MASTER THESIS
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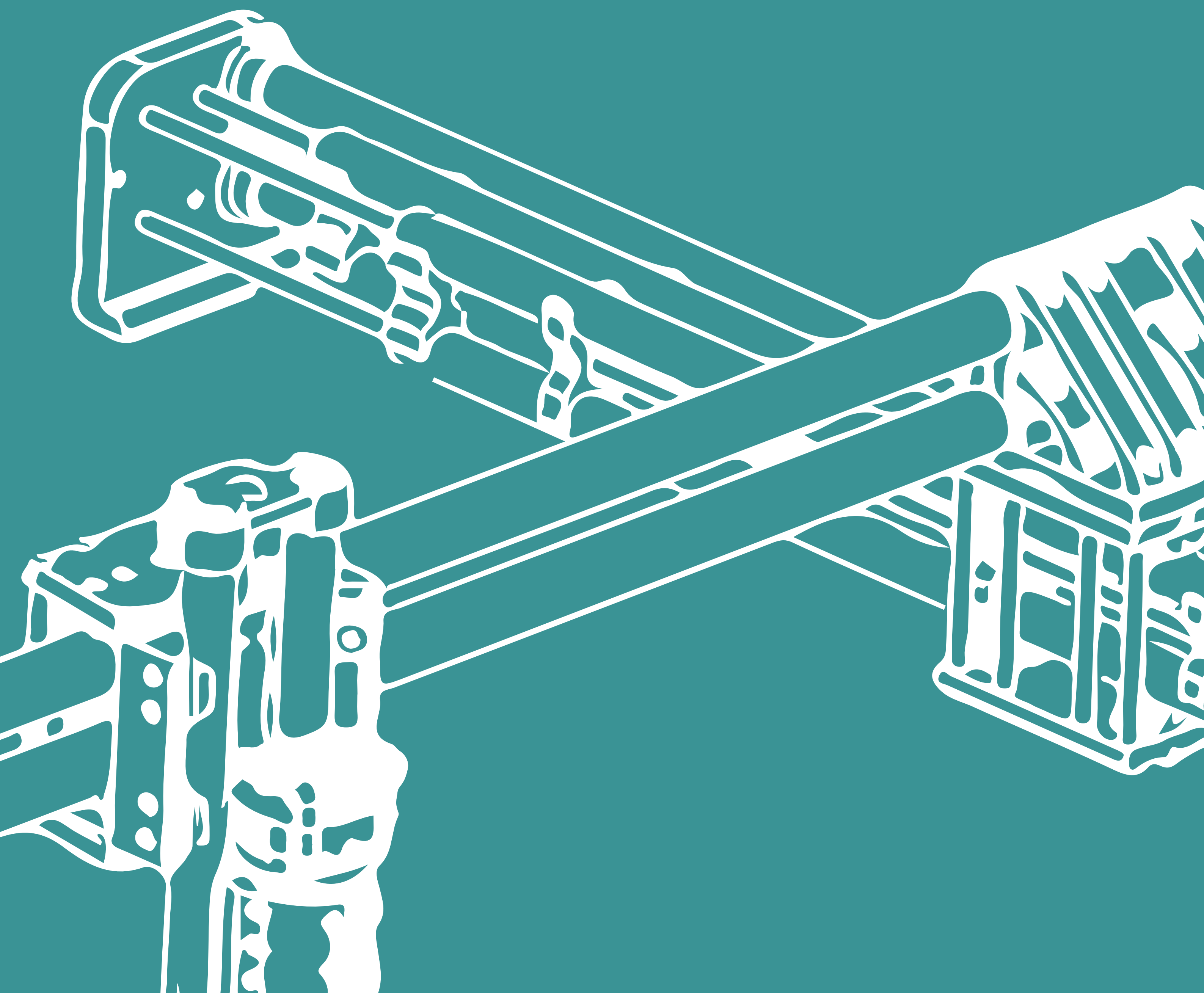
DESIGN OF A RESIZABLE CNC ROUTER



Design of a resizable Computer Numerical Control Router

Master of Science
Integrated Product Design

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PREFACE

This thesis is part of the final evaluation of the Master Integrated Product Design at the Delft University of Technology.
This graduation project differentiates itself from regular and more conventional projects since no company or 'project owner' is involved. This project has been set up and created from my own personal ambitions, motivation and interests.
Because of the lack of a project owner, other than myself, it has at times proven difficult to pinpoint certain aspects regarding the context of the project. In a more conventional graduation project the context can be related to the company in question. However during this project this context had to be explored and researched beforehand. Since the context had been derived from my personal ambitions and motivations. This has led to a different method of researching during the project compared to the more conventional approach.

By taking a closer look at existing solutions and machines, a better understanding and possible requirements can be derived to successfully achieve this assignment. A number of fitting design tools, techniques and methodologies have been implemented during this project. Figure 1 shows a visual overview of the design process taken, in order to successfully finish the project. The process can be categorized into three different phases; The Research/Analysis Phase, The Idea Generation Phase and the Embodiment/Materialisation Phase.
For an elaborate explanation of the three design phases and their respective methods see appendix B – Design Approach.

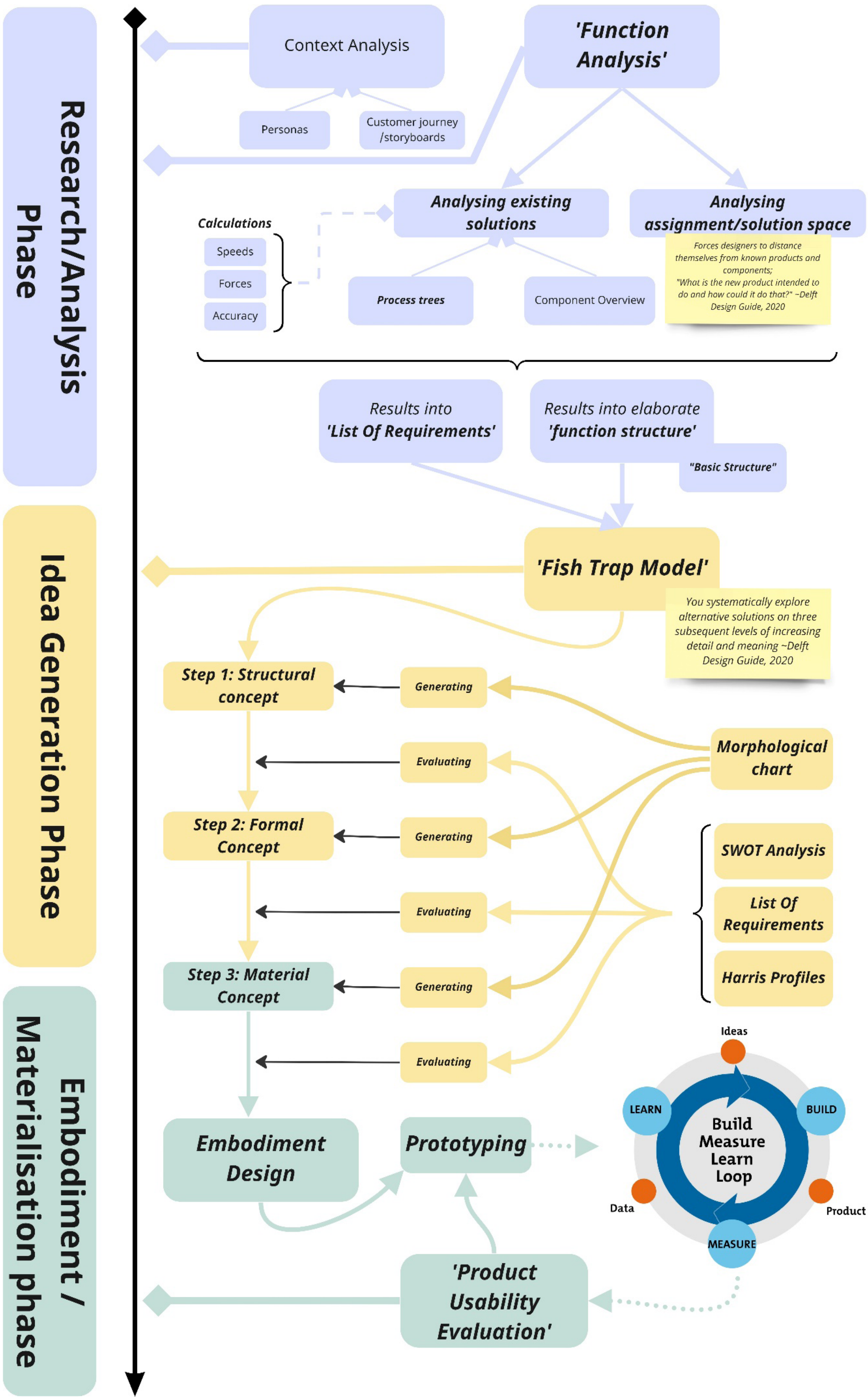

Figure 1: Design process

ACKNOWLEDGEMENTS

First of all I would like to start with expressing my gratitude to my family and friends. They have been a great help during the duration of this graduation project. I would like to thank them for providing me with words of encouragement and motivation when needed. As well as helping me carry my prototype around campus and up to the fourth floor of the faculty when we thought it would not fit in the elevator.

Secondly I would like to thank my supervisory team; Ruud van Heur and Adrie Kooijman. Not only have they been a great help in terms of supervision but they knew how to challenge and help me, in order to motivate when needed. They were also are not afraid to give me a figurative ‘schop onder de kont’. Which I really appreciated and also needed at some points during the project.
The supervision and the, at times, critical view during, and outside, of the meetings have greatly helped with achieving the results documented in this thesis.

Finally I would like to thank Jongeneel Schiedam with Jaap van Helden and Richard Waanders in particular. I would like to thank Jaap for arranging a visit to the Timber and Building Supply mill in Utrecht and Richard for allowing me to film my prototype at the timber and building supply shop at Jongeneel Schiedam.

ABSTRACT

Computer numerical control (CNC) routers, mills and lasers have enabled engineers, designers and hobbyists to create various complex forms and designs through the process of subtractive manufacturing. Whereas CNC-routers and -lasers are generally used to machine flat 2D shapes out of stock sheets of various kinds of materials, CNC mills are used to create full 3D designs. Even though the machines are capable of creating very intricate and detailed parts, the machines themselves are very large and rigid contraptions. Owning a CNC machine often involves making the decision of either giving up a large amount of workspace, simply to be able to house the machine itself and manufacture large parts. Or saving space by choosing a desktop style CNC machine which comes at the cost of a smaller build area and lesser capabilities.
In order to allow the user to not have to choose between workspace or build area the following design statement was created;

Designing a 'one size fits all' resizable CNC router to enable designers, engineers and hobbyists to manufacture (large) parts without the need to compromise valuable workspace. Providing true flexibility to the user in terms of work- and build area.

This design statement laid the foundation for the entire project. In order to fulfil the statement, a resizable CNC router was designed and a fully functional prototype was created.

The concept of this resizable router was achieved by taking a closer look at existing solutions and machines as well as the different users and contexts in which the machines operate, in order to gain a better understanding and derive requirements for the design. The process taken during the project could be categorized into three different phases; The Research/Analysis Phase, The Idea Generation Phase and the Embodiment/Materialisation Phase. A number of fitting design tools, techniques and methodologies have been implemented during the three different phases of the project. Respectively the most important design tools/techniques that have been implemented were;
A 'Function Analysis' which resulted in a 'Function Structure' (which formed the basis for the List of Requirements), 'The Fish Trap Model' which was used to generate ideas and create the concept and finally the most important model used during this project was the 'Build Measure Learn' (BML) loop. The Build Measure Learn loop was kept in mind during the entire process of this project, it describes a process of prototyping, evaluating and reiterating in order to create functional and valuable prototypes in a fast-paced manner.

With the help of the previously mentioned design tools, methods and techniques a design was realized for a resizable CNC router. This design was supported and evaluated with the help of the creation of a fully functional prototype.

INTRODUCTION

01

Computer numerical control (CNC) routers, mills and lasers have enabled engineers, designers and hobbyists to create various complex forms and designs through the process of subtractive manufacturing. Whereas CNC-routers and -lasers are generally used to machine flat 2D shapes out of stock sheets of various kinds of materials, CNC mills are used to create full 3D designs. Even though the machines are capable of creating very intricate and detailed parts, the machines themselves are very large and rigid contraptions. Owning a CNC machine often involves making the decision of either giving up a large amount of workspace, simply to be able to house the machine itself and manufacture large parts. Or saving space by choosing a desktop style CNC machine which comes at the cost of a smaller build area and lesser capabilities (see figure 2). Since currently no machine provided the user with a balance between the actual physical footprint of the machine itself and the build area itself a market gap can be identified. This market gap provides an opportunity to provide the user with a grip on flexibility in terms of work- and build area.

Figure 2: Size comparison of a professional CNC machine (left) and a desktop CNC machine (right)

PROBLEM DEFINITION

02

The desire to have a grip on true flexibility in terms of work area is not something new. Different users (engineers, designers, makers and technical personnel) have tried to tackle this desire to save space when owning a CNC machine. A more recent development in this field is the mounting of the entire machine to a wall or foldable workbench(see figure 3). Both ‘solutions’ do in fact provide a way to save work area on the literal work floor by moving the machine to a wall or folding it out of the way for storage purposes. However for both scenarios the user is still limited and constricted to the dimensions of the mounted CNC in question. This limits the user in gaining a true flexibility in terms of work area in the workshop as well as build area of the machine itself.

Figure 3: Wall mounted (left) / Foldable workbench (right)

Providing an all-in-one and ‘one size fits all’ solution to the previously mentioned problems will be the goal of this graduation project. Being able to manipulate the X-, Y- (and Z-) axes of the machine to every desired dimension, at every given moment, enables users to resize the entire machine to the (at that time) available space. The ability to resize the router to every desirable dimension enables the user to decide how much workspace the router will occupy and for how long. The user could resize the router to its largest dimensions to be provided with a very large build area. While resizing the router to its smallest dimension will provide an easy way of storing the machine when the operations are complete. This provides the user with true flexibility in terms of work area in the workshop as well as build area of the machine itself.
Because of the flexibility of the machine, a ‘on size fits all’ style of designing can be achieved when looking at the target groups. Even though the context of the machine will be more targeted towards the ‘casual’ users and the ‘semi-professional’ users, the flexibility and versatility of the machine enables it to be implemented in a lot of different contexts and work environments.

ASSIGNMENT

03

Designing a 'one size fits all' resizable CNC router to enable designers, engineers and hobbyists to manufacture (large) parts without the need to compromise valuable workspace. Providing true flexibility to the user in terms of work- and build area.

For this project a CNC router will be used as case study. The biggest challenge that will be addressed during this project will be the mechanical aspects of the machine. Creating resizable axes while maintaining a stiff construction for the router to function, will be the main concern. Manipulating the X- and Y- axes at every moment to the desired dimension is a key element to this design. Another large aspect of the machine that will be addressed during this project will be that of the 'ease of use'. Enabling users to resize the machine to their liking will only be beneficial when designed with the ease of use in mind. When resizing the router will prove either too difficult (which mostly relates to the casual users and users without a technical background), or too time consuming(which relates to the professional users, such as engineers and other technical personnel, for whom time is money), users will disregard this aspect of the machine. To limit the scope of this project the router will be limited to cutting softer types of wood such as spruce and poplar, instead of (soft)metals such as aluminium. Reason being that to be able to machine metals, a much stiffer construction is required in comparison to machining wood.
The design of the CNC router will be delivered in the form of a prototype to illustrate the outcomes of the project. This prototype will be used as a demonstrator during the final presentation.

ANALYSIS

In this chapter a number of analyses have been performed, these analyses can be categorized by a general analysis of CNC routers, a context analysis and finally an analysis of the resizability and therefore of the assignment itself.

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4.1 CNC Routers general analysis

CNC machines are used for precise cutting, drilling and shaping of materials. As mentioned before, the three most common types of CNC machines include: CNC- routers, mills, and lasers. While they do share a lot of similarities in terms of function, there are significant differences between them in terms of their use cases.
CNC Routers are primarily used for cutting, drilling and routing wood, plastics, and non-ferrous metals. They typically have a large table with a spindle that moves in multiple directions to achieve precise (mostly 2D) cuts.
CNC Mills, on the other hand, are again used for the cutting, drilling and shaping of multiple types of metals. CNC- mills are typically more expensive than CNC- routers, but they are also more versatile and have a higher level of precision. They are mostly utilized to create 3D shapes.
CNC Lasers, as the name suggests, use a laser to cut and engrave materials, including wood, acrylic, glass, and metals. Unlike CNC routers and mills, CNC lasers do not use physical cutting tools, which makes them ideal for intricate and detailed designs.
As mentioned before in chapter ‘Assignment’, the CNC router will be used as a case study during this project. Figure 4 shows an illustration of a general CNC router.

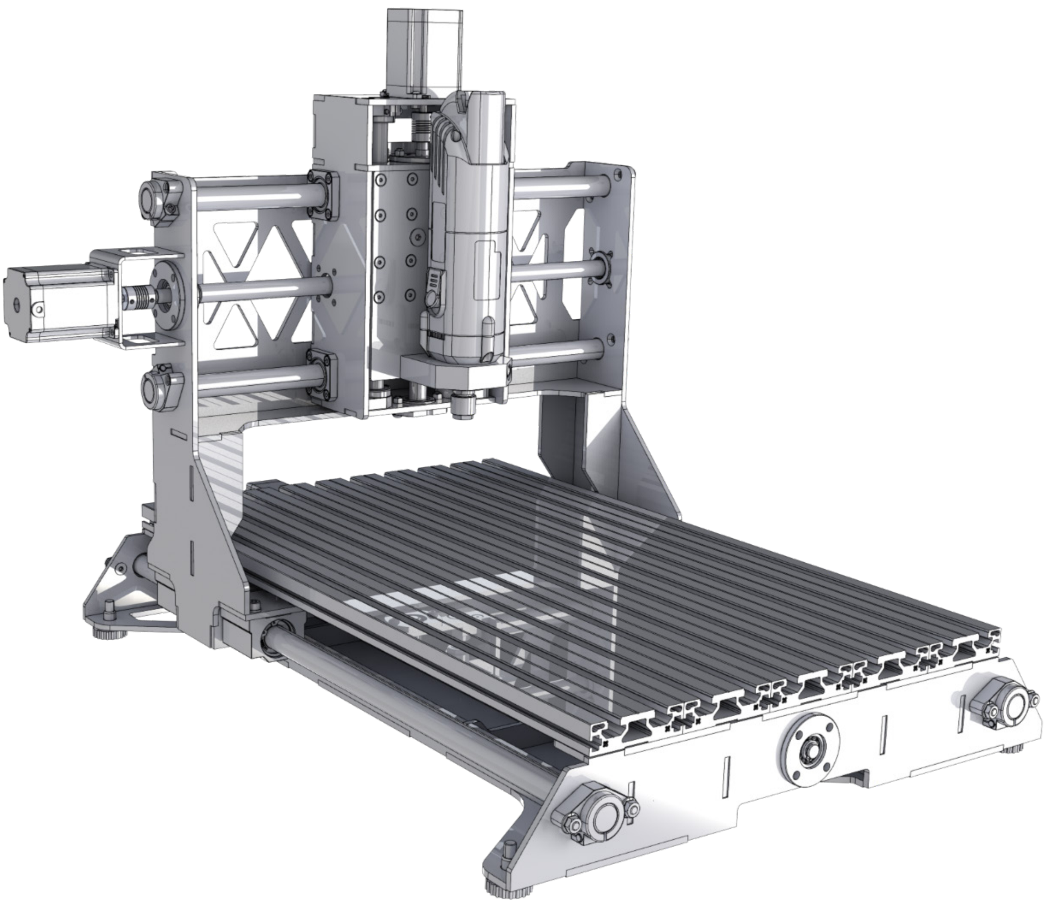

Figure 4: General CNC router

4.1.1 Working principle

Generally speaking a CNC machine works by translating the rotational movement of a motor to a linear motion.
However before the machine can create a movement it needs information from the user which type of motion is required. The working principles of CNC machines are based on the execution of G-Code(MARLIN, 2023), which is a programming language used to control and direct the movements of the machine.
G-Code is a series of commands that define the exact movement and the speed of the machines components. These commands are interpreted by the CNC machine's control software, which then translates them into movements of the machine's components such as the motors.
The entire process of using a CNC machine can be organised into three steps(See figure 5); CAD, CAM and Cut(Winston Moy, 2017).

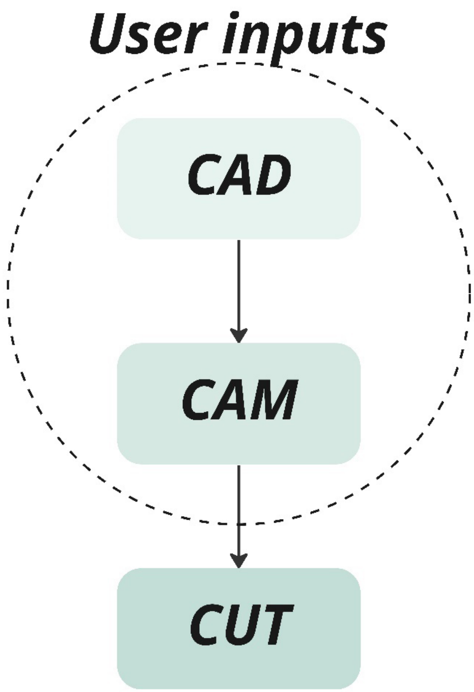

Figure 5: General CNC workflow

Starting with CAD (Computer-Aided Design); Creating a 3D model. Acquiring this 3D model in real-life will be the machining end goal of the entire operation.
The next step in the process is CAM (Computer-aided Manufacturing); defining the process required to machine the 3D model from a stock piece of material. This step is done by the user and will determine how the machine actually will machine the model. This process will lead to a G-Code that can be used for the final step of the operation.
Cut; Executing the G-Code to acquire the 3D model in real life, which is machined from the stock piece of material.

Both the steps of CAD and CAM can be classified as user inputs and will vary for each operation. The final step; cut, however will remain the same for each of these different operations.
Figure 6 shows the steps that follow the general function of every CNC router; Cutting material to shapes and dimensions that have been specified by the user.
Achieving this general function is done by moving a cutting tool(spindle or router) to specific X-, Y- and Z- coordinates throughout the machine's available working area. To achieve this movement motors are actuated and their rotational movement is translated to a linear movement. This translation can be done in a number of different ways. To translate the rotational movement of the motor to a linear motion within the axis, the motor can be connected to a screw, a belt or a gear rack. This connection can be achieved by making use of couplers in case of a screw, pulleys in case of a belt or a pinion in case of a gear rack. To keep the linear motion on track and guiding this across the axes a guide is required. This guiding of the motion can be achieved in multiple ways; Linear rails, linear rods or V-slot rails. (For a more elaborate overview of the components that make up the linear movement see Appendix C). After the step of translating the movement the cutting tool reaches its destination of the specified coordinates.
Between these two steps an optional third step can be present, which is required when a different cutting tool is required; The step of changing the cutting bit; the tool change(figure 7). Within this step the machine pauses its movement in order for the user to provide a tool change and prepare the machine with the appropriate cutting bit. When this step is finished the operation can be resumed.

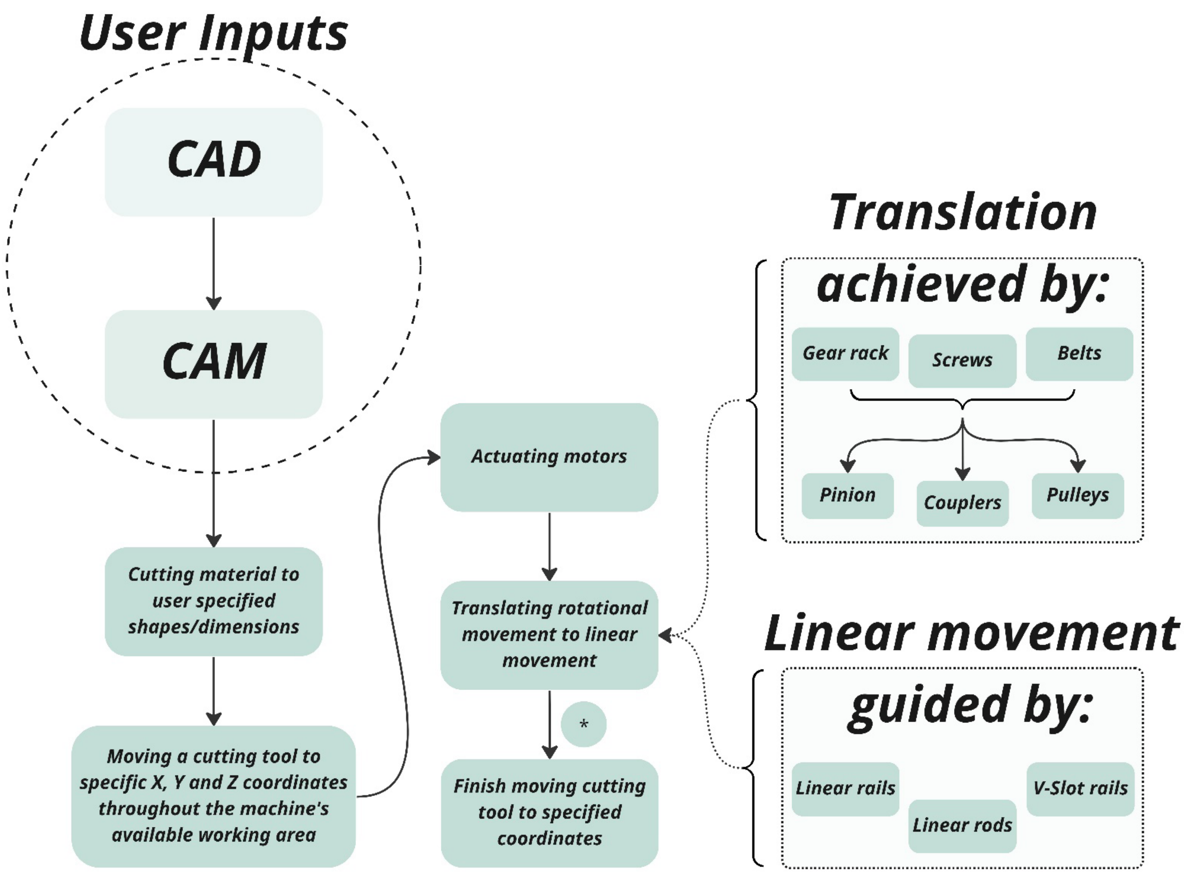

Figure 6: General CNC workflow elaborated

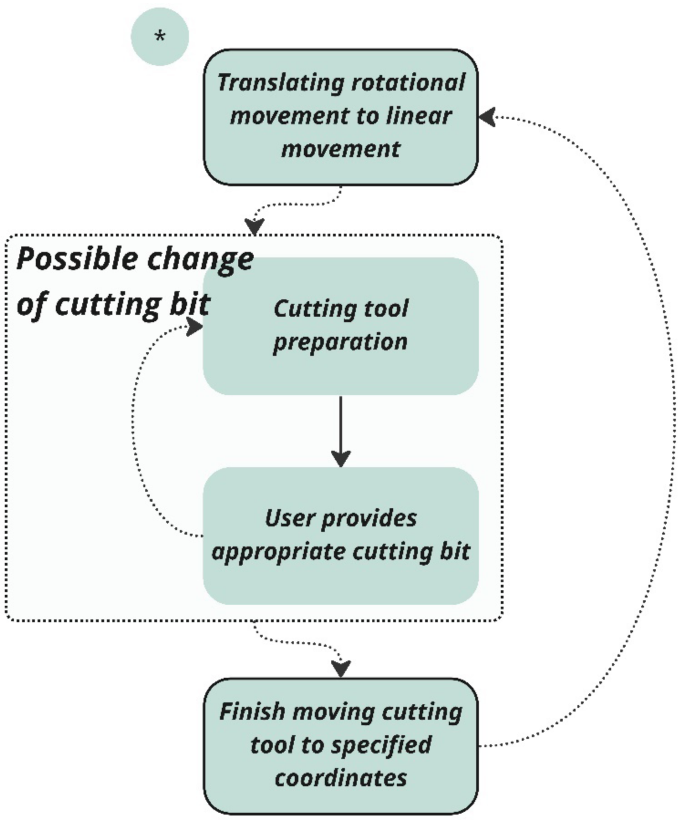

Figure 7: Changing cutting bit (tool change)

4.1.2 CNC router Types

Generally speaking CNC routers can be divided into two different types; Fixed gantry CNC machines and Moving gantry CNC machines.

