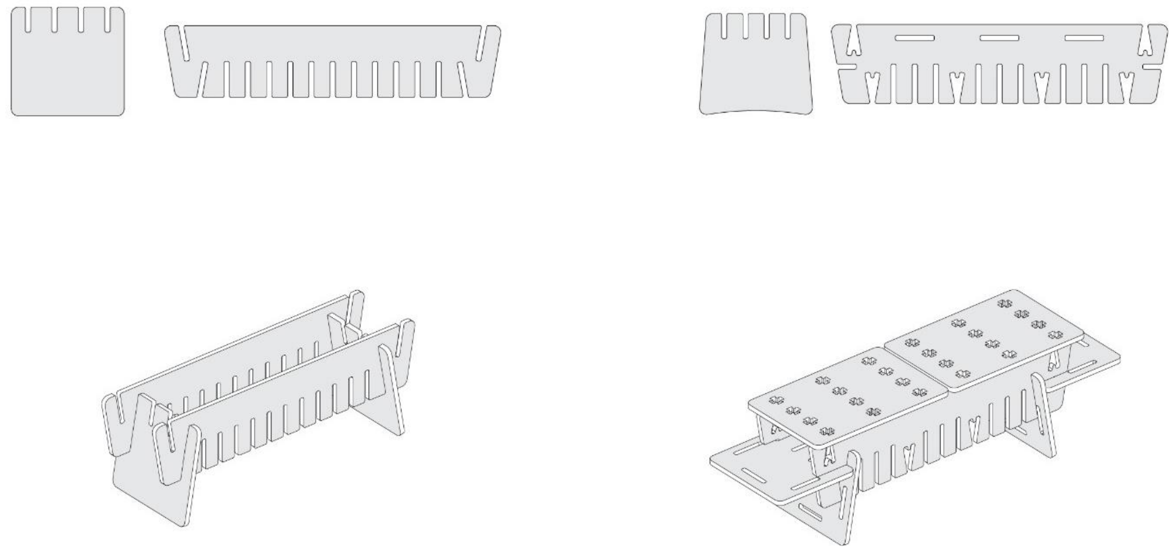
Comb Frame v2 study models



Comb Frame v2 study models

Comb Frame v2 study models

Comb Frame v2 study models

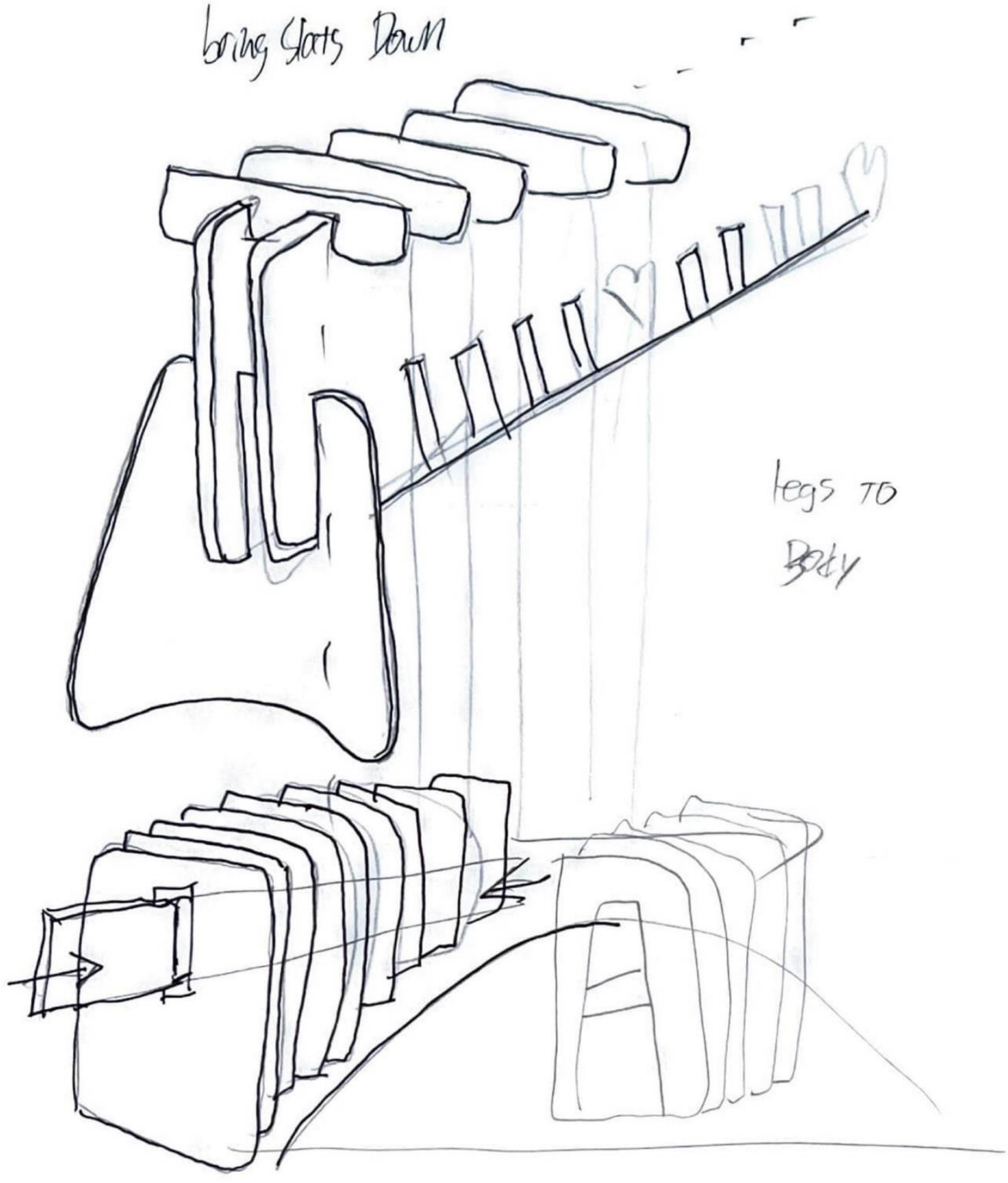


Comb Frame v3 & v4 CAD design diagrams

