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Master Thesis

Guidelines for Designing and Producing Joinery with a Five-axis Water Jet Cutter

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2. **Abstract**

This consolidation thesis speaks about a period spent helping operate a five-axis water jet cutter. In an effort to test the limits and benefits of the water jet cutter in a certain productive direction, the aid of an experienced furniture designer was enlisted. A set of joinery designs were designed and prepared for cutting to display how this machine can deserve its place in the world of end-product furniture manufacturing and be of great benefit to the discipline of joinery that exists in the majority of the things assembled around us.

The world of joinery is vast. Behind it stands centuries of experimentation, cultural integration, material sciences, data collection, and life cycle observation. Researching joinery would lead us to believe that it is heavily invested in wood and carpentry. After having spent an internship in researching, understanding, and operating a high pressure five-axis water jet cutter, I was convinced that the water jet cutter would be an ideal tool to create joinery out of far stronger and more diverse materials than wood.

Direct and simple material joinery can mean that complex assemblies would require less parts to be created, less knowledge to be assembled, and less time to become a product ready for use. We are living in a fast growing world with a constant eye out for sustainability. In this scenario, less parts and less tools could surely mean a step in the right direction.

Based on my fondness of design, manufacturing, my last two academic years in this program and my hours of research and internship in the field, I have chosen to work on a set of guidelines that aim to demonstrate the experiments that took place and to solidify further the methods of designing, manufacturing via water jet, and assembling different types of joinery to prove its flexibility and ability to traverse materials and manufacturing methods, in this case, using the water jet cutter.

This thesis report will cover a brief history of joinery, manufacturing and water jet cutting along with the case studies that were documented after a series of in-house tests. This would demonstrate findings and result in a helpful guide that would aid aspiring designers and manufacturers broaden their sense of what is possible and what is required to produce joinery using a five-axis water jet cutter.

3. **Abstract** (In Italiano)

Lo sviluppo di questa tesi nasce dall'esperienza formativa di tirocinio, caratterizzata e focalizzata sull'utilizzo e lo studio del funzionamento di una macchina per taglio ad acqua a cinque assi. Nel tentativo di testare limiti e vantaggi di tale dispositivo, all'interno di specifiche direzioni produttive, è stata introdotta la figura esterna di un designer, esperto nel settore dell'arredamento e del design di mobili. Al fine di dimostrare come tale macchina possa introdursi nel mercato del furniture design e acquisire un ruolo di beneficio per la disciplina della falegnameria, è stato necessario sviluppare una serie di progetti specifici, con l'obiettivo di dare spazio e risalto a questa tecnologia.

Il mondo della falegnameria è vasto: secoli di sperimentazione, integrazione culturale, studio e analisi dei materiali, nonché di raccolta dati e di osservazione delle varie tipologie di artefatti intorno a noi, hanno indubbiamente portato alla concezione del mondo della falegnameria come principalmente orientato all'utilizzo del legno nelle sue più svariate forme e nature, come risposta al contesto della carpenteria.

È proprio durante il periodo di tirocinio trascorso, orientato alla ricerca, alla comprensione e all'utilizzo di una macchina per taglio ad acqua a cinque assi ad alta pressione, che è nata l'idea di introdurre tale dispositivo come supporto per lo sviluppo di componentistiche nel mondo della falegnameria. L'obiettivo prevede lo sviluppo di un'alternativa utile e innovativa nel mondo della carpenteria, introducendo l'utilizzo di materiali diversi e maggiormente resistenti rispetto al legno.

La progettazione di connessioni semplici e dirette nel mondo della falegnameria rappresentano un'ottimizzazione delle soluzioni progettuali: minore è il numero di parti da realizzare, e dunque da assemblare, più rapido risulterà il processo per raggiungere un prodotto pronto per l'uso. Viviamo in un mondo in rapida crescita, con un occhio sempre attento alla sostenibilità: in questo scenario, meno componenti e meno strumenti potrebbero sicuramente rappresentare un passo cruciale nell'ottimizzazione di tale realtà produttiva.

Partendo dall'ambito del design che più mi appassiona, la produzione industriale, i due anni accademici di studio in questo programma e le ore di ricerca e stage sul campo mi hanno portato a sviluppare una serie di linee guida che puntino a dimostrare la flessibilità e le capacità di tale tecnologia produttiva come supporto al mondo della falegnameria, tramite lo sviluppo di connessioni fisiche, con materiali diversi rispetto al legno. In questo contesto, gli esperimenti che ho avuto occasione di condurre durante il tirocinio sono stati fondamentali per consolidare ulteriormente la mia conoscenza nell'ambito dei metodi di progettazione, produzione e assemblaggio di diverse tipologie di artefatti.

Partendo da un'introduzione al mondo della falegnameria, della produzione e del taglio tramite getto d'acqua, con una documentazione specifica di casi studio sviluppati all'interno del contesto di tirocinio, la tesi ha come obiettivo finale lo sviluppo di linee guida per aspiranti designer e progettisti, che permettano di ampliare le conoscenze nel contesto industriale, orientando all'utilizzo di una macchina per il taglio tramite getto d'acqua a 5 assi come supporto al mondo della falegnameria.

4. **Introduction and Background**

To be able to express the work I am doing today, I will briefly express a line of events that occurred that shaped the person I am today and positioned me in a manner that suits this particular study that has become part of my life for the past year.

I was introduced to manufacturing in a very moderate way by my father. In my home country, Lebanon, my father traded in building materials and I found great adventure in accompanying him to work at a very early age. I saw how excavators remove gigantic pieces of a mountain and crush it between teeth of steel and vibrations to retrieve gravel. The images shone in my mind as I grew older and I kept an eye out for anything around me that I did not understand. I made it my goal to understand how things are made and later on I started researching how different things are mass produced and I discovered a passion for learning more about manufacturing.

After having completed five years of academia in architecture and design school, I attained a bachelor's degree in architecture. Over the two years that followed, I had the chance to work with two architecture firms that also designed and manufactured furniture for their projects, with the second office being run by a creative and ambitious architect and product designer, specifically additive and subtractive methods involved in furniture creation. His love for furniture design and manufacturing spread to many that worked under his supervision and thus, I found myself greatly interested in joining his path.

After having been exposed slightly to the world of modern-day manufacturing, I applied for the master's degree of design and engineering in early 2020. After having completed my course work in the master's degree program, I sought an internship in the Mechanical Engineering Department Laboratory where I was to help operate the five-axis water jet cutter along side an experienced technician.

After expressing my fondness for furniture design to my internship advisor, at the time, along with my previously acquired knowledge and experience with my past firms, it was found plausible to establish a line of contact between the lab and my previous employer who eagerly agreed to send over certain joinery designs that we could use to test the abilities of the five-axis water jet to create joints using materials other than wood. Later, we shall discuss the reasoning behind these tests, the processes and the findings that came as a result that I documented afterwards.

Another thing I enjoy is the use of technology to bridge a gap between the three nodes of a product's existence, beauty, price and quality. We have a notion in our mind that the three nodes cannot be bridged easily in the sense that if something is of high quality and beauty, it cannot be but of a high price. However, we can alter materials, use different production techniques, and execute many more changes to realise an alteration of a product that exists or possibly even new products.

5. **Thesis Preview**

This theses, as I have chosen with the aid of my professor and supervisor, will document a process I have come to enjoy greatly and find great potential in; the creation of joinery, a sophisticated and delicate craft, one that exists all around us, by a water jet cutter, a machine that displays great power and accuracy in performing extremely precise tasks on a wide variety of materials thanks to its ability to cut while keeping itself and the material cool along with its ability to run for long intervals of time and cut extremely thick parts. All in an effort to prove the water jet's validity in this realm.

The first part of the report will examine the field of joinery. Its validity can be seen all around us. The more effort is put into designing joinery, the more efficient the manufacturing process and the better the quality of the resulting product. The skills required to perform joinery will also be covered as this is a guideline for the methods of manufacturing joints.

The second part of the report will handle the realm of the water jet with its respective history and a storyline of how and why it came to exist as well as its current state of being. We will see the advantages of this process along with the knowledge needed to perform it and of course the machines that make it happen.

The third part of the report will display the experiments that had been done to show the potential of integrating water jetting and the art of joinery along with the events that occurred to shape the experiment itself. We will see the results of an experimentative process that yielded data we used to calibrate better the machine every time for the cut that followed and for the joint that followed. We will show how the original design was made along with the software used to create it, we will then show how this design was manufactured and the problems we overcame as we understood how to learn and adjust for the future cuts.

Finally, we will sum-up with a conclusion on how joinery must be approached further on by the water jet cutter should we strive to make it better in an effort to create products of various materials that can be quickly manufactured and easily assembled in a few steps without the need for several parts and tools.

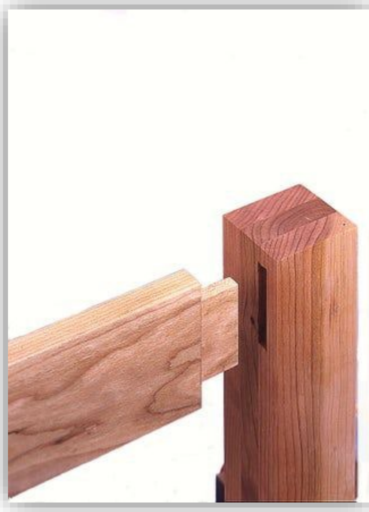
6. **Joinery**

In an effort to grasp this thesis properly, we must first have a basic understanding of what joinery is along with the range we will be committing to. It is for that reason that we cannot simply include a history of a science that has been around since man lived in caves. Hence, we will start of with a general definition of joinery and start setting borders for our scope of work. We will briefly discuss its history to show how it started and how it transformed like every ageless study to fit its time period. The types of joinery methods are infinite and we will limit our scope to the joinery methods that we had produced during our experimentative process. We will see what these methods are comprised of along with their usages. As mentioned in the introduction, since this thesis is a consolidation thesis that amounts to a guideline on how to produce joinery via a five axis water jet cutter, we will be establishing certain skills required for committing and working in this medium. We will have, as well, a section dedicated to the current state or state of the art of joinery. In that section, we will also see and learn from how an industrial furniture manufacturing giant was able to traverse a difficult economic time by making its products simpler to transport and assemble. This ease of assembly owes much to the successful joinery used.

6.1. **Definition**

"Joinery is a part of woodworking that involves joining pieces of wood"(1), natural or processed, or synthetic materials, to come up with more complex results. A range of woodworking joints use mechanical fasteners, binding agents, or adhesives, while others simply use wooden elements like dowels. Further on, we will discuss this vocabulary and its mutated rendition that came up as we use materials different from wood or any material that has similar physical properties.

The joint itself gets most of its physical characteristics from the raw material used to create it. It attains its strength and resilience as well as its ductility come from the material used to make it. However, another key determinant of the physical capabilities of certain joints has to do with the joint itself, how it is performed and loaded. Different types of joints are used for different types of jobs.



Figures 1A & 1B. Pictures of classical wood joinery methods. The Box Joint (Left) and the Mortise and tenon (Right)

6.2. **History of Classical Joinery**

The history of wood usage itself flows like a river throughout recorded history. Old empires relied on it for ships, defences, weapons and everyday tools; periodic cultures relied on wood for wheels, windmills, constructions and more; modern day reliance on wood is involved mainly with construction and furniture. It was even the subject of the first book published by a developing Royal Society troubled by the high demands of a seafaring empire. **(2)**

Figure 2A, 2B & 2C. Wood used in making ships, wagons and accommodation (1)(2)(3)

The earliest discovered evidence of woodworking dates back 1.5 million years back. It links to a found stone axe that appears to have had a wooden handle. Archaeologists and anthropologists focus on stone, bronze and iron tools to appoint where they are used to depict the "ages of man". The "Age of Wood" deserves to be mentioned for all that it had given man. **(3)**

Figure 3A & 3B. Pictures of old and ancient tools that included wood and other materials connected by means of grooves

Many well known joinery methods use the exact material properties of wood without using any additional methods of fastening or gluing. We recognize that every different culture has its own methods and practices for joinery, however, the most well known are simply the ones most documented and they happen to be the Japanese methods. Secondary to those are the Indian and Egyptian methods. Although the latter were not documented as properly as the Japanese methods. It is, beyond any doubt, one of the most intricate as we can observe it in pieces of furniture that have survived for the past 5000 years. (4)

Figure 4A, 4B & 4C. Ancient joinery methods belonging to Japan (Left), India (Up) and Egypt (down).

The west understood the importance of these joints and experimented with some of their own. However, by the time the west picked up on these methods, they decided to hide the joinery unlike their eastern counterparts that showed great pride in displaying their several hundreds of types of joints. It is also believed that the Asian societies made sure to keep their work visible to show that the joints were in fact there and no glue or nails had been used since both were not ideal in the humid weather of the orient. It is true as well that the type of wood that was mostly used at the old times at those parts of the world was usually very humid and did not hold well with the glue that existed then and even the ones that exist now. [(4)]

Figure 5. Exposed Joinery showing a 4-tipped mortise and tenon joint (4)

It is notable as well that wood joinery is long from extinct. As we discussed in the opening introduction, manufacturing processes change form but rarely die out. It keeps evolving to fit the cast we give it in the world we live in. The point of this theses comes to show that the limits of this mould are actually far greater than it appears at first. As mentioned earlier, we want to set guidelines for keeping this craft alive and use it to its full potential through displaying the great efficiency behind performing it under the power of the modern water jet cutter. By that, we would have kept the idea alive but with different means.

Figure 6. Joinery done by hand requiring skills and craftsmanship

6.3. **Materials Involved** (Wood)

As mentioned earlier, joinery is greatly viewed as a media were wood dominates the arena. It is fitting to speak about the general properties of wood to see where it fails and why it allows, and at times, necessitates using other materials. This will, in turn, show beyond doubt the importance of the water jet cutter because materials other than wood cannot be cut and shaped with the methods used typically for wood.

Thus, to a high extent, joinery methods either rely or are understanding of the properties of wood. Wood is anisotropic: its material properties are different along different dimensions. Split boards or fractured joints are frequently the result of gluing boards with the grain running perpendicular to each other. Despite being created by great craftsmen, furniture from the 18th century did not take this into consideration. Works including joinery today are just as at risk as those of older times with air conditioning and heating drastically changing the humidity and temperatures of rooms and by that altering the setting and the expected life span of the piece. We keep this in mind as a disadvantage of wood in joinery as well when we state that a change of material would not be a bad idea to begin with in an effort to enhance the craft of joinery. In this sense, we care for the outcome to which we will determine the best means of manufacturing instead of hanging on to a certain pattern that requires a delicate and well maintained atmosphere. [5]

Figure 7. Failed mortise and tenon joint

Certainly different types of wood have different strengths and physical properties. However, it is notable that pieces of wood of similar dimensions can have different strengths for a variety of reasons with one of them being the direction of the grain at which the piece is stressed. Wood is one of nature's examples of composite materials; it is composed of fibres glued together by a natural binder. In hind-sight, we know that wood is stronger when it is stressed along the grain. The reason for that is that the long fibres are stronger than the glue that holds it together. We can witness this when we try to split wood along its length. This is definitely a disadvantage of using wood for long lasting and tight joints.

Just as it has innate strengths and weaknesses, the outside world holds great influence over the properties of wood. Wood happens to stretch side-ways if faced with humidity. Of course the type of wood, the amount of humidity, and the length of exposure have much to do with how the wood reacts. Fibres that usually deliver nutrients and water up a tree when it is alive, still have the ability to hold and release water from humidity even after the tree is cut and already being used as lumber in construction, furniture, or other places. The result would be expansion and contraction that leaves the joint flawed and not precise. Some craftsmen use the part of the tree that are further from the centre. These parts are usually dryer in nature and its fibres are exponentially far more compressed and thus hold less water when exposed to humidity. (6)

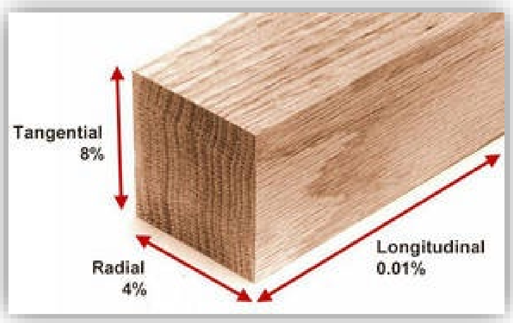


Figure 8. Wood expands when exposed to water more tangentially and radially than longitudinally (5)

Finally, it must be mentioned that natural wood can have small discrepancies that are at first not visible to the naked eye. Upon transporting the lumber or through its life-time, micro-cracks can become larger and the wood might bend or break. This, in turn, makes it necessary to strengthen it or even change it if found feasible.