Fixed gantry

A fixed gantry CNC router is a type of machine where the cutting tool(spindle/router) remains in a fixed position and the material is moved underneath it on a work bed(see figure 8). This design is often preferred for cutting thicker or more dense materials as it offers more stability and support to the cutting tool and gantry as a whole. This is due to the fact that the gantry does not have to be moved, making the gantry applicable for a more 'beefy' and more heavy duty design. This type of design is often used for machines with a smaller work area that are focused on creating very intricate and detailed parts.
In this design the cutting tool acts as the X-axis and Z-axis, while the work bed acts as the Y-axis.

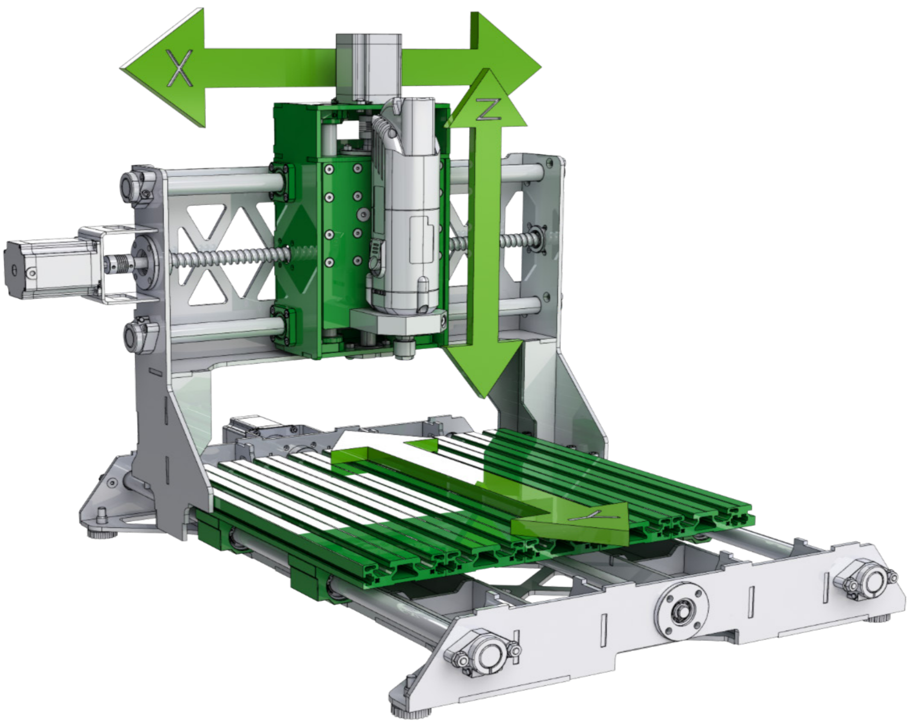

Figure 8: Fixed gantry CNC router

Moving gantry

A moving gantry CNC router, on the other hand, moves the cutting tool along a moving gantry while the material remains in a fixed position on the work bed(see figure 9). This design is often used for larger machines with a larger work area. Since the 'to-be-cut' material does not have to be moved, much larger work pieces can be machined. However, the moving gantry is not as stable as the fixed gantry and may lead to less accurate cuts since the moving gantry might be more applicable to vibrations which can negatively impact the precision of the cuts.
In this design the gantry acts as all three axes; The X-, Y- and Z-axis.

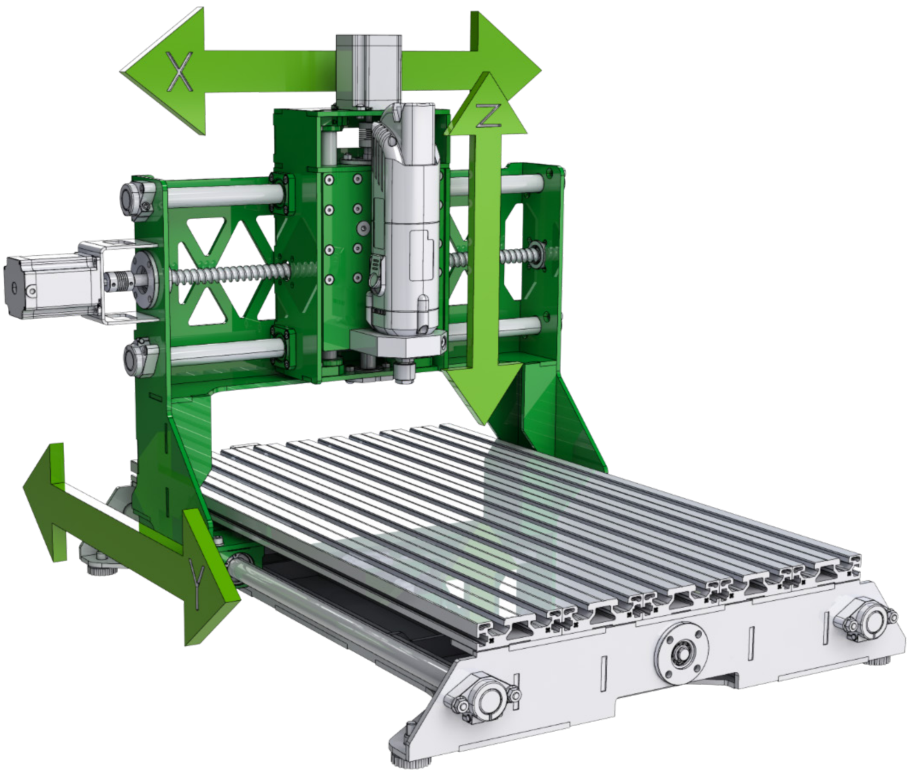

Figure 9: Moving gantry CNC router

Besides the two types that are mentioned above a lot of different archetypes can be identified in the field of CNC machines in general. However for CNC routers the two previously mentioned types are the standard(CNC Chronicle, 2023).

4.1.3 Current solutions

The desire to have a grip on true flexibility in terms of work area is not something new. Different users (engineers, designers, makers and technical personnel) have tried to tackle this desire to save space when owning a CNC machine. A more recent development in this field is the mounting of the entire machine to a wall or foldable workbench(see figure 3). Both 'solutions' do in fact provide a way to save work area on the literal work floor by moving the machine to a wall or folding it out of the way for storage purposes. However for both scenarios the user is still limited and constricted to the dimensions of the mounted CNC in question. This limits the user in gaining a true flexibility in terms of work area in the workshop as well as build area of the machine itself.
Since both solutions actually utilize an ordinary CNC router to 'solve' the problem, the same general workflow that has been described in paragraph 4.1.1 Working principle applies. The only difference is the added step of storing the machine and folding it away when not in use in case of the folding workbench.

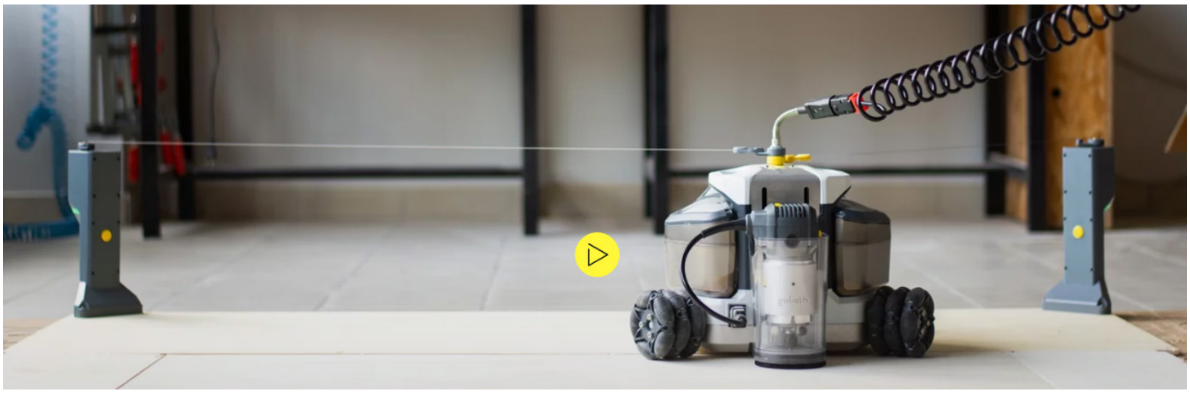

Figure 10: Goliath CNC

There are also two other concepts that claim to be a solution to the problem at hand; One of these is the Goliath CNC which is a router mounted on an omnidirectional robotic platform(GoliathCNC, 2020)(see figure 10). The second is the GrowCNC which is a modular CNC router that fits within a large trunk similar to a suitcase(develop3D, 2012)(see figure 11). The modularity of the machine is directly related to its axes, which can be swapped out for larger or smaller modules. These two concepts actually do include new steps in the workflow for the user in order to provide a 'solution' to the problem at hand. In order to properly analyse these two concepts, again Function Analyses have been performed. Figure 12 shows the function analysis of the GoliathCNC.

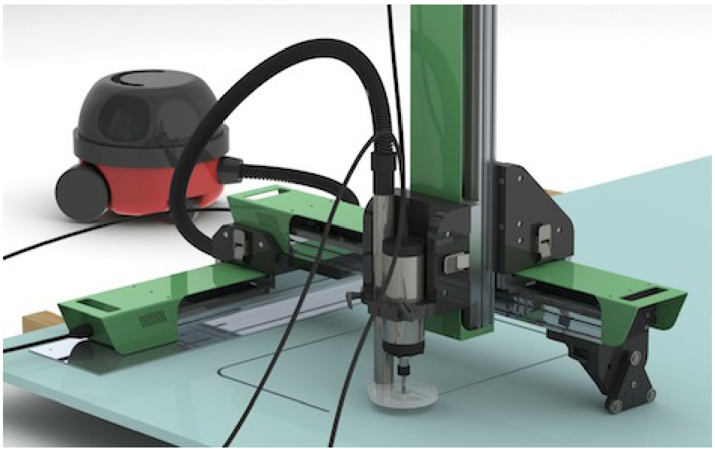

Figure 11: GrowCNC

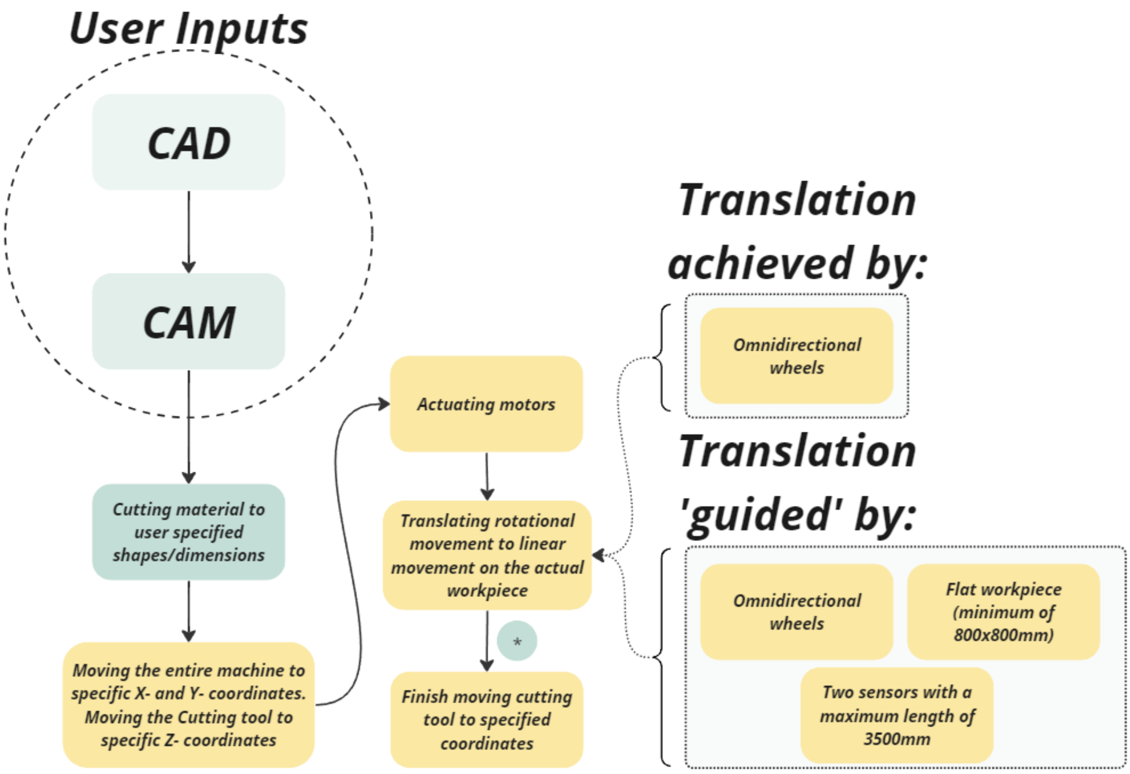

Figure 12: Function Analysis GoliathCNC

At first glance this CNC concept looks like the perfect solution to the problem at hand. The router is mounted onto an omnidirectional platform which is then placed on top of the stock material, essentially allowing for an ‘infinitely’ large work area. However when taking a closer look at the mechanical aspects of the machine and its capabilities, it becomes clear that there are some flaws within the design/concept.
When looking at figure 12, the largest difference lays within/after the step of translating rotational movement to linear movement. The machine makes use of omnidirectional wheels to move about the work area which in this case is the actual workpiece. Two battery powered sensors are connected to the machine through wires to make up for any small mistakes/inaccuracies the machine might encounter. Because of these sensors the machine has a maximum build area of 3000x2000mm. Because of the size of the machine itself and the fact that it is machining on top of the workpiece a minimum build area of 800x800mm(which is still quite large) is required for the machine to not fall off of the piece. Providing a claimed accuracy of 0.1mm (GoliathCNC, 2020).

Since the router is mounted directly on top of a small-scale free moving and rotating cart, the workpiece and the omnidirectional wheels acts as the guidance for the linear movement. This means that the workpiece itself needs to be perfectly straight and flat in order for the concept to work properly. Which is often not the case when working with a nature product such as wood(Houthandel Jongeneel, 2023). When the workpiece is not perfectly flat, the omnidirectional machine will have trouble moving around and accurately knowing where it is. Which could possibly lead to a loss of steps or even failing the operation entirely even with the sensors attached.

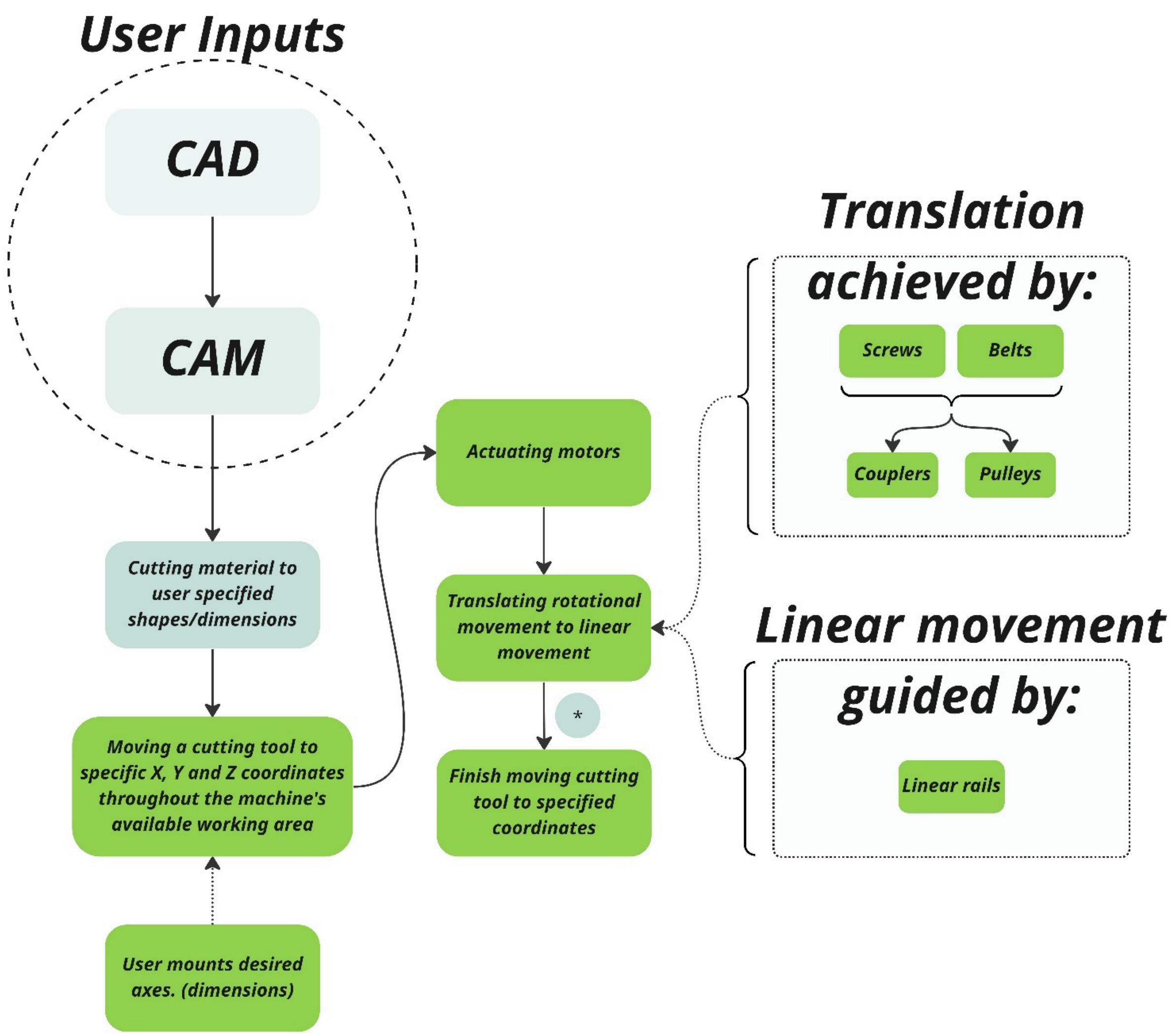

Figure 13: Function Analysis GrowCNC

The GrowCNC is a modular CNC machine that fits within a large trunk similar to a suitcase(develop3D, 2012). Since this concept has never reached a commercial level of development, no functional data is available regarding, for example, accuracies or actual build area. This concept was ended in the form of a prototype.

The modularity of the machine is directly related to its axes, which can be swapped out for larger or smaller modules, allowing the user more flexibility in terms of work/build area. However does leave the user with a large number of rigid axis modules that require a storage solution.

The prototype itself did include a trunk, but this only housed the standard sized axes not the possible larger or smaller axes modules. Again leaving the user with a large number of rigid modules(when the user does not want to be limited in terms of build area) without a provided solution to store these.

When looking at figure 13 one can identify an extra step in the function analysis; the mounting of the desired axes. The axes are mounted onto the machine by plates that are held together by a number of magnets. These plates in turn are held together by small latches. Another difference to the function analysis is the fact that this machine uses both screws and belts in order to translate the movement. To guide this movement, linear rails are applied in this design.

Figure 14 illustrates the conclusion of the previously mentioned analysis of the four current ‘solutions’. The four solutions have been compared to each other for four different criteria; Space saving, Storage capability, One size fits all and Provide Flexibility.

Space saving is related to the ability to save space at the location in which the CNC will be used. As can be seen in the figure, all solutions provide the user with some form of space saving capabilities, with the Goliath CNC coming out on top because of its small size.

The storage capabilities provide the same results as the previous criteria. The foldable workbench and wall mounted CNC both provide a way of storage, however still take up an entire wall or another large area at the location. The GrowCNC provides the user with a large trunk in which they can store the standard sized modules, however does not provide a solution to possible other/larger modules.
Because of its small size the Goliath CNC again comes out on top within this criteria.

The criteria One size fits all relates to the user of the machine. Will the user be able to understand/operate the machine and is it capable of delivering the expected outcome. Also how intuitive will the machine be for users already familiar with a CNC router. The only machine that did not pass this criteria was the Goliath CNC because of its rather non standardized and possibly even controversial working principle.

The final criteria relates to Providing flexibility in terms of work/build area. Does it provide the user with the option to be in full control of the size of the work/build area? Both the wall-mounted and foldable workbench CNC did not pass this criteria since a standard non flexible CNC router is mounted to the ‘solution’.

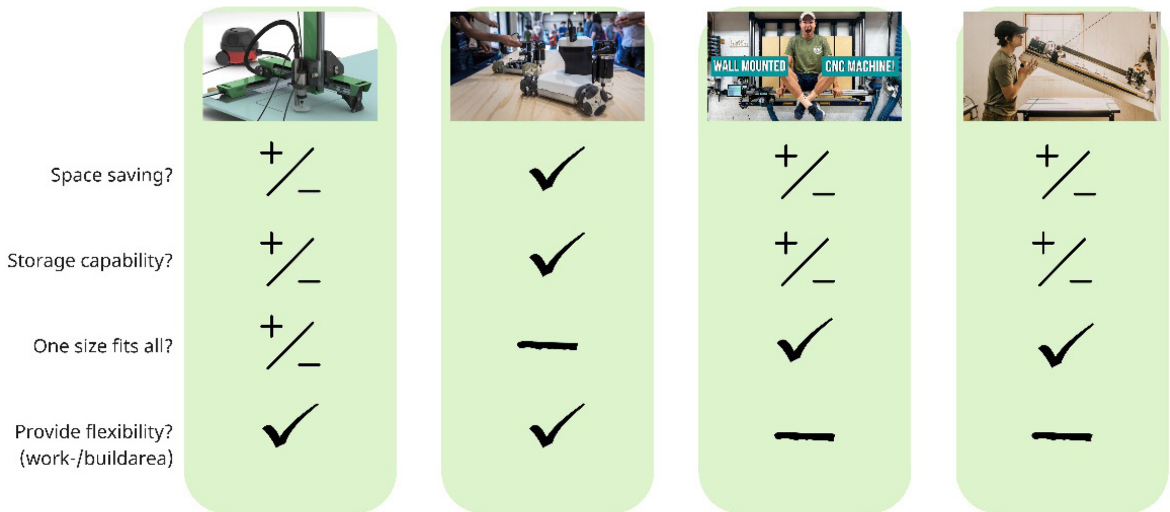

Figure 14: Conclusion of Current Solutions Analysis

4.2 Context Analysis

In order to gain a better understanding of the context in which the resizable router would operate, a context analysis has been performed. Starting with identifying users, exploring use cases and performing desk research.

4.2.1 User characteristics and Use Cases

Within the context of CNC routers a large number of different users can be identified. Most of these users can be categorized by three different types; The casual user(figure 15), the professional user(figure 17) and the semi-professional user(figure 19).

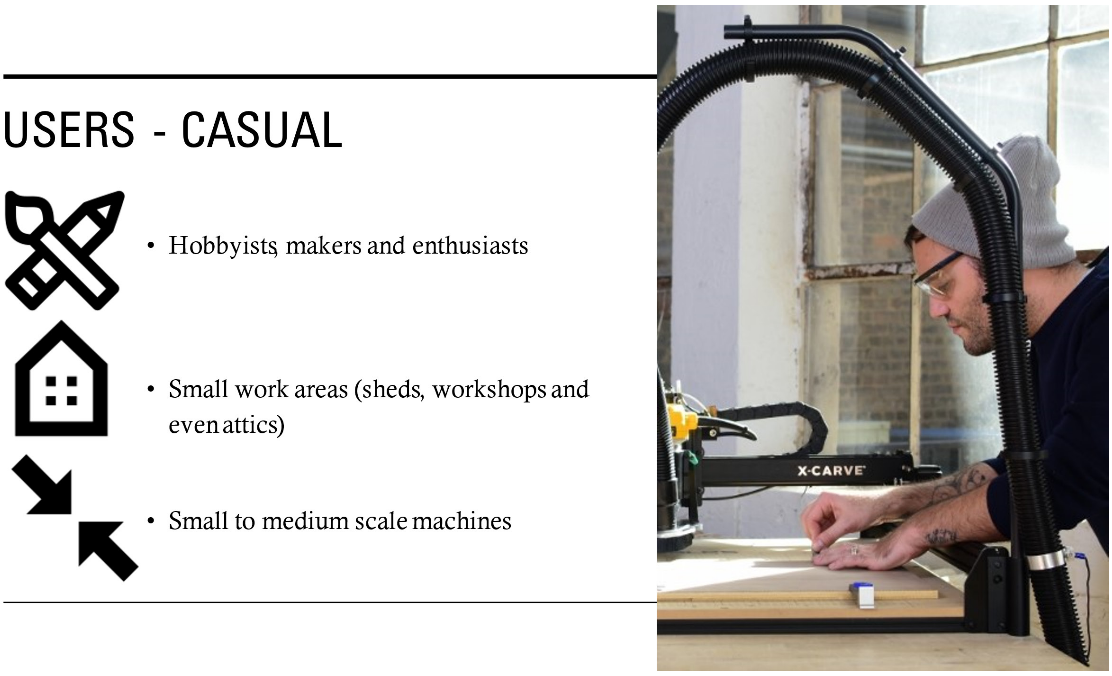

Figure 15: The casual user

The casual user is typically a person who is simply enthusiastic about the technology and uses it to manufacture their own work. This user can for instance be a hobbyist or a model builder and/or maker (CNCZone, 2017). They usually don't have the same operating space as a professional and often use a spare room, a shed, a small workshop or even an attic. Because the lack of space for a larger scaled machine the user is required to obtain a machine which can fit to the designated space. But generally speaking they make use of smaller scaled machines. For each casual user this will be different, however they can benefit from using a resizable system.

Figure 16 shows a use case in which a casual user wants to start a CNC operation. In this use case a birdhouse has been chosen as an example of a project, which a casual user could make using a CNC router.

The first thing the user needs is a design for the birdhouse. A 3D model can be created through CAD software. When the user has created their design they can start collecting their materials from which the bird house will be created. When the desired materials are selected the user can start the CAM process, in which they specify all parameters and specifications required/desired.
The more casual user tends to have a smaller work area which often consists of a spare room, shed or even an attic. Because of this the user will have to make room for the machine prior to setting up the machine itself. Which consists of securing the workpiece, connecting the dust collection system (in this case a vacuum hose) and mounting the appropriate bit for the job. After all these steps the CNC operation can finally be started and the user will be left with all the pieces in order to build their birdhouse. In case the user has made a mistake during the CAM process(which will only be found during the CNC operation) they have to revise their CAM operations.