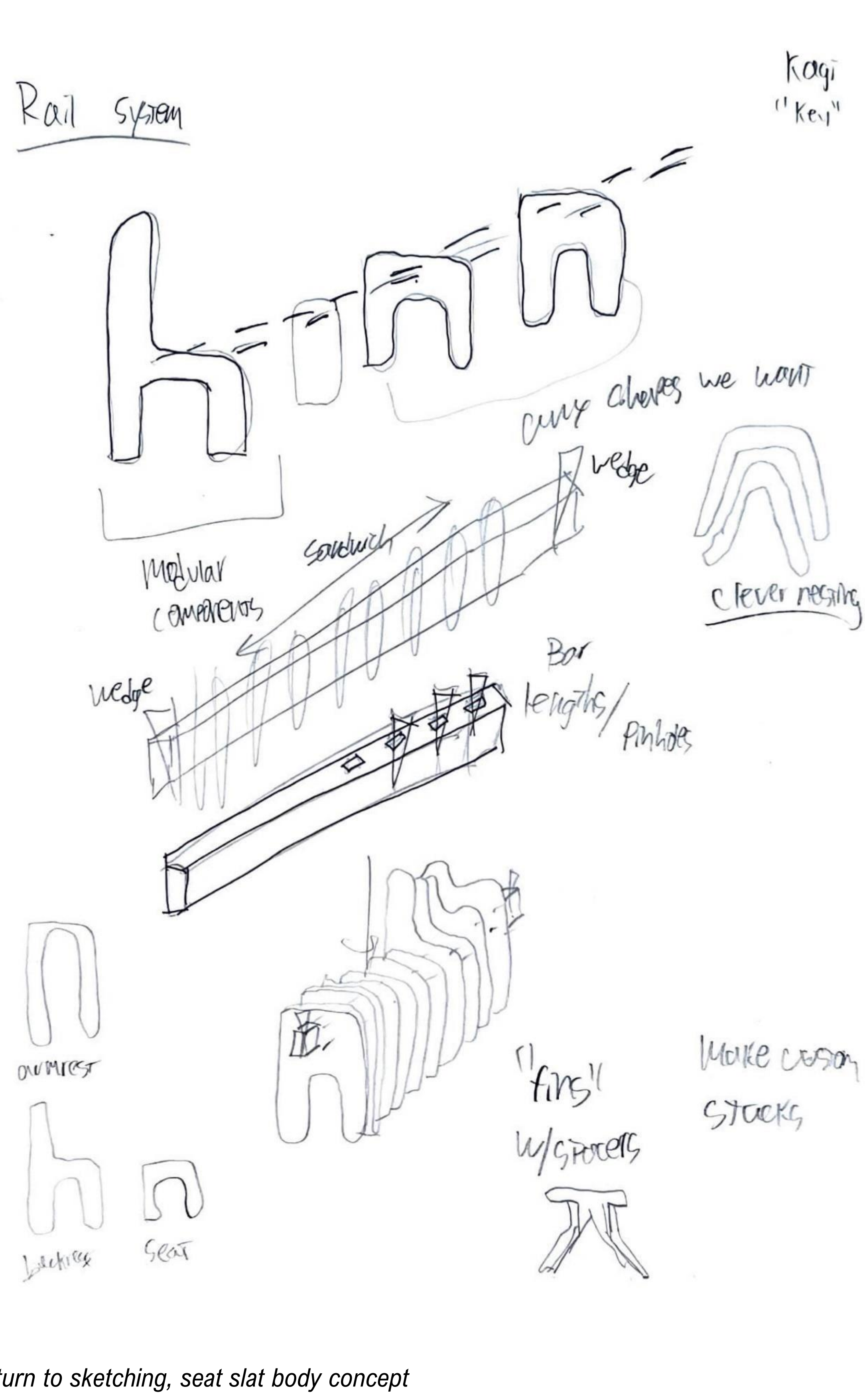
Comb Frame 4 study models

Comb Frame v4 study models

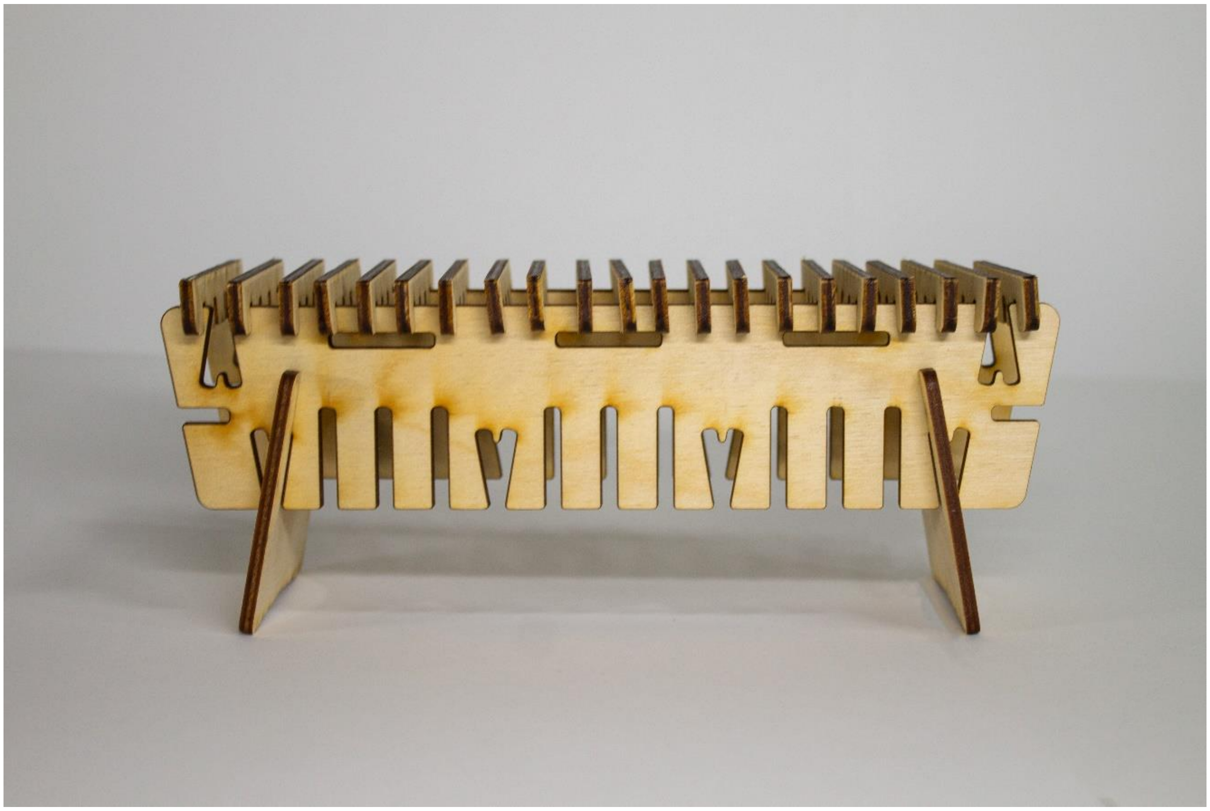
Comb Frame v4 study models



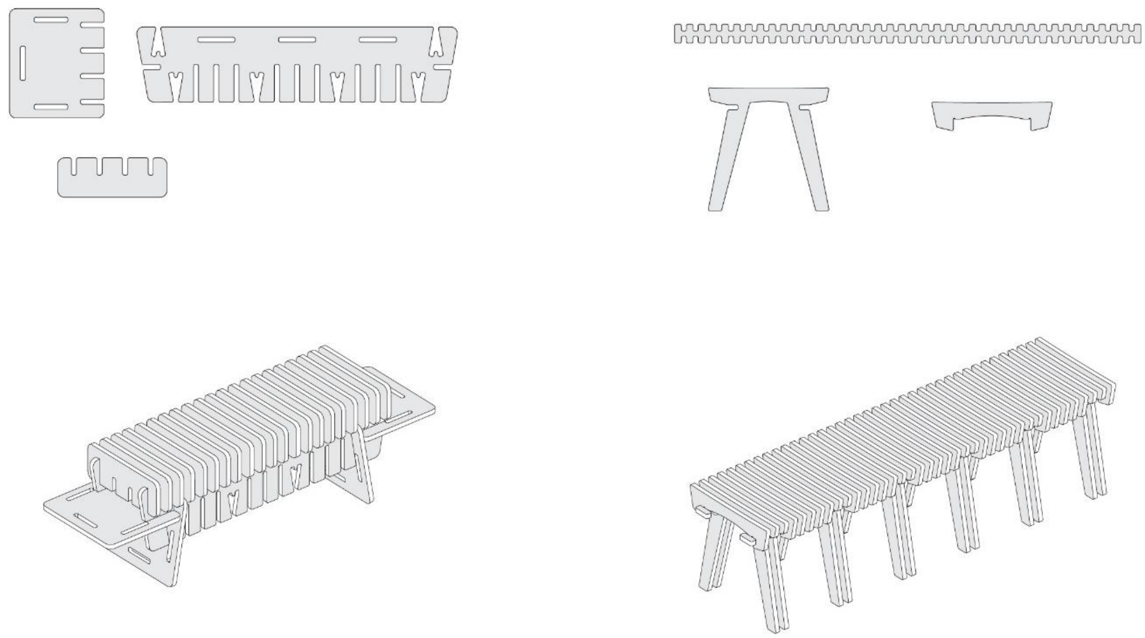
Return to sketching, seat slat drop down concept