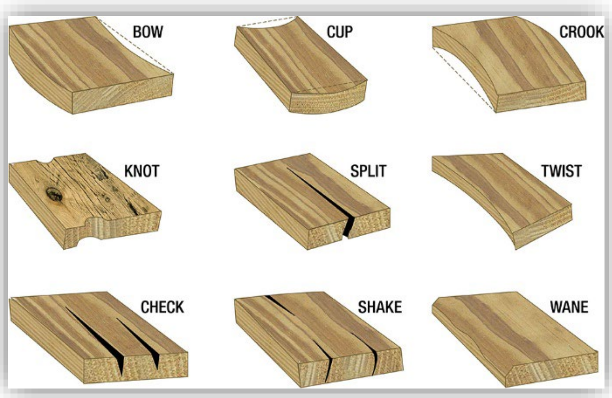


Figure 9. Wood deforms either naturally or under changes of temperature and humidity

We cannot underestimate the role wood has and always will play in our world. But it is notable to say that all that we had mentioned before about the problems one can face using wood, would not exist or exist in a manageable manner in other materials. We would like to think that using wood is always the most sustainable option, the reality is that wood offers its craftsmen several risks upon ordering it and working with it. Just as much, it brings with it problems to the user that has to maintain it and replace it if anything were to happen to it. One reason for the inadequacy of using wood to mass produce is having highly sought after types of wood away from the people that want to have it.

6.4. **Different Types of Joinery Methods**

We will start this sub-chapter by speaking about the methods used to perform these connections. Then, we will display various types of joints that are most commonly used in this craft.

Dowels

Dowels are protrusions that can secure wood joints without the aid of any extra adhesives, screws, or other materials. This can be seen in a joint called the pinned mortise and tenon. Sometimes, dowels are used for reinforcements of joints. A tiny rod is inserted internally into a joint to strengthen and align it. Natural timbers are utilized with traditional joints since they just require the wood itself as in the butt joints. Dowel joints are especially helpful for pegging together flimsier, less expensive composite materials, such as laminate-faced chipboard, and in situations where there are few available woodworking equipment.

Figure 10. Mortise and tenon joint with securing pin

Biscuit Joints

In this scenario, craftsmen use small pieces they would have cut earlier and insert them into grooves that they would have made into the pieces of wood they want to join together. This is coupled with glue most of the time and the result is irreversible.

Glue

Timber can be joined with glue quite successfully if both surfaces are edge grain. An adequately bonded junction might even be more durable than a single piece of wood. On end-grain surfaces, however, glue is noticeably less effective. Animal glue produces joints that can be deconstructed using steam to weaken the binding because it is soluble in water.

Fasteners

Screws and nails are the most used mechanical fasteners and the least complex. Screws and nails are often used with glue as well to create very strong joints. Sometimes, mechanical fasteners are used when the craftsmen don't have time to wait for the glue to set. Joints that employ glue or fasteners are irreversible most of the time since the glue becomes part of the material and the fasteners remove part of the material or at least augment it as they are being placed in. [(7)]

Furthermore, we will be seeing, for the first time in this report, the actual joints. As we mentioned earlier, it is impossible to write about all the types of joinery methods that exist all over, hence, we will display the types of joints that we took into consideration as we tried to design and implement our own joints. This part is of great importance since we will later be discussing its feasibility in different materials.

Joinery Method Name	Joinery Method Image	Description
Mitered Butt Joint		The end of a piece of wood is butted against another piece of wood. This is the simplest and weakest joint.
Half Lap Joint		The end of a piece of wood is laid over and connected to another piece of wood. Due to a large surface area of long-grain to long-grain wood and glue surface coverage, this is a very strong joint.
Mortise and Tenon		A stub (the tenon) will fit tightly into a hole cut for it (the mortise). This is a traditional method of jointing frames for doors, windows, and cabinets. This joint is a good strong joint to use.
Biscuit Joint		A wooden oval is glued into two corresponding crescent-shaped slots.
Dovetail Joint		A form of box joint where the fingers are locked together by diagonal cuts.

Figure 11. Table displaying the types of joinery methods we will be focusing on

6.5. **Usages on Different Scales**

These wooden joints have deserved their placement in the wide range of products they are involved in. We can see joinery being used in the micro scale as well as the macro scale, in items that are rare and unique and others that are widespread and in items that are expensive and others that are relatively cheap.

A butt joint, for example, is nothing more than when two pieces of wood are placed most often at a right angle, or square with respect to the other board. It is usually fastened using mechanical fasteners. This type of joint is often used in wall framing on construction sites. In such a scenario, we are not looking for beauty and longevity, simply strength and reliability. (8) One step further would be the mitered butt joint that has either ends of the wooden pieces cut at an angle, usually 45 degrees. The result would be an invisible end grain hidden by the slanted face of the other piece so the result is aesthetically better. (9)

Another example we see often is the half lap joint. Here, the structural integrity of the wood is greatly diminished since a groove has to be cut at a depth equal to almost half the depth of the piece being used. As a joint it is stronger than the butt joint but it does require that we use thicker pieces of material to achieve the same result. This type of joint is preferred for corners in construction and furniture skeletons. (10)

For even more aesthetically pleasing finishes as in exposed structural beams and branching, we can use the mortise and tenon joint which is basically a hole in one piece and a protrusion of another piece. It is considered a very elegant joint and if properly crafted, does not require glue for its attachment. We mention as well that this specific method is also used by blacksmiths and stonemasons in their respective crafts with metal, stones, and combinations of various materials. (11)

A similar joint is the biscuit joint. We had previously expressed how the biscuit can be used to reinforce a joint. In this case, it is a single joint that functions as the mortise and tenon joint. However, it does not offer the same strength as the biscuit is usually one fifth the thickness of the material used whereas the knob in the previous joint is usually greater than one third of the material being joined. The advantage of this joint lies in its ease of manufacturing and fitting. (12)

We move on to discuss three renditions of one joint, the dovetail. Firstly, the through dovetail joint is where trapezoidal pieces of wood are removed from either parts that are to be connected. These parts would use the protruding trapezoidal forms to fit inside the now vacant trapezoidal space that has been created. Next, we have the half-blind dovetail joint that owes its name to having the part that holds the sleeve not cut all the way through. This connection is aesthetically pleasing as well and is often preferred if we are using two typed of wood in one joint. These joints are usually used for drawer fronts. The third mutation of the dovetail that we will talk about is one that has a groove with a trapezoidal profile that allows the protruding trapezoid of another piece to slide through it, hence its name it sliding dovetail. (13)

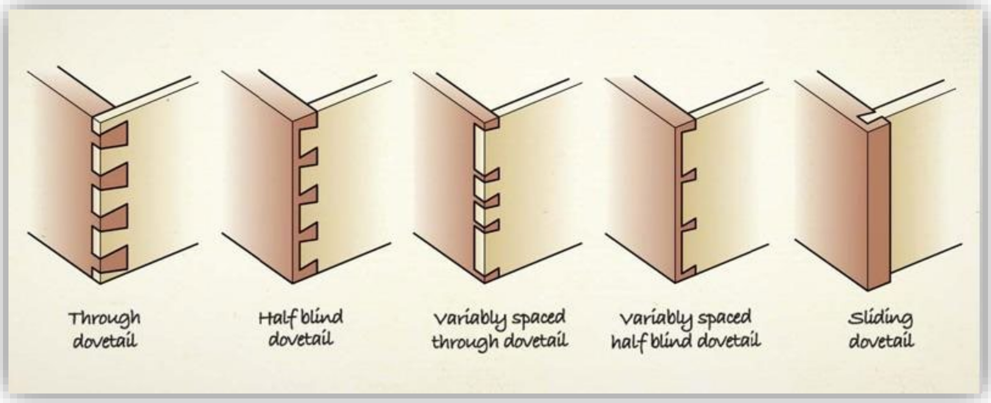


Figure 12. Different types of dovetail joinery methods (6)

As we have seen, the joinery methods mentioned above were only a handful of those that exist. They offer a good enough representation of joinery in general. We have established through these examples that there is a wide variety of joinery techniques employed in many situations depending on needed strength and aesthetics. We maintain that some joinery methods require supplementary elements be it glue, screws, dowels, or other mechanical fasteners.

6.6. **Current State** or State of the Art

After having discussed earlier the several situations certain joinery methods are used in, we can speak now in a more general sense about the current state or state of the art of joinery. The world has been indeed witnessing a paradigm shift from the days people pre-ordered woodwork and furniture for entire rooms versus the way things are today were people find assembling furniture themselves a recreational activity.

The design, manufacturing and assembly of wooden products that included joinery had always been almost exclusively the work of trained craftsmen. Things changed slowly with every population boom and economic shake. Everyone needed chairs, tables, closets, drawers and more. People started taking matters into their own hands and took the manufacturing process to their homes. People started shopping for raw materials instead of finished products. This can be traced back as far as the 1910s [(14)] but is seen most recently with the population boom of the 1950s. During that time, the bigger part of the world was still recovering from a world war that ripped through all the largest continents of the world and specifically through the most progressive economies back then. The ongoing of the cold war made sure to strain the world economically as well.

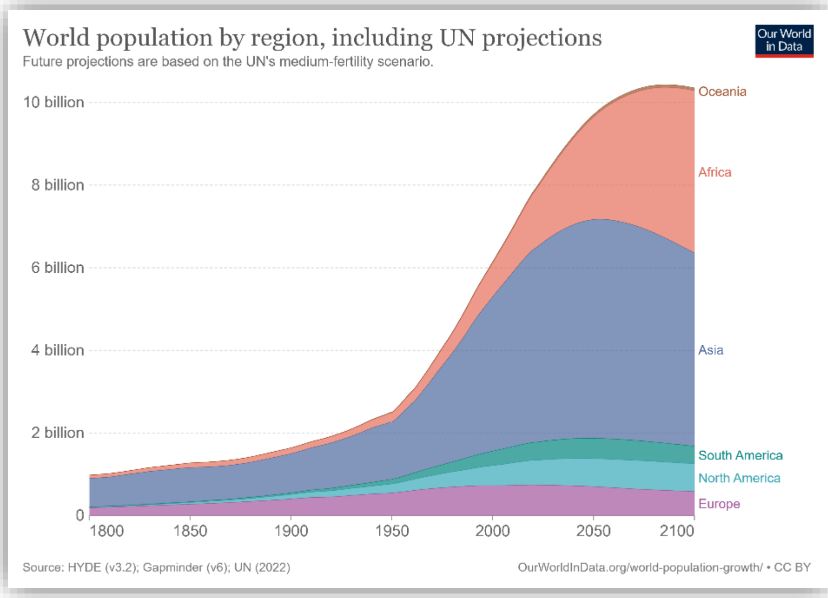


Figure 13. Chart showing the population spike of the last 70 years

The term "Do it yourself" came to existence and had become widely used in the 1950s with people wanting to pay less for modifications they wanted to execute in their homes without the direct help of professionals. People were buying raw and semi-raw materials along with the tools necessary to transform these materials into material possessions. The economic benefits, coupled with the lack of product availability and the fondness of owning customized items pushed people to seek empowerment and uniqueness by creating their own surroundings.

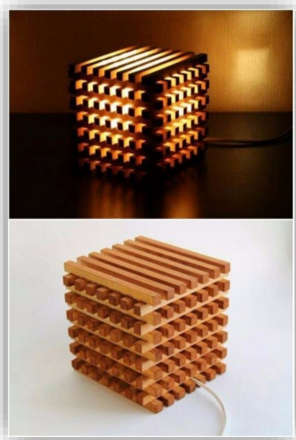


Figure 14. Home-made furniture. Some of it is better crafted (Left) than others (Right)

This fuelled a self-made and anti consumerist mentality amongst people seeking self-sufficiency. This took manufacturers by surprise. The idea that anyone is capable of actually creating rather than having to enlist the help of paid specialists. Large manufacturers that were not stopped by world wars had then found themselves breaking down under the force of an anti-consumerist crowd. A chain of studies was initiated and large corporations decided that to remain in business, they had to join these crowds and cater to their new desires. We will discuss here how this integration occurred as well as what it meant for the niche of wooden joinery.

A quick jump back to ancient history, Italian archaeologists discovered the ruins of a Greek structure that was 2600 years old. What was exciting about this specific find is that the structure came with assembly and manufacturing details depicting that the people that created this structure had little to no direct contact with the actual people that had to put it together or use it. That would have been the oldest discovered assembly manual. **(15)**

In North America, DIY magazines were being published in the first half of the 1900s. **(16)** Popular Science Monthly (founded in 1872), Popular Mechanics (founded in 1902) and Mechanix Illustrated (founded in 1928) gave readers a method to stay up to date on practical knowledge, skills, techniques, tools, and materials. In the beginning, a lot of the content was focused on the requirements of readers who lived in small towns or rural or semi-rural areas. By the end of the 1900s, people had been using video tapes that held tips and instructions on how to manufacture what they needed.

Figure 15. Early magazines focusing on giving knowledge to hobbyists and early DIYers

Today, these magazines have come to be a very small percentage of consumable material about DIY. With a few clicks, Pinterest, YouTube, Instagram and more are ready to give you thousands of ideas ready for you to just start creating.

Figure 16. DIY Furniture ideas on Pinterest

Figure 17. DIY Video Instructions from YouTube

As an initial reaction to this DIY wave, industrial giants tried to simplify manufacturing processes. It was in the 1990s that these giants started narrowing their product focus, tightening control, becoming flexible, and improving customer relationships. (17) Another key factor critical to our work now would be that these giants started working on a long lasting resolution. We will use the well-known IKEA as an example.

Figure 18. IKEA, An Industrial Giant in the world of Easy Assembly Furniture

We look at IKEA, the giant that tip-toed and inched its way into the world of DIY. After monitoring what the market was asking for, IKEA set out to supply the world with relatively cheap furniture in large quantities and a contemporary appeal. Certainly not everyone ran after IKEA. But without a doubt, many started purchasing its products. It gave a people the same feeling of self-sufficiency they were after, coupled with the convenience of not having material wasted or waiting to be disposed of. We can learn much from the journey IKEA took to reach such a global audience, often mutating to comply with the cultural demands of certain crowds as such was the case in Japan where IKEA originally failed, retreated, and re-entered successfully.

IKEA became a universe rotating around its consumers instead of working hard on pulling it to them, it worked on reaching them. What we care about here and for the sake of our thesis is that people all around the world displayed an eagerness to assemble their furniture and the world around them. It is the reality we are now inevitably part of.

At the micro scale, we go back to our main topic of joinery. Most IKEA products come with an assembly manual. This manual depicts the product growing in steps as you grab more pieces and fix them together usually by means of mechanical fasteners. It is at this part of the relationship that IKEA puts the load on the uninformed consumer and their ability to actually put the product together. In this scenario, the complexity of the product, the variations in fasteners, and the unavailability of certain tools makes a project that was supposed to take an afternoon, take a couple of weeks. This inconvenience, along with the poor quality of some of the products, added to the times the unexperienced consumer disassembles and reassembles a joint, all lead to a bad experience sometimes and a poor result that leaves the user disappointed. The idea of having less parts arises. Less parts and tools and the ability to use strong and variable materials would solve many problems and inconveniences and this is what drives our thesis proposal forward.

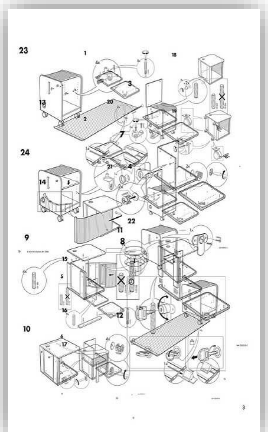


Figure 19. Sometimes, IKEA assembly manuals are not ideal due to the presence of many parts

Figure 20. Sometimes, IKEA furniture is not of the highest quality

6.6.1. **An IKEA Change of Mentality** (A Case Study)

If you look at the average dining table found in every home, dorm or office, you'll see most have side planks placed at the top of the legs right below the table top to prevent racking, warping, and disfiguring.

Figure 21. Classical table with Aprons

These side planks are connected to each other as well by means of corner brackets that are either of wood or metal. These serve to hold the planks as well as the legs to the table top with rigidity. These different materials and added costs weigh down on IKEA that wants to find a good quality to cost ratio. So IKEA decided to experiment with alternative methods of joinery.