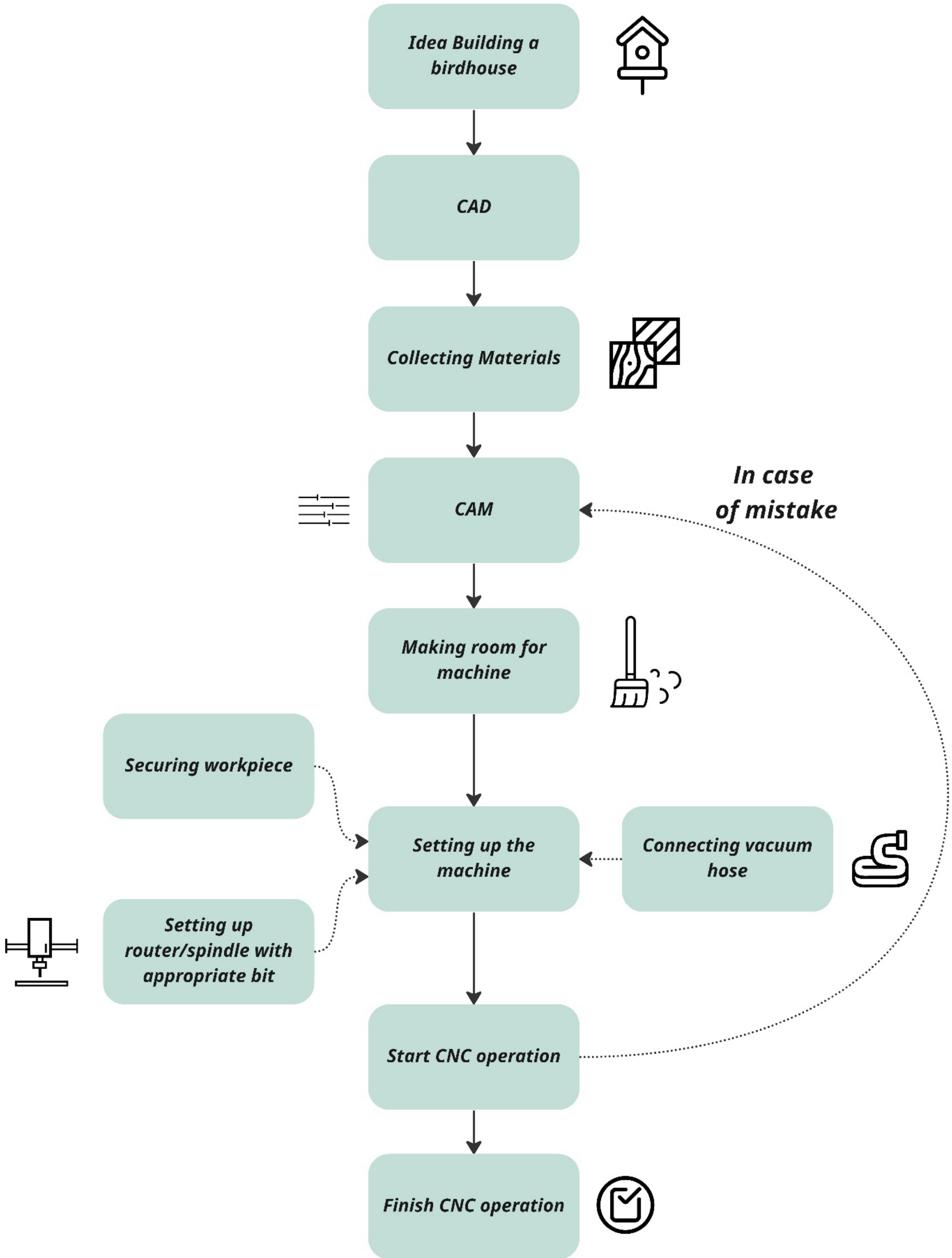

Figure 16: Use Case Casual User

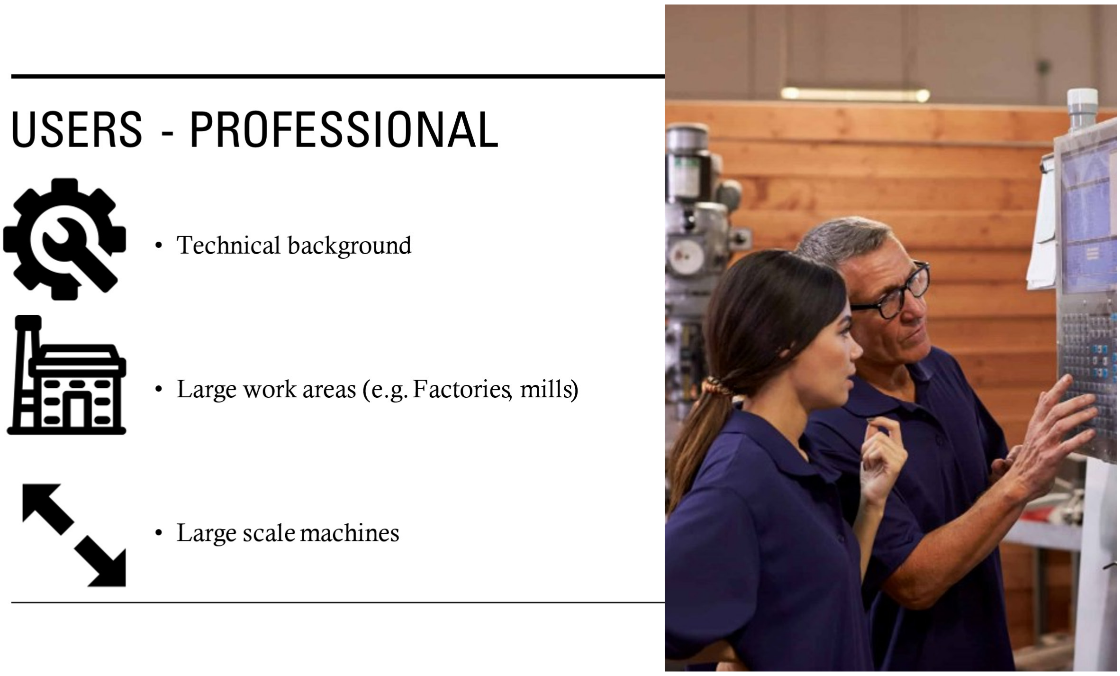

Figure 17: The professional user

The professional user is usually a person with a technical background and/or profession. You can often find them in fields such as the automotive-, aerospace- and timber and building industries (RapidDirect, 2022). This user often operates in a larger work area, such as factories or lumber mills, and therefore need more workspace. They typically work to make larger batches of a product which in turn also requires a larger space. In this scenario the user is required to use a larger scaled machine. This for example could mean that the user is looking for a flexibility in the CNC machine and wants a customisable operating system for all scales of work.

Figure 18 shows a use case in which a professional user has been requested to start a CNC operation.
Prior to the operations of the CNC operator, a request for a CNC operation will be received by the company in question. This request will be done through the form of a technical drawing which will be translated to G-Code(MARLIN, 2023) by a CNC programmer. This CAM data is then given to the CNC operator. They will then collect the priorly requested materials and mount these to the large scale machine. The materials will or will not cover the entire work area of the machine depending on the size of the material in question. When the material is secured the operation can begin.

When the operator identifies an error caused by a mistake/wrong setting in the G-Code they will have to feedback to the CNC programmer in order to solve the problem at hand. When all errors are solved or no errors were present at all the operation will be finished. After which the operator can remove the finished workpiece from the machine.

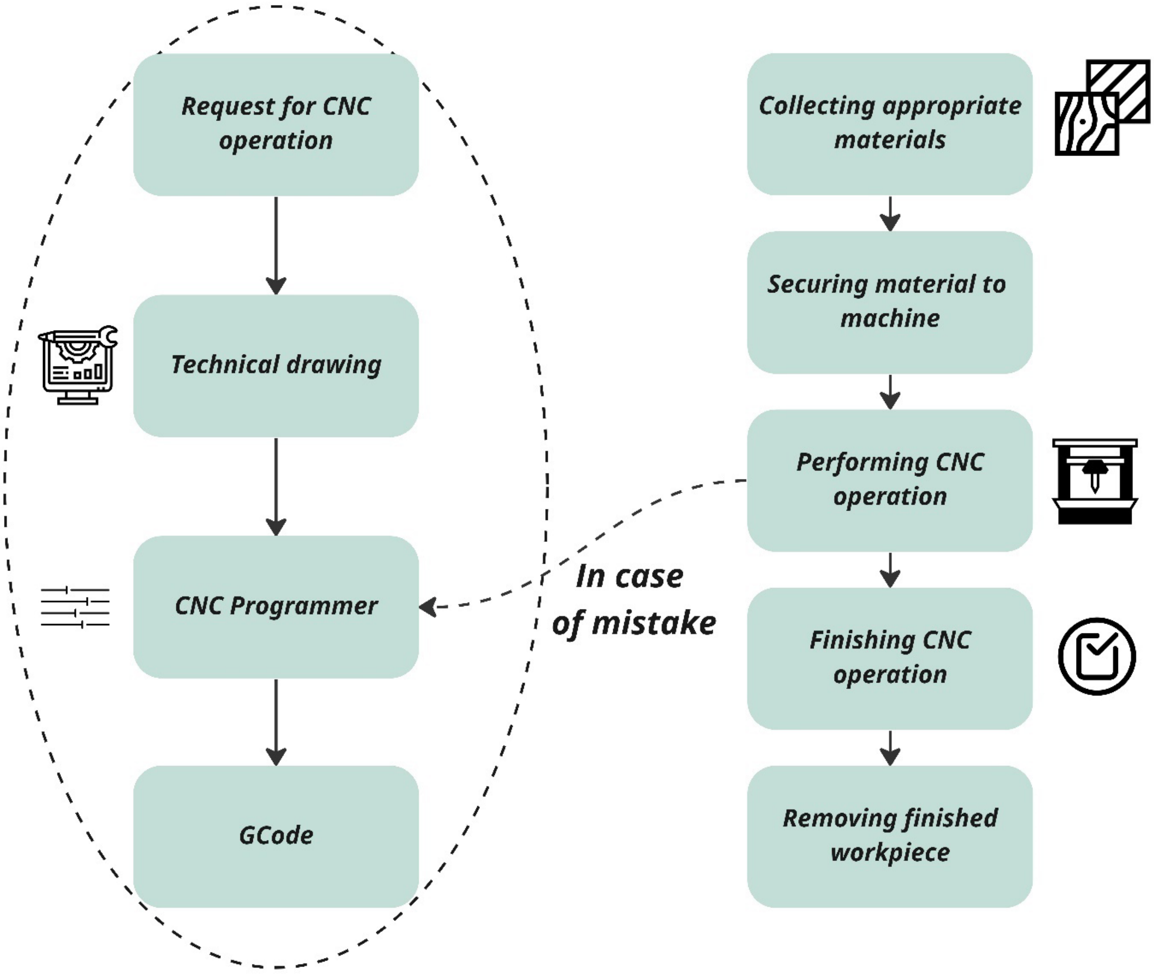

Figure 18: Use case Professional User

KLAAS

- Semi-Professional user
- Operates in a workshop of 19 m^2.
- Owns a Sorotec XL (build area 1500x1050mm)
- Active member of the CNCZone Forum.

Figure 19: The semi-professional user

The third user is the semi-professional user. This type of person is usually described as a combination of the two previously mentioned. This user is often seen using a CNC machine in a professional setting but simply does not have the space available to house a full-on professional machine. This user can for instance be a contractor, a small architectural firm or a small timber and building supply shop. They often settle for a smaller mid-range machine or decide to outsource their CNC work (Jongeneel, personal communication 2022). Some do have the space to house a machine but don't use it often, or use it to create different scales of products. In this case they would benefit to have a machine which can be resizable to fit their needs.

Figure 20 shows the use case in which a semi-professional user wants to create a scale model and wants to use a CNC router in order to achieve this.

The first step for the user is again to create/provide a CAD model. Since not every Semi-Professional owns a CNC router a lot of them will have to outsource the operation. In which they have to provide the details to the CNC service provider after which they will be left with (after a given amount of time) a finished workpiece. One can argue that a Semi-Professional user who does not own a CNC router is actually a costumer of the professional user.
When the Semi-Professional does in fact own a CNC router they can start collecting their materials after which they can start the CAM process, in which they specify all parameters and specifications required/desired. Afterwards they can mount the materials to the machine which is located at a specific location at the workplace(e.g. a dedicated table or a separate room). They can then start the CNC operation and remove the workpiece when it is finished.

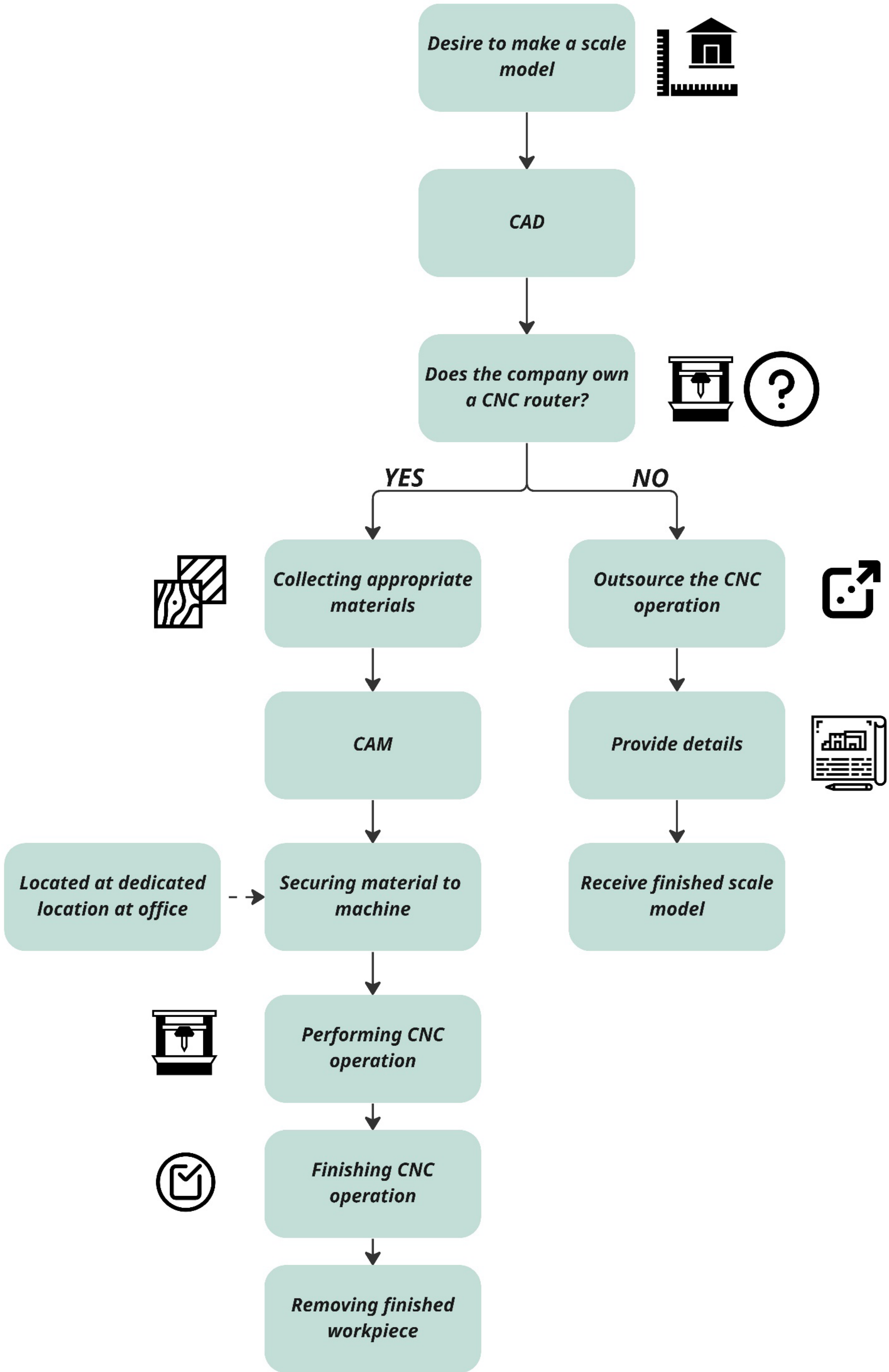

Figure 20: Use case Semi-Professional User

All three types of users have a desire for flexibility in terms of work area in common. When more work area can be utilized, more parts can be manufactured or other projects can be realized. For the casual and semi-professional users this could mean more available space for different types of side-projects. While for the professional user this could mean an increase in production. Providing a solution in order to offer a grip on true flexibility in terms of work area when owning or working with a CNC machine will prove beneficial for alle types of users.

As mentioned before different types of users may exist, a lot of users actually share similarities and overlap with multiple user types.

4.2.2 Desk Research

In order to gain a better understanding of the users and the user context, a questionnaire had been created and sent out/posted to multiple woodworking and CNC router groups on multiple Social Media platforms. Unfortunately this questionnaire did not receive enough useable information from the targeted user group, so in order to continue with the context analysis, the forum; CNCZone was consulted(CNCZone, 2021). On this forum almost 5100 owners of various CNC machines come together to share ideas, ask questions and share projects. A small number of these users have posted pictures of their CNC router workspace. These pictures can be found in Appendix D. By analysing these pictures, the following updated personas for a casual user(figure 21) and a Semi-Professional user(figure 22) have been created. When looking at the persona for the casual user one can identify Olivier. He is a hobbyist and maker, someone who is creative and not afraid to create his own solutions. He owns his own CNC router which he uses to create personal projects in his small garage.
When taking a look at the Semi-Professional user; Klaas is identified. Klaas is very knowledgeable about the field of CNC machines. He likes to share this knowledge at the CNCZone forum to help newer users such as Olivier. Klaas owns his own small workshop from which he operates his larger size machine to manufacture commissioned parts.

After analysing the pictures that have been retrieved from the CNCZone forum, another requirement for the resizable CNC router could be updated. Since the work areas of the users all allow for quite a lot of storage capabilities a single resizable axis would still suffice in order to provide the user with a flexibility in terms of work area.

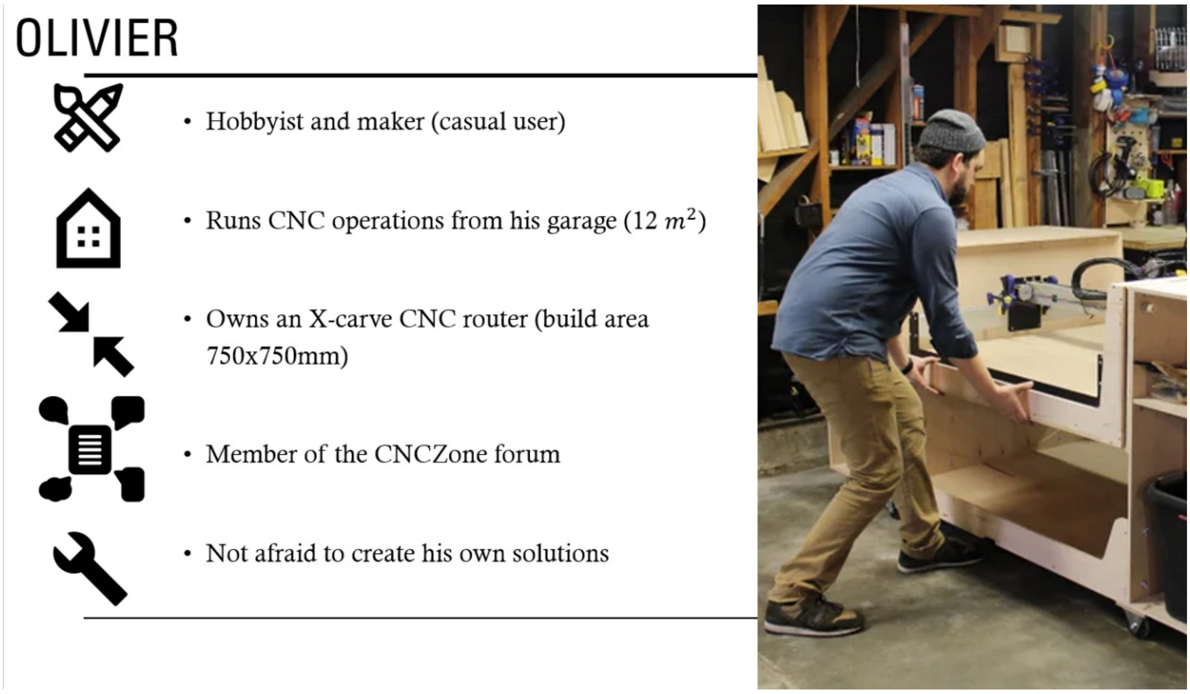

Figure 21: Updated Persona of a casual user.

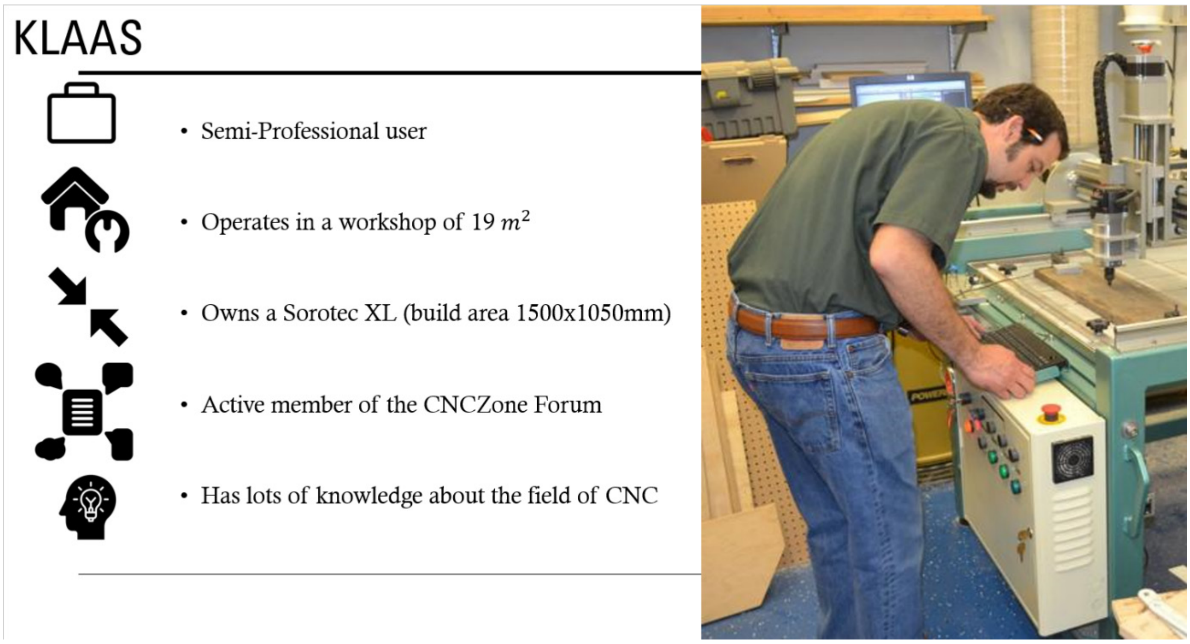

Figure 22: Updated persona of a Semi-Professional user

4.3 Resizability

As mentioned before, providing true flexibility in terms of work- and build area is the main goal of this project. Realizing this true flexibility was done in the form of allowing the user to manipulate the Y-axis of the CNC router to any desired size(of course within limits). The true challenge within this project was creating a system in which the X- and Y- axis of the system are mounted together in a way that allows the Y-Axis to have a variable length while maintaining the required strength and stiffness.

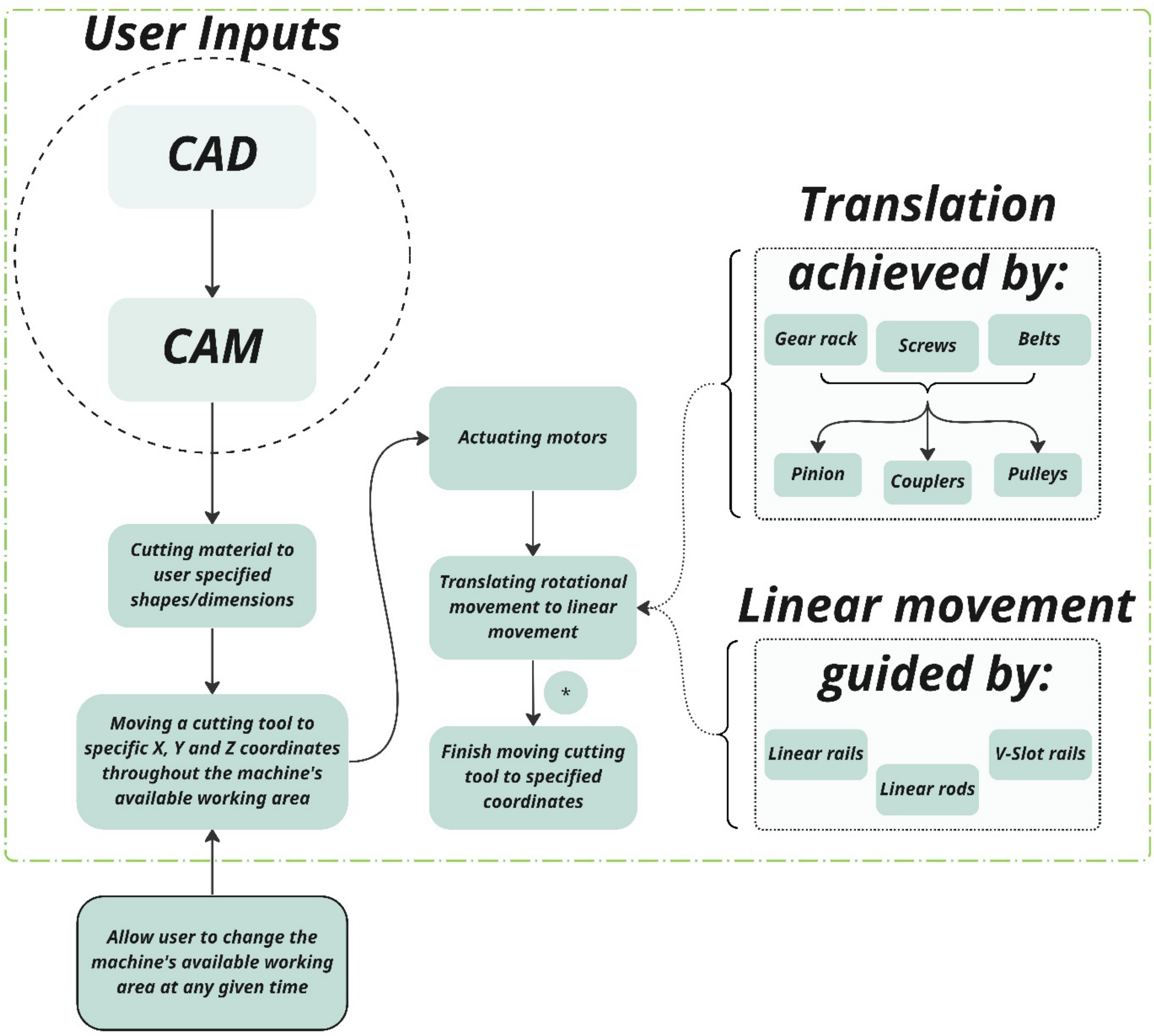

Figure 23: Function analysis assignment

To gain a better understanding about the assignment itself and its solution space, another function analysis has been created. The function analysis of the machine, in which the to-be-designed solution would be implemented, is rather similar to the one illustrated in figure 6. With one large difference; Another step can be added before the step of 'Moving a cutting tool to specific X, Y and Z coordinates throughout the machine's available working area'. Figure 23 shows the extra added step. Since the working area of the machine will now be up to the user, the extra step includes; Allowing the user to change the machine's available working area at any given time.

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The additional step illustrated in figure 23 has been elaborated into a function structure of the resizable CNC router this graduation project revolves around(see figure 24). Allowing the user to change the machine's available working area at any given time (when the machine is not in operation) is the main purpose of the machine in question. In order to achieve this the Y-axis will have a variable work length of between 1220(minimum length) and 2440mm(maximum length). Whereas the X-axis will have a fixed work length of 1220mm.Which together makes up a maximum work area of the size of a standard sheet of plywood (Jongeneel , 2023). The axes will be mounted perpendicular onto each other, in order to move a cutting tool(which acts as the Z-Axis) to specific X and Y coordinates throughout the machine's available work area. The Z-Axis of the machine will need to be able to clear 18mm thick material. However it also need to be able to move freely over the material when the machine is cutting into it. An additional couple of millimetres will be needed to provide the needed clearance.

The cutting tool in question needs an RPM range of at least 12000 – 24000 RPM in order to cut common/popular 'soft' types of sheets/plywood(CNCRouterbits, 2023) readily available in building and timber supply shops. Such as Pine, Poplar, Birch and MDF (Jongeneel, 2023). The max Z-depth of the machine will be 18mm, which is again derived from the size of a standard sheet of stock material.

The axes will be powered by stepper motors which are readily available in a number of different specifications and strengths(for an overview see appendix E). The choice of using stepper motors was made by analysing existing CNC Routers which have similar capabilities (see appendix F).

The maximum (travel) feedrate of the machine when in operation should be between 7000 and 10000 mm/min, which has been derived from analysing multiple similar CNC routers. Figure 25 shows the outcomes of this analysis.