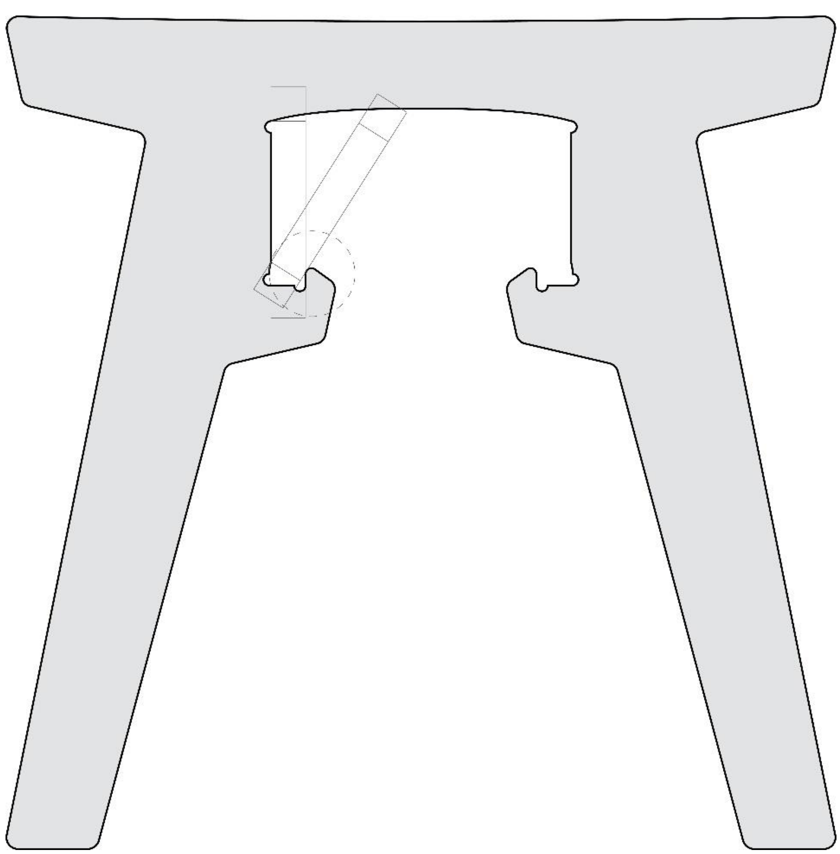
Return to sketching, seat slat body concept