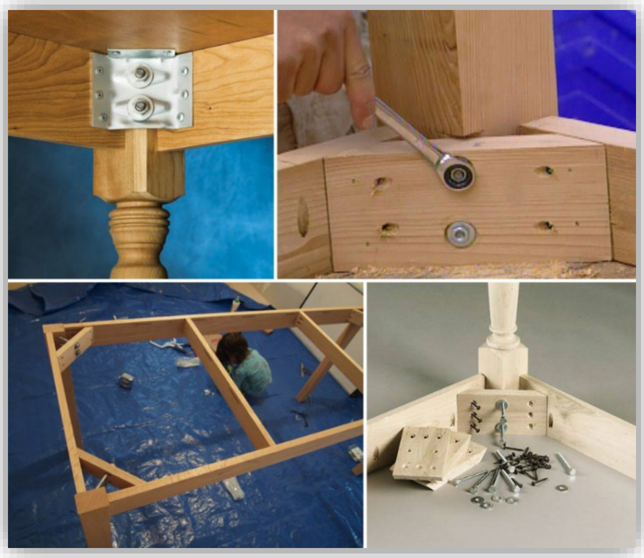


Figure 22. Many additional pieces are needed to secure the top-apron-legs assembly

By creating a new type of mortise and tenon joinery method using a new wood shaping technique, they were able to use less tools to create the table top, cut it and make it ready to accept its new leg directly. The leg in turn was carved a the top to have the piece that would allow part of it to get inserted into the previously cut table top. The assembly is then held together by means of just one screw that holds a wedge that restricts any loose fitting leg. (18)

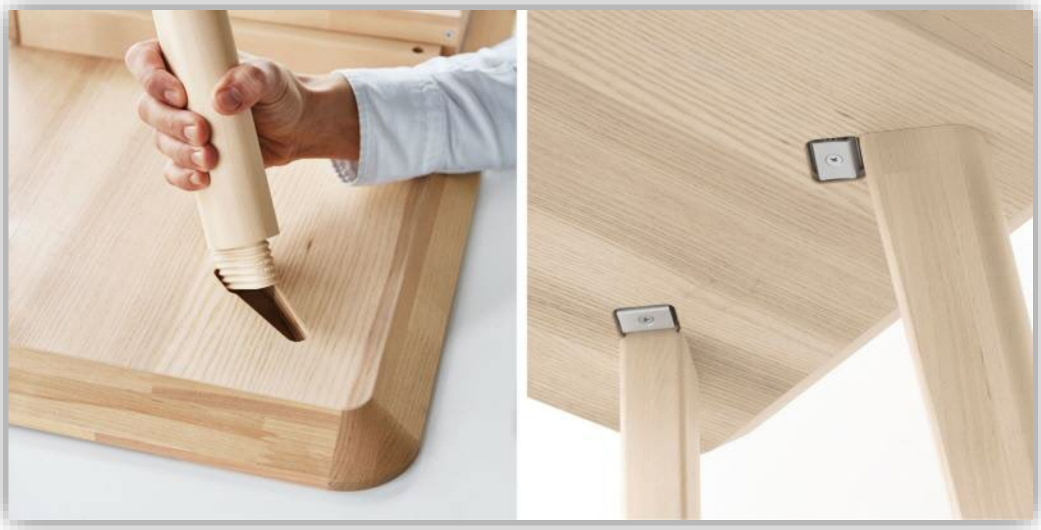


Figure 23. Leg is inserted directly into the top and a dynamic wedge is screwed in place

By committing to their message of good quality at low cost, understanding the skill set of the average consumer in assembling joinery and accepting the most important fact that joinery is there to change with time to suit its environment, IKEA was able to mutate and already existing joinery method that eventually resulted in a new cost-efficient line of products that people enjoyed setting up and using.

It is our love for design and engineering that always drives us to be resourceful and use materials and tools that are at our disposal to redesign and rethink designs and respective development and manufacturing methods. All of what had been aforementioned pushes us to find solutions, again, in an effort to triangularly bridge the cost, beauty, and utility chasm.

6.7. **Knowledge Needed to Practice Joinery**

In this portion of our study, we will be handling the matter of how to become knowledgeable in joinery. What determines if someone is fit to create joinery and make it simple yet strong enough so that the average individual could put it together and rely on it as part of their life. There are several studies that bring up a certain set of skills one must learn. Technical knowledge and a little bit of physical strength can go a long way in shaping the modern day craftsmen. Constantly keeping up with trends and market needs along with improving the aforementioned skills can help one excel in their career.

A proper craftsmen must have a sense of the end product they are working on. They must visualise the users accepting and relying on it. Most importantly, to help the idea become a reality, a craftsmen must have a clear understanding of the capabilities of their tools. Basic wood knowledge, as you could imagine, is a must. To ensure structural stability, a craftsman has to identify defects in the raw material they are working with wherever possible. Add to that the fact that these days, these craftsmen are faced daily with several other materials they might have to incorporate in their work to produce an intended result.

An added step would be that this person could make themselves capable of producing a reference blue print for the assembly process. This stems back to a point mentioned earlier and that is the makers ability to place themselves in the shoes of the less knowledgeable user that has to actually assemble the product and make sure every joint is well set. Before going further into the skills that one must have, let us limit the trade to what concerns a few settings where new joinery creation could be of benefit.

The settings are to include elements that could be used in furniture design, commercial carpentry, restoration or preservation of previous products or projects, industrial settings, and possibly scenic details and finishing.

Firstly, a craftsmen of joinery must have skills in mathematics. To calculate the accurate dimensions of a project and determine how much material is needed and to exact the expenses so not to exceed a set ceiling. Algebra and geometry at a basic level can definitely make or break the project and the entire career path of an aspiring craftsman.

Secondly, although we would like to create parts that are easy to assemble by the average abled person, the creation of these parts from raw materials can necessitate the existence of a certain level of physical strength. The transportation of material as well as the operation of some tools and machinery might require this.

Thirdly, communication is key. When craftsmen operate in team environments as they usually do, it is imperative that the directly communicate concerns and thoughts with their colleagues to avoid future problems. Communication insures that safety is maintained and instructions are followed. Constant verbal and written reporting of statuses is necessary to maintain a time limit. It goes without saying that communication is also of great importance when bridging a gap between people of various levels of knowledge in the field where an experienced craftsman is on one level, a new craftsman is on another and a customer or user is at a totally different level.

The fourth skill set would be an eye for details. Firstly, this allows a craftsman to inspect the raw material before handling it. Secondly, for the sake of precision, a craftsman has to see the detail in every cut. When small imperfections accumulate, the strength and integrity of the entire project is set back. Mistakes that snowball from small detail mistakes can cost money and use up time, driving up the cost of projects which does not benefit any party involved.

Fifth would be a skill set linked to a mindset. I learned at an early stage of my education not to point at any problem without having a possible solution or two ready for its resolve. This ability allows quick response to problems when repairs are needed or alterations are critical. A well functioning product is the result of a manufacturing process well-maintained by craftsmen with an open mind and a welcoming mentality towards failure and learning from previous mistakes.

Sixth would be dexterity. The ability to move ones hands around a project and its manufacturing process without causing undue pressure and problems to the process. Sensing the material, and harbouring a feel to what every movement we make can result in, is a skill that is built around expectations, trials, failures and experience. Operating touch-sensitive tools is another area where this skill is expressed.

Seventh is something that concerns us greatly and sets the stage to what we plan on accomplishing. Mechanical skills are key in manufacturing. Mechanical skills is equaled in importance to the willingness of individuals to learn about the methods by which machines and tools operate. It would be wrong to believe that craftsmen, with their hand-held tools, are moving the planet forward everyday. Billions of individuals rely daily on the existence of tens of billions of products being readily available. These quantities come directly from the successful daily operation of millions of process with many millions of machines. The willingness to learn more about machines is a big part of a craftsman's life. The ability to operate multiple types of machines make people more qualified to produce the quantities of goods we need. (19)

6.8. **Local Overview**

After covering the history of joinery, the materials involved, be it wood or the fasteners of different materials, the collection of the different joints and joinery methods that are involved, the different scales at which joinery is employed, the state of the art of joinery and the knowledge needed to practice joinery, we hope to have established the first third of our study.

As mentioned earlier, our end goal is a guideline explaining how joinery can be performed using a 5-axis water jet. Displaying a small part of the vast culture that is joinery was a must. We have seen how this art is as old as recorded history and we cannot function without it. We add that it has gone a long way from simply inserting wooden shafts into rocks to create ancient hunting tools to funky dowel for an IKEA table. We have seen together the flexibility of joinery in its existence all around us. It is seldom that we have around us a product that does not require at least one kind of joinery technique. It is the present details of assemblies all around us.

As design engineers, we are constantly trying to improve manufacturing processes. As mentioned earlier, this improvement displays itself in the form of higher quantities, less costs, less environmental impact, higher client satisfaction and more details.

Going further, we will be discussing the realm of water jet cutting. This wonder of the modern day manufacturing world cannot go unnoticed for all that it could do. We are looking to stop creating smaller parts of raw materials from bigger parts of raw materials. Our future hopes are to create items directly ready for packaging or assembly directly after its cutting on the water jet bed.

7. **Water Jet Cutting**

7.1. **A General Look at Manufacturing**

At the start, it all begins with an idea that has to be developed and brought to life for it to serve a purpose or several. Every once in a while, an idea or a concept is developed and much of it is needed. Hence it becomes imperative that one has to manufacture the quantities. Manufacturing, in simple terms, is the production of items at a large scale using knowledge, materials, tools, and machinery.

Certainly we all understand that the way we manufacture today is very different from the way older societies did. Not only do we have machines, but these machines as well have become more efficient and still do with every passing day. The quantities it produces has answered inversely to the amount of energy needed to operate it.

Manufacturing, throughout its history, has given way to glorious machines that responded to all kinds of questions and problems and helped move nations and create our world. Several machines and techniques saw several evolutionary cycles and adaptations to answer to the needs of respective time periods. This constant adaptation allows us to believe that means of manufacturing can traverse history and cannot remain property of the time period that created them.

In the 18th century, and specifically in the 1780s, man’s harnessing of the power produced by steam allowed people to power machines and produce items in large scales. This focus on “Powering the Machines” gave rise to more efficient methods of using allotted resources to mass produce goods.

In the 19th century, and specifically in the 1870s, manufacturers came to divide labour, construct assembly lines, and introduce electricity wherever possible in production processes in an effort to even make more efficient, the making of products. At this time, true efficiency was realized and globalized and people started to design for production keeping in mind the necessity to understand the amount of material that would be needed along with the time that has to be used up and the man power that has to be introduced for every production process.

In the 20th century, and around the 1960s, automation and numerically controlled production was sweeping continents, producing with accuracy and incredibly high numbers, all kinds of products ready for an already competitive market. Less craftsmen were needed and more engineers and technicians were employed to overlook manufacturing processes of vast arrays of goods with some meant to answer needs and others to answer wants. Machines had become the hands and legs of societies, pushing nations politically, financially, and ideologically, fuelling an already existing and competitive world even further.

Centuries of manufacturing evolution can be eclipsed by that that it had undergone in the last three decades. Cyber systems, the production of real and virtual collectable data, artificial intelligence, and complex algorithms made to detect and analyse millions of data entries per second, have paved the way for producers to realize a product life cycle. By determining that, manufacturers could perfect the design of certain goods. To perfect the design of a product, we need to understand its function, the people that would be using it, the setting under which it would operate, and its expected life span; having done so, we might choose to change parts, forms, and materials. By administering changes, we would directly be affecting the resource consumption of any product's development and that is quite the intent of industry 4.0, more products, lower costs, and fewer or no mistakes.

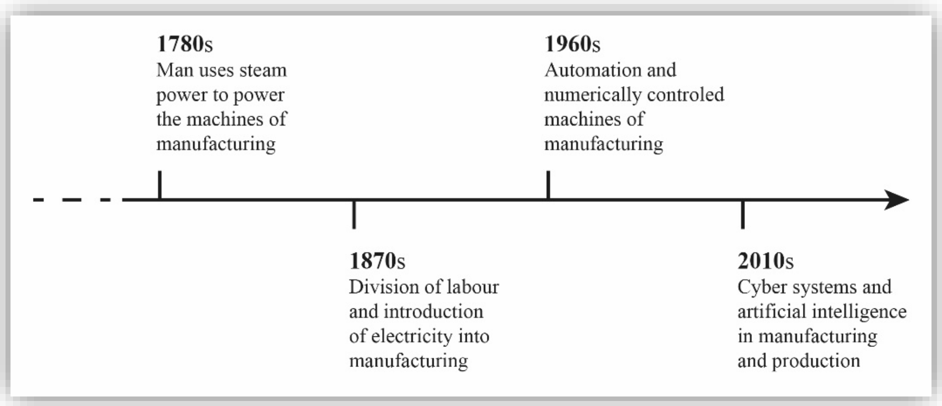


Figure 24. Manufacturing Timeline (7)

As a general concept, the world of manufacturing is viewed as the creation of finished products from raw materials through a set of basic processes, secondary processes, material property enhancing processes and finishing operations. Some processes are physical or chemical processes that change material geometry, properties, and appearances. Other processes include production and assembly. There is always the possibility of having manufacturing processes composed of a sequence of operations.

From an economic standpoint, manufacturing is said to add value to the material by changing its shape or properties or by combining it with another material in an effort to answer to a certain need brought forward by future consumers and users. We can view a chart representing briefly what manufacturing could include. We will see were water jet cutting fits in in this chart.

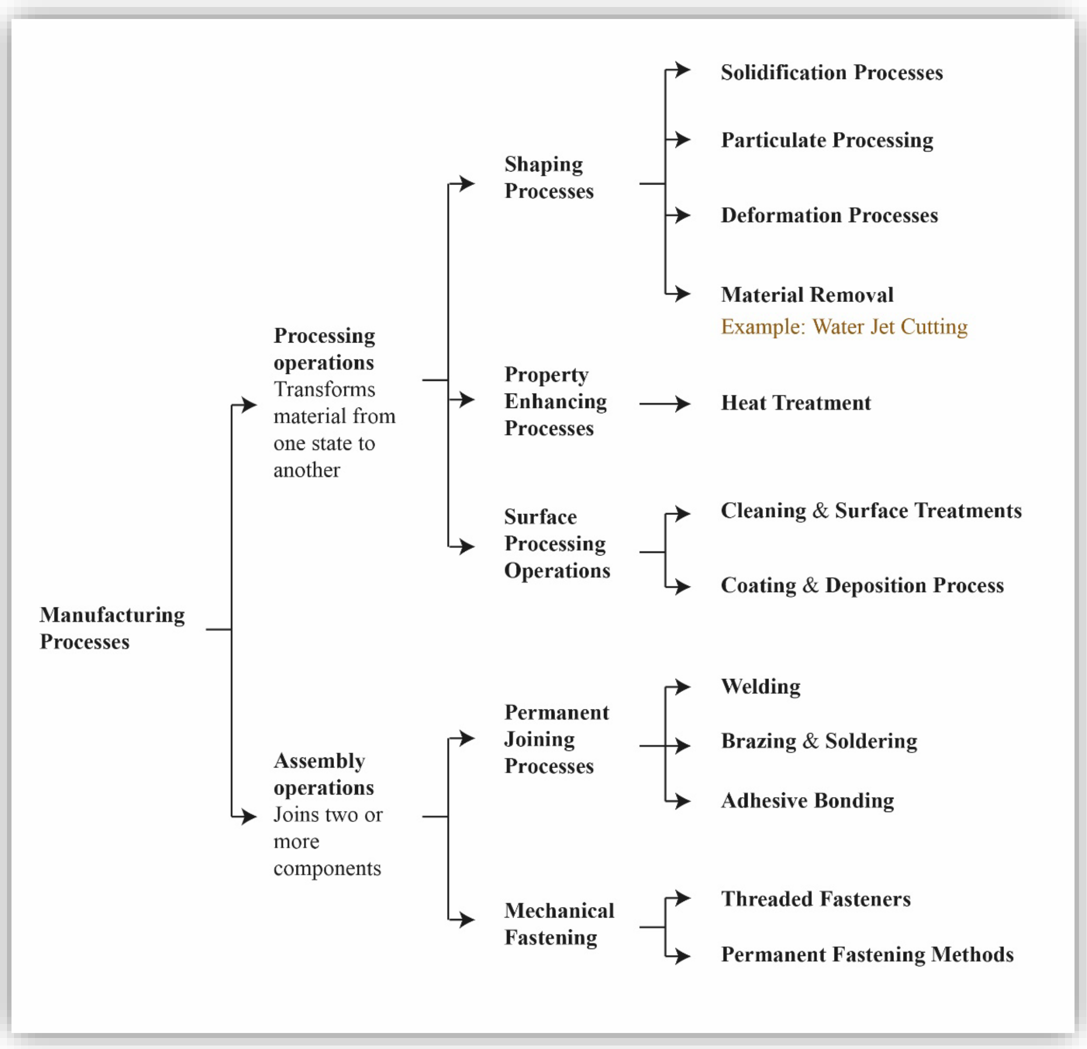


Figure 25. Manufacturing methods chart (7)

7.2. **Definition of Water Jet Cutting**

Water jet cutting is, in simple terms, the usage of pressurised water that is usually mixed with an abrasive substance and directed by means of the components of the water jet to cut various types of materials found on the bed of the cutter. The cut is defined by a designer, an engineer or a team based on design and technical requirements. The cut is then performed by a technician in a controlled environment where the machine exists.