Hardware\CNC	ShapeOko	X-Carve	MPCNC	BOBSCNC	StepCraft	AvidCNC	GoliathCNC
Steppermotor	Nema 23	Nema 23	Nema 17/23	Nema 17	Nema 17/23	Nema 23/34	N/A
Spindle/Router specs	Makita RT0700 710W 10000-30000RPM	Makita RT0700 710W 10000-30000RPM	Makita RT0700 710W 10000-30000RPM	Makita RT0700 710W 10000-30000RPM	2kW Spindle 2000-24000 RPM/ 800W Spindle 7000-25000 RPM	3kW Spindle 6000-24000RPM/ 6,5kW Spindle 6000-24000RPM	Makita RT0700 710W 10000-30000RPM
Spindle/Router weight	1.8kg	1.8kg	1.8kg	1.8kg	3kg	12kg	1.8kg
Max Build Area	790x790 mm	750x750 mm	Up to user	Up to user	594x833 mm	1260x2460 mm	2000x3000 mm
Max feedrate	10.000 mm/min	7620 mm/min	7200 mm/min	10.000 mm/min	12.000 mm/min	10.000 mm/min	2500 mm/min
Accuracy/ Tolerances	0,05mm	0,075mm	0,05mm	0,05 – 0,1mm	0,025mm	0,0127mm	0,1mm

Figure 25: Outcome of existing router analysis

For the details of this analysis see Appendix F.

The router should be able to generate a cutting feedrate of 3360 mm/min. This number has been calculated with the help of the following formula:

$$Chipload = \frac{Feedrate}{(N_{flutes} * RPM)}$$

Where the Chipload describes the thickness of a single chip removed during a cutting operation. The feedrate describes the speed at which the cutting tool moves through the material. The N_flutes describes the amount of flutes (cutting edges) on the cutting tool. And the RPM describes the Rotations Per Minute of the cutting tool.

The formula can then be used to calculate the maximum cutting feedrate by rewriting:

$$Feedrate = Chipload * N_{flutes} * RPM$$

The maximum feedrate of 3360 mm/min has been found by implementing the ideal Chipload for a sheet of Soft wood/plywood, using a cutting tool with a 6mm diameter(see appendix G) which leaves us with a chipload of 0,07mm. The number of flutes for the cutting tool has been set to 2, which is the standard for softer types of wood (CNCRouterbits, 2023). And finally the maximum RPM of our cutting tool has been implemented (24000 RPM). Which leaves us with the following calculation:

$$0{,}07mm * 2 * 24000RPM = 3360\, mm/min$$

The function structure illustrated in figure 24 formed the basis for the List of Requirements.

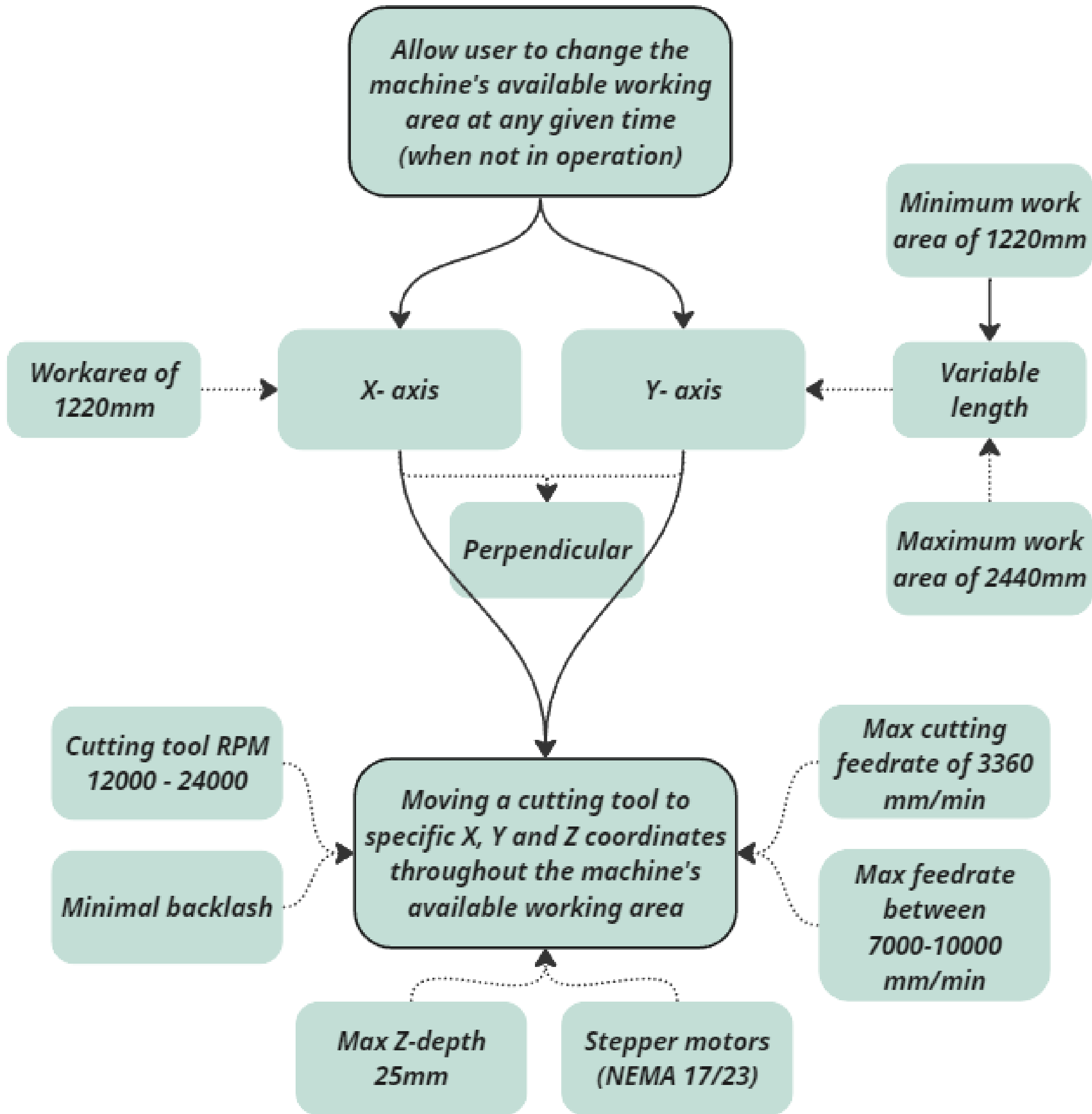


Figure 24: Function structure

LIST OF REQUIREMENTS

05

The following requirements and wishes have been formed following the function structure described in chapter 4.3 Resizability and are structured by their importance;

- The machine must provide the user with true flexibility in terms of build- and work area.

Contextual

- The user must be able to manipulate the Y- axis at any given moment when the machine is not in operation.
- The X-Axis must be able to be folded parallel to the Y-Axis for storage capabilities.
- The machine must be able to run 2(.5)D operations.

Mechanical

- The machine must be able to cut common/popular ‘soft’ types of sheets/ plywood readily available in building and timber supply shops(with a maximum area of 2440mmx1220 and a maximum thickness of 18mm);
  - Pine
  - Poplar
  - Birch
  - MDF
- The machine must have a maximum build volume of 2440X1220x25mm.
- The cutting tool of the machine must be able to reach a minimum of 12000 RPM. (CNCRouterbits, 2023)
- The cutting tool of the machine must be able to reach a maximum of 24000 RPM. (CNCRouterbits, 2023)

The machine must be able to deliver a maximum cutting feedrate of 3360 mm/min. (chipload of 0,07mm(6mm tool diameter/softwood), 24000 RPM and a 2 flute cutting bit).

Wishes

- The machine can be equipped with a dust shoe.
  - The dust shoe must be able to connect to a standard vacuum hose.
- The machine should use stepper motors.
- The cables located on the machine itself should be secured in such a way. that they will not affect the cutting operations or be affected (damaged) by the cutting operations.

THE CONCEPT

06

In order to satisfy the requirements stated in Chapter 5 List of Requirements multiple ideas were generated. These ideas were generated with the help of morphological charts. These morphological charts were filled by combining existing techniques and CNC components which were categorized in three categories; Resize; which encased the components and techniques that could be used for the resizing of an AXIS.

Drive; This category consisted of components used for creating a motion within CNC machines.

And finally, Guide: This category consisted of components used for guiding the motion that makes up the working principle of CNC machines.

The filled morphological charts are illustrated in figure 26.

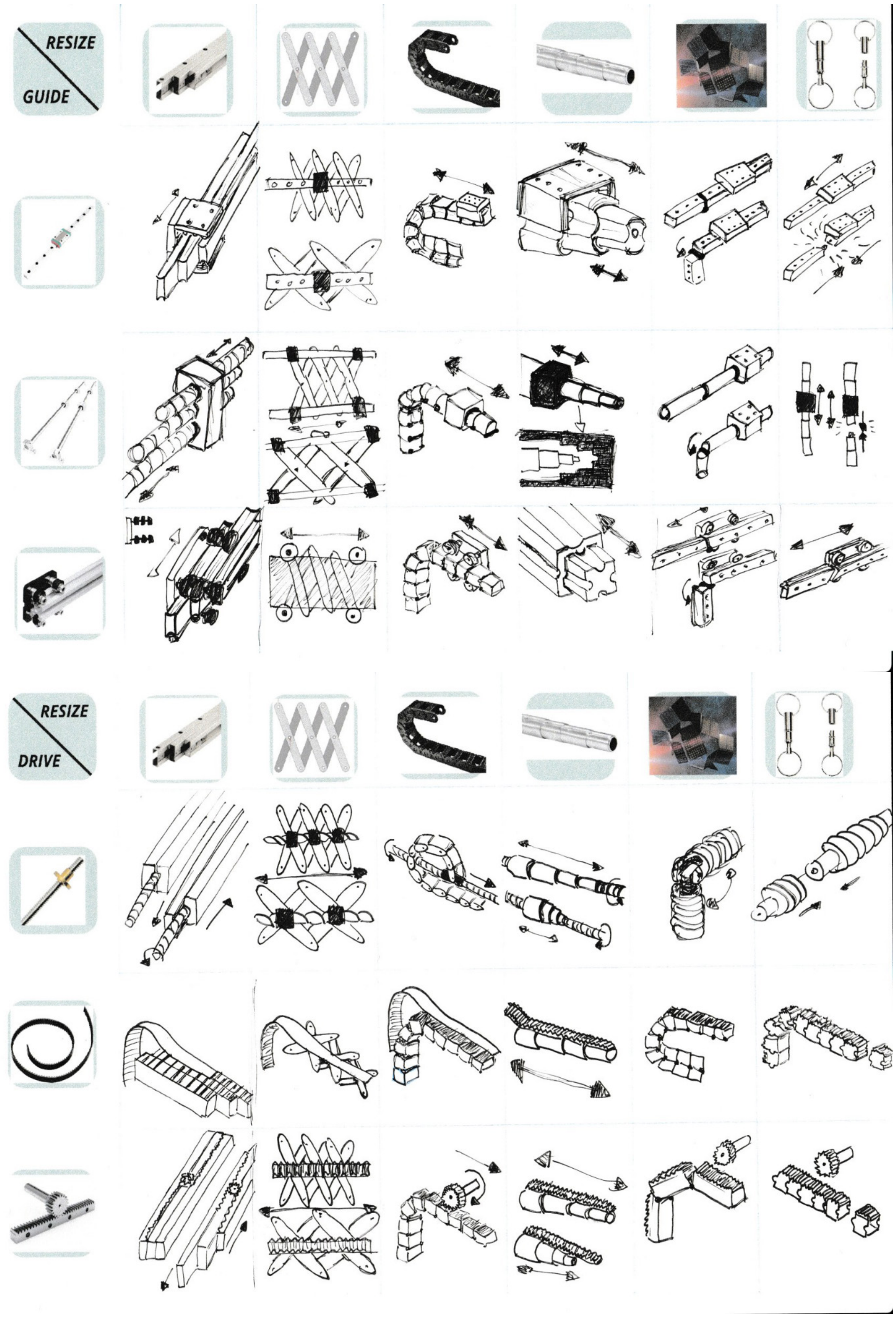


Figure 26: Morphological Charts

After creating the combinations stated in the morphological charts, they have been clustered in the following three categories; Folding, Extending and Modular. As the names suggest these categories included the ideas that enticed folding, extending and finally the ideas that included modularity.
After creating these three different clusters it became apparent that there existed quite a lot of similarity between multiple different ideas. In order to limit the amount of different ideas the similar ideas were again clustered and afterwards, with the help of the List of Requirements excluded until a single cluster of ideas could be formed. This idea cluster is illustrated in figure 27.
For a more elaborate overview of the idea generation see appendix H.

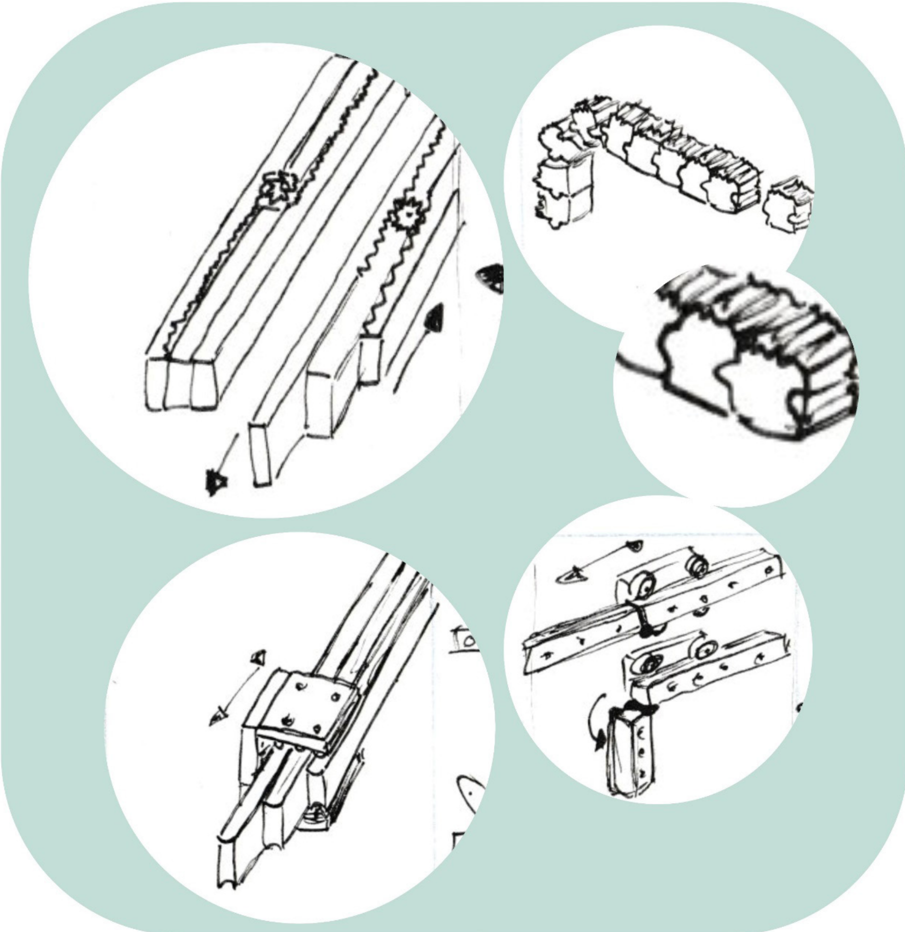


Figure 27: Idea Cluster

The cluster of ideas shown in figure 27 was the basis for the design of the resizable axis (the Y-axis).Which was based on a sliding mechanism primarily used in extendable dining tables (see figure 28). This axis consists of three separate moving ‘beams’ that act as guide rails for the carriage, on which the X- and Z-Axes will be supported. The carriage in question has been equipped with a form of ridges that allow the ‘fixed-sized axis’(the X-axis) to be pivoted in parallel to the Y-axis for storage purposes.
Figure 29 illustrates the ‘fixed-sized’ axis (the X-axis) which will hold the router. Putting these two axes together formed the foundation for the main concept (see figure 30).

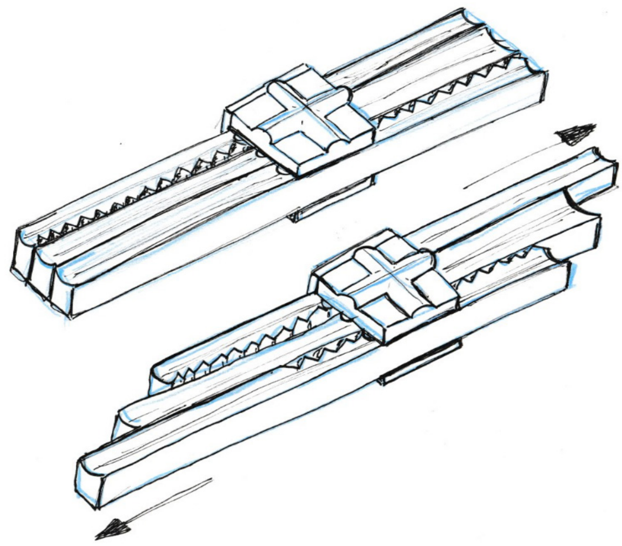


Figure 28: Resizable Axis (Y-axis)

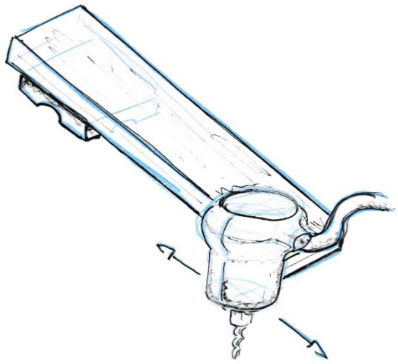


Figure 29: 'Fixed-sized' Axis (X-axis)

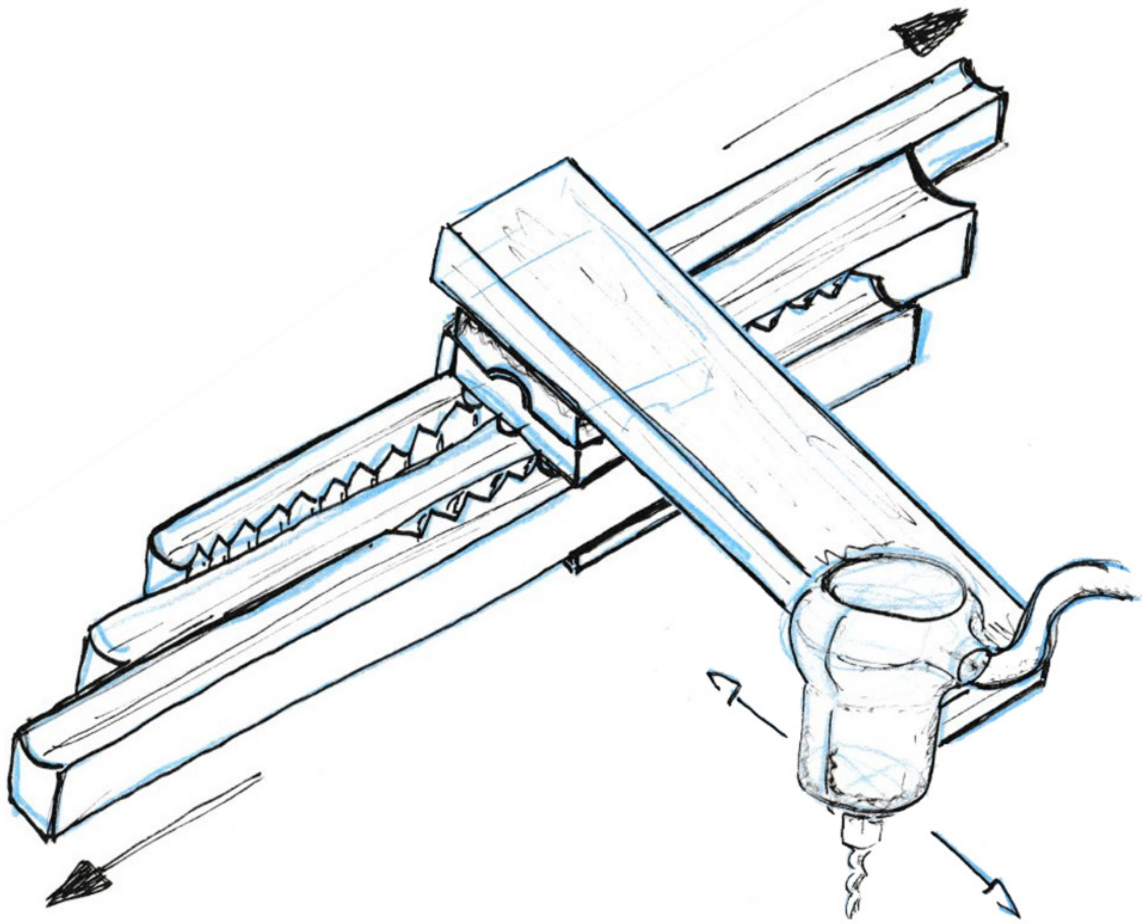


Figure 30: The Concept

In order to determine the proper maximum dimensions for the resizable router and its axis, two formulas have been derived. As can be seen in figure 31, four variables have been illustrated; A: the depth of the X-Axis, B: The width of the X-Axis carriage, C: The width of the router gantry and finally D: The depth of the router gantry.

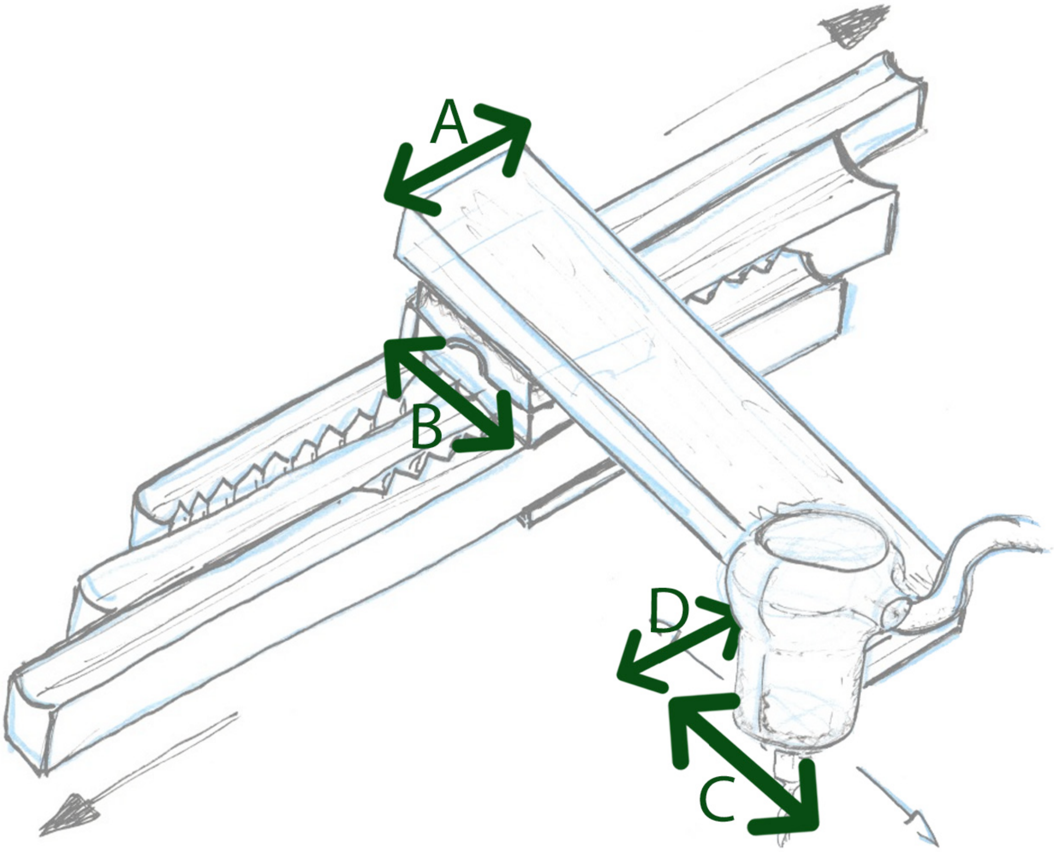


Figure 31: Router dimension variables

The maximum needed length of the X-Axis can be calculated using the following formula:

$$XMaxLength = DwAx + B + 2 * (\frac{1}{2}C)$$

In which DwAx represents the desired work area for the X-Axis; 1220mm (see chapter 5 List of Requirements).
The maximum needed length of the Y-Axis can be calculated using the following formula:

$$YMaxLength = DwAy + A + zD$$

In which DwAy represents the desired maximum work area for the Y-Axis; 2440mm (see chapter 5 List of Requirements).

Filling in these formulas provides us with the maximum lengths of both the X-Axis and the Y-Axis;

DwAX = 1220mm
B = 170mm
C = 170mm

$$XMaxLength = 1220 + 170 + 2 * (\frac{1}{2} * 170) = 1560mm$$

DwAY = 2440mm
A = 150mm
D = 150mm

$$YMaxLength = 2440 + 150 + 150 = 2740mm$$

As mentioned before, the X-Axis will be able to be pivoted parallel to the Y-Axis for storage purposes of the router. Since the length of the X-Axis is fixed this measurement can used as baseline for the minimum length of the Y-Axis, since this has to support the X-Axis when pivoted. Meaning that the minimum length of the Y-Axis will also be 1560mm.

6.1 Hardware

6.1.1 Router

To satisfy requirements; The cutting tool of the machine must be able to reach a minimum of 12000 RPM. (CNCRouterbits, 2023) and The cutting tool of the machine must be able to reach a maximum of 24000 RPM (CNCRouterbits, 2023), as described in chapter 5 List of requirements. And because of its popularity within similar CNC machines (see Appendix F CNC Router Comparisons) and its readily availability it was decided to implement the Makita RT0700C router in the design of this resizable CNC router. This router has a variable RPM range of 10000-30000 RPM, has a maximum power rating of 710 Watt and only weighs 1.8kg. For the full datasheet of the Makita RT0700C see Appendix I Datasheet Makita RT0700C.

The weight of the router has led to the additional requirement; The machine must be able to carry a cutting tool of 1.8kg.

Max Output Force

With the choice of this router its maximum cutting force(Newton) could be calculated using the following formula;

$$CuttingForce = \frac{CuttingTorque}{CuttingToolRadius}$$

In which the CuttingTorque describes the maximum torque the machine is capable of delivering in Newton/meters. And the CuttingToolRadius describes the radius of the chosen cutting tool/endmill in meters.

In order to calculate the maximum cutting force the router is capable of, first the cutting torque needed to be calculated. The following formula could be used to calculate the cutting torque;

$$CuttingTorque = \frac{CuttingPower}{2\pi * RPM/60}$$

Within this formula the CuttingPower describes the maximum power of the router in Watts(710).

The RPM describes the rotations per minute of the router.

By filling in the formula of the cutting torque for both the maximum RPM(30000) and the minimum RPM(10000) of the router, the cutting torque range of the router could be found;

$$CuttingTorque_{MaxRPM} = \frac{710}{2\pi * 30000/60} = 0{,}226N/m$$

$$CuttingTorque_{MinRPM} = \frac{710}{2\pi * 10000/60} = 0{,}678N/m$$

By dividing the found cutting torques with the radius of the chosen cutting tool in meters(0,003 meter since a cutting tool of 6mm in diameter will be used(see Chapter 4 Analysis)) the cutting force could now be calculated:

$$CuttingForce_{MaxRPM} = \frac{0{,}226}{0{,}003} = 75{,}33\ Newton$$

$$CuttingForce_{MinRPM} = \frac{0{,}678}{0{,}003} = 226\ Newton$$

These cutting forces describe the maximum force which the router is capable of delivering for its minimum RPM and its maximum RPM.