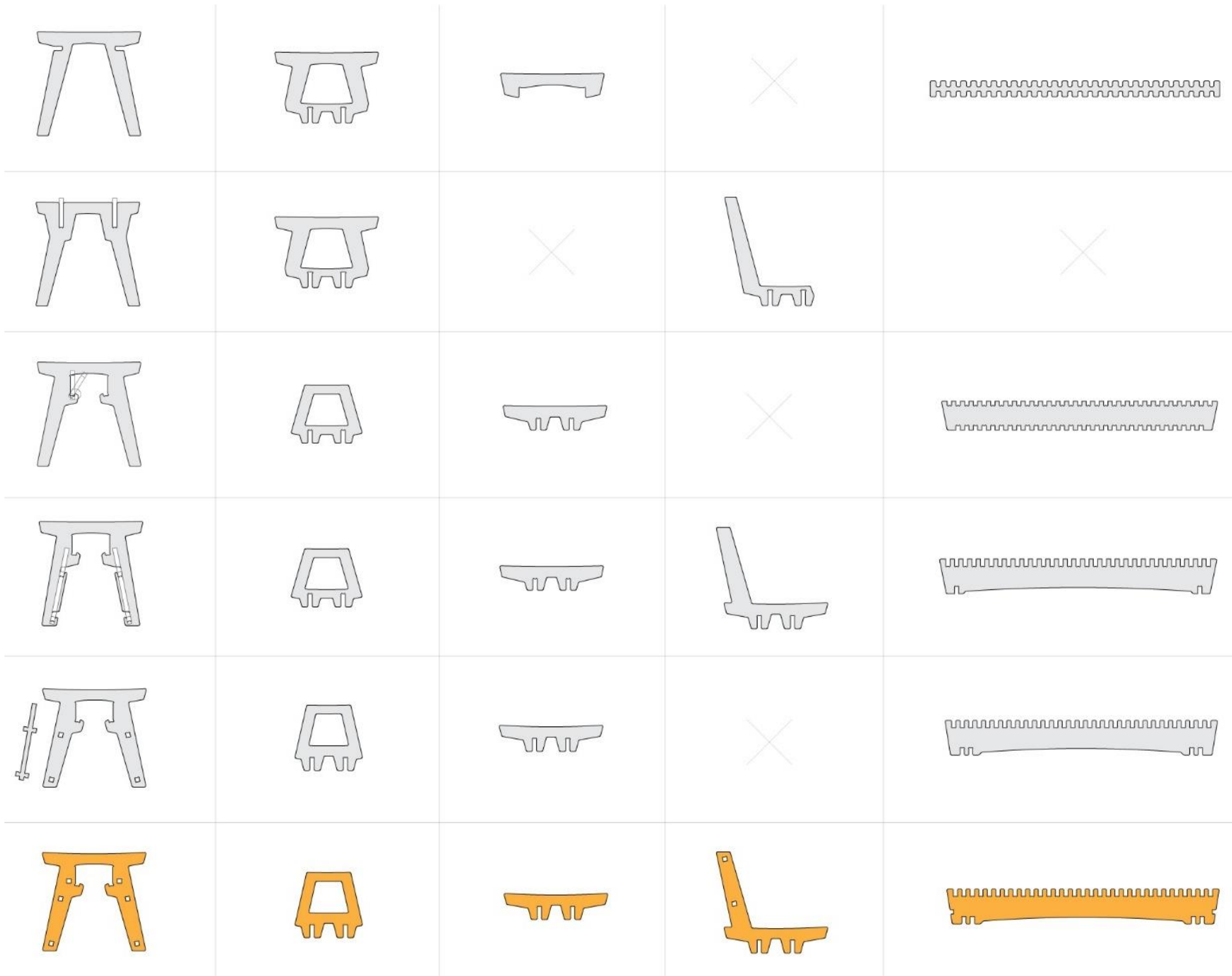
Comb frame v5 Study Model



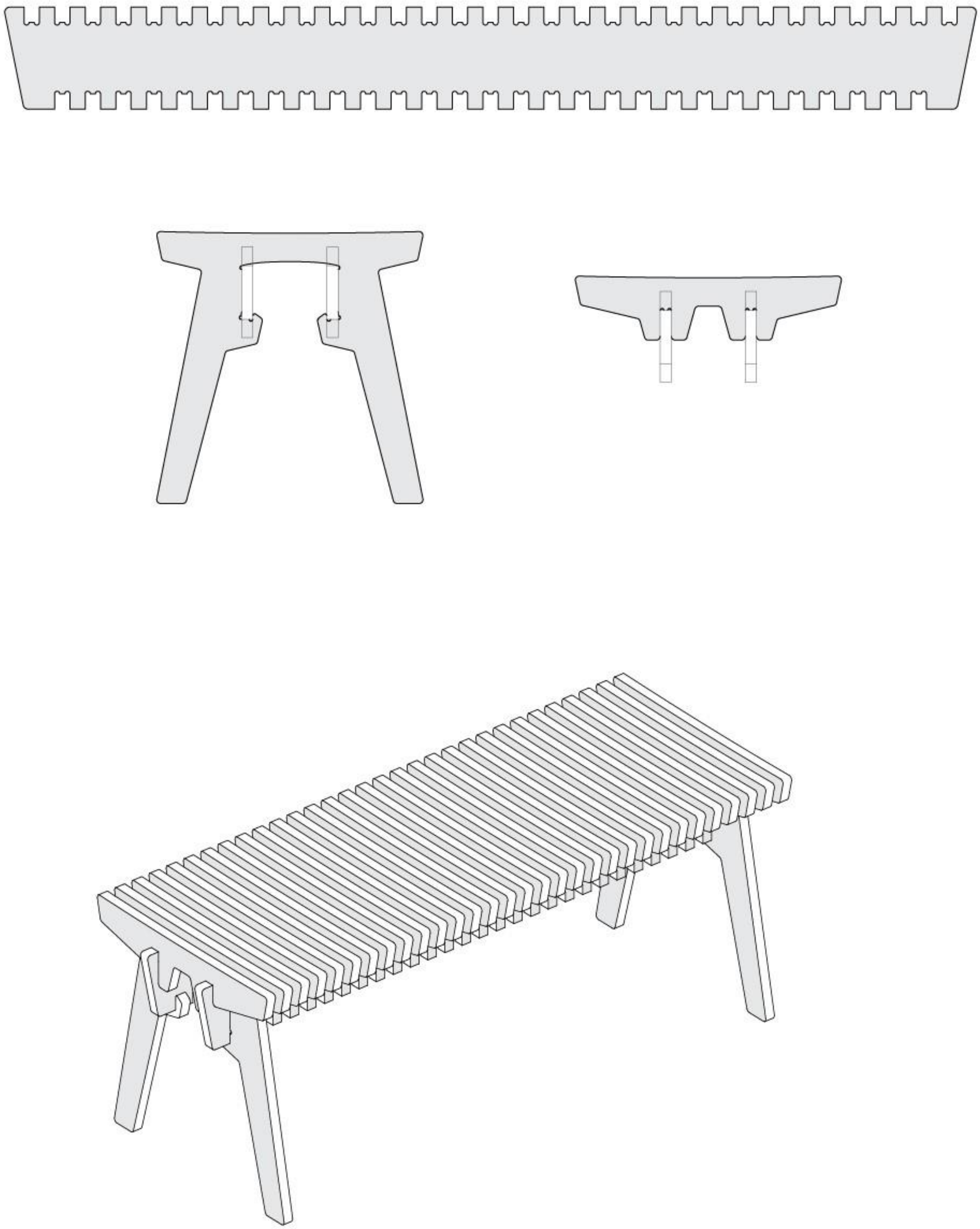
Comb Frame v5 & v6 CAD design diagrams



The Twist-Lock leg frame



Twist-Lock design development diagrams, iteration grid

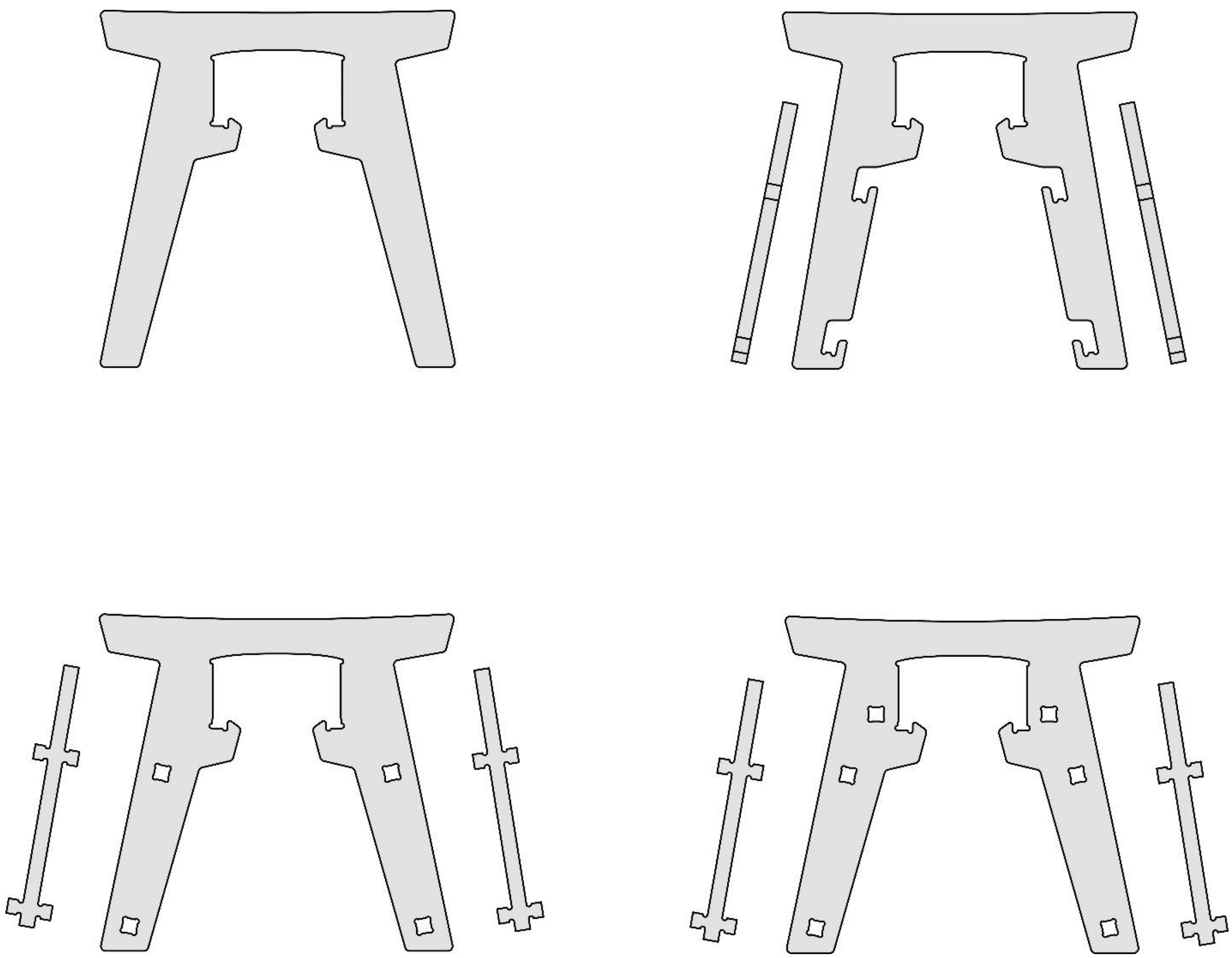


The Twist-Lock bench system, version 1 diagrams

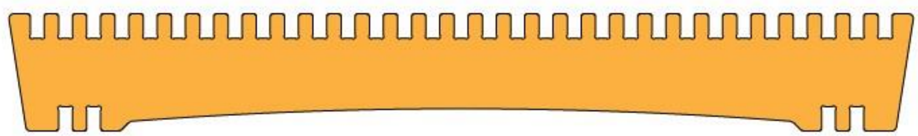
The Twist-Lock bench system study model

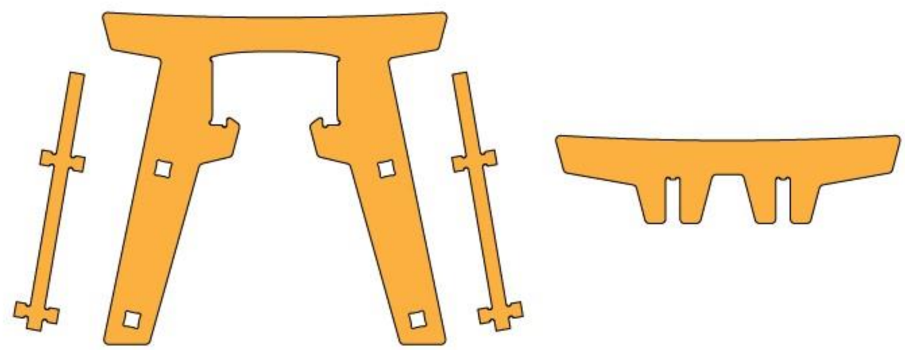
The Twist-Lock bench system study model with modules