Further on, we will talk more about these different types of materials and the fields where water jet cutting exists. We will present a brief history of the process and how it works, along with the industries it is part of and the different types of it. We will compare it to existing methods of subtractive manufacturing. We will finally speak about the exact water jet cutter we used to perform our own cuts before we move on to talking about these cuts.

7.3. **History of Water Jet Cutting**

Certainly water jet cutting was not as strong as it is today. It went a long way from being used at low pressures to cut paper in the 1930s to cutting marble and steel today at extremely high pressures. In the 1950s, it was developed and strengthened to cut soft plastics. Not long after that, and just before the turn of the decade, it was used at a much higher pressure to cut very strong materials used in aviation. It was too strong in fact that it ruined the raw material and thus the manufacturing process had to be changed. **[20]**

It kept advancing and getting more convenient as abrasive material was decided to be mixed in with the water. That, coupled with the now more available and reliable pumps, made it possible to produce and use water jet cutters at high quantities. The aviation, automotive and oil sectors drove this manufacturing process to become much better and led to the development of seals that prevented leakage after prolonged periods of usage. Furthermore, the components of the machine of regulators and nozzles kept getting more efficient as more effort was put into it.

By the end of the 1980s, the abrasive water jet cutter had begun being used globally. It was at this stage that the mixing chamber was perfected and carbides materials made the chamber stronger in the sense that it could now allow for the withstanding the high-pressures making sure the process remains accurate over time. **[21]**

Further evolution of the water jet cutter took place and the five-axis water jet cutter was created with axis of freedom allowing it to cut intricate shapes and we see that most of the changes today occur on the more micro levels and industrial giants producing these machines are always trying to make their parts stronger of course, but what is most notable is the focus given to the soft wares that are developed to transform designs into cutting commands for the machine.


Tuesday, November 18, 1986 Vol. 17 - No. 37

University of Rhode Island, Kingston, R.I.

HOW DOES IT WORK? Senior Charles Burnham learned how to operate this complicated piece of machinery.

One of a kind water jet

Figure 26. Newspaper article about an early water jet (8)

7.4. **How Water Jet Cutting Works**

All water jet cutters follow the same principal of functioning. Water is pressurized by a high pressure pump to reach ranges of 210 MPa to 620 MPa. The pressure intensified water is sent through high pressure tubing to the nozzle of the water jet. The stream passes through an orifice that focuses the water into a beam, then it passes through the mixing chamber were it is mixed with the abrasive material such as garnet or aluminium oxide. The beam of water then exits the chamber through the nozzle at speeds upwards of 700m/s.

This steady stream of pressurized water and abrasive first hit the surface of the material we are cutting. It creates a pierce hole with the abrasive material eroding away the surface of the material and boring through it. Once the other end is reached, the machine moves its nozzle assembly to cut lines and curves through the material that could reach thicknesses of up to 25cm at times with the nozzle being between 2mm and 5 mm away from the surface thanks to the power of the abrasive water jet cutter that is almost 1000 times stronger than the pure water cutter. [22]

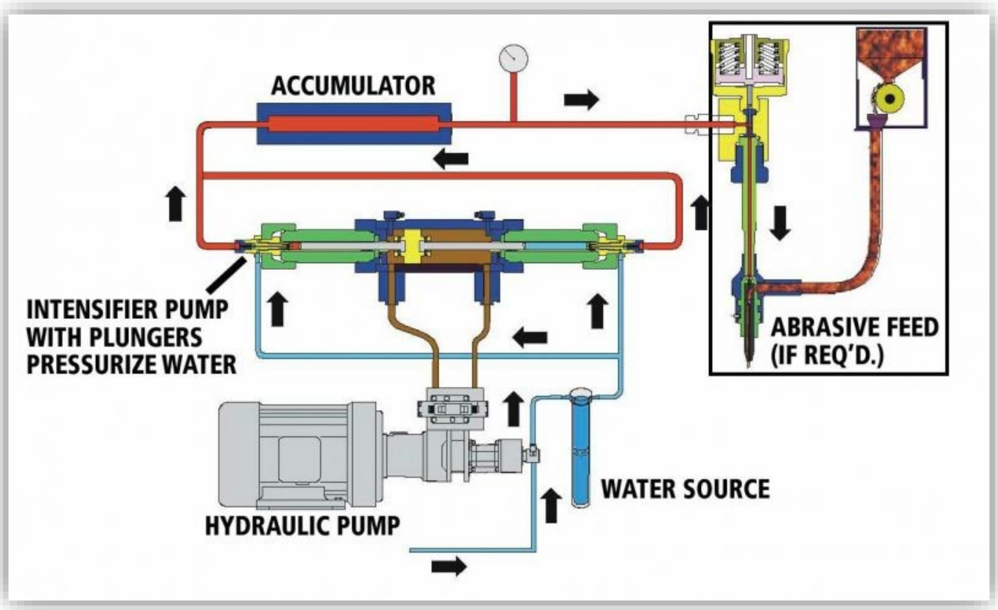


Figure 27. Water jet operating infrastructure (9)

7.5. **Materials that can be Cut and Fields of Application**

In the aerospace industry were we have cuts requiring complex and accurate precision, steel, brass, Inconel and aluminium are cut and used in the aerospace industry for turbine blades, wing parts, landing gears and brake parts.

In the auto industry, both methods of water jet cutting are used. Pure water jet cutting is used to shape interior carpets, insulation and head linings an minimal material is wasted. Bad fumes are not generated and clean surfaces omit the need for other finishing processes.

In medicine, high pressure spiral water crushes and sucks liver parenchymal cells while treating tumours. Cutting with the water jet does not produce heat that could damage other organs. Varying the flow rate allows cutting human skin with minimal trauma, bleeding, and postoperative problems.

In cutting glass, the water jet cut can be performed in a way to not damage the glass's structure. We can achieve these cuts with an excellent level of detail.

In gastronomic industries, water jet cutting is an approved method of cutting food. It is clean and helps reduce wastage. It's precise, accurate and capable of cutting meat, fish, poultry, pastries, and frozen foods to precise and perfect shapes with pure clean water and the high speed allows for efficient processing of products.

In cutting electronics, it reduces costs and increases efficiency when applied to cutting circuit boards whether empty or populated. It is also used to strip wires from the many layers forming it without damaging the wire. [29]

It is worth mentioning as well that we couldn't list every single field of application, but with all that was said, it is understandable that there is no limitation for this process in terms of materials. We can even say that with properly controlled environments, we can even cut wood without damaging it.

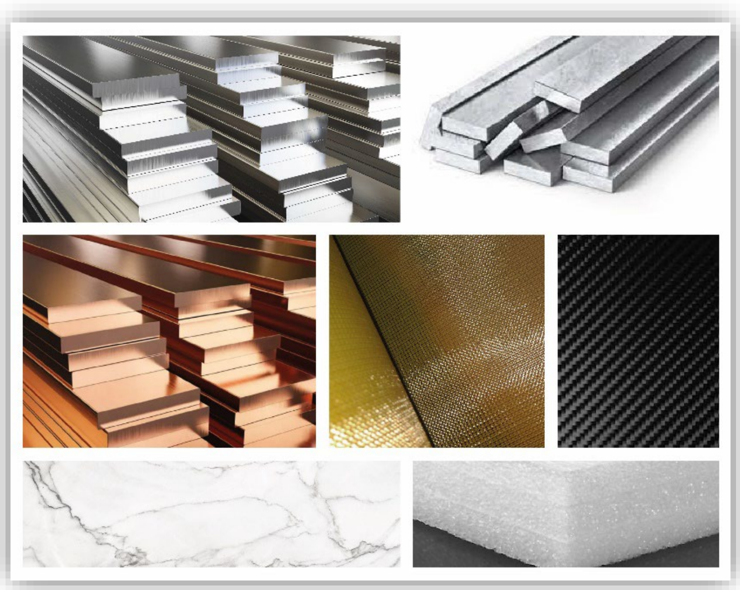


Figure 28. Of the many materials that can be cut by the water jet cutter (10)

7.6. **Water Jet and Other Subtractive Manufacturing**

As mentioned earlier, water jet cutting is one of several manufacturing processes that fit under the title of subtractive manufacturing processes. These processes are performed either manually or through computer numerical control or CNC. We will briefly discuss different subtractive manufacturing methods and what it is used for and we will, further on, be discussing the advantages of water jet cutting. [(23)]

A subcategory of material removal processes includes turning, drilling, boring, milling and reaming. This subcategory is used in many industries that require the reshaping of hard thermoplastics, thermoset plastics and soft and hard metals. In these scenarios, the work piece can be stationary, turning or moving in general.

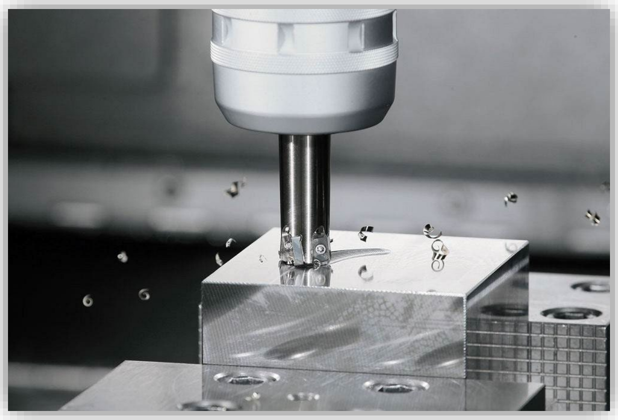


Figure 29. Milling (11)

Figure 30. Turning (12)

Figure 31. Boring (13)

Another subtractive manufacturing method is Electrical Discharge Machining. This method is used for hard metals. Material is subtracted from the work piece by recurring current discharges between two electrodes, with a dielectric liquid between it and subject to an electric voltage. (24) This process allows the machining of hard materials at high quality tolerances. This method has been very well in producing prototypes.

Figure 32. Electrical Discharge Machining (14)

Laser cutting is also termed a category of subtractive manufacturing. It is used for cutting thermoplastics, wood, acrylic, fabrics and metals. A strong laser burns through materials. Laser cutting technology is used at a wide variety of ranges from schools and small businesses to the automotive and aerospace industry. Notable disadvantages of laser cutting is the high temperatures that could affect the structural integrity of certain products when cut along with the fumes that cutting some materials produces. It is not surprising that a major disadvantage of the laser cutter is its high power consumption.

Figure 33. Laser Cutting (15)

7.7. **Water Jet Today - State of the Art**

Water jet cutting is used for a wide variety of materials as mentioned before. Some of these materials include plastics, hard and soft metals, stone, glass, and composite materials.

The advantages of the water jet are plenty and include: The fact that there is no real material limitations, no heat is produced during the operation which allows the machine to run over long periods without breaking a part or destroying the material, the workpiece is never distorted and no hazardous waste is produced by the water and abrasive garnet mixture. Another key advantage is the fact that this process could be used without following it up with finishing processes. This lower costs and means time is spent properly. This matter will be exploited further on in our study. (25)

Figure 34. 3-Axis Water Jet Cutter operating Vertical while cutting (16)

Certainly water jet cutting isn't the ideal manufacturing method for everything around us. We will be discussing the disadvantages of water jet cutting to determine the limitations of the process to know how far we can go with our practices. Some disadvantages include longer cutting times than other methods. Certainly some thicknesses cannot even be cut by other processes, but sometimes, for small thicknesses, it is much faster to use other methods. Another disadvantage that we faced while working with the machine is that the internal parts have to be manually checked. For example, the orifice jewel has to be checked or else it would ruin the inside mechanics of the mixing chamber and the entire working end. Sadly, the thicker the pieces are the less the accuracy of the machine to cut at accurate tolerances. We do mention again that it comes with the territory since not many other processes can reach these cutting thicknesses at the low time and cost of the water jet. The last disadvantage we will be mentioning is the high starting costs. To prepare the infrastructure to use the machine takes a lot of work. The machine requires minimal operation costs but it does cost much to get started with it all. (26)

7.8. **The Water Jet Cutter that we Used**

The machine is the 5-axis water jet cutter Primus 322 Metal by Intermac. Its maximum jet pressure is 380 MPa and the work table size is 4 meters in length and 2 meters in width. [27]

7.8.1. **The 5-Axis Water Jet Cutter**

5-axis water jet cutting is probably older than most people believe it to be with the first one being launched as early as 1987. Usually, water jet cutters operate along three axes, X and Y by means of an overhead gantry that moves the cutting head horizontally, upwards and downwards. In the 5-axis water jet cutter, we have an extra two dimensions, the A that allows for an angle from the perpendicular and the C that rotates around the Z-axis. With these added dimensions, we are able to cut at an angle, cut curved edges and even compensate for the tapered edges that are produced by normal vertical cutting of thick materials as discussed in the disadvantages mentioned before.

Figure 35. 5-Axis Water Jet Cutter operating tilted while cutting (17)

7.8.2. **Knowledge Needed for Machine Operation**

The knowledge needed to operate the machine takes us back to the knowledge needed for performing joinery. Mathematical skills, physical strength, team communication, an eye for detail and mechanical skills are a big requirement for running a machine this big and this strong. However, exclusive skills needed could be seen as guide lines as well for safe cutting to reach a good finishing quality. Firstly, cutting materials with an air gap can be difficult since the stream diverges inside the gap. Secondly, using a smaller abrasive mesh could mean a slower cut but ensures a better quality finish. Thirdly, from a business perspective, cost estimations are done by length calculation usually after the rate of cutting is determined by the machine software. Fourthly, upon cutting materials of varying thicknesses, we can change the speed of the cutter as well as the pressure to ensure that we are not wasting resources – time and materials. Fifthly, it is important to properly design the part. The cuts have to be designed to be cut by this machine from the start to achieve precise tolerances. We will be seeing these guidelines in action further on.

7.8.3. **Safety Measures Involved**

Cutting via a high pressure water jet cutter is nothing short of extremely serious no matter the material being cut, its thickness or the time the cut takes. It is for that reason that we obeyed strict safety measures that are in place to keep everyone safe in the first degree as well as make sure that the machine or the workpiece material is not harmed throughout the operation.

7.8.3.1. **Preparation**

At this level of the operation, we are making sure the machine is ready as well as the product we are about to cut. We make sure that the water valves are open, the machine is not producing any abnormal sounds and the air pressure valve is opened. A visual inspection around the machine is performed to make sure there are no obstacles in the way of any moving parts. The dumper containing the abrasive mesh is checked to see if it contains a respectively fair amount to start with. We check as well that the water level is not too high or too low. It is ideal to be a few millimetres below the top of the vertical metallic waves holding the workpiece.

7.8.3.2. **Preparing the Workpiece**

We inspect the material we plan on cutting and make sure it is set on its flattest side. We can use the compressed air gun to blow off any water or dust that is on the surface in order to put markings to centre the machine later on directly before the cut can begin. Weights are added to hold the piece in place so that it does not move anywhere and result in unwanted cutting. These weights have to be put while keeping in mind that the cutting head cannot touch any of it or we would be risking the nozzle of the machine.

7.8.3.3. **During the Cut**

After the origin is set and the file is put into the software and is ready to be cut. Everyone must clear the area around the water jet cutter. In our lab, luminous barriers at the door do not allow the machine to operate if someone or something is in its way. If this sensor is set off, the machine stops directly and does not operate again unless a key is turned manually on the outside operating system of the machine located at a distance from the machine itself. After the cut is complete, the cutting end of the machine retracts to its home position and the machine displays a message signalling the end of the cut and the allowance for entry or getting close to the machine.

7.8.3.4. **Retrieving the Cut Material**

Gloves have to be worn at this point. The material is elevated as gently as possible and drained from any water that might have accumulated on the work piece during cutting so to avoid water spills and slips. We wear gloves so the water and abrasive mesh mixture, that now also includes molecules of whatever material we cut, does not stick to our skin and cause irritation. We wear the gloves as well to avoid cuts from any sharp edges that were either there before cutting or that have come to exists after the cut. Long sleeve gloves are used should we want to retrieve small parts that could have had fallen in the water tank of the bed.