Maximum Required Force

By reusing the previously mentioned formulas, and implementing two new formulas, the maximum required force to cut 18mm of soft plywood could be calculated.
The following formula (Shapeoko Enthusiasts. Feeds and Speeds, 2022) was implemented in order to calculate the required Cutting power in horse power(which can later be derived to Watts);

$$RequiredCuttingPower = \frac{MRR}{K}$$

Within this formula, MRR describes the Material Removal Rate (the amount of material removed by the cutting tool per minute) in mm^3/min and the K describes a material specific constant that describes how much material in mm^3/min can be removed per minute using a single horsepower.
To determine the material removal rate the following formula can be used:

$$MRR = WidthOfCut * DepthOfCut * Feedrate$$

Within this formula the WidthOfCut describes the width of the cut made in the material by the machine as seen from above, in millimetre. The DepthOfCut describes the depth of the cut in the material made by the machine. The feedrate describes the speed at which the machine move through the material in millimetre per minute.
In order to find the maximum required force the following variables have been implemented:

K= 30 in^3/min (Shapeoko Enthusiasts. Feeds and Speeds, 2022) = 491611,92 mm^3/min.
WidthOfCut = 6mm (diameter of cutting tool).
DepthOfCut= 18mm (maximum thickness of the to-be-cut material).
Feedrate= 3360 mm/min (see chapter 4 - Analysis).

Implementing these variables will result in the maximum required force needed to cut 18mm of plywood in a single pass with a cutting tool of 6mm in diameter at the maximum cutting speed of 3360 mm/min;

$$MRR = 6 * 18 * 3360 = 362880\ mm^3/min$$

The material removal rate was then implemented in the formula to calculate the required cutting power;

$$RequiredCuttingPower = \frac{362880}{491611{,}92} = 0{,}738\text{ HP} = 542{,}90\text{ Watt}$$

The required cutting power could then be implemented in the formula to calculate the required torque for both the maximum and minimum torque of the router;

$$RequiredCuttingTorque_{MaxRPM} = \frac{542{,}90}{2\pi * 30000/60} = 0{,}173\ N/m$$

$$RequiredCuttingTorque_{MinRPM} = \frac{542{,}90}{2\pi * 10000/60} = 0{,}518\ N/m$$

Finally the required cutting torques were implemented in the formula of the required cutting force;

$$RequiredCuttingForce_{MaxRPM} = \frac{0{,}173}{0{,}003} = 57{,}67\ Newton$$

$$RequiredCuttingForce_{MinRPM} = \frac{0{,}518}{0{,}003} = 172{,}67\ Newton$$

6.2 Electronics

In order to drive the three different axes of the resizable CNC router, different electronic components were used. The main infrastructure of the router revolved around the use of, as mentioned before, stepper motors.
To drive these stepper motors the implementation of a stepper driver was necessary. In this case the TB6600 stepper drivers were used because of its plug and play and versatile capabilities(Maker Hardware, 2020). These drivers can be used with a large variety of stepper motors since its output current and micro steps can be altered with the flick of a number of switches.
In order to power the stepper drivers and in turn also the stepper motors, a power supply was also implemented. To ensure enough voltage and current could be supplied, as well as a level of future proofing the concept(in case more drivers/motors had to be added), a power supply of 24V and 20A was used.
To control the stepper motors the implementation of a micro controller was also necessary. For this use case an Arduino UNO was used. The Arduino UNO will be powered by the computer that will run the software program which will be described in the next paragraph.
For the wiring diagram of the electronic system of the CNC router see J Wiring Diagram.

6.3 Software

The software that has been uploaded to the Arduino UNO, in order for the CNC router to function as expected, was an opensource software named GRBL (GRBL, 2023). This software has been around since 2009 and can be best described as a free community-based and opensource project that allows the Arduino Uno to interpret G-Code commands. The GRBL software can be used with almost all used CAM software currently available, making it a great addition to the CNC router.

In order for the Arduino UNO to actually receive the G-Code commands that are generated by the CAM software, a G-Code Sender was necessary. For this use case another opensource software has been implemented; Universal G-Code Sender (UGS, 2021).
Universal G-Code Sender or UGS for short is a graphical interface that allows the user to connect to their GRBL interpreting device. Within this software the user is able to control the CNC machine, alter machine settings (such as resolution(steps/mm) or feedrate(mm/min)) and able to run machining operations all from the same interface(see figure 32).

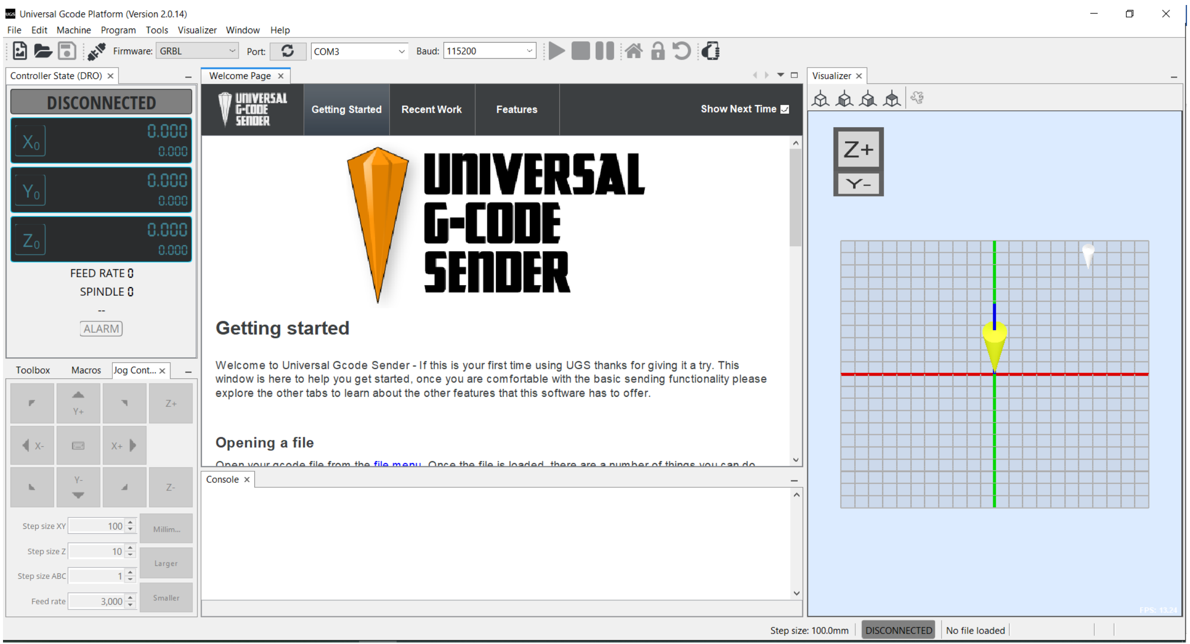


Figure 32: Universal G-Code Sender Interface

6.4 Y-Axis

Figure 33 shows the resizable Y-Axis. This axis ensures a minimum work area of 1220mm when resized to its smallest size and a work area of 2440mm when resized to its largest work area.

6.4.1 Rack and Pinion System

In order for the Y-axis to be made resizable, a double rack and pinion was introduced. As described in Appendix C, a rack and pinion system consists of a gear track(rack) and a pinion(gear) (see figure 34). This system is used to create a linear motion.

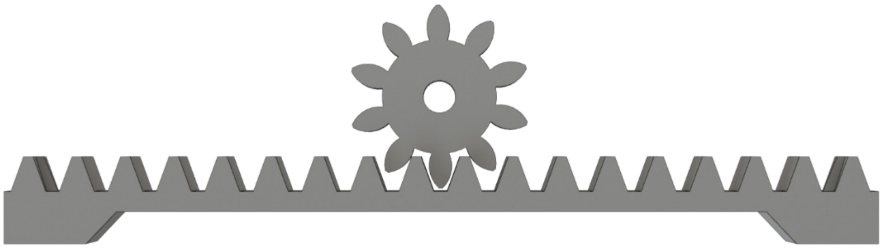


Figure 34: Rack and Pinion

By introducing two racks, mirrored from one another but connected only by a single rotating spur, a resizable axis could be realized. By rotating this single spur but keeping its location fixed, the two racks will move in opposite parallel directions (see figure 35).

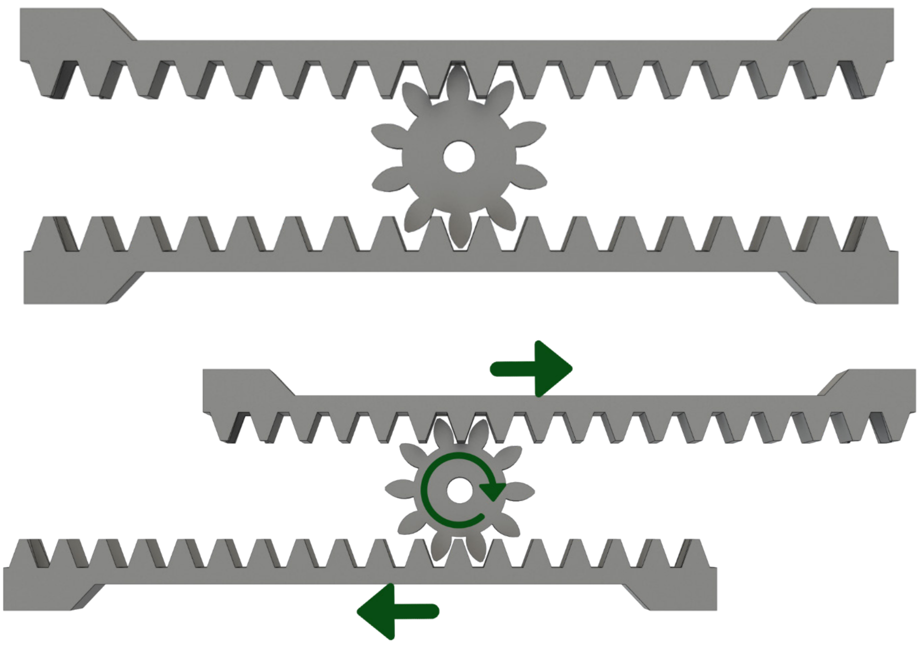


Figure 35: Double Rack and Pinion non-extended (top), extended (bottom)

Figure 33: Y-Axis

In order to test this concept of resizing using a double rack and pinion system, a prototype was created. The first step in this prototyping process was designing a profile that could be used in combination with the double rack and pinion system. These profiles would be used as the guidance for a linear moving carriage.
In order for this carriage to move across these profiles it was decided to use ball bearings, specifically 608-Z ball bearings (SKF,2023). These ball bearings consist of an all-metal housing, are widely and readily available and provide 'low-friction and high-speed capabilities'.

Initially a profile was designed to accommodate the use of two hardwood (Meranti) beams that would act as both the rack and pinion and the guidance system (see figure 36).This idea however was quickly abandoned since the manufacturing of these beams would prove too costly when implemented in the final design (Personal communication Jongeneel, 2023). Another deciding factor for abandoning this design was the material itself. Since wood remains a nature product it also possessed slight inaccuracies in its profile. The use of a different type of 'harder' hardwood could possibly have improved this, however the required accuracies and tolerances for the profiles could not be reached with the tools that were at the disposable at the time of prototyping(see figure 37).

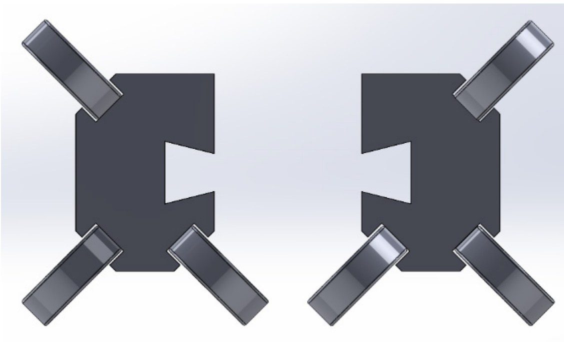


Figure 36: Meranti Rack and Pinion and Guidance profile

Figure 37: Manufactured Meranti Profiles

Similar to the design of the MPCNC (see appendix F), the following profile design made use of conduit on which the bearings acted as wheels (see figure 38). Within this configuration the cart that would hold the bearings would be able to rotate along the conduit which is not desired.

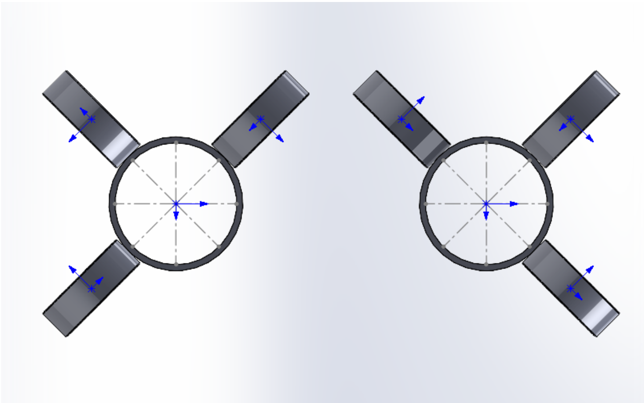


Figure 39: Double conduit profile

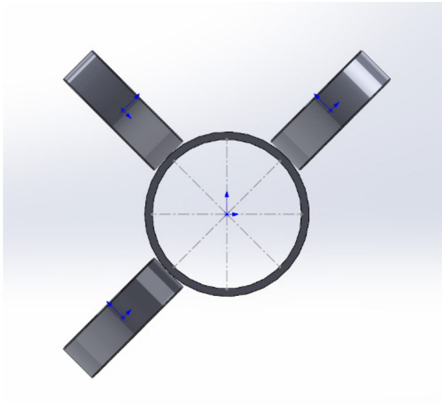


Figure 38: Conduit profile

Adding a second conduit beneath the first one mitigates this rotation and restricted the degrees of freedom when the wheels would be connected in order to form the desired carriage (see figure 39). This addition also mitigates the use of the two wheels in between the conduits, since connecting the bearings in a single carriage will ensure the desired number of degrees of freedom.
Figure 40 shows the bearings in a connected carriage. Because of its open configuration and its thin body the carriage was able to flex quite a bit. This flexure left the carriage either too loose or either too tight across the conduit beams. A different way of mounting the bearings to the carriage was necessary. A way in which the connection of the bearings to the conduit did not rely on the tolerances/flexure of the carriage body.

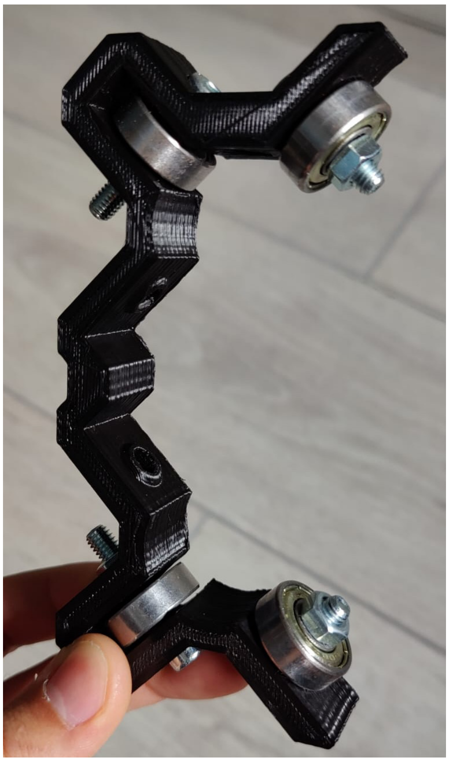


Figure 40: Carriage Prototype

Connecting the rack and pinion system to the conduit beams had been done in the following prototype displayed in figure 41.

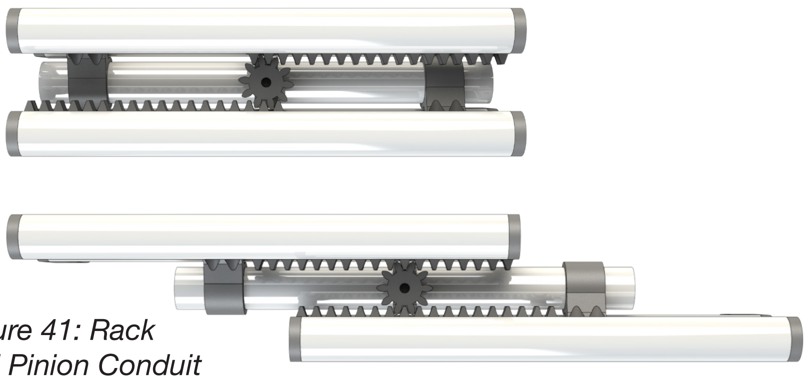


Figure 41: Rack and Pinion Conduit prototype

Comparing the 3D model (figure 42) to the actual prototype of this design (figure 43), it became apparent that the real life prototype had a lot more unwanted degrees of freedom. This had to do with the small parts that held the two sliding conduit beams together. A lot of unwanted movement/flexure in the mounted assembly was present, making the two sliding beams sag when connected.

As can be seen in figure 43 as well, the current design of the system actually consists of three conduit beams. However in this design the middle beam actually only serves the function of connecting the two sliding beams together(which it did not do very well).
In order to counter the previously mentioned issue of the carriage and the total assembly, two main takeaways had to be taken into consideration when creatin the final design of the CNC router;

- A different way of mounting the bearings to the carriage was necessary. A way in which the connection of the bearings to the conduit did not rely on the tolerances/ flexure of the carriage body.
- The conduit beams have to be connected to each other in order to limit its degrees of freedom.
- The middle conduit beam should be connected to the two sliding beams in such a way that it can serve a guiding purpose for the carriage as well. Theorizing that more guiding beams will create a stronger connection between the X- and Y-axis when the machine is in operation and in general.

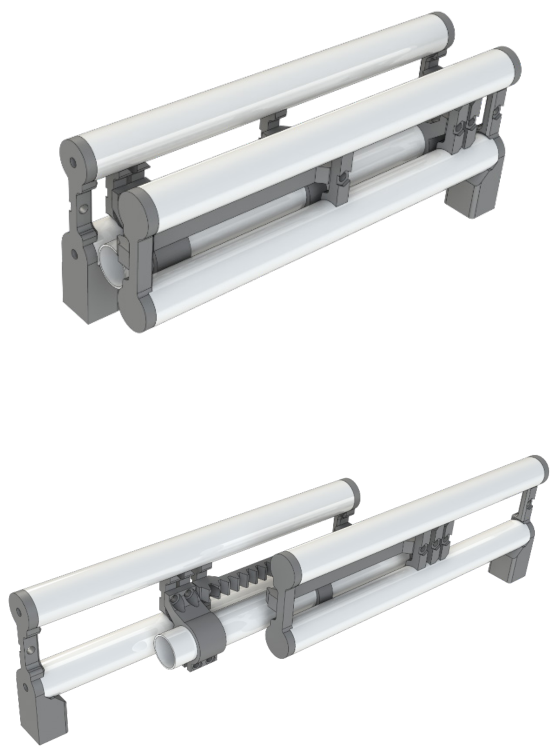


Figure 42: Rack and Pinion Conduit 3D model

Figure 43: Rack and Pinion Conduit Physical Prototype

As described before, the resizable Y-axis consists of three beams that will be able to slide in order to facilitate a work area of up to 2440mm. These beams are made up of 28mm 'CV-Buis'. The choice for this type of conduit was made for their very strong nature. As well as the fact that these conduits are very straight because of the material from which they are manufactured.
The three conduit beams that make up the Y-Axis can be seen in figure 44. Two of the three beams that make up the Y-Axis are actually the same just mounted mirrored from each other. These two beams hold the racks that form the basis of the rack and pinion system. The racks are held in place by supporting brackets. These supporting brackets ensure that the two conduits, that make up a beam, are situated perfectly parallel from each other. While at the same time also preventing bending from the conduits. Two of these supporting brackets have a geometry that allows it to grab onto the middle beam in addition to only holding the side beam. This 'double' support bracket ensures that the side beams are restricted in their degrees of freedom and provide the needed rigidity to the axis. These double support brackets can be seen in figure 45.
The gear that makes up the pinion in the rack and pinion system also can be seen in this figure. This Pinion is located at the middle of the middle beam.

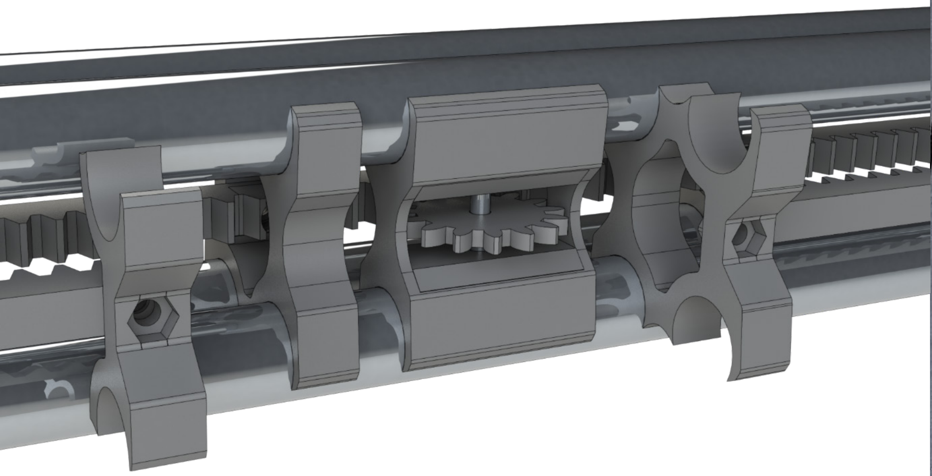


Figure 45: Double Bracket and Pinion

Figure 44: Y-Axis Conduit Beams

To provide an extra level of rigidity to the axis and limit the degrees of freedom of the beams even more, it was decided to mount them to both of the end plates that enclose the axis as a whole(see figure 46). For the mounting of the beams 1350mm of threaded rod was used. At the end of these lengths of threaded rod a 3D printed piece was fitted that fitted within the conduits perfectly. In order to allow the threaded rods to slide in and out of the conduits a sliding bearing was introduced to the end of the conduits. Ensuring that the threaded rod would allow a sliding motion when the axis was resized. Suspending the beams between the two end plates that enclose the axis. The entire axis (in both sizes) can be seen in figure 47.

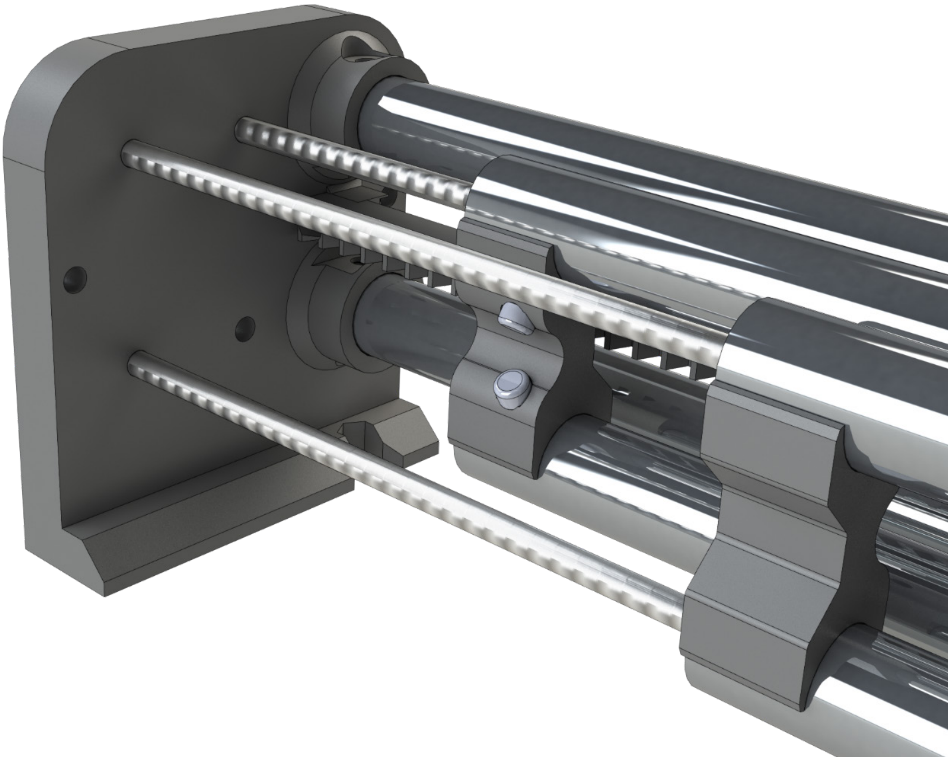


Figure 46: Mounted Threaded Rods

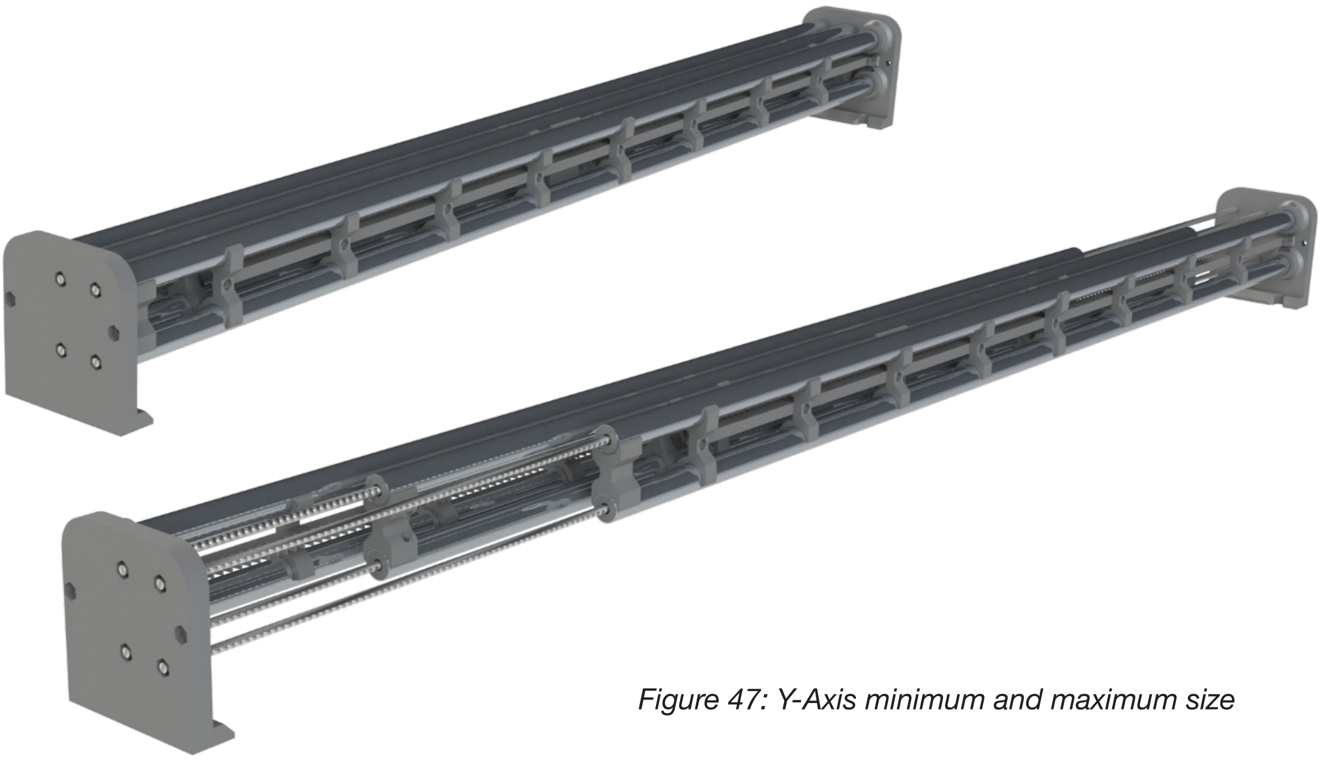


Figure 47: Y-Axis minimum and maximum size

6.4.2 Linear Motion System

For the motion system of this resizable axis a GT2 timing belt was chosen (see appendix K GT2 Belt Datasheet). These belts are belts with a rounded tooth profile, that match the profile of the accompanying pulley on the motor exactly. This way a minimal amount of backlash is introduced. Belts are a lightweight option for linear motion. However belts can stretch over time and can start to sag, which can lead to slipping of the belt which in turn leads to skipping of steps of the stepper motor. This skipping of steps in turn leads to a loss of linear motion, making the machined parts not dimensionally accurate. The longer the belt, the more sag is introduced. Unless idler pulleys are installed to make the belt support itself (RepRap, 2015).