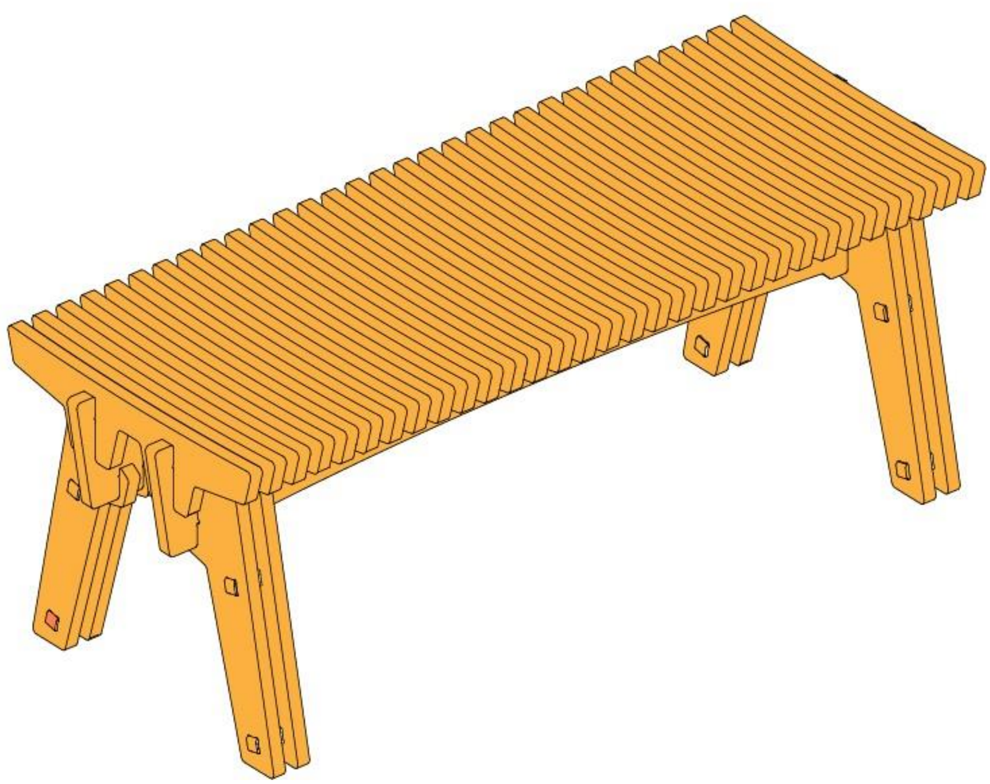
The Twist-lock bench system Study Model



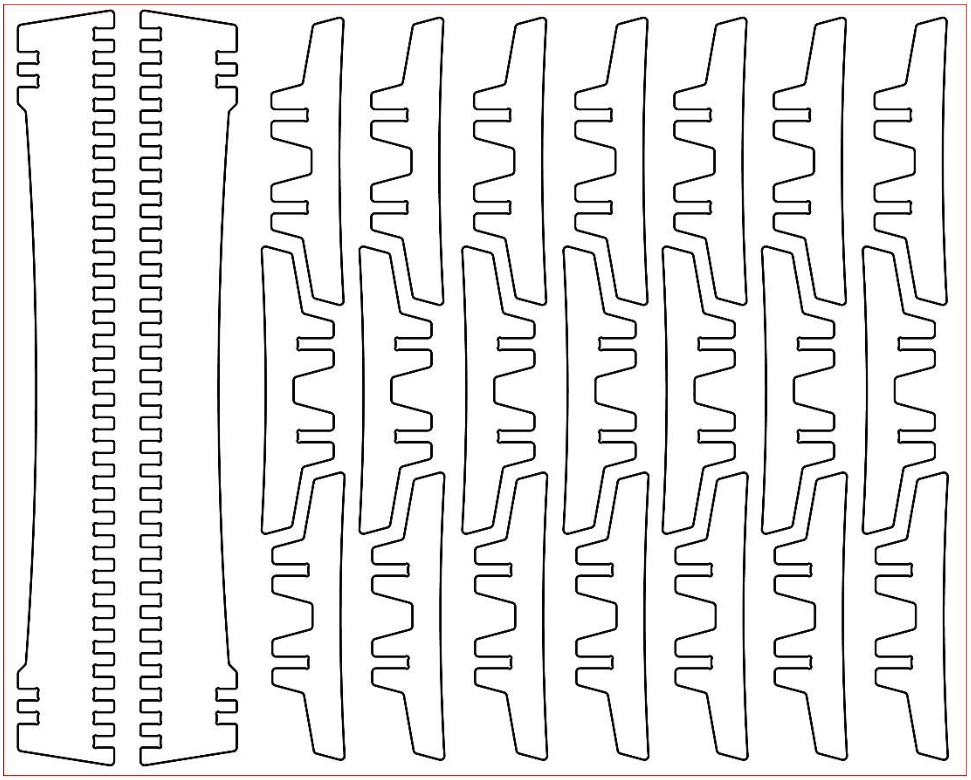
Twist-lock bench system leg brace development