7.8.4. **Quality Checking**

Edge quality for water jet cut parts is determined on the range between Q1 all up to Q5. Q1 indicates a rough edge finish; the higher the number, the smoother the result. For thin materials, the difference in cutting speed for Q1 could be as much as 3 times faster than the speed for Q5. For thicker materials, Q1 could be 6 times faster than Q5. For example, 100 mm thick aluminium Q5 could be 18 mm/min and Q1 would be 110 mm/min, so almost 6 times faster. [28]

Cutting quality can be checked firstly visually by the naked eye. The next level would be checking it by analogue indicators. A step further could be by means of a microscope. A microscope allows us to see the paths the abrasive stream took through the structure of the material and it would be easier for us to determine the sub-levels of the qualities (For example: High quality Q4 could still exist without reaching the level of Q5).

What follows will be the most important part of our journey, the actual cuts that we performed will be presented along with the problems we encountered and the resolves we reached. We would be proving the actual implementations of combining the science of joinery with the subtractive manufacturing method of water jet cutting.

8. **Our Application of the Water Jet Cutter in Joinery**

8.1. **The Internship**

As mentioned earlier, and after having completed my course work in the Master's of Design and Engineering, I applied to intern at the Laboratory of the Mechanical Engineering Department, Building B23, Side B (Manufacturing and Production Systems Research Line). The idea of working in the realm of manufacturing always made sense to me. I was always drawn to the part of the product life cycle that is related to actually making the physical item. My work at the lab would mean my involvement mainly in the process of "water jet cutting" along with what surrounds this process including, and not limited to, alterations to provided designs, handling the equipment needed for project production, and assisting the individuals in the lab in producing visual data and infographics of the various processes and equipment.

On a theoretical level, I gained great knowledge in software transforming designs to production files along with the changes that one has to apply in order to obtain that file. In other words, I learned how to change a design file to fit the machine and the process to obtain the result the designer wanted. I was able to understand the many tolerances that could be manipulated to achieve a fine level of finishing with as least resources used. To give you an example would be that we were able to change the cutting speed of the machine making it faster on the thinner parts when working with materials of various thicknesses. Although we could have set the machine to cut the highest thickness along all the cut, we changed the speeds to reduce material usage as well as machine strain. The result ensured that the client would pay less and the machine and its parts would live longer.

I also learned greatly about the safety regulations that have to be met during general production process and specific material cutting regulations from constantly checking air and water pressures to ensuring proper air circulation standards were always met inside the lab as well as inside the specific machining zones since every machine has its own operating zone.

As mentioned, a set of experiments were performed to produce joinery using the water jet. The material used was aluminium. What follows will be a demonstration of the designs and the findings that were the results of our experimentation. After that, we will conclude with an overview of what had been mentioned and a conclusion for our study along with a view into what the future could hold.

8.2. **Our Experimentation**

These pieces have been produced to test the accuracy of the water jet. The data obtained helped us achieve a higher level of accuracy through finding methods to compensate for all the mismatches we have come across during the process. We aim to perfect these tests that are small yet very important. By proving that a high level of accuracy can be reached, we would prove the efficiency of the water jet and its ability to be greatly competitive in the world of furniture manufacturing. The strength of the machine is greatly visible through its power to cut not only relatively thick materials but also through its ability to handle composites and fragile materials as well. We were also able to enlist the help of a previous furniture designer I had worked with to come up with some joinery designs that we repeated to reach better results.

8.3. **Joinery Methods Trials**

Through the experiments we conducted and the joinery we produced, we picked up certain details and results that we saw fit to be used in a general sense whenever we would like to cut joinery using the water jet cutter.

8.3.1. **Joinery Method I –** Dovetail at an Angle

8.3.1.1. **Local Brief**

This was the first joinery method we experimented with. The plan was to create a joint that could allow for the creation of an angle between two pieces using the dovetail joinery method. We needed to understand firstly how the angle of the cut is to be determined. Secondly, we needed the joint to be simple enough to assemble quickly. Thirdly we needed the parts to stay in place once assembled.

8.3.1.2. **Design**

Figure 36. Joint I - Dovetail at an angle

The angle we aimed for was 16 degrees in this specific design. We determined that this angle had to be split equally between the two parts so each would hold an inclination of 8 degrees. Once properly aligned by means of the inclined edges that are now faced upon each other, the side ways motion is restricted by the dovetail joint. In order to hold it in place, the two parts of the dovetail joint were designed to bear two grooves that would align upon proper assembly to become a hole ready to accept a conical pin that is forced in to restrict detachment.

8.3.1.3. **Materials and Dimensions**

The material chosen was Aluminium 1100. The thickness of the workpiece was 8 mm. The material finishing was Semi-Polished. The end joint would be of 3 pieces (The 2 pieces to be joined and the pin to hold them in place).

This cut used up 1.3 kg of Abrasive Material and 25 litres of water and took 4 minutes.

8.3.1.4. **Design for Manufacturing**

We will observe now the dimensions of the pieces we cut.

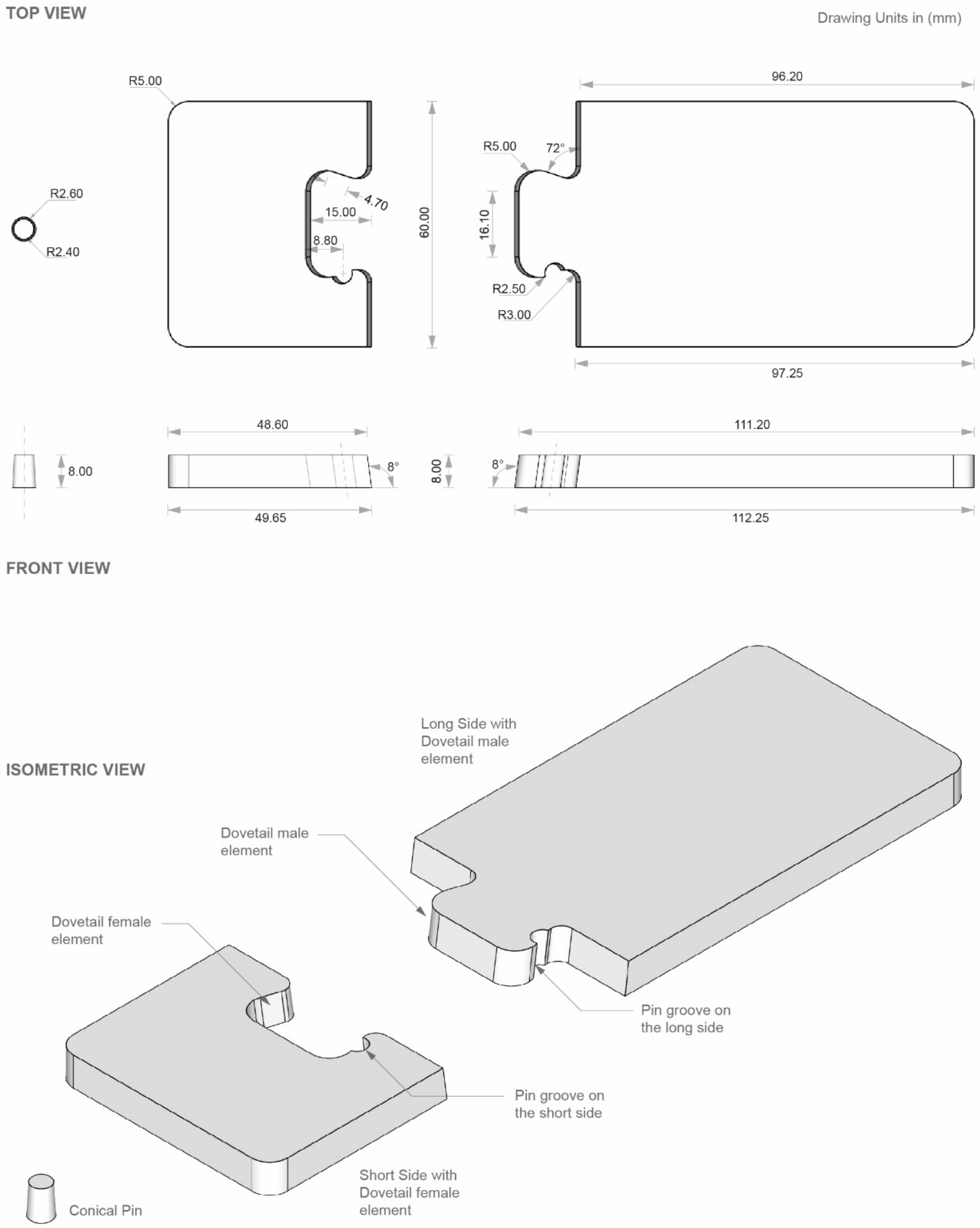


Figure 37. Dimensions and Isometric of the Joinery method I

8.3.1.5. **Assembly Steps**

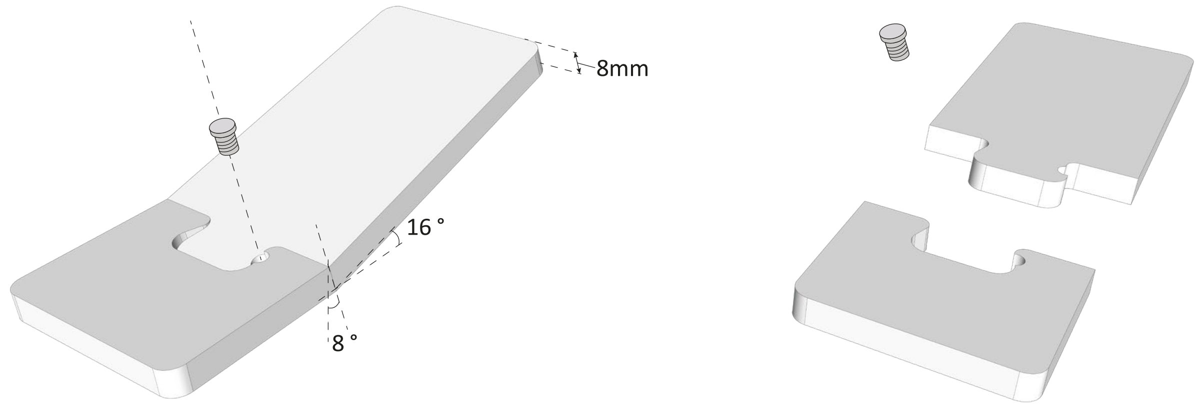


Figure 38. Part Assembly of Joinery method I – the pin was not threaded but we plan to use a self threading screw

8.3.1.6. **Results and Quality Check**

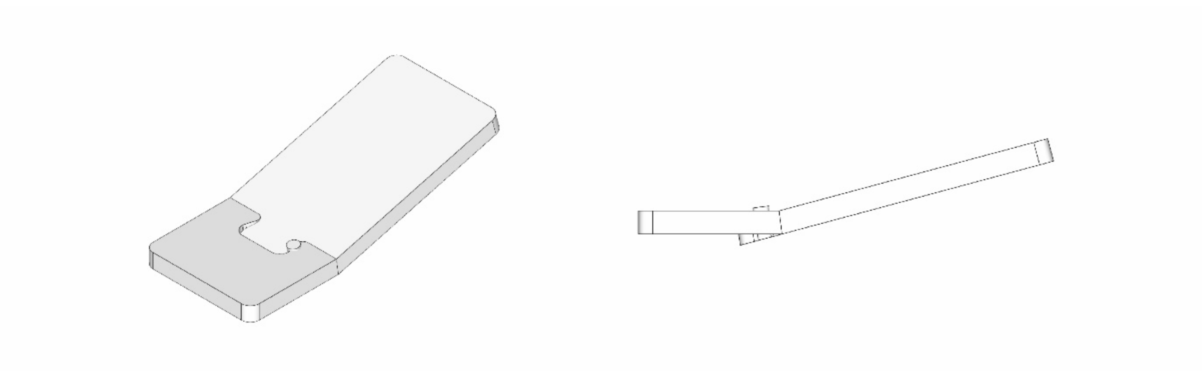


Figure 39. Assembled Joinery method I

It is suggested that instead of threading the hole, we can use a self threading screw of steel that would run through the hole.

The hole is conical but not a result of our design, but rather because of the machine.

The jet diameter is 1mm on top and 1.5mm on the bottom so that is a 0.5mm difference of stream diameter over 8mm of Aluminium

8.3.2. **Joinery Method II** – Half-lap and Pin

8.3.2.1. **Local Brief**

This was the second joinery method we experimented with. The plan was to create a joint that could allow us to link two pieces of variable planes. It was determined that since we are no longer working with wood, we could allow two of the final joint directions to exist as a single piece with the second piece interlocking in the previous piece with a pin to hold the pieces in place as we did in the first joinery method we experimented with; that would be one advantage of aluminium over wood. This time, the pin was chosen to be more visible.

8.3.2.2. **Design**

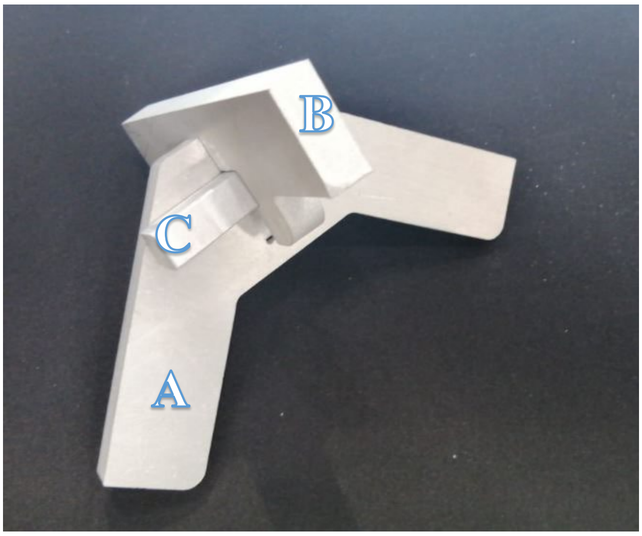


Figure 40. Joint II - Half-lap and Pin

The part A would be a piece of two nodes along two axes, we shall call them the X and Y axes for ease of explanation. The second part B would fit into the first piece at its angle by means of a half-lap joint. The pieces are kept in place with respect to each other by means of a wedge shape pin C that is inserted between the first piece and a connecting element deviated from the main body of the second piece.

8.3.2.3. **Materials and Dimensions**

The material chosen was Aluminium 1100. The thickness of the workpiece was 10 mm. The material finishing was Unpolished - matt. The end joint would be of 3 pieces (The 2 pieces to be joined and the wedge to hold them in place).

This cut used up 2 kg of Abrasive Material and 36 litres of water and took 7 minutes.

8.3.2.4. **Design for Manufacturing**

We will observe now, the dimensions of the pieces we cut.