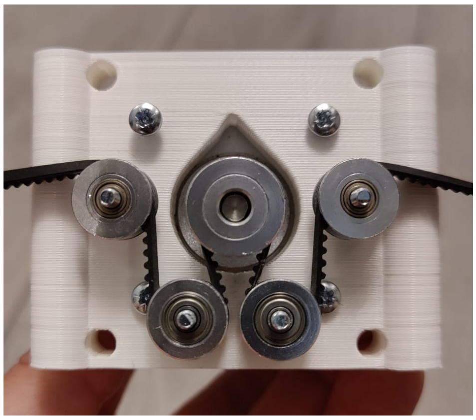


Figure 48: Motor holder & Idler pulley orientation

In order for the belt to support itself a motor holder design was made that introduced the use of idler pulleys in a specific orientation. Figure 48 shows this motor holder and the idler pulley orientation. Contrary to idler pulley orientations that are used in lightweight applications (e.g. 3D printers or laser engravers/cutters), this orientation of the belt across the drive pulley (the pulley mounted to the stepper motor) wraps around the drive pulley. Using 14/15 of the 20 teeth available on the drive pulley. Whereas the belt in more lightweight applications only tend to use around half of the teeth available (see figure 49).
The wrapped around orientation and the use of more teeth of the pulley gives the motor more grip on the belt (Adrie Kooijman Personal Communication, 2023), making it easier to distribute the force necessary for the linear motion.

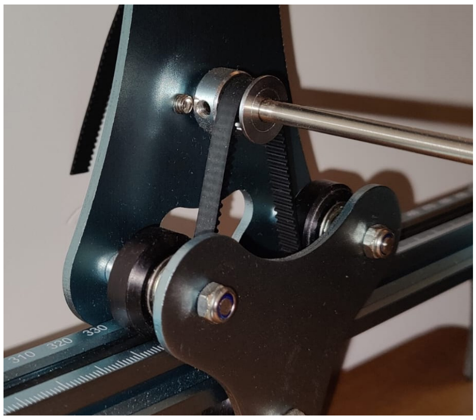


Figure 49: Motor holder & Idler pulley orientation on a laser engraver

In order to remove any more sag from the belt and tension it properly along the axis, a belt tension design was created. Fixing the belt to one side of the axis and inserting it into a ‘tensioner’(see figure 50) allows the user to properly tension the belt when more tension is needed, by tightening the bolt on the back of the tensioner. Because of the geometry of the tensioner and the way the belt fits in it, the belt is properly fixed making tensioning of the belt a rather simple act.

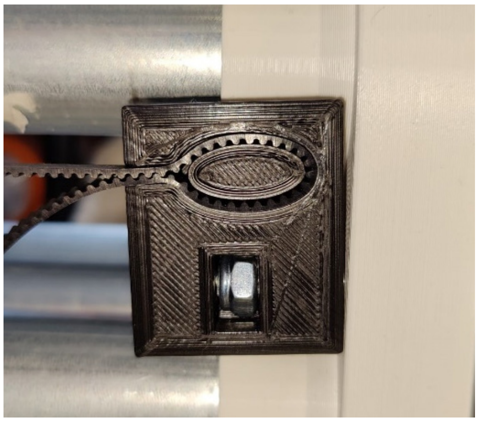


Figure 50: Belt Tensioner

By connecting the design of the motor holder and the tensioning system the motion system was created. The motor generated a linear motion across the belt when it rotated, moving itself along the axis.

6.4.3 Carriage

As mentioned before, a different way of mounting the bearings to the carriage was necessary. A way in which the connection of the bearings to the conduit did not rely on the tolerances/flexure of the carriage body.
In order to satisfy this takeaway a different way of mounting the bearings to the guide beams was designed. Figure 51 shows this redesign. As can be seen in the figure, this redesign consists of a small 3D-printed piece that holds two bearings at an angle and also holds two bolts that allow the bearing holder to be mounted to the carriage.
Figure 52 shows the entire carriage with the bearing holders mounted.
As can be seen from figure 52 and 53(The real life version of the carriage), the bearings are mounted to two plates in a triangular structure. These two plates are mounted to the conduit beams with the help of threaded rods in order to ensure proper mounting and seating. The threaded rods ensure the required tension between the two plates in order to 'sandwich' on to the conduits with the help of locknuts.

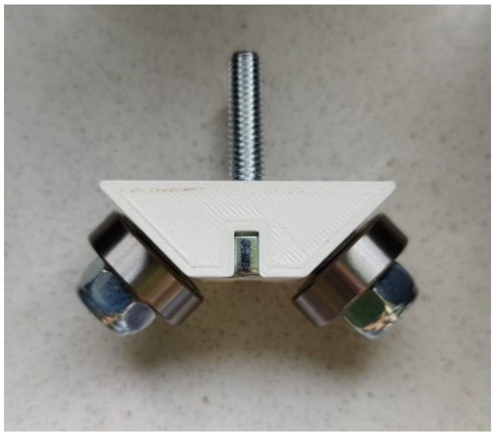


Figure 51: Bearing holder mountable to carriage

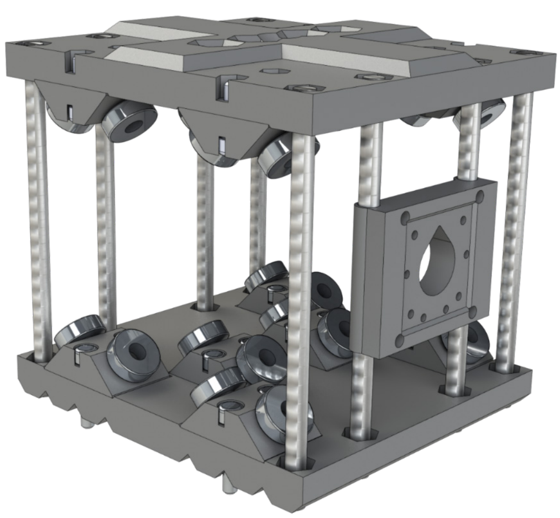


Figure 52: Y-Axis Carriage

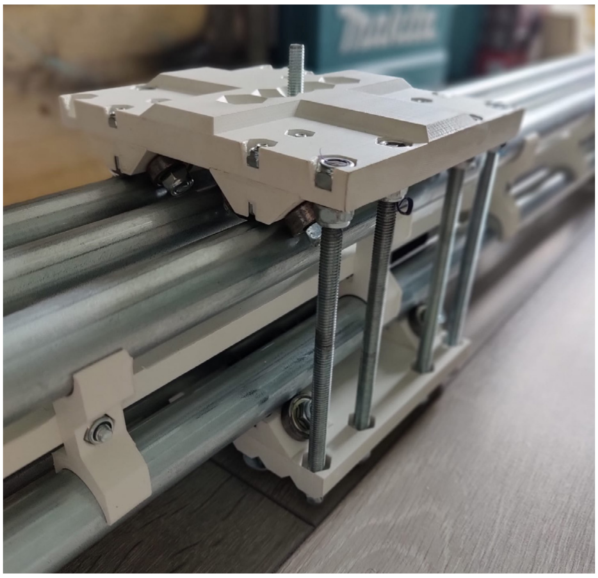


Figure 53: Y-Axis Carriage mounted to conduits

6.5 X-Axis

Figure 54 shows the X-Axis. This axis functions as a rigid axis and facilitates a work length of 1220mm.

6.5.1 Linear Motion System

Similar to the motion system of the Y-Axis, the X-Axis uses the same motor holder and idler pulley orientation to facilitate the linear motion of the axis.
The motion is therefore also ensured with the help of GT2 Belt. Connecting one side of the belt in a fixed manner while placing the other side in the belt tensioner ensures that the user is able to properly tighten the belt when necessary.
The belt tensioner of this axis works in the same manner as that of the Y-axis. Figure 55 shows the belt tensioner for this axis. As mentioned before, this tensioner works in the same way as that of the Y-Axis. By tightening the bolt located on the back of the tensioner, the belt moves back and tightens the belt accordingly.

Figure 55: Belt Tensioner

The main difference between this axis compared to the Y-Axis is the size of the conduit that has been used. For the X-axis 38mm aluminium conduit was used with a 2mm wall thickness. This choice has been made with the total weight of the axis in mind and also because of the availability of the aluminium tubing.

Figure 54: X-Axis

In order to properly move the X-axis along the Y-Axis, a design had to be made in order for the axis to be supported on both sides of its conduits. For this design a plate was used on which bearings have been mounted in order to follow the motion of the axis. These mounted bearing would act as wheels when the axis was in motion.
Connecting the conduit to the plate has been done by create a round mounting point for the conduits to be seated. These mounting points could then be clamped to the conduit and bolted to the plate itself.
Figure 56 shows the supporting plate.

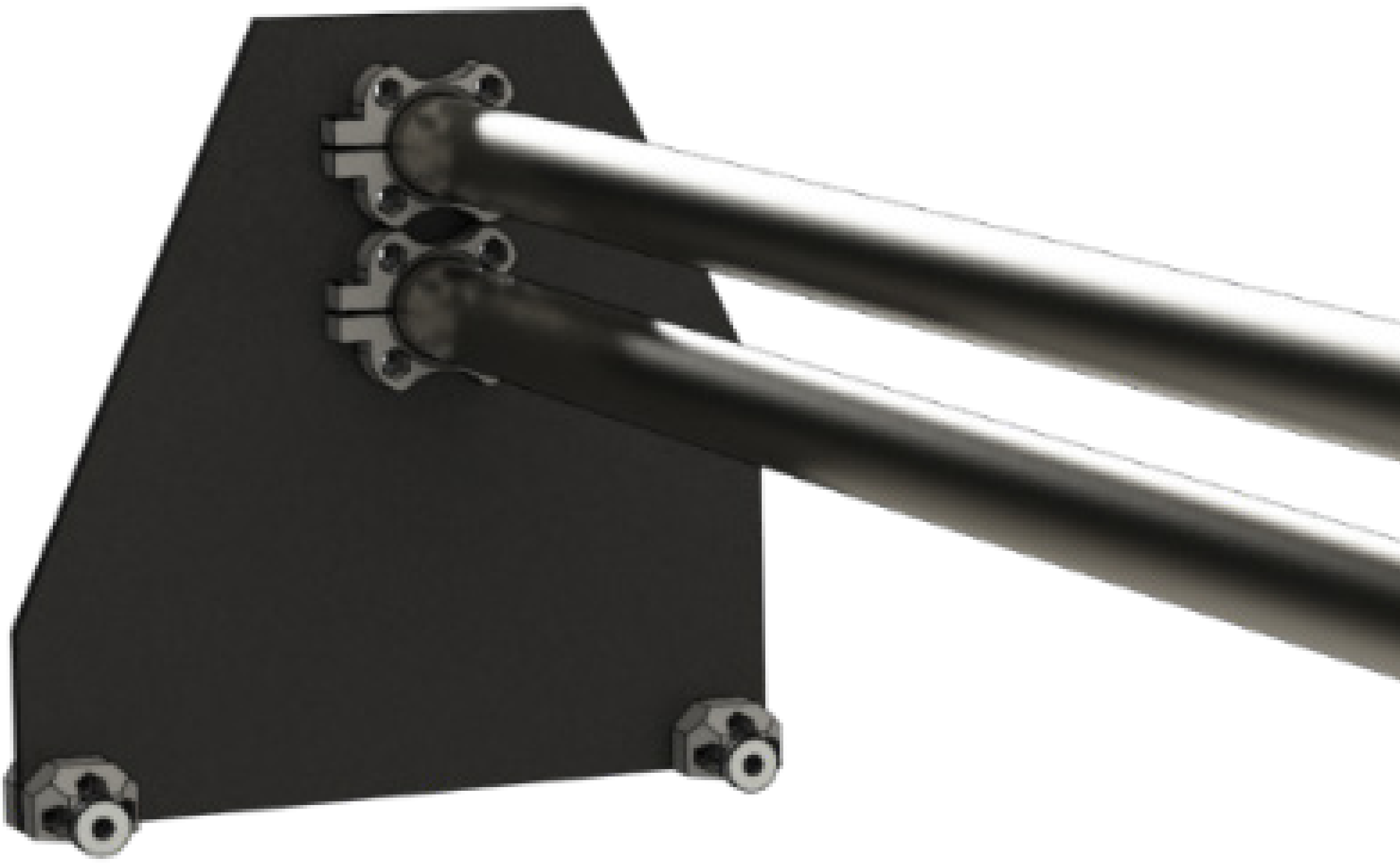


Figure 56: X-Axis support plate

6.5.2 Mounting Plate Pivot Point

In order to properly secure the X-Axis to the Y-Axis and create the desired folding design a mounting plate was designed with a symmetric form on top of it. In this case a plus sign was used. The Y-Axis carriage mounting plate had the positive side of the plus side while the mounting plate of the X-Axis had the negative side. The edges of the plus sign were chamfered in order to create a seating motion when the X-Axis was rotated parallel to the Y-Axis for storage purposes.
Figure 57 illustrates the act of mounting the X-Axis to the Y-Axis carriage. The Y-Axis could afterwards be secured by tightening a single bolt, positioned in the middle of the two plates. Untightening this bolt would loosen the connection between the two mounting plates in order to provide the axis with the needed slack in order to pivot the axis parallel to the Y-Axis.
Figure 58 illustrates the motion of pivoting the X-Axis parallel to the Y-Axis.

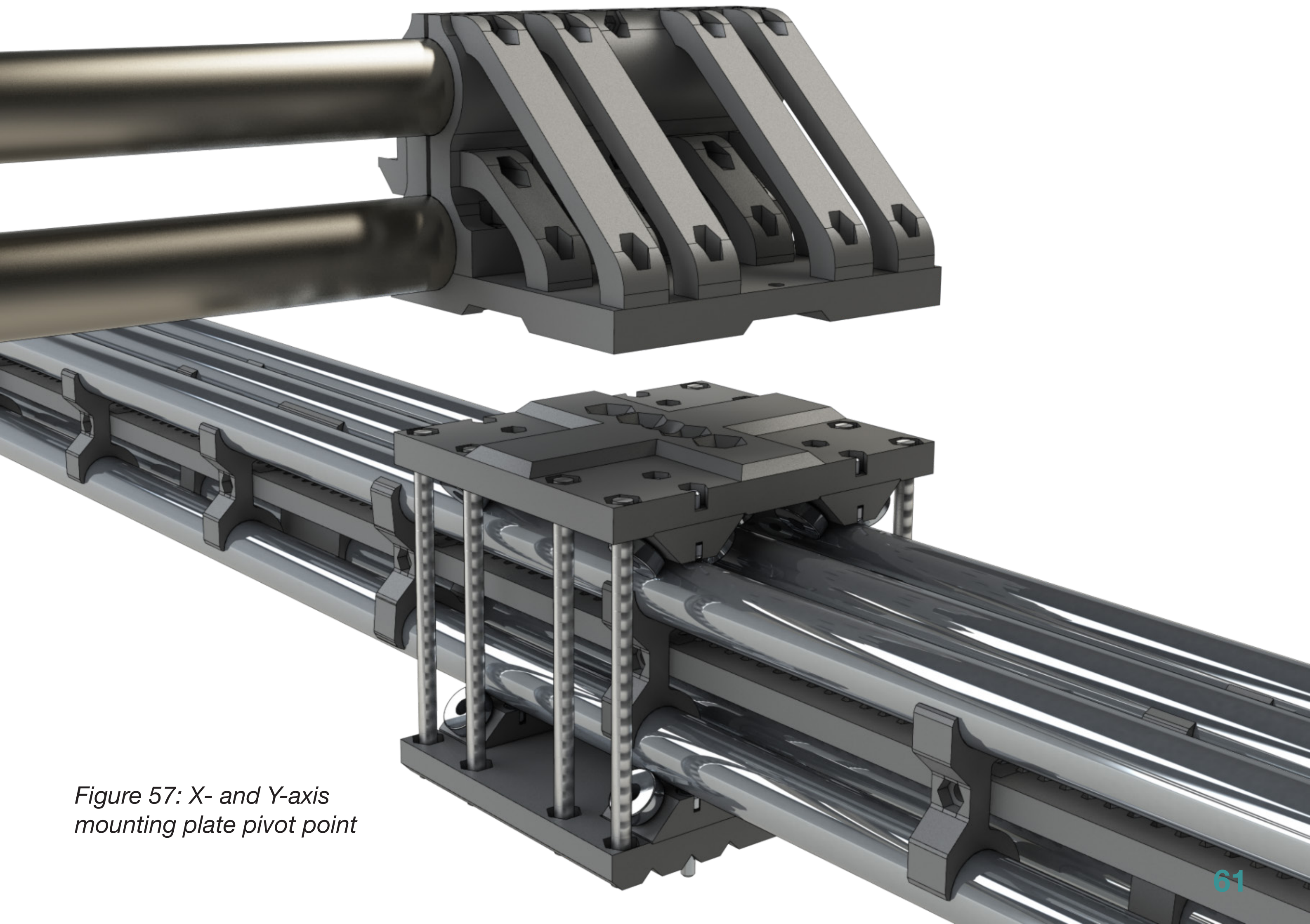


Figure 57: X- and Y-axis mounting plate pivot point

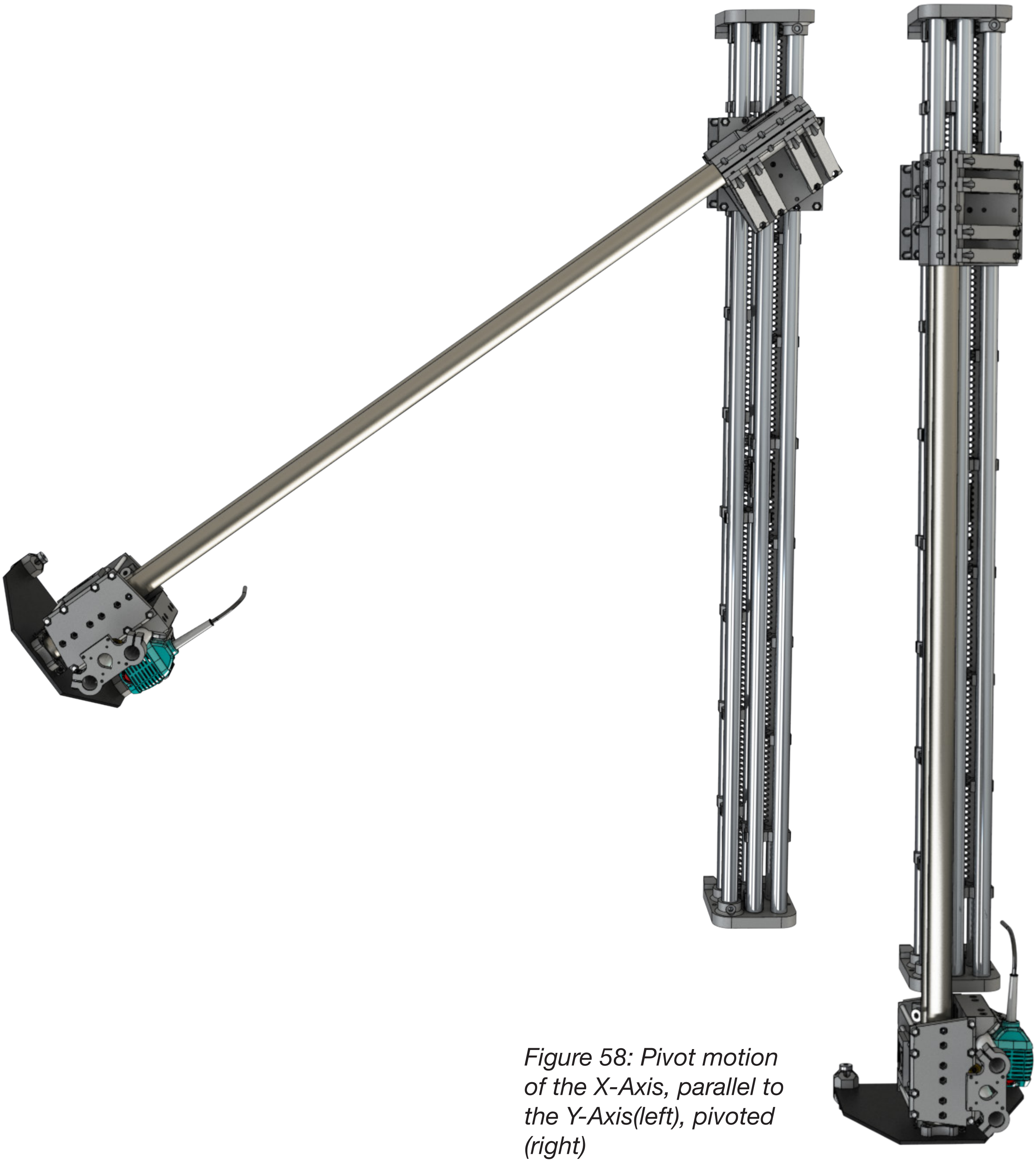


Figure 58: Pivot motion of the X-Axis, parallel to the Y-Axis(left), pivoted (right)

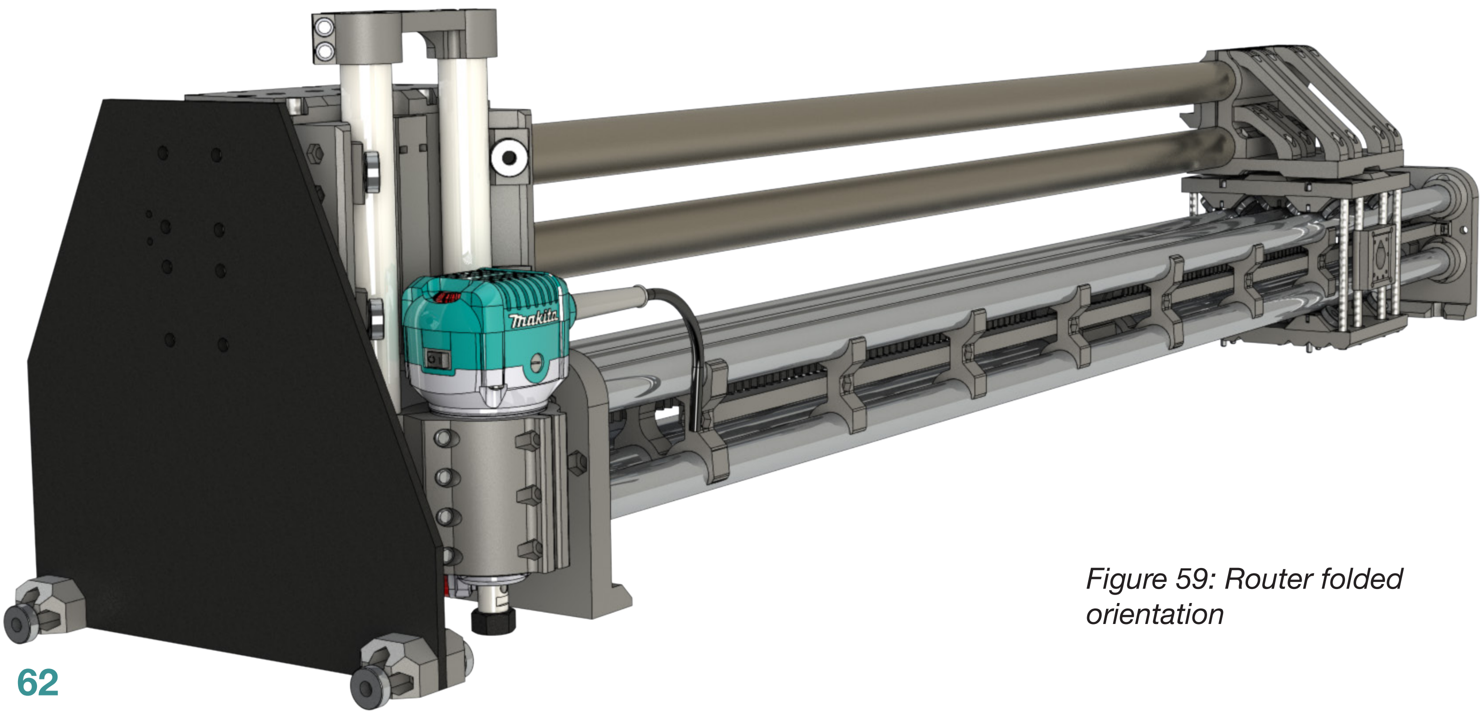


Figure 59: Router folded orientation

6.5.3 Carriage

Similar to the Y-axis, the X-axis uses the same design of bearing holders(only slightly larger to ensure a 45 degree seating on the 38mm aluminium conduit) to ensure that the carriage(figure 60) can move across the conduit beams to ensure linear motion. The bearing holders are mounted again to two plates that are connected by threaded rods. The only difference between this carriage and that of the Y-Axis is the side plate that is mounted across from the motor holder. This side plate holds the Z-Axis. See the next paragraph(6.5 Z-Axis) for an elaborate overview of the Z-Axis.

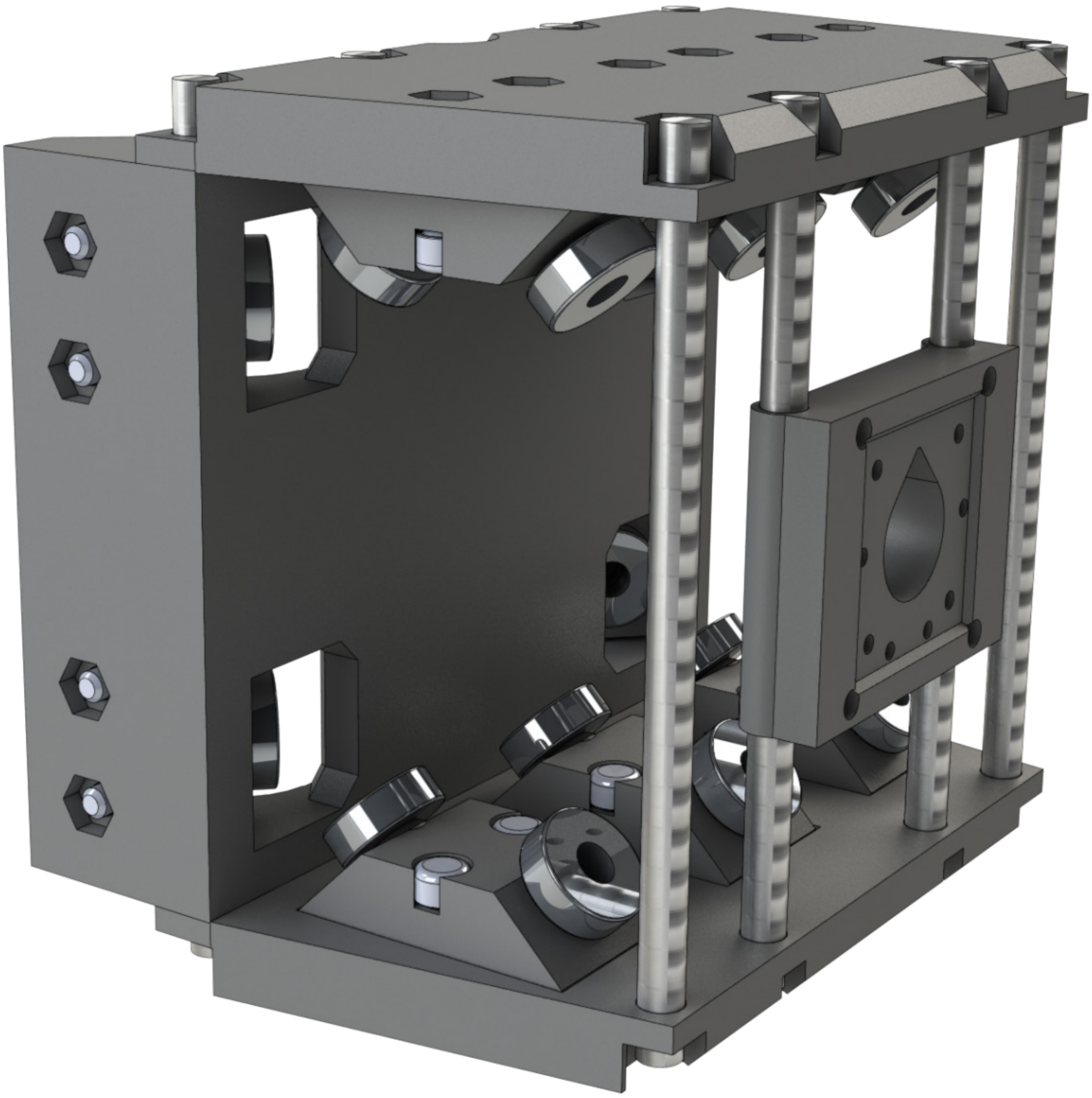


Figure 60: Carriage

6.6 Z-Axis

Figure 61 shows the other side of the carriage described in paragraph 6.4.2 Carriage.
As can be seen in the figure, this side of the carriage has the same bearing holders mounted to its sides in a vertical orientation. These bearing holders hold the vertical conduit beams of the Z-Axis displayed in figure 62.