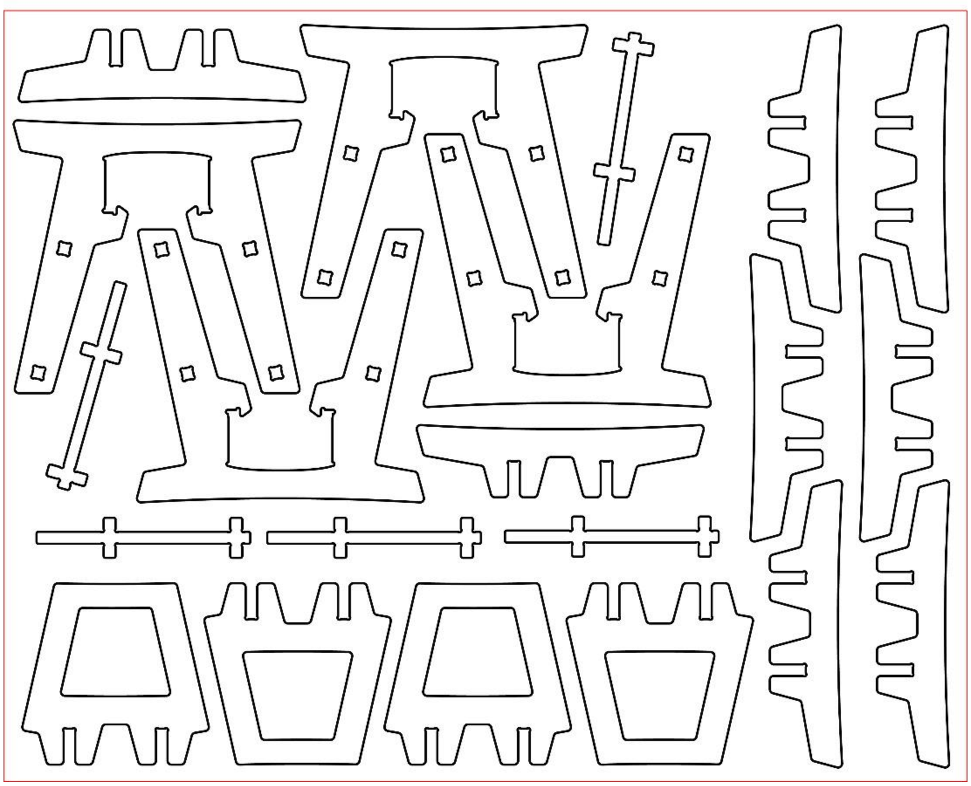




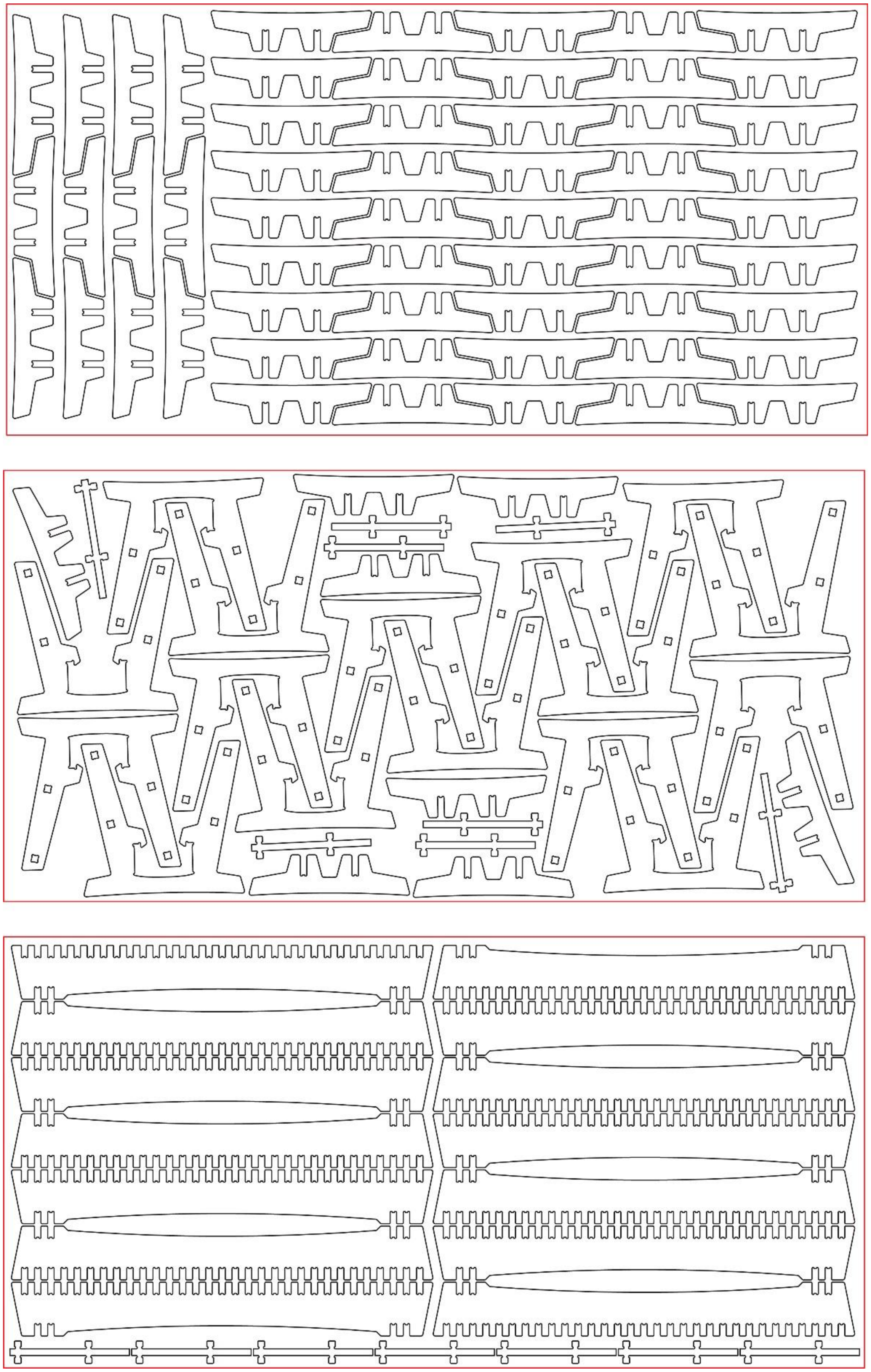


The Twist-Lock bench system, fully realized.

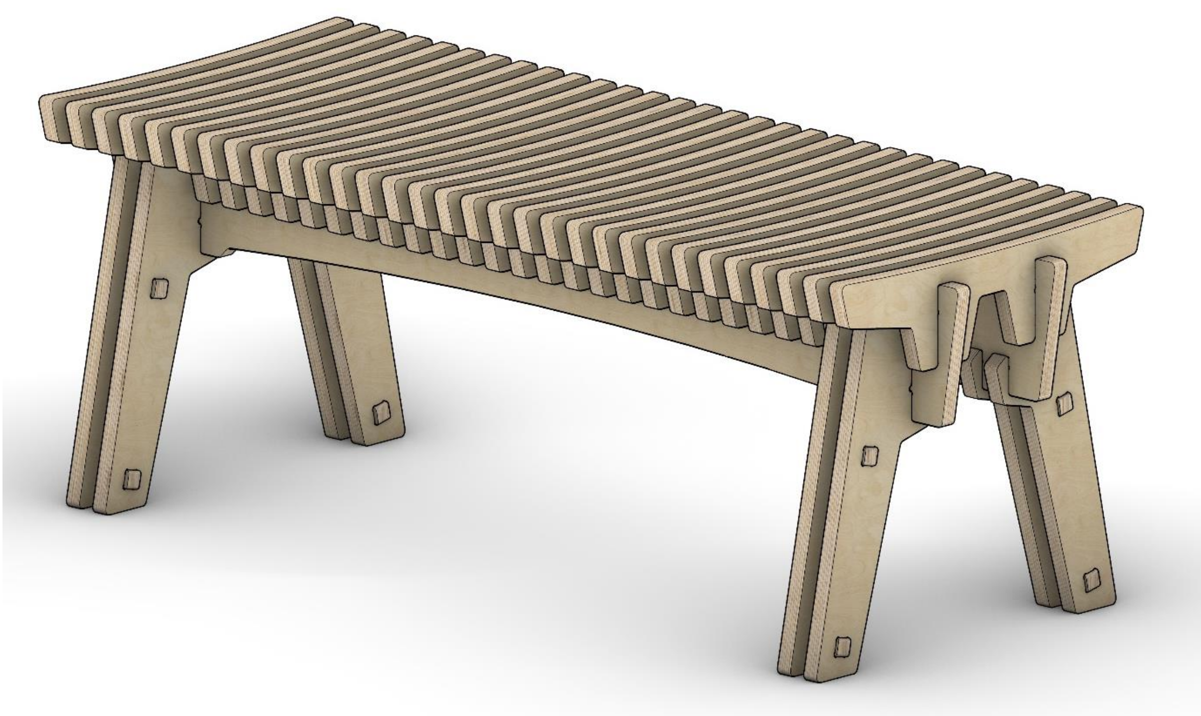




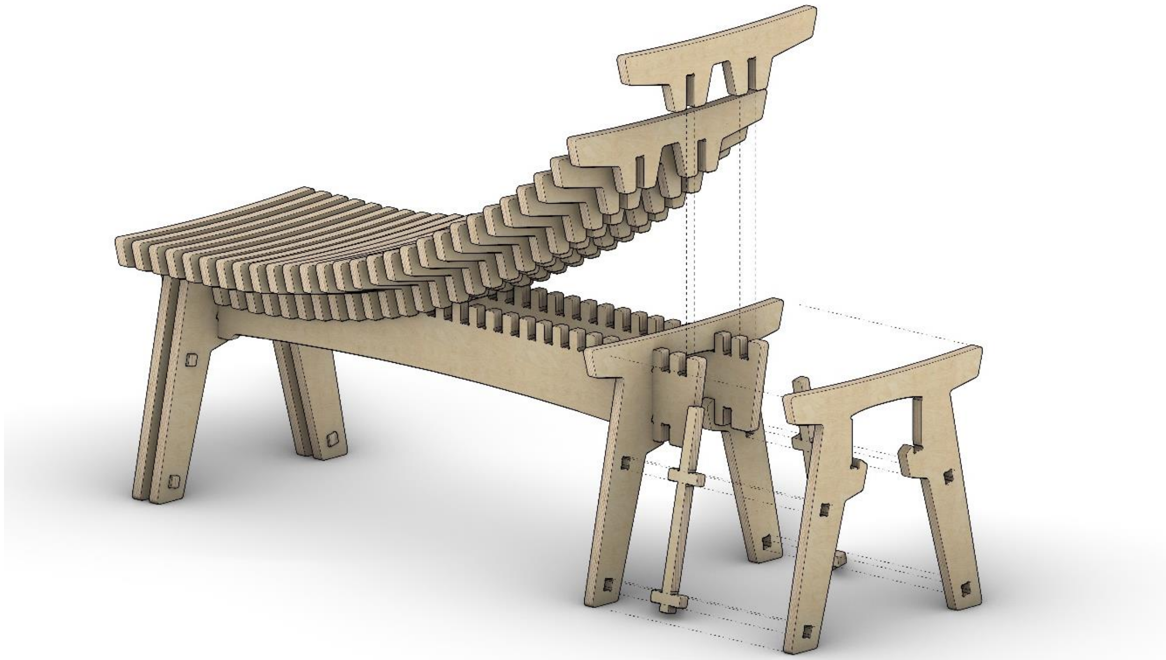
Plywood layouts for my CNC production.