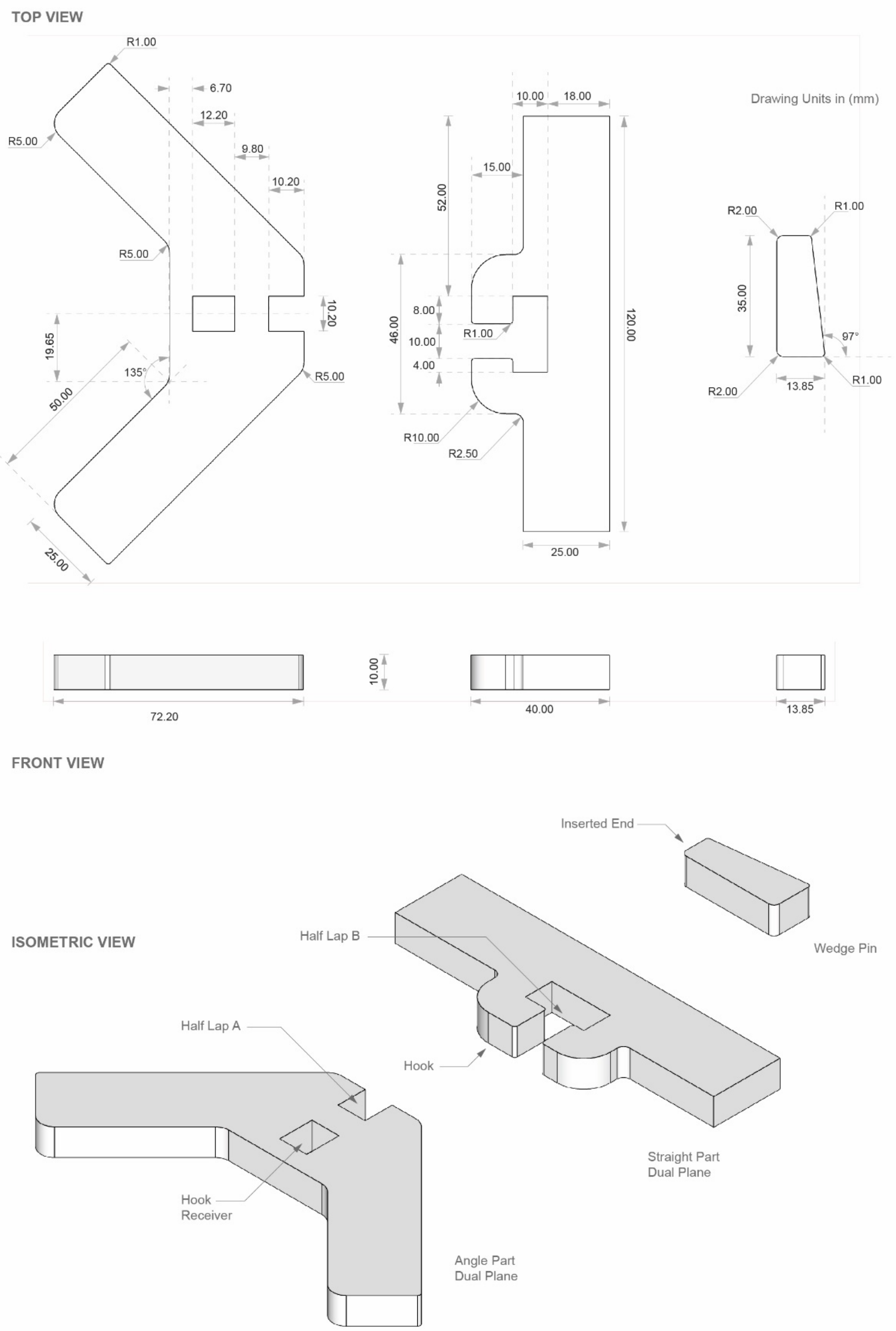


Figure 41. Dimensions and Isometric of the Joinery method II

8.3.2.5. **Assembly Steps**

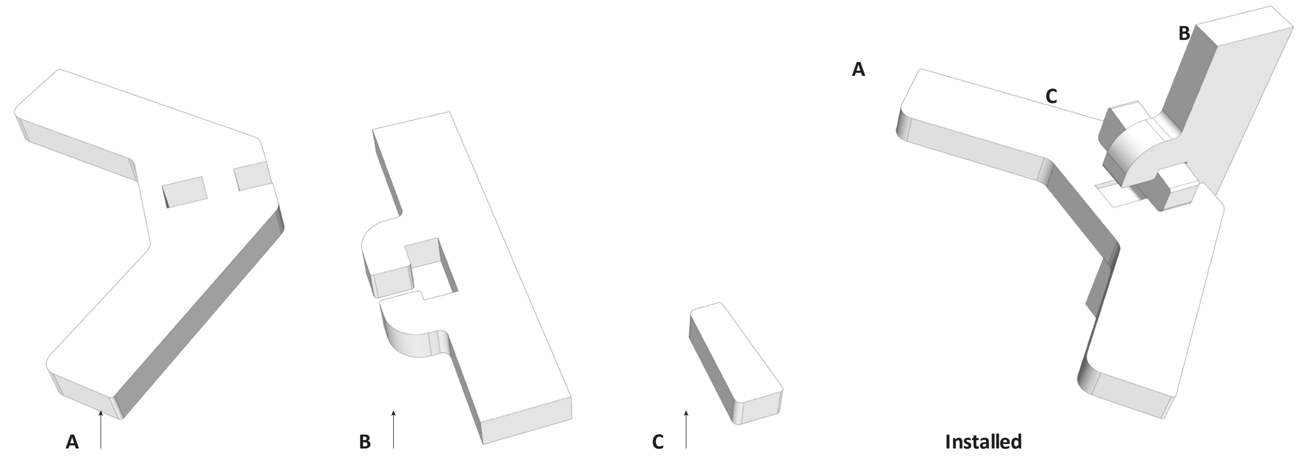


Figure 42. Part Assembly of Joinery method II

8.3.2.6. **Results and Quality Check**

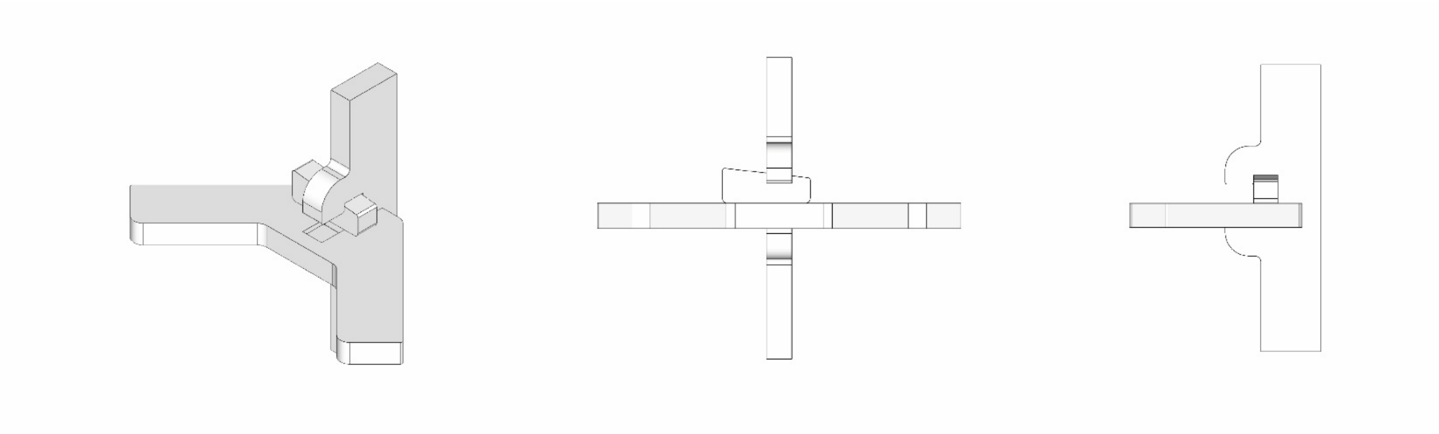


Figure 43. Assembled Joinery method II

The fillet that the machine is leaving at the corners is not allowing the pieces to fit as it must. A gap is forming. Multiple gaps are aesthetically unappealing and the joint is not stable. To eliminate this, loops are to be incorporated in the designs at the inward corners.

The loop is to have a radius greater than that of the jet [greater than 1mm] so the overall diameter of the loop has to be greater than 2mm and preferably not equal to 2mm.

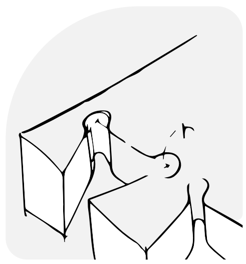


Figure 44. The Corner Loop

8.3.3. **Joinery Method III –** Multiple Flush Dovetails

8.3.3.1. **Local Brief**

This was the third joinery method we experimented with. After our first trial with the single dovetail, we needed to try the conventional dovetail where the entire node of the workpiece is cut to form several dovetails and the other is cut to receive the dovetails. We wanted to test the accuracy of the water jet and for that, we decided to not include an extra component to hold the pieces in place. In this scenario, the pieces were held together just by the joint.

8.3.3.2. **Design**

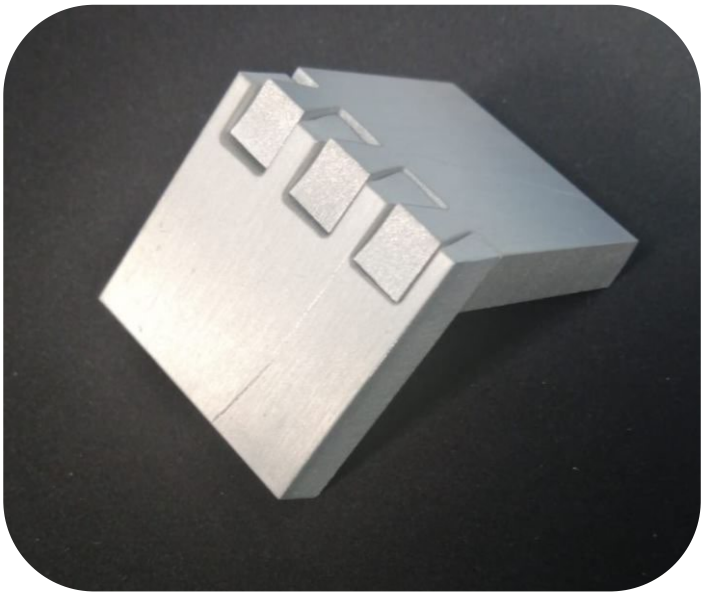


Figure 45. Joint III – Multiple Flush Dovetails

As mentioned earlier, we wanted this joint to be made of only two parts. It is very tricky and difficult for a craftsman to perform an angled continuous dovetail. Hence, we tried to perform it using the water jet cutter. We cut out two profiles and both had an angle. This design allowed us to measure the degree of reliability we were to expect from cutting.

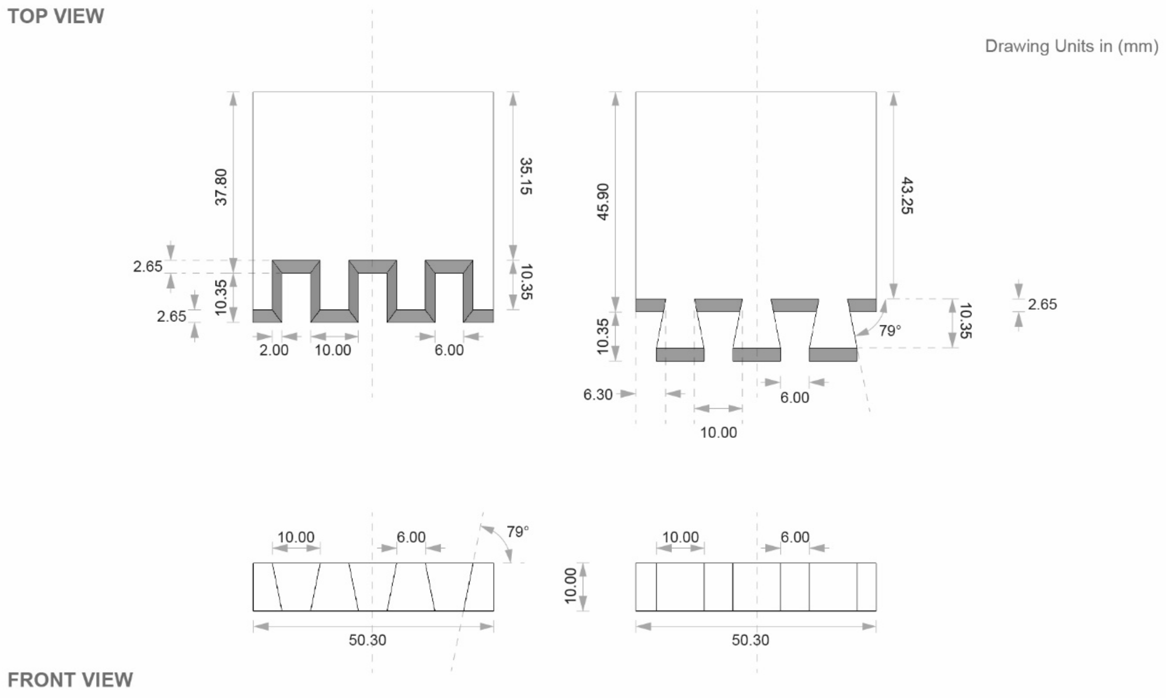
8.3.3.3. **Materials and Dimensions**

The material chosen was Aluminium 1100. The thickness of the workpiece was 10mm. The material finishing was unpolished - matt. The end joint would be of 2 pieces.

This cut used up 1 kg of abrasive material and 20 litres of water and took 4 minutes.

8.3.3.4. **Design for Manufacturing**

We will observe now, the dimensions of the pieces we cut.



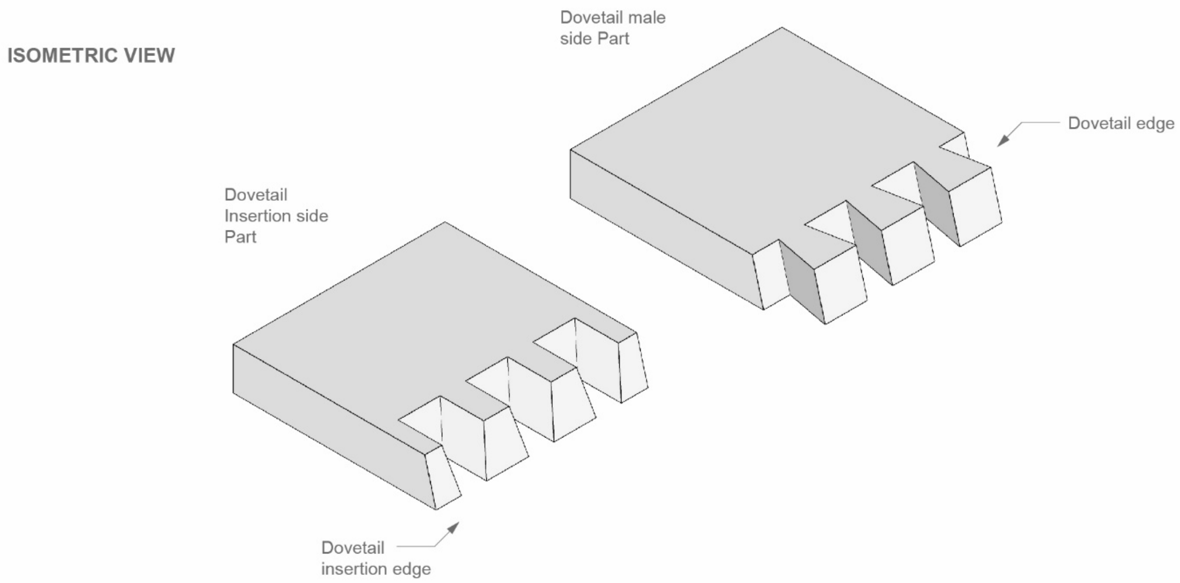


Figure 46. Dimensions and Isometric of the Joinery method III

8.3.3.5. **Assembly Steps**

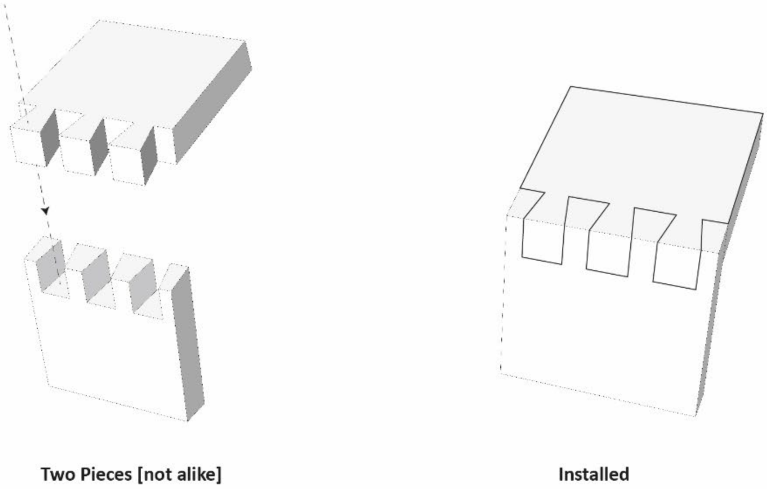


Figure 47. Part Assembly of Joinery method III

8.3.3.6. **Results and Quality Check**

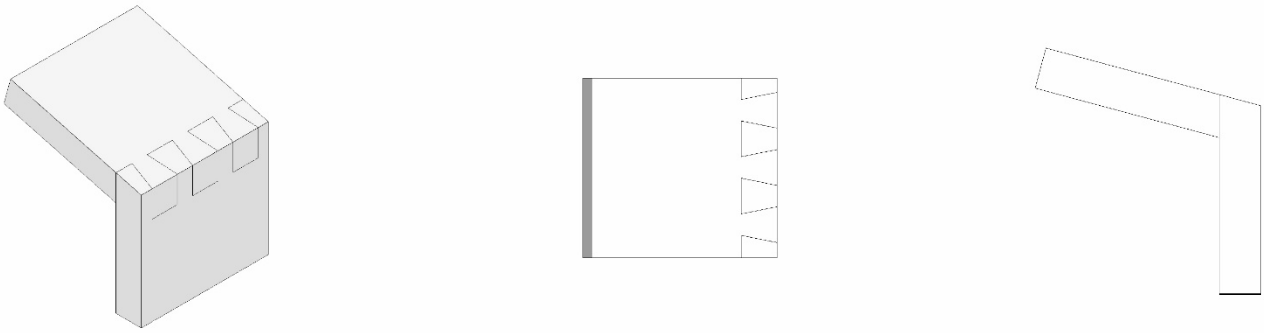


Figure 48. Assembled Joinery method III

The water jet left us with straight edges at the upper face of contact with the water jet. The exit face left very wobbly edges. When the pieces were joined, the gaps were very visible.