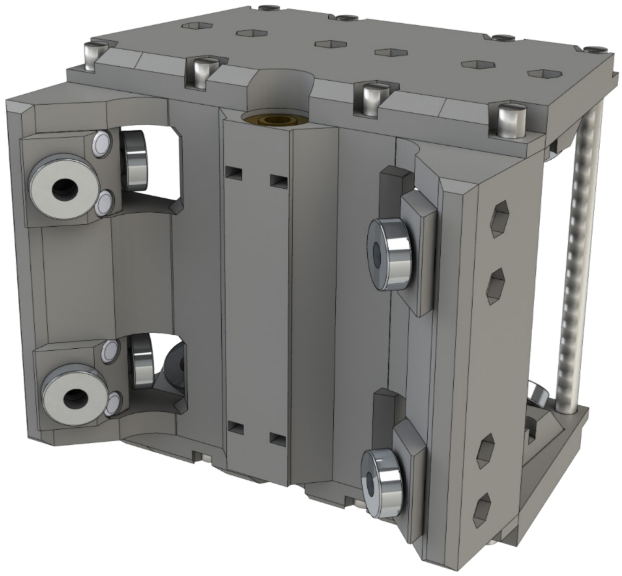


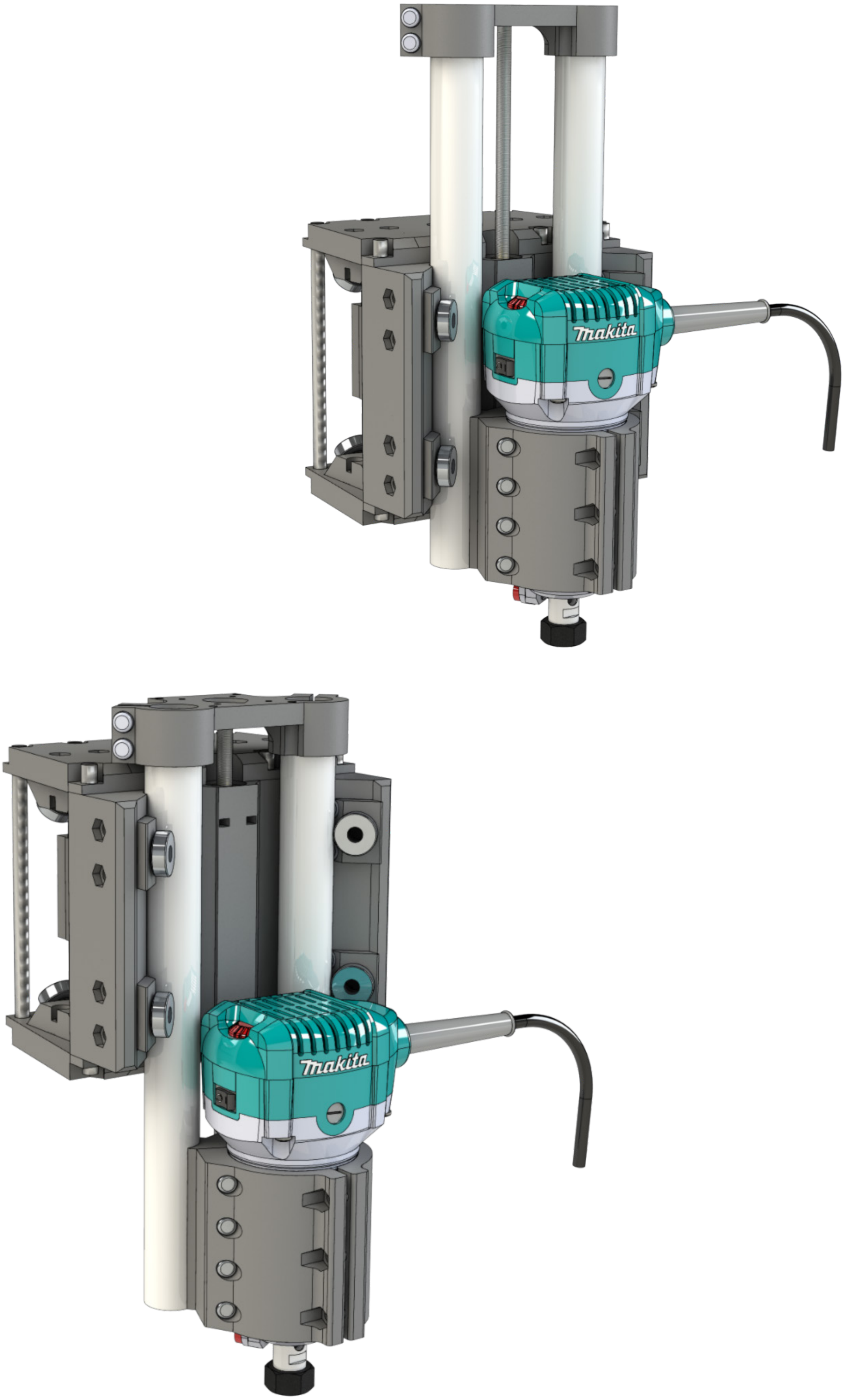
Figure 61: Carriage Z-Axis Side

The Z-axis consists of two vertical conduit beams, a motor holder that is mounted to the top of these beams and a holder for the router described in paragraph 6.1.1 Router. This router holder works by placing the router into the holder and tightening the three bolts orientated vertically across the holder.

Figure 62: Z-Axis

In order for the Z-Axis to function as intended, it is equipped with a T8x2 lead screw (see Appendix L T8x2 Lead Screw Datasheet). This lead screw has a diameter of 8mm and a pitch of 2mm. This lead screw is connected to the carriage by accompanying flange nuts. These flange nuts are embedded/mounted on the top and bottom of the carriage by M3 bolts and lock nuts.
By mounting the lead screw to the motor (with a coupler) which is connected to the Z-Axis and inserting the lead screw in the flange nuts that are mounted to the carriage the linear motion of the Z-axis is ensured. When the motor rotates the lead screw it creates a vertical linear motion of the Z-axis. Figure 63 shows the vertical linear motion that is created when the motor rotates the lead screw.

Figure 63: Vertical linear motion of Z-Axis



6.7 Router Assembly

Connecting all previously mentioned axes together forms the assembly of the router. Figures 64, 65 and 66 show the router in its different orientations and modes.

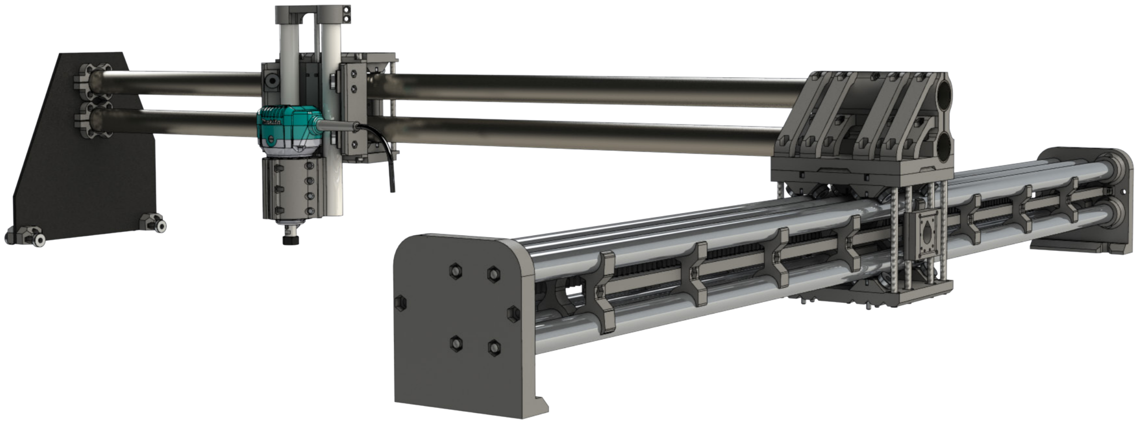


Figure 64: Router Assembly

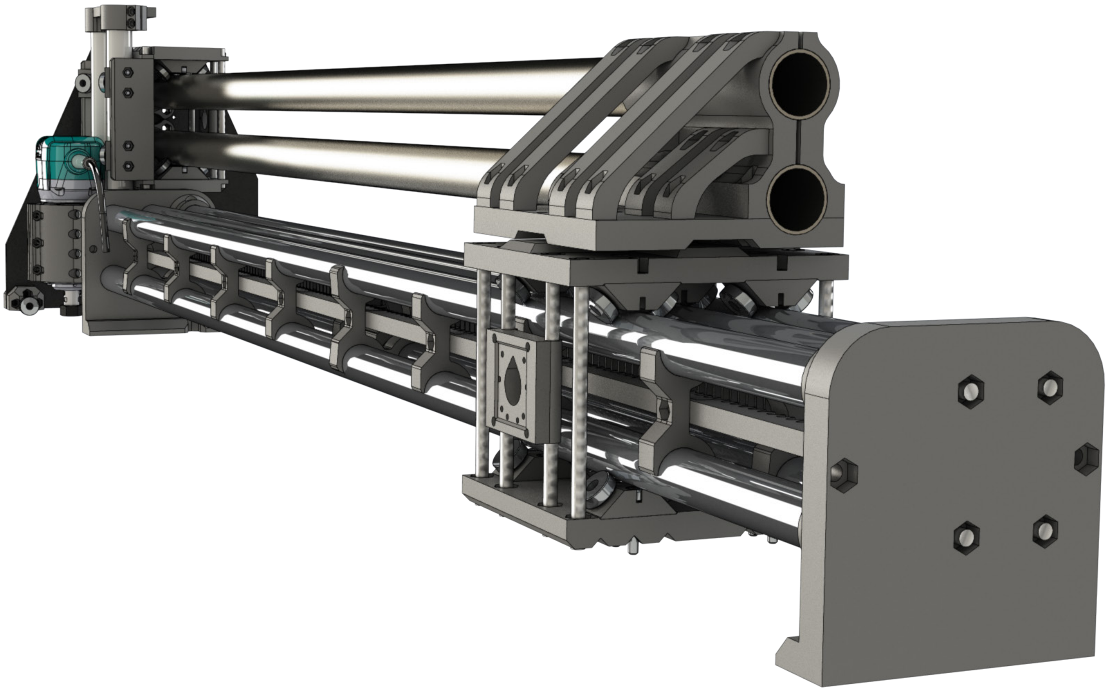
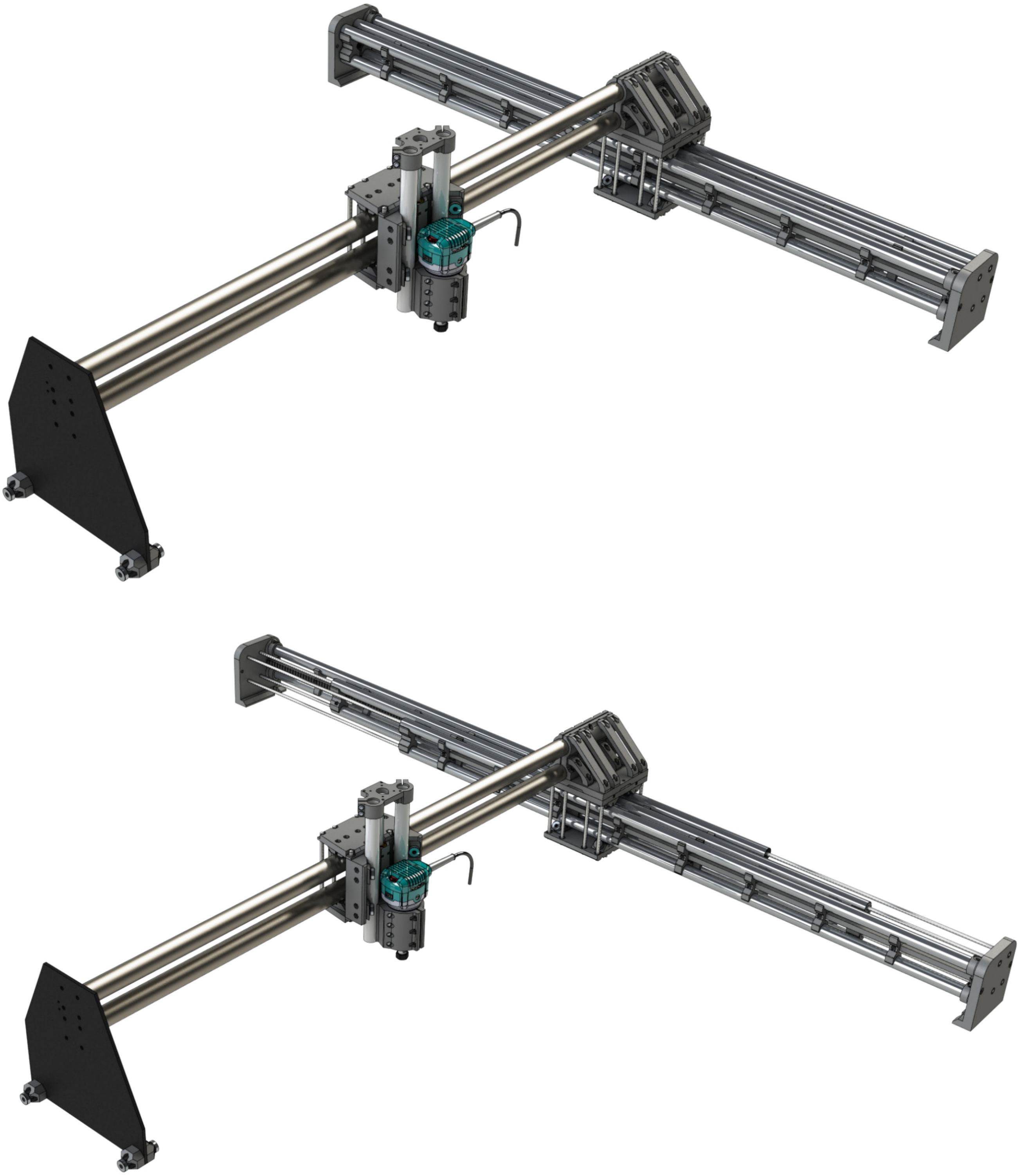


Figure 65: Router Assembly - folded

Figure 66: Router Assembly – minimum size (above) maximum size (below)



In order to determine what the effect is of cutting into material on the axes of the router calculations have been made.
As mentioned before in chapter 6.1.1 Router, the maximum cutting force applied to the router will be 172,67 Newton. By implementing this force into a static environment a moment could be calculated along the Y-Axis Carriage. Figure 67 shows the Free Body Diagram of this static situation.
within this situation the Force F equals the maximum cutting force of 172,67 Newton. This force F is applied 1300mm away from point A which describes the pivot point of the Y-Axis Carriage.

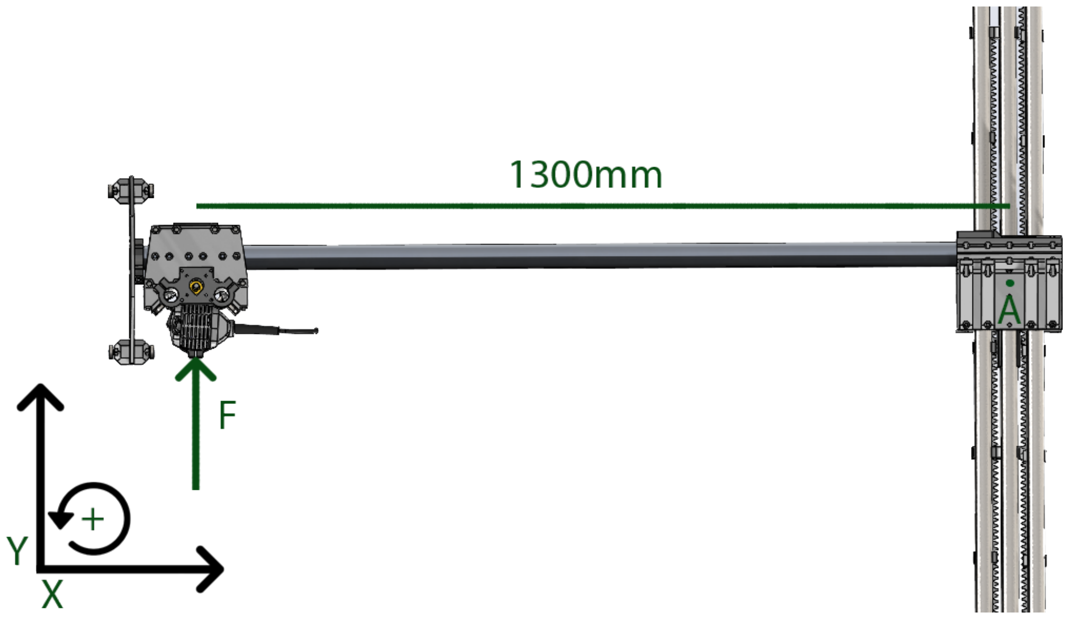


Figure 67: Router Assembly Free Body Diagram

In order to calculate the moment applied to the Y-Axis Carriage the following formula was used:

$$M = F * r$$

In which M describes the Moment in Newton/meters, F describes the Force in Newton and r describes the distance between the force and the point of rotation in meters. Since F=172,67N and r=1,3m the formula followed:

$$M = 172{,}67 * 1{,}3 \;=\; 224{,}471 \text{ N/m}$$

Since the moment creates a counterclockwise rotation it is described as negative. Therefore the moment applied to the Y-Axis Carriage is -224,471 N/m.

By applying the found moment onto the Y-Axis carriage, the deflection of the axis could be found when a Finite Element Analysis(FEA) was performed. Figure 68 shows the FEA of the Y-Axis. The purple cyclone on top of the carriage describes the moment applied to the carriage. The green arrows at both ends of the axis describe fixtures which were applied in order to anchor the axis for the simulation.

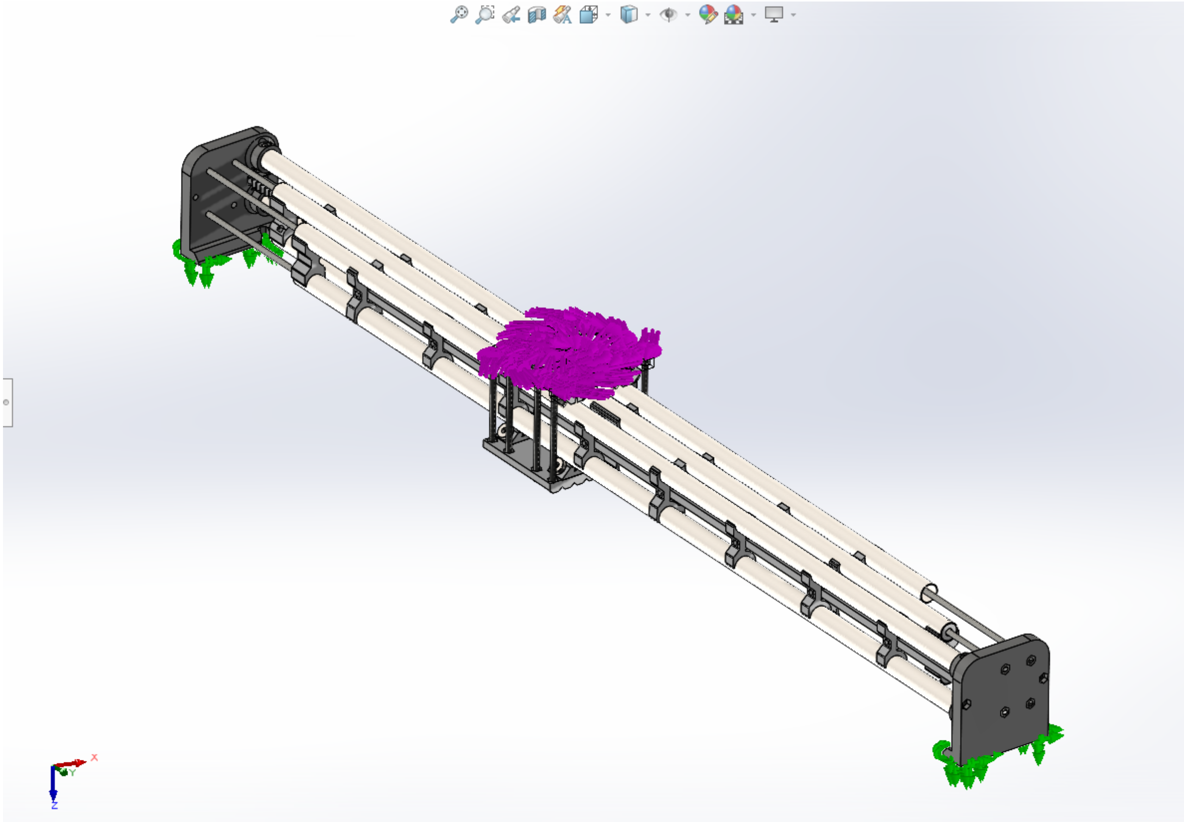


Figure 68: Router Assembly Free Body Diagram

After running the analysis and seeing the results displayed in figure 69, it became clear that the carriage itself only had a displacement of around 0,09mm(green). While the very end of the axis experienced a deformation of almost 0,2mm.

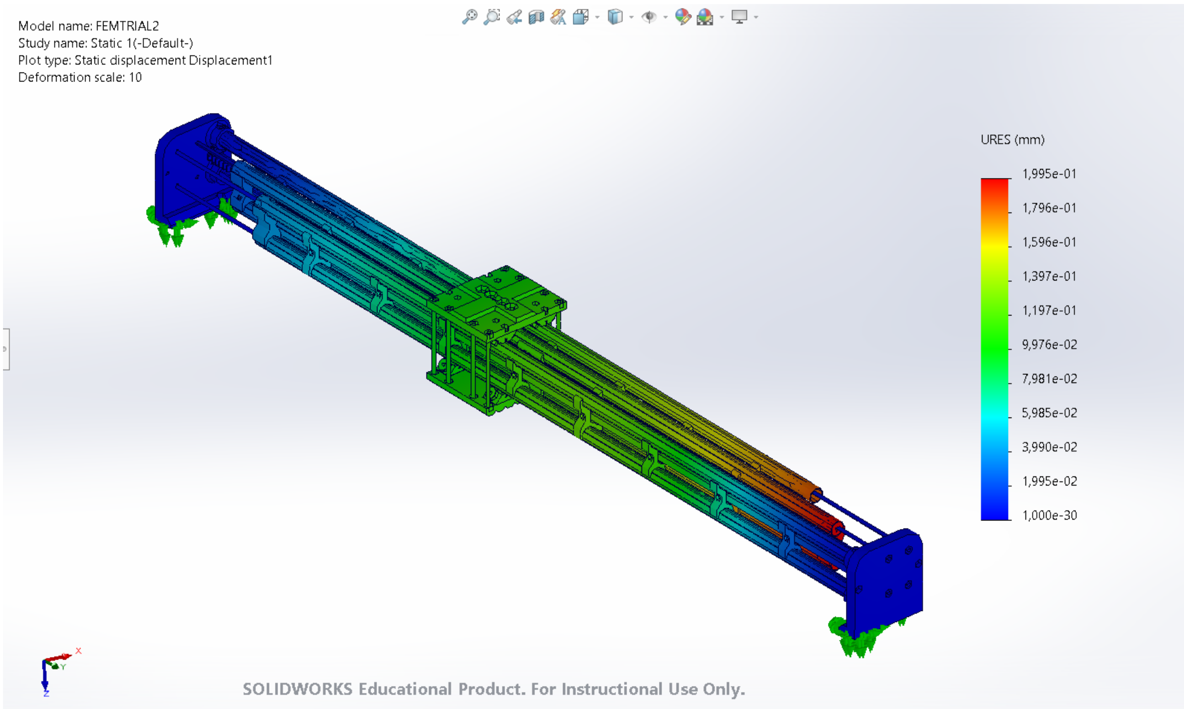
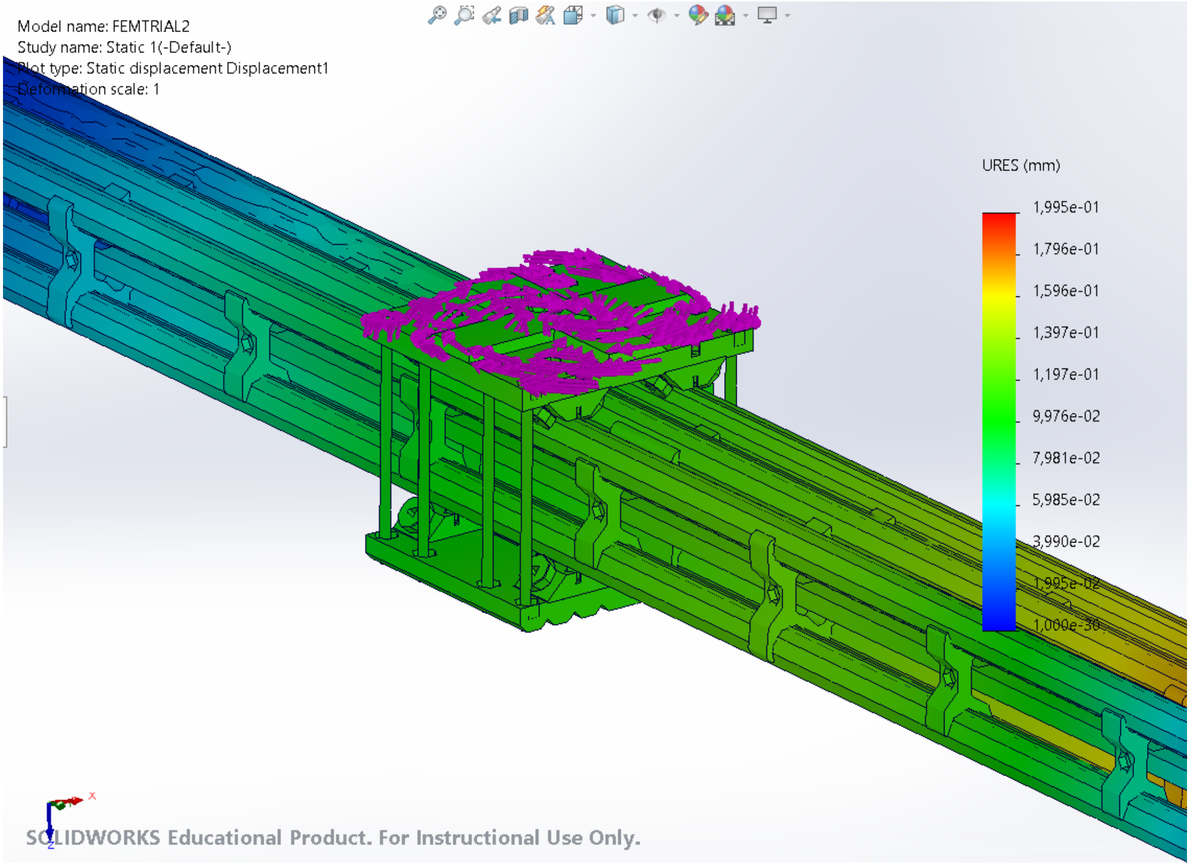


Figure 67: Router Assembly Free Body Diagram



The displacement that is experienced by the Y-Axis was adapted to the X-Axis in SolidWorks to determine the displacement present at the end of the X-Axis. It could then be determined that the maximum displacement that occurred when a 0,09mm displacement in the Y-Axis Carriage was present was 1.5mm. This number does not sound very high, however when realising that similar machines are capable of providing tolerances of 0,1mm this number is quite large.

On a positive note, the displacement that is described is determined by taking the maximum cutting force which the machine is capable. Cutting an 18mm thick sheet of plywood at the maximum cutting feedrate of 3360mm/min at a single pass is not something the average user will do very often.

TESTING AND EVALUATION

In order to properly evaluate the performance of the resizable CNC router, multiple tests have been conducted with the help of the physical prototype.