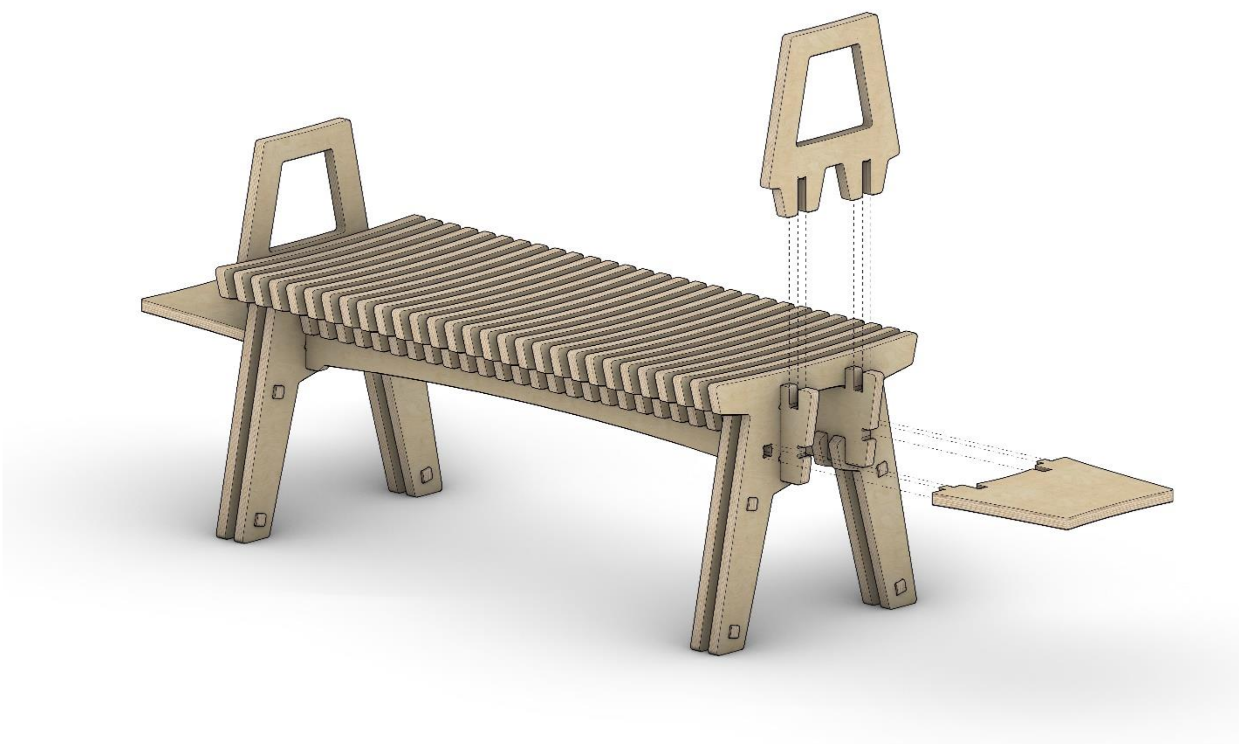


Plywood layouts for CNC mass production.