The speed of the machine has to be slowed down in an effort to reach a straight edge on the exiting face as well.

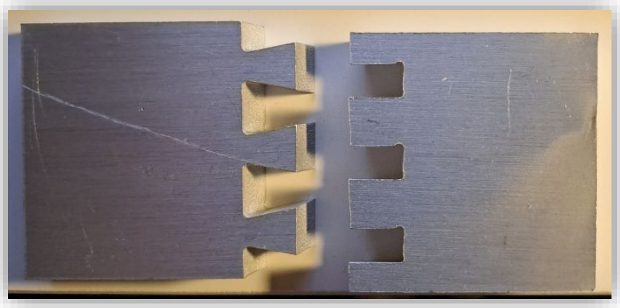


Figure 48a. Seeing the wobbly edges at the bottom (right) vs the straight cuts of the top (left)

8.3.4. **Joinery Method IV –** Mortise and Tenon

8.3.4.1. **Local Brief**

This was the fourth joinery method we experimented with. After testing the accuracy of the water jet with the previous joinery trials, we recalibrated the water jet cutter to adjust for all the mismatches. We wanted to create a mortise and tenon joint where we would show how we can connect an end piece to a flat piece at an angle (Like the connection of a table top to the table legs). In this scenario, the pieces were held together just by the joint itself.

8.3.4.2. **Design**

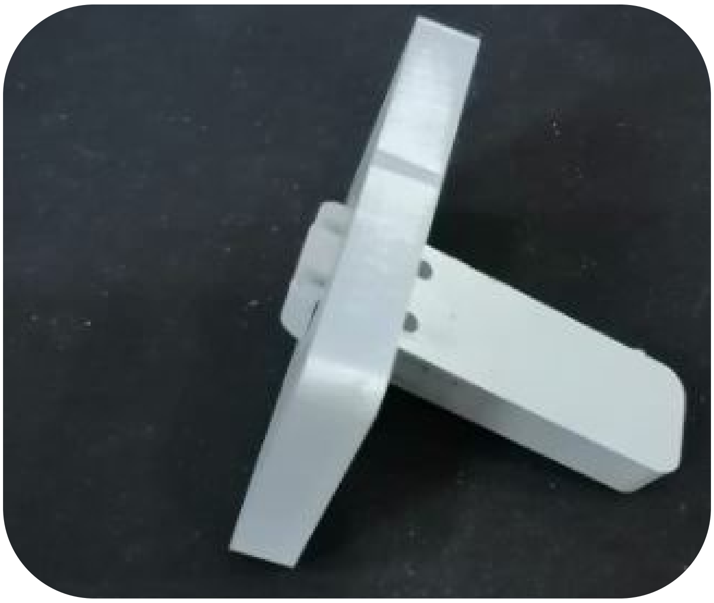


Figure 49. Joint IV – Mortise and Tenon

As mentioned earlier, we wanted this joint to be made of only two parts. This part had to include a shaft piece that fits into a flat piece at an angle and stay stuck in place by means of small tolerances exercised on the piece.

8.3.4.3. **Materials and Dimensions**

The material chosen was Aluminium 1100. The thickness of the workpiece was 10 mm. The material finishing was Unpolished - matt. The end joint would be of 2 pieces.

This cut used up 1 kg of abrasive material and 22 litres of water and took 4 minutes.

8.3.4.4. **Design for Manufacturing**

We will observe now, the dimensions of the pieces we cut.

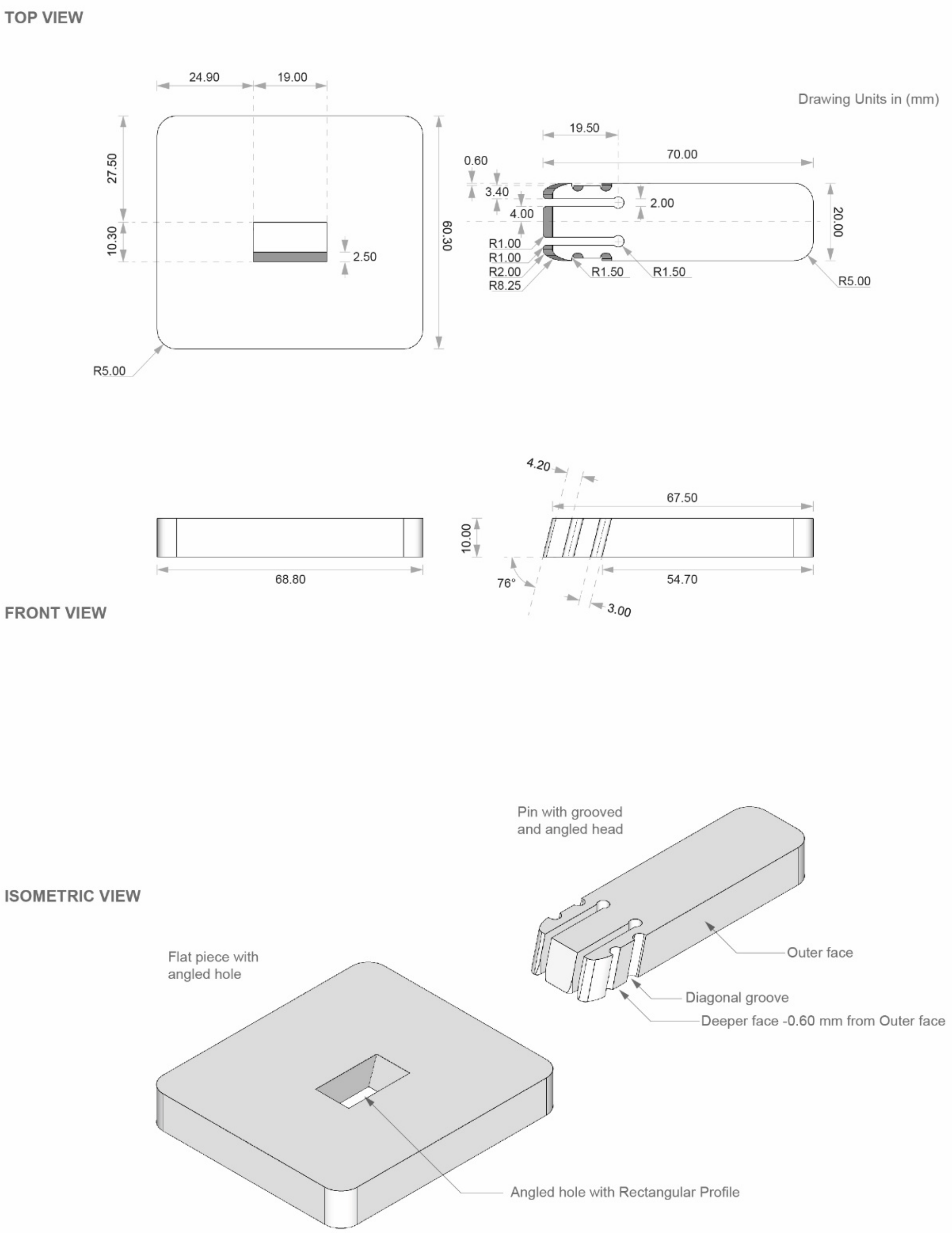
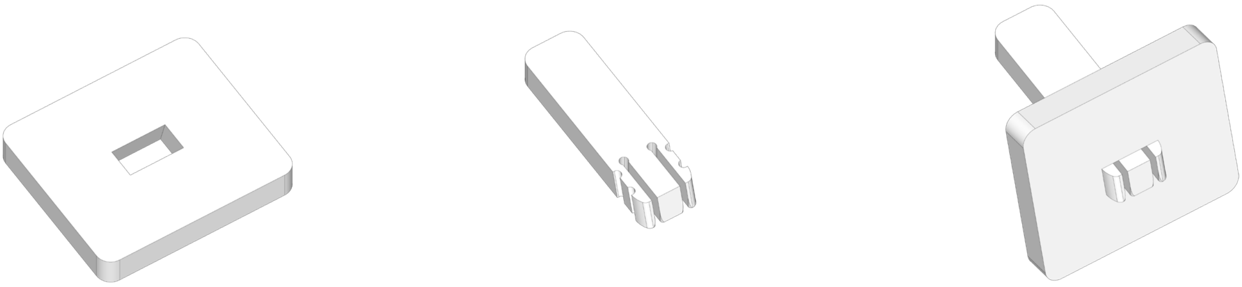


Figure 50. Dimensions and Isometric of the Joinery method IV

8.3.4.5. **Assembly Steps**



Hole **Key** **Installed**

Figure 51. Part Assembly of Joinery method IV

8.3.4.6. **Results and Quality Check**

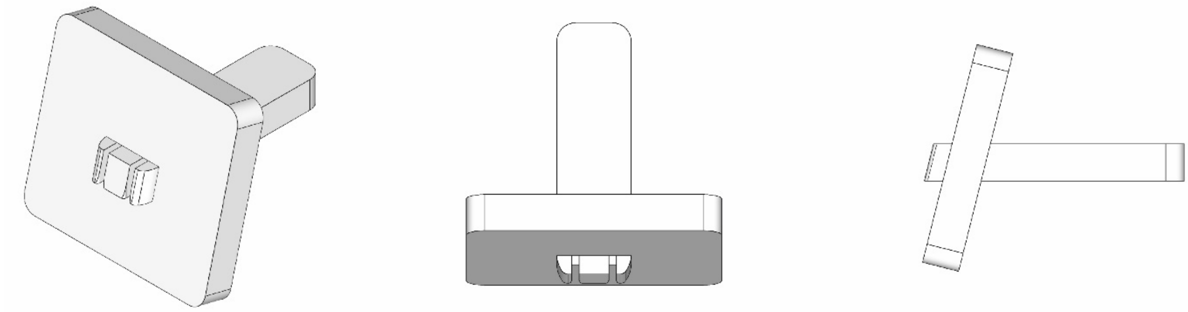


Figure 52. Assembled Joinery method IV

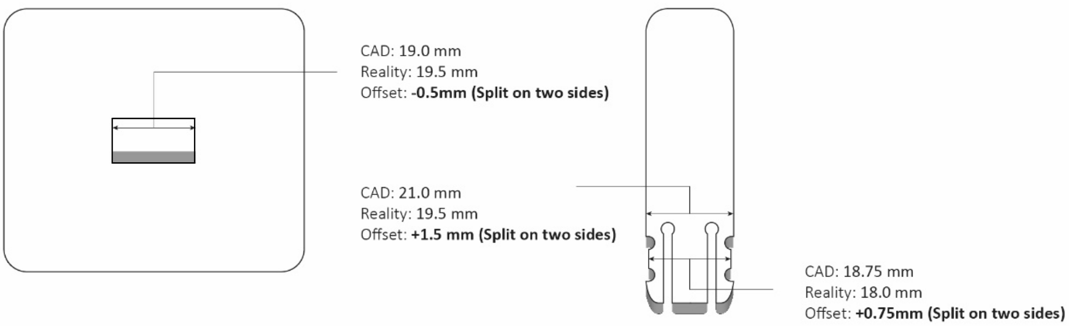


Figure 53. Discrepancies after Cutting

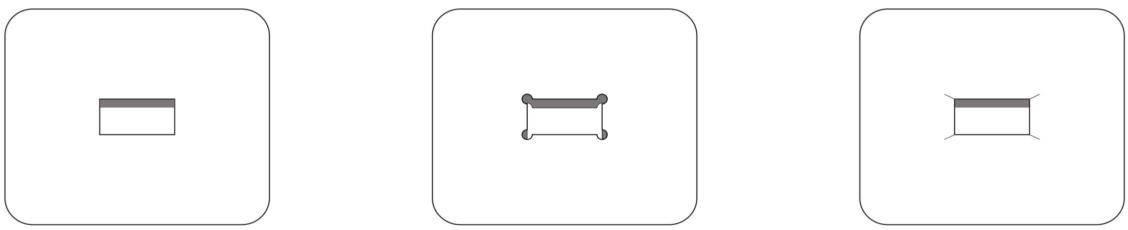
Great improvement was seen upon the correction of the hole part of the joint. By splitting the 0.5mm offset on the two flanking sides, we were able to obtain an exact 19mm opening. The old key was used and the 0.5mm difference was enough to hold it in place. However, the key has to be repeated as well with its own necessary compensation offset.

At the moment, we can see that the compensation offsets are differing between parts. Many factors are causing this:

- The sequence of the cuts (we note that the same sequence was used in the corrected/compensated part).
- The general geometry of the cut (to be observed in all other cuts to get a clearer idea).
- Machine vibrations (the metallic waves under the piece we are cutting) [We can find a way to fix the piece to the edge of the machine].
- The machine itself could be applying an error at a certain location or along the X or Y axes.

8.3.4.7. **Re-Design**

Instead of having to change the overall size of the gap, we relied on the way by which the water jet cutter operates. Since the smallest diameter of the jet stream in 1 mm across, instead of adding looped corners, we drew lines in the redesign CAD file and that was enough to ensure that the resulting corners will not have filleted edges but rather the corners would not exist at all in the sense that the corner itself was pushed away from the gap by making sure the line was directed outwards of the gap as seen in the figures.



Initial Hole Part - 1

Notes

From previous testing, we understood that there is no way of cutting an angle without a fillet. Ofcourse this fillet in the circular radius of the water jet stream.

Hole Part - 2

Notes

In an effort to obtain a 90 degree filletless angle, it was proposed to add small loops at the corners where necessary

Hole Part - 3

Notes

It was then proposed to use the actual characteristics of the waterjet to resolve the issue. A simple CAD line was added at the corner and the machine relieved us of the fillet

Figure 54. Steps of the Re-designing process

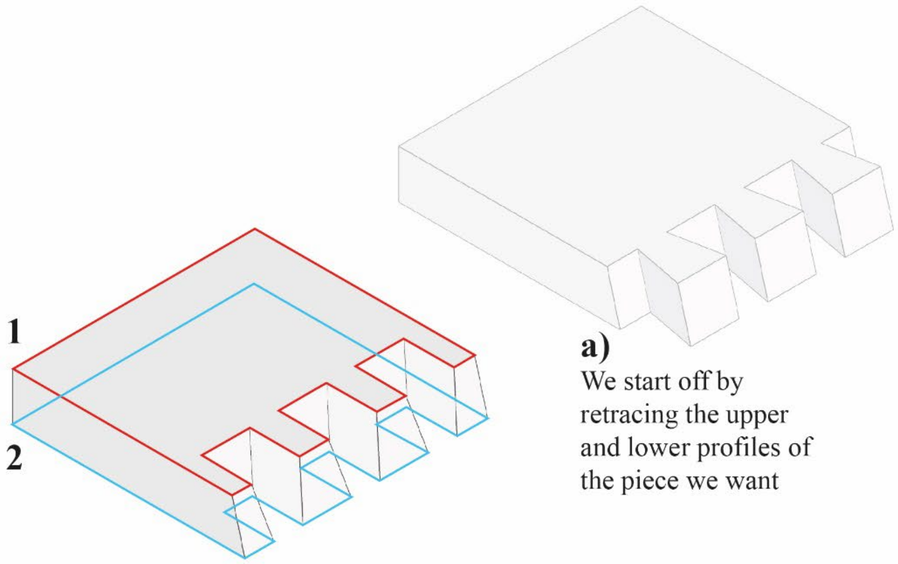
Figure 55. Loops versus Lines

8.3.4.8. **Results and Quality Check**

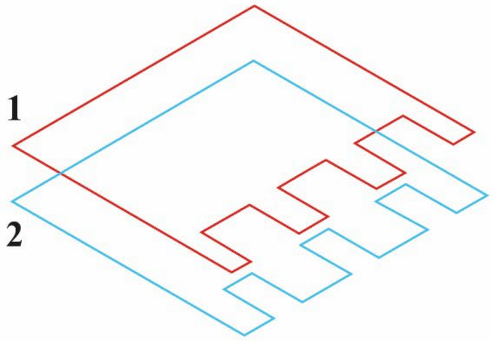
The results were exceptional. We were right to change the loops into simple lines. It saved time and resources and ensured a gap no larger than what is necessary. We would apply a cut-line-corner wherever applicable as in joinery method II where we have a pin being inserted. The pin is a wedge and is not of a circular profile, hence, this design change can be implemented there as well to result in a better fit.

8.4. **How to Cut at an Angle**

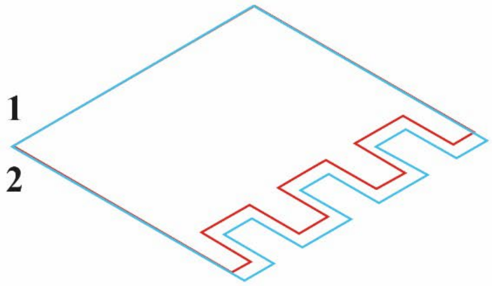
One of the greatest advantages of the 5-axis water jet cutter is the ability to cut at an angle. To do so requires no intervention at the level of the physical set-up of the machine itself. However, the CAD file to be used has to be well designed and must include two layers with one representing the top profile of the part to be cut and the other representing the lower profile. Upon setting the two profiles, the file has to be imported into the software of the respective water jet cutter and the two layers have to be specified as either top layer or bottom layer with the distance between them set in the machine to be similar to the thickness of the material to be cut. Below, we can see the example of the third joinery method and how we were able to accomplish it using the 5-axis water jet cutter.



a)
We start off by retracing the upper and lower profiles of the piece we want



b)
We move the profiles to a separate file



c)
We place the two profiles over each other.

d)
In the software that is directly connected to the water jet cutter, we identify which is the upper profile and which is the lower with the thickness of the material between it

Figure 56. How to perform an angled cut using the 5-Axis water jet cutter (Example of the Multiple Flush Dovetails

8.5. **Kerf Compensation**

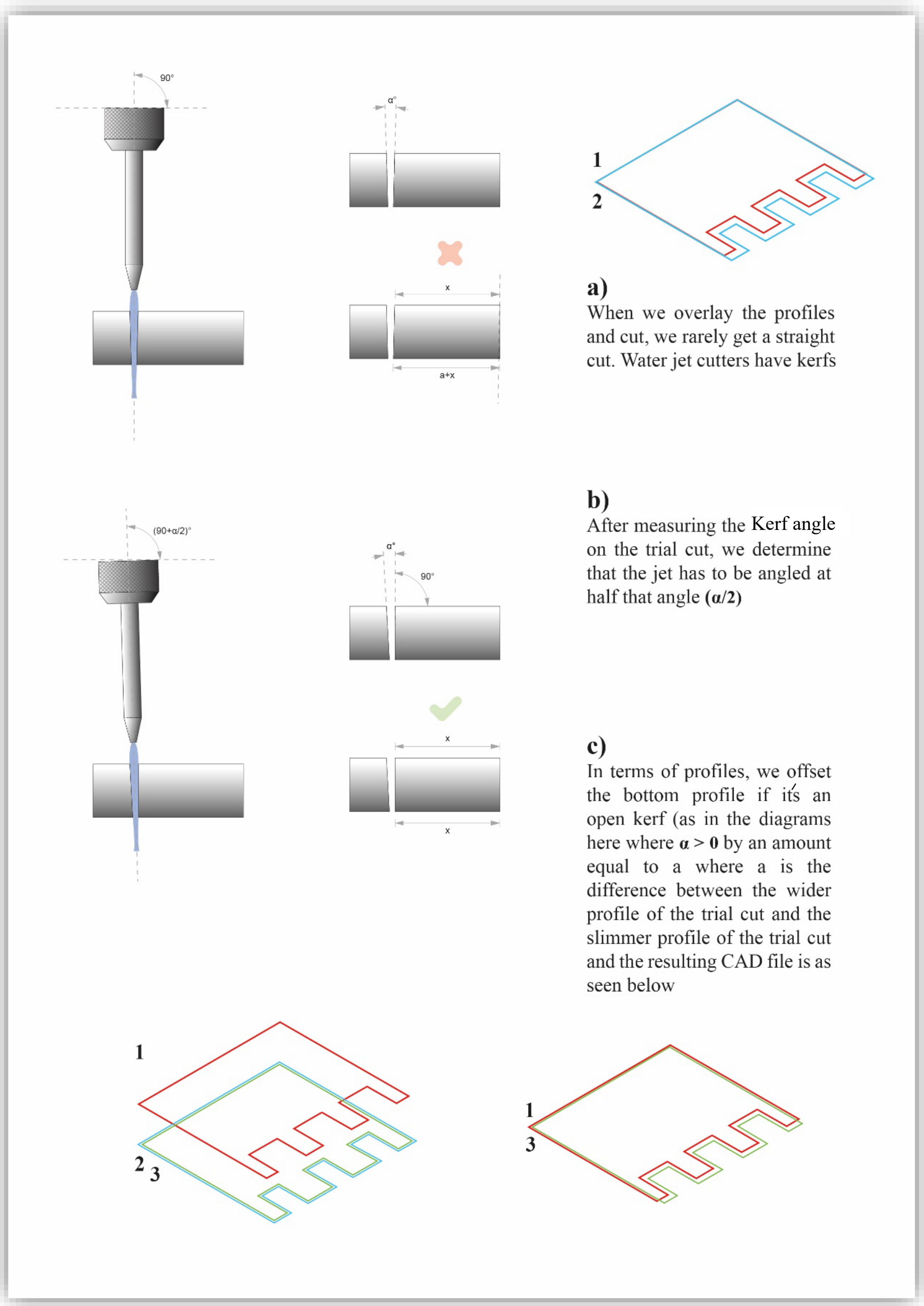


Figure 57. Method by which to compensate for Kerf

9. Resulting Guideline

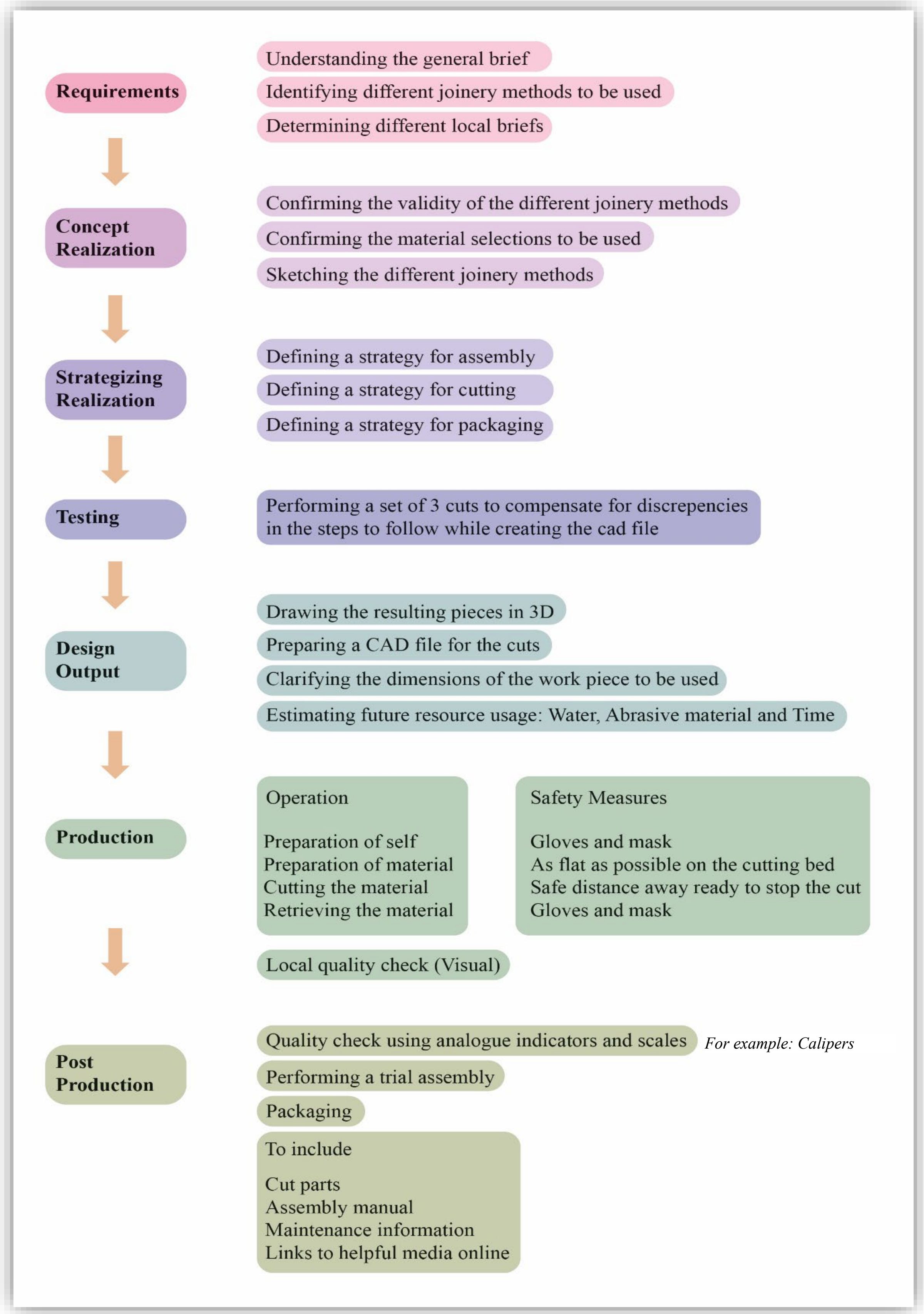


Figure 58. The resulting guideline to cutting joinery with a 5-axis water jet cutter

10. **Conclusion**

In the thesis, we set to display the validity of the 5-Axis water jet cutter as a means to create products ready to be assembled directly after it has been cut. One can directly draw a plan in their minds of how this could be done. But since there are no set guidelines that trace the interference of both fields, we set it upon ourselves to create it.

We discussed a brief history of joinery and how it exists all around us in all kinds of shapes and sizes. We focused on wooden joinery and took it to its roots to better understand the smallest parts and concepts relating to the field.

We went on to discuss the water jet itself and how it remains a majestic giant in the world of production and manufacturing. Just as is the case with joinery, there is no apparent limit to what this process can be part of. Water jet cutting is used for all that ranges between cutting cucumbers at a factory to creating parts for space rockets.

Most importantly, we were able to see how classical joinery methods translated into new forms at totally new strengths using aluminium, in our case, cut by a 5-axis water jet cutter. Complex assemblies requiring glue and mechanical fasteners were reduced to less parts using the physical characteristics of new materials. Less parts, as we had stated earlier, means an easier job assembling the fixtures and less time to become a usable product.

The guideline came as a result of the demonstrative experiments that took place during my tenor as an intern working in a laboratory housing several machines with one of them being the 5-axis water jet cutter.

Upon following this guideline and paying attention to the steps and the safety measures, an aspiring designer, manufacturer or any creator is able to broaden their sense of what can be performed with the means at hand and again we restate that the possibilities we have resemble in quantity the amounts of types of materials we can cut – infinite.

11. References

(1) Online source: International Timber website: internationaltimber.com <https://internationaltimber.com/resources/whats-the-difference-between-a-carpenter-and-a-joiner/>

(2) Online source: <https://www.nature.com/articles/507166a>

(3) Online source: <https://www.nature.com/articles/d41586-020-03378-y#:~:text=The%20earliest%20evidence%20for%20woodworking,clinging%20to%20stone%20hand%20axes>

(4) Huntley, Michael (20 January 2009), "Michael Huntley demystifies the furniture making techniques of Chinese craftsmen prior to 1900", Wood Worker's Institute, GMC Publications, archived from the original on 22 January 2013

(5) Online source: <https://ProWoodworkingTips.com/>

(6) Wood Movement, WoodworkDetails.com Archived 2012-12-15 at the Wayback Machine

(7) Bob Hunter (December 20, 2006). "Visiting Fein and Festool Power Tools in Germany". Wood. Retrieved November 23, 2020.

(8) Online source: <https://www.thesprucecrafts.com/how-to-make-a-butt-joint-3536619>

(9) Online source: <https://www.thesprucecrafts.com/mitered-butt-joints-3536614>

(10) Online source: <https://www.thesprucecrafts.com/basic-joinery-half-lap-joints-3536621>

(11) Online source: <https://www.thesprucecrafts.com/creating-a-mortise-and-tenon-joint-3536636>

(12) Online source: <https://www.thesprucecrafts.com/tips-for-better-biscuit-joints-3536610>

(13) "Dovetail | Etymology, origin and meaning of dovetail by etymonline". Retrieved from online source: <www.etymonline.com. Retrieved 2022-03-09>

(14) Gelber (1997). Do-It-Yourself: Construction, Repairing and Maintaining Domestic Masculinity. American Quarterly. doi:10.1353/aq.1997.0007

(15) Ancient Building Came With DIY Instructions Archived 30 January 2012 at the Wayback Machine, Discovery News, Mon Apr 26, 2010

(16) eCirc for Consumer Magazines". Alliance for Audited Media. December 31, 2012. Archived from the original on April 18, 2014. Retrieved June 21, 2013. Retrieved from online source: <https://www.popularmechanics.com/>

(17) Online source: <https://www.positivevision.biz/blog/how-manufacturers-need-to-respond-to-changing-market>

(18) Online source: <https://www.youtube.com/watch?v=TOq3Bgln_K0>

(19) Online source: <https://www.artofmanliness.com/living/leisure/7-skills-you-should-have-learned-in-high-school-wood-shop/>

(20) Franz, Norman C., High Velocity Liquid Jet Archived 2014-01-31 at the Wayback Machine, filed May 31, 1968, and issued August 18, 1970.

(21) Hashish, Mohamed, Michael Kirby and Yih-Ho Pao, Method and Apparatus for Forming a High Velocity Liquid Abrasive Jet Archived 2014-02-27 at the Wayback Machine, filed October 7, 1985, and issued March 10, 1987.

(22) Online source: <https://www.iqsdirectory.com/articles/water-jet-cutting.html>

(23) Online source: <https://formlabs.com/blog/additive-manufacturing-vs-subtractive-manufacturing/>

(24) Jameson, E. C. (2001). Electrical Discharge Machining. SME. ISBN 978-0-87263-521-0. Archived from the original on 2011-09-28.

(25) Online source: <https://www.resato.com/en/knowledge-center/blogs/five-benefits-of-waterjet-cutting>

(26) Online source: <https://ballardmachineworks.com/2016/07/02/advantages-disadvantages-waterjet-cutting/>

(27) Online source: <https://www.intermac.com/en/stone/waterjet-cutting-machines/primus-series-2>

(28) "Waterjet Relationship Parameters". Archived from the original on 2010-09-09.

(29) Online source: https://www.techniwaterjet.com/waterjet-vs-edm-cutting/

12. Picture References

(1) https://www.artisanboatworks.com/wooden-boat-restoration

(2) https://www.turbosquid.com/it/3d-models/old-wooden-wagon-2-max/941019

(3) https://fineartamerica.com/featured/old-wooden-house-in-field-michael-interisano.html

(4) https://jro-furnituremaker.com/section/198142-Furniture.html

(5) https://logic-bespoke.com/why-does-timber-move/

(6) https://www.branchingoutwood.com/blog/tools-iii-veneer-tools-intro-dovetails

(7) Charts redrawn from slides and lectures taken during the masters studies – Manufacturing Course

(8) https://flowwaterjetblog.com/2015/03/10/so-what-is-stream-lag-taper/

(9) https://www.performancewaterjet.com.au/how-waterjet-works

(10) Various generic material libraries

(11) https://www.canadianmetalworking.com/canadianmetalworking/article/cuttingtools/the-versatility-of-multifunctional-milling-tools

(12) https://www.kirkstallprecision.co.uk/cnc-turning/

(13) https://www.penntoolco.com/blog/the-different-types-of-drill-presses/

(14) https://get-it-made.co.uk/resources/what-is-electrical-discharge-machining

(15) https://www.lasersystemseurope.com/feature/cut-above-thick-plate-processing

(16) https://www.sigma-vvu.cz/en/products-and-services/cooperation-in-production/water-jet-cutting/

(17) https://www.resato.com/en/knowledge-center/blogs/the-versatile-possibilities-of-waterjet-cutting

13. **Thankyou Note**

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-Samer