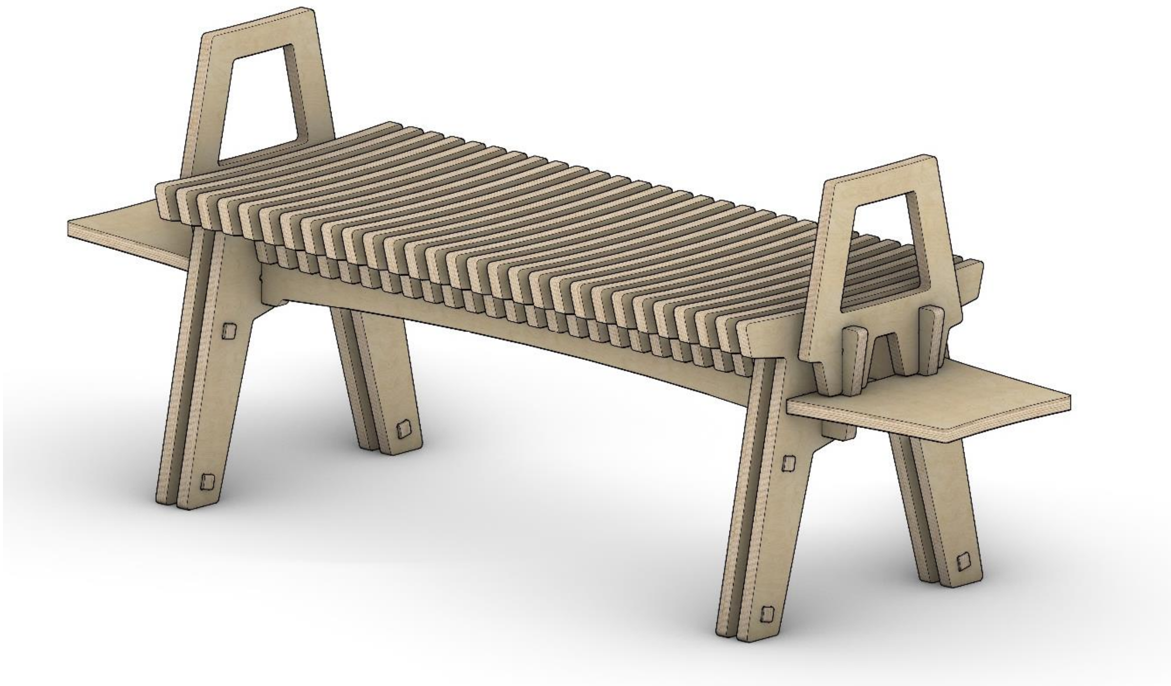
Presentation renderings

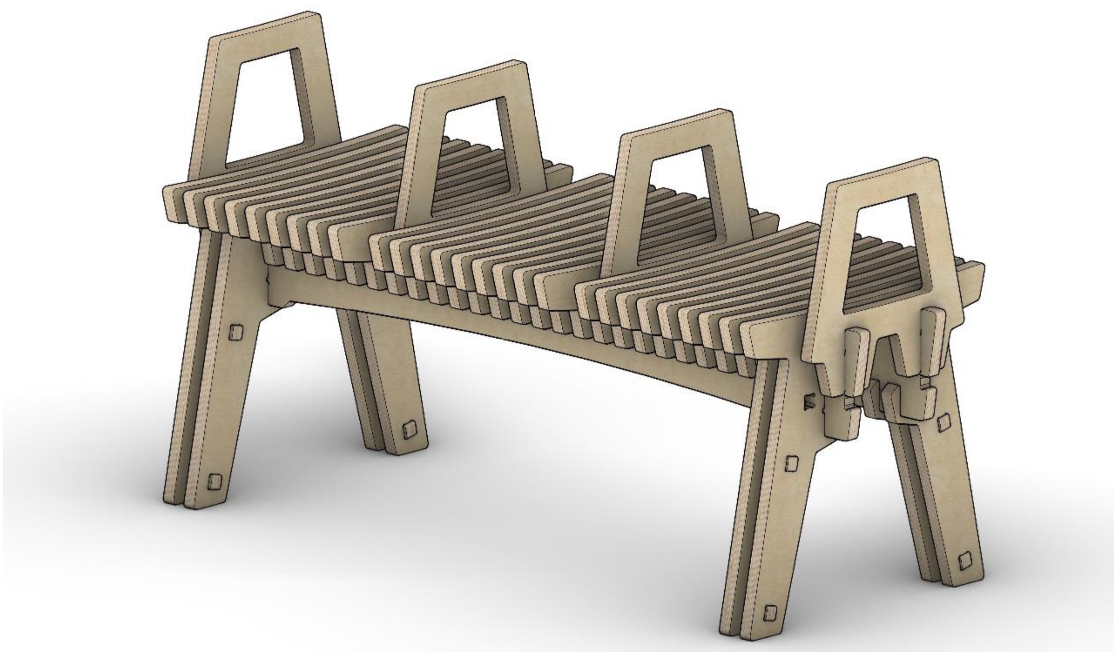




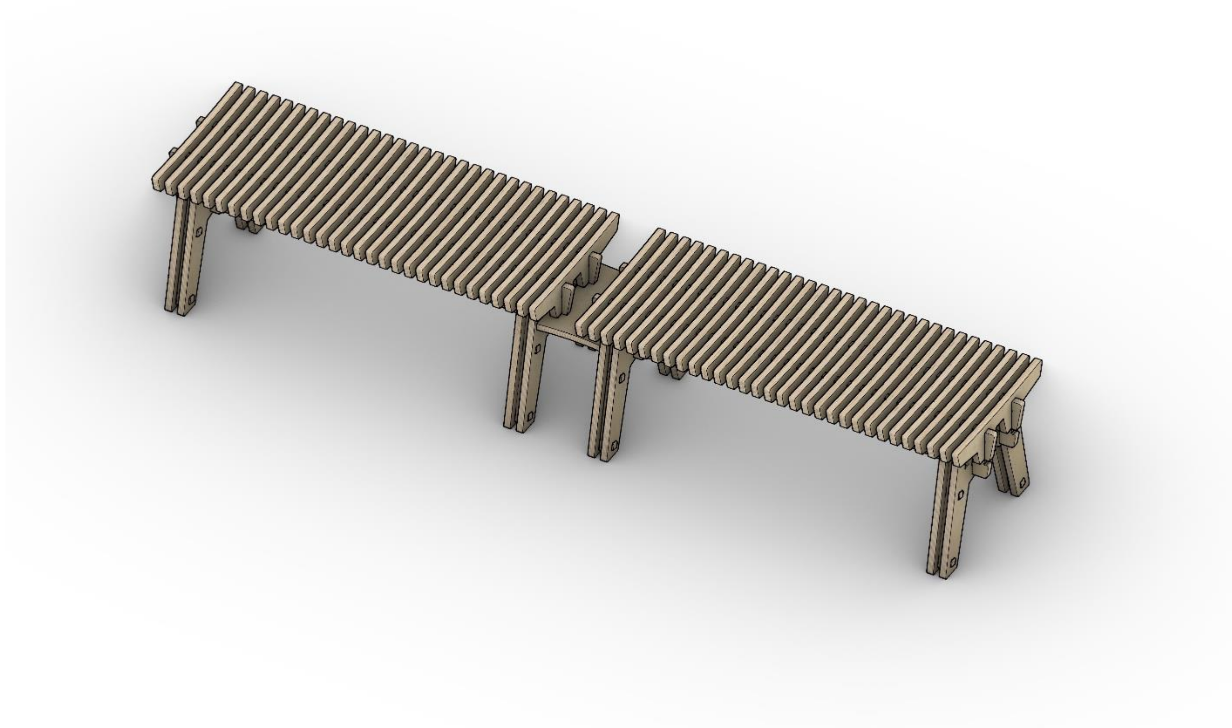
Exploded presentation renderings

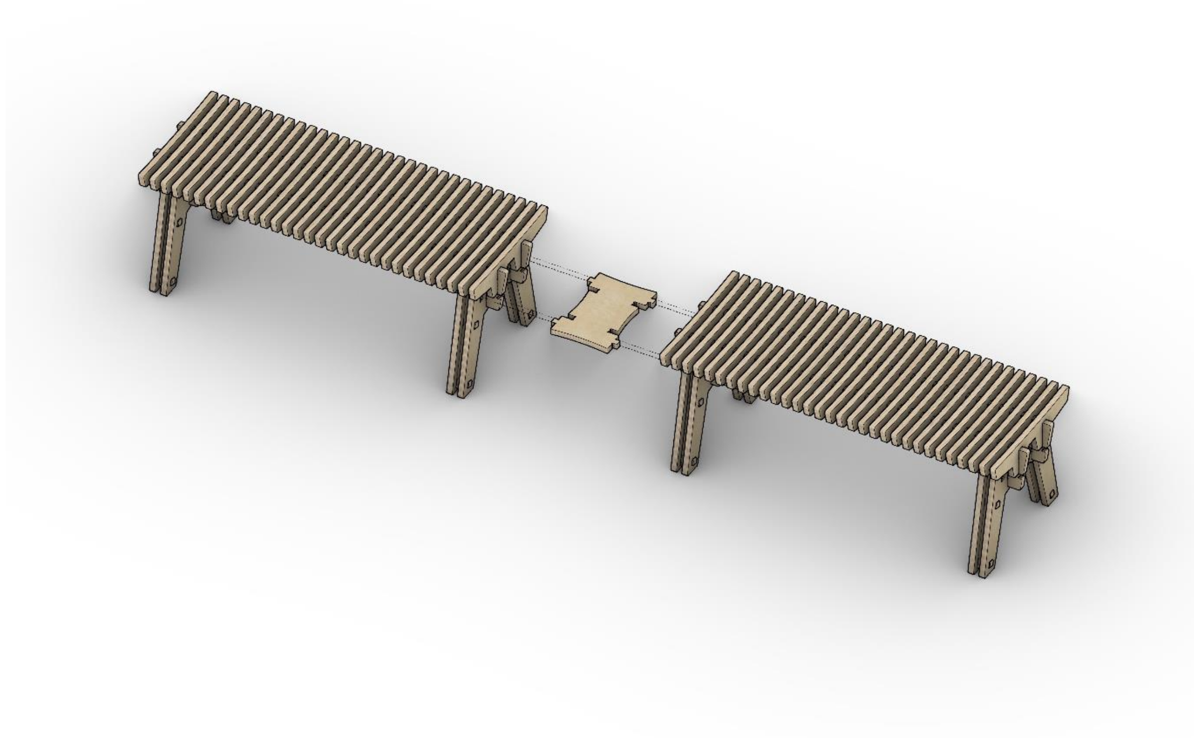
Presentation configuration renderings



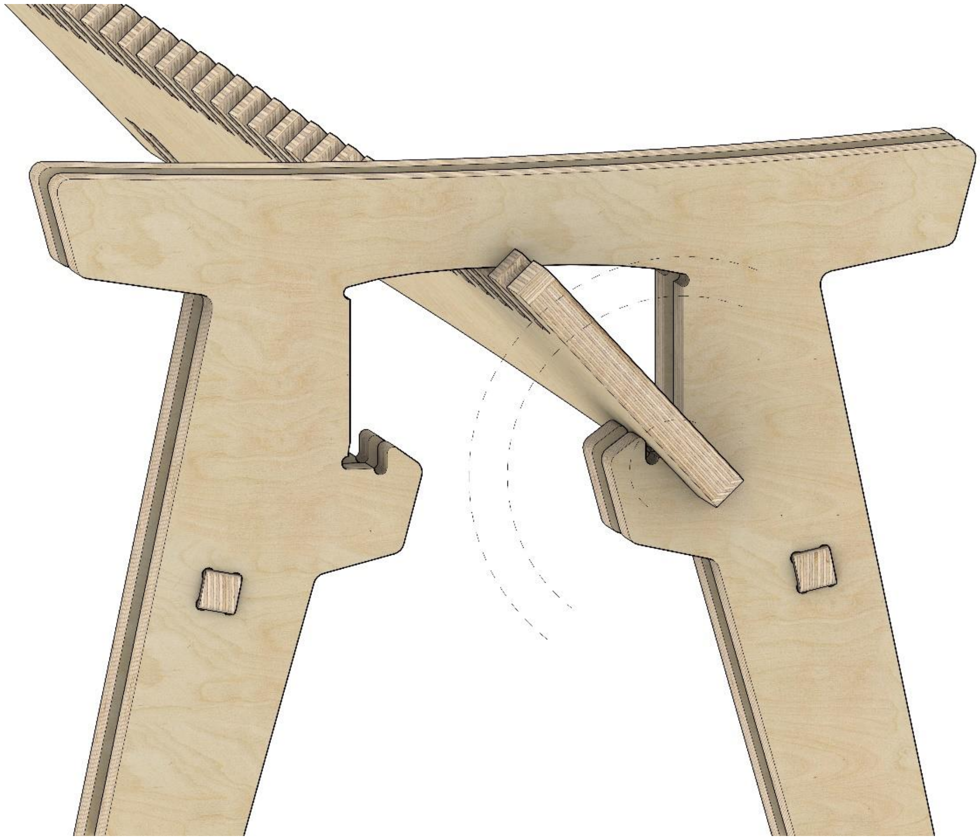


Presentation configuration renderings





Presentation connector component renderings



Presentation Twist-Lock detail rendering

Completed bench

Completed bench

Completed bench

Completed bench