07

7.1 Dimensional Accuracy

Prior to performing actual cutting operations, each individual axis was tested for their dimensional accuracy to see whether the achieved movement matched the expected movement of the axis. Figure 70 shows the test that was conducted with the Y-Axis.

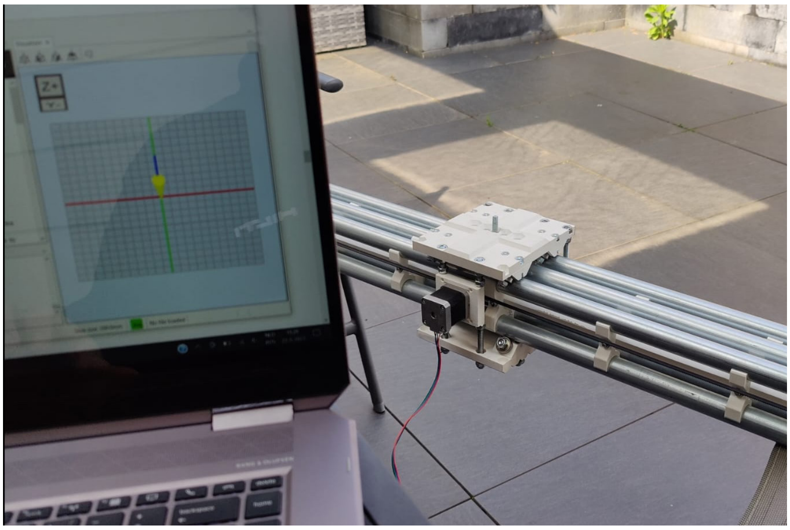


Figure 70: Y-Axis Test

After all three axes were tested individually and their dimensional accuracies were properly defined, the router could be fully assembled. The next step was to test whether the expected performance could be reached when all three axes were working together simultaneously, when the router was fully assembled. Figure 71 shows the fully assembled router during this previously mentioned test.
During this test it became apparent that when the Y-axis carriage (and therefore the entire X- and Z-Axes) was moved a swinging motion was introduced. This swinging motion was caused by the connection between the Y-Axis carriage and the X-Axis(as described in chapter 6.5.2 Mounting Plate Pivot Point) not being strong enough and causing the end of the X-Axis to be dragged along(lagging behind) instead of moving perpendicularly along the Y-Axis carriage.

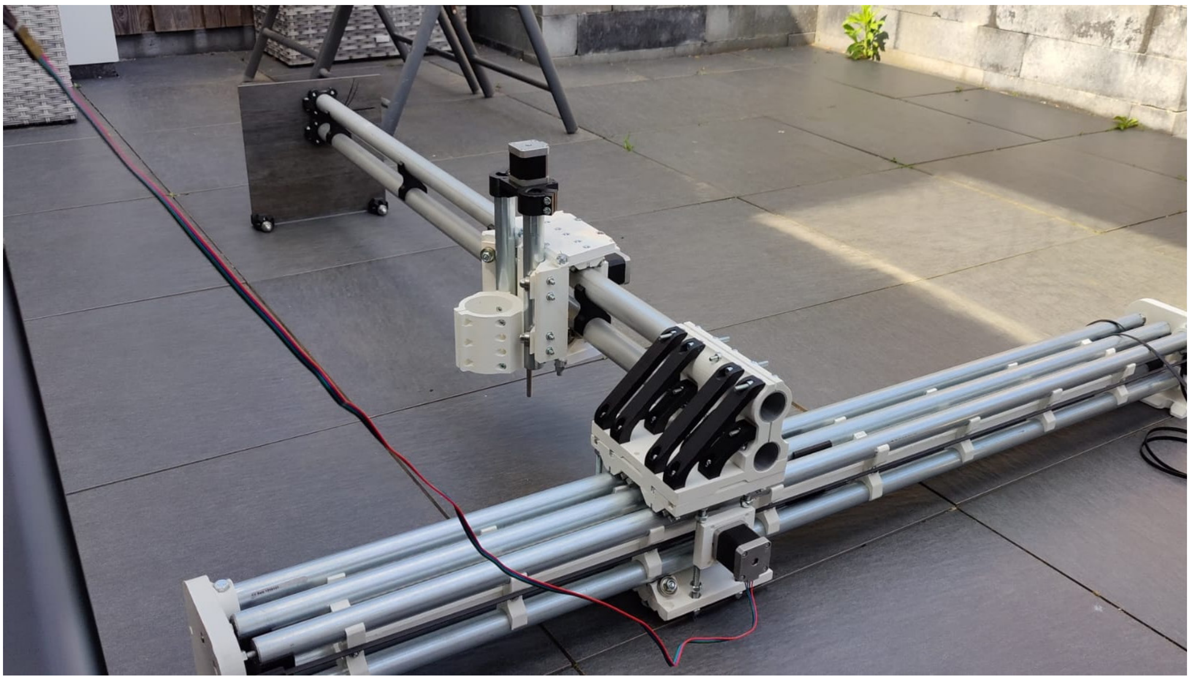
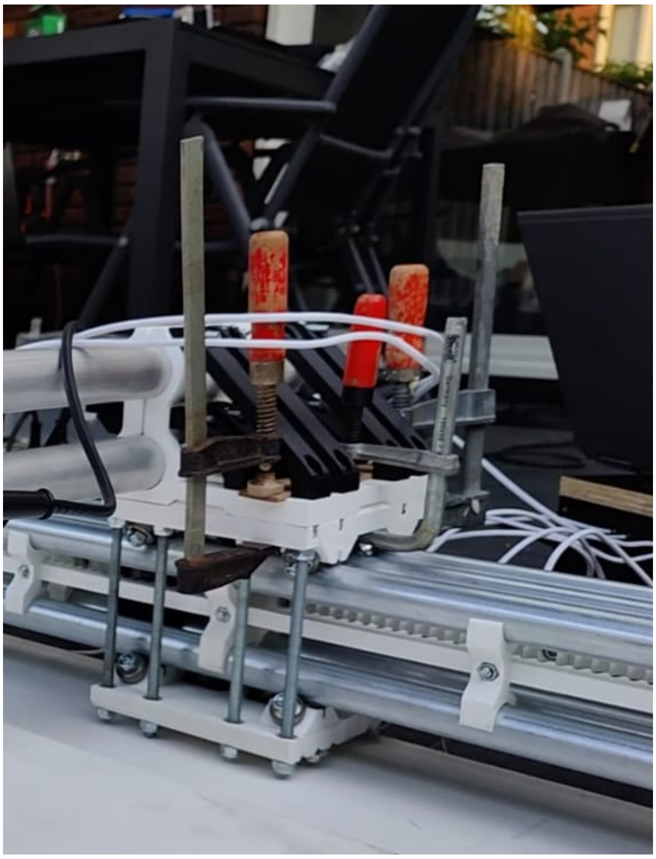


Figure 71: Fully assembled router during testing



In order to verify whether the issue was in fact caused by the connection between the two mounting plates, a temporary test setup was created using multiple clamps (see figure 72). These clamps held the two mounting plates together to try and remove any movement between their connection. After some initial movement tests the first cutting operation could be performed.

Figure 72: Temporary test setup; clamps

7.2 Initial Cutting Operation

As mentioned before, after introducing the temporary clamps to the two mounting plates the first cutting operation could be performed.
This cutting operation consisted of a series of lines that were placed randomly on a sheet of 18mm thick primed popular. This cutting operation was performed with a feedrate of 2000 mm/min and an RPM of 22000 with a cutting depth of 0.5mm. Figure 73 shows the end result of this initial cutting operation.

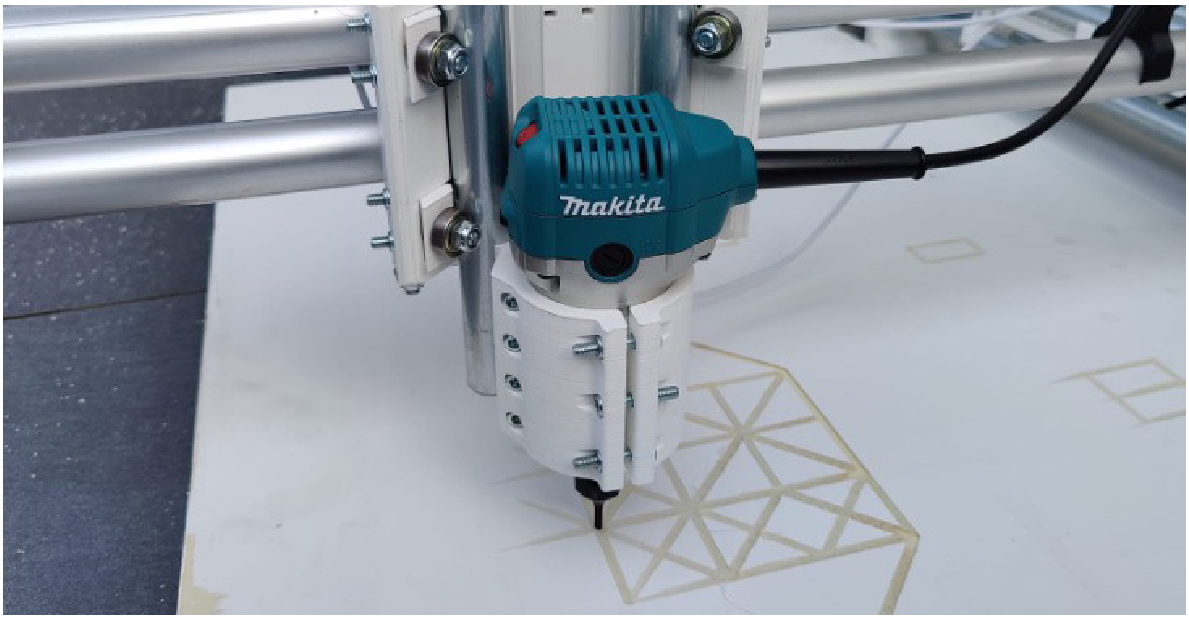


Figure 73: Initial cutting operation

At first glance this cutting operation looked like a success with clean and straight lines. However upon closer inspection the lines appeared to contain a slight curvature. Figure 83 shows this curvature of the lines.

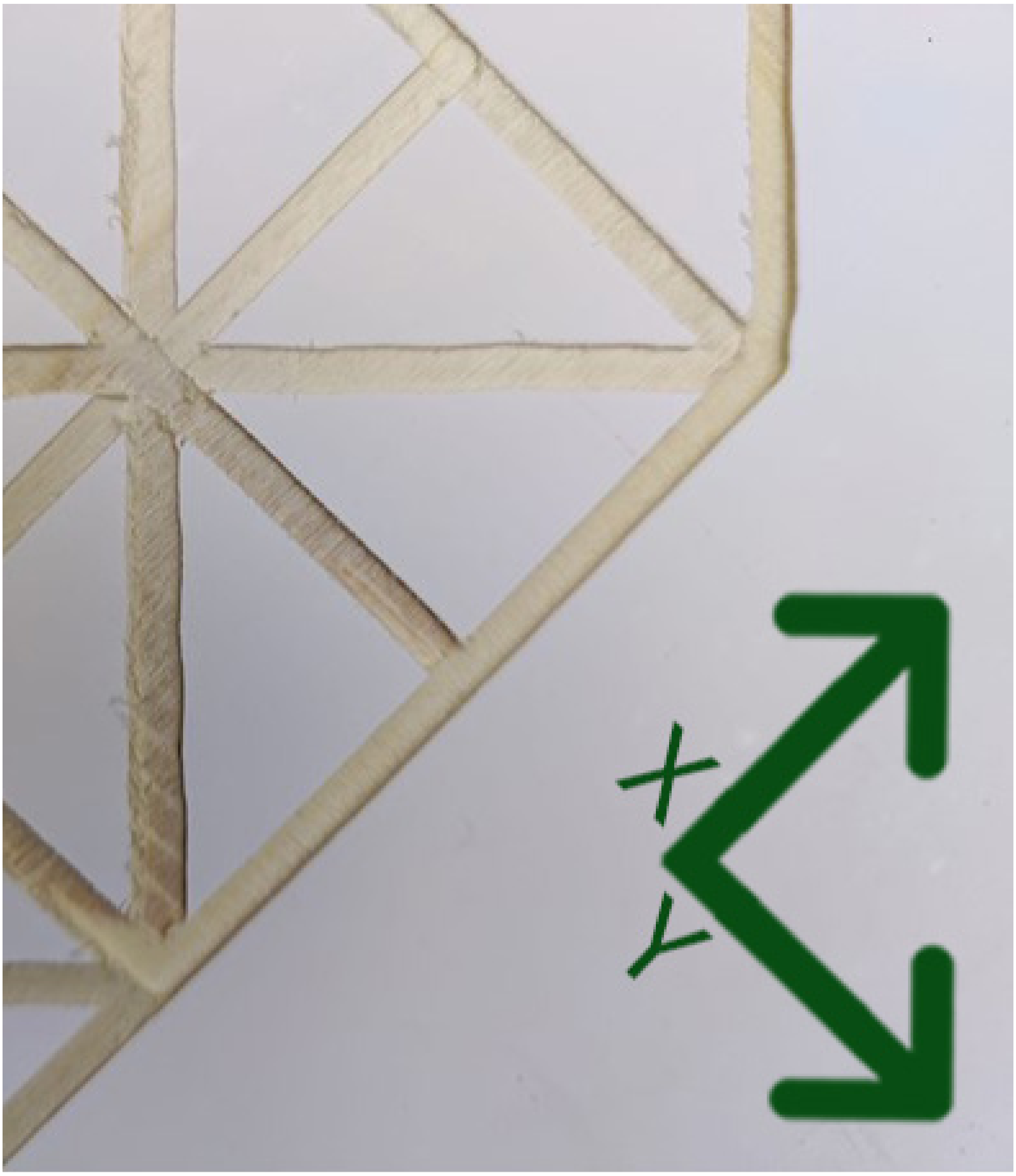


Figure 74: Initial cutting operation; result

When taking a closer look at figure 74 one can identify that the lines that have been created in the X and Y direction, individually, both are relatively straight. However when looking at the lines that have been cut diagonally(and therefore in both the X and Y direction simultaneously) it became clear that the swinging motion of the X-Axis, as discussed in chapter 6.7.1 Dimensional Accuracy was still present.
In order to solve this issue of the swinging motion, an iteration was implemented. This iteration is described in chapter 7.4 Iteration Second Y-Axis Motor. By implementing this iteration the machine was capable of correctly performing the desired cutting operations.

7.3 Cutting Operations

As mentioned before, implementing the iteration described in chapter 7.4 Iteration Second Y-Axis Motor, the machine was capable of correctly performing the desired cutting operations.

7.3.1 Square Test

In order to test whether the machine was square, multiple engraving operations have been performed. These operations were all performed at a feedrate of 2000 mm/min and an RPM of 22000. Figure 75, 76 and 77 shows the engraving operations that have been performed in order to test the machines squareness. Figure 75 shows the result of engraving a small square of 50x50mm. While figure 76 shows the results of engraving a diamond shape of 50x50mm. Figure 77 shows the result of engraving a 100x500mm rectangle

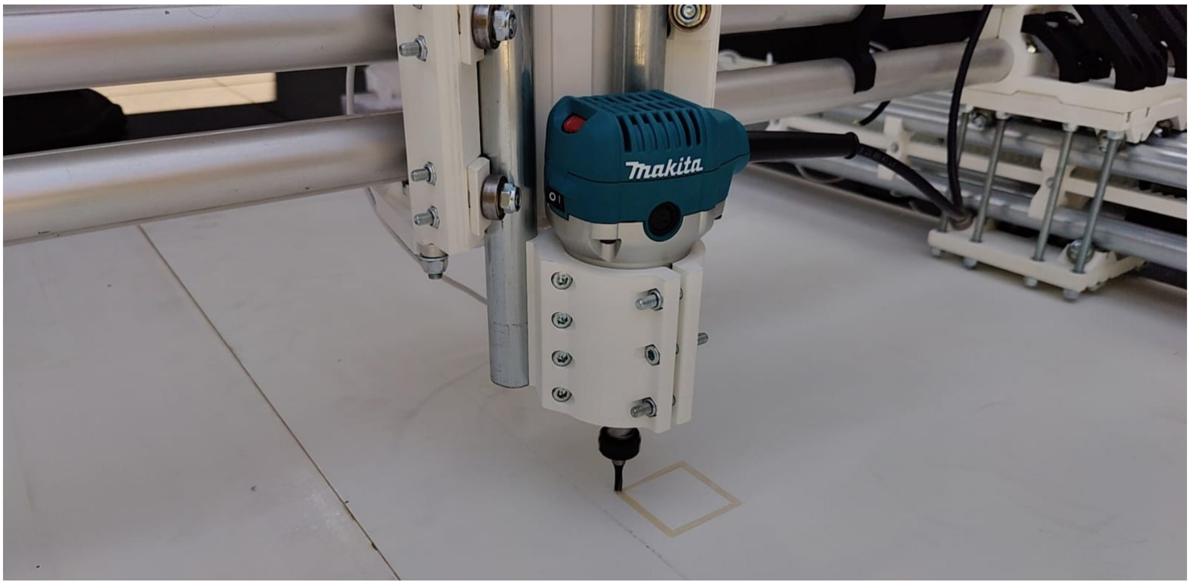


Figure 75: 50x50mm Square

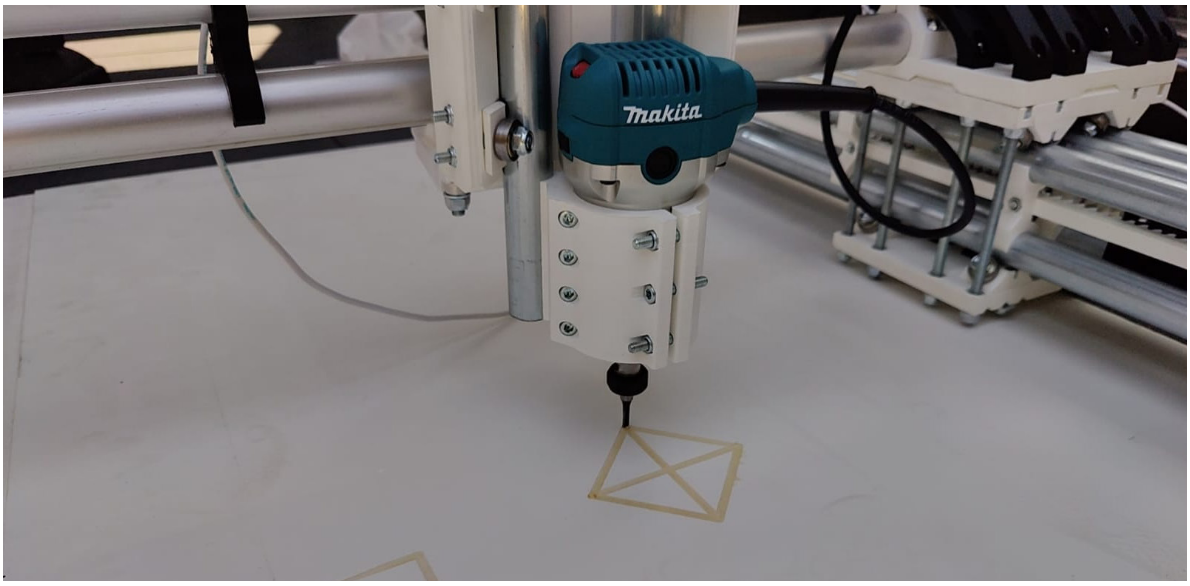


Figure 75: 50x50mm Diamond

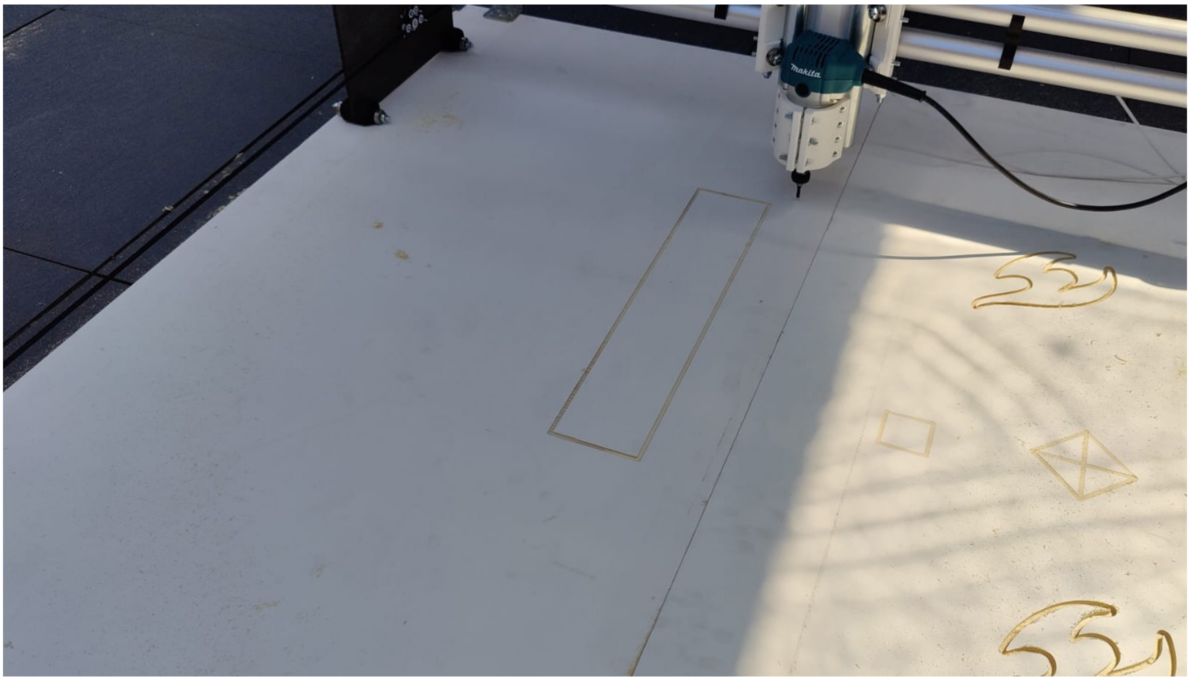


Figure 77: 100x500mm Rectangle

After checking all the results of the square tests it became apparent that the machine was in fact square and was therefore capable of engraving and cutting dimensionally accurate shapes. Figure 78 shows the check of the rectangle for squareness.

Figure 78: Rectangle squareness check

7.3.2 18mm pine cutting test

After verifying that the machine was capable of square cuts, the next step was to verify whether the machine could actually mill the maximum required thickness(18mm).
In order to test this requirement, an operation was created for milling a 18mm thick square of 100x100mm out of a piece of pine plywood. For this operation, again a feedrate of 2000mm/min was used, accompanied with an RPM of 22000(see figure 79).

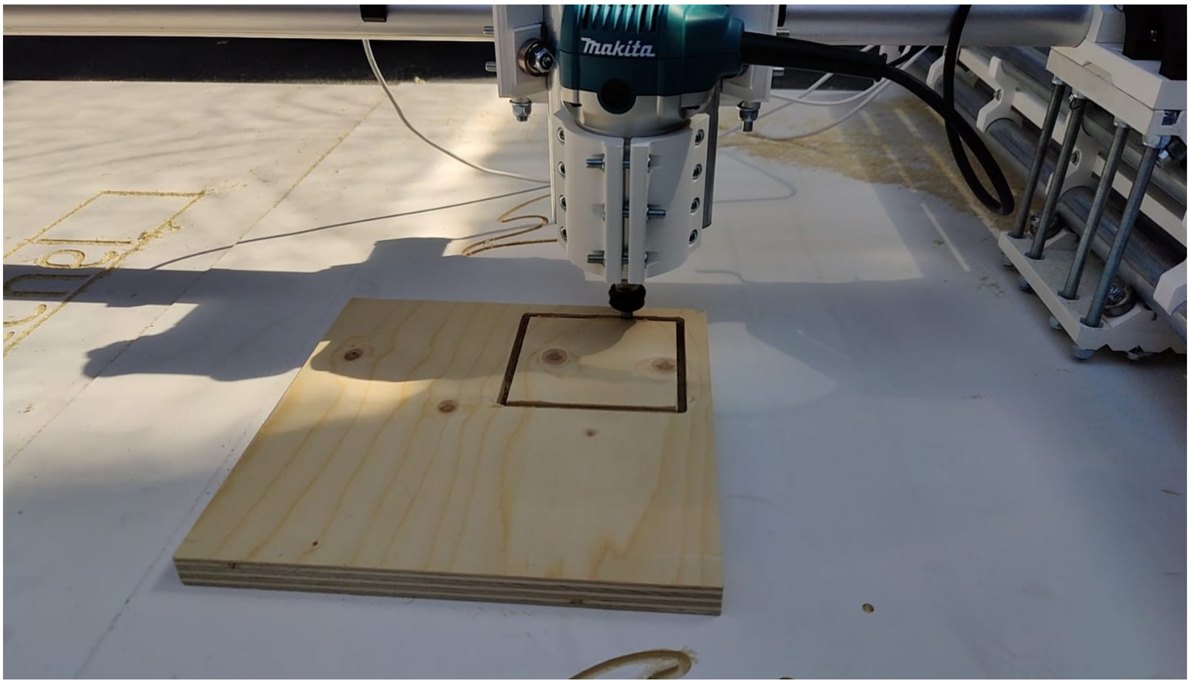


Figure 79: 100x100x18mm milling operation

After successfully completing this milling operation the resulting square was again checked for its squareness as well as its dimensional accuracy. As can be seen in figure 80 the resulting square was in fact square. When measuring its dimensions however, it became apparent that the square deviated ever so slightly from the desired 100x100mm.
The actual dimensions measured 99,65mm on both sides.
Since both sides measured the same dimension, acquiring the desired 100x100mm from the milling operation was only a matter of tuning the amount of steps the machine takes in order to move a single millimetre.

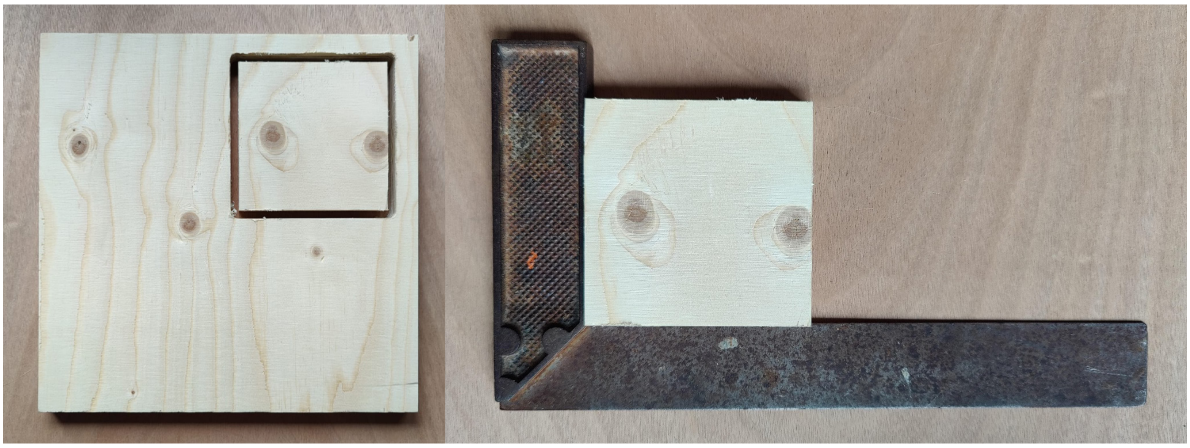


Figure 80: 100x100x18mm milling operation; result

7.4 Iteration Second Y-Axis Motor

As mentioned before in chapter 7.2 Initial cutting operation, in order to counter the swinging motion of the X-Axis a new iteration was implemented.
Since the swinging motion was still in effect even after clamping down the connection between the two mounting plates, a different approach was necessary.
The swinging motion was the result of the very end of the X-Axis dragging along the Y-Axis carriage(on which the start of the X-Axis was mounted), instead of both sides moving in parallel. In order for both sides of the axis to move in parallel, the idea of adding a second Y-Axis motor at the end of the X-Axis was implemented(see figure 81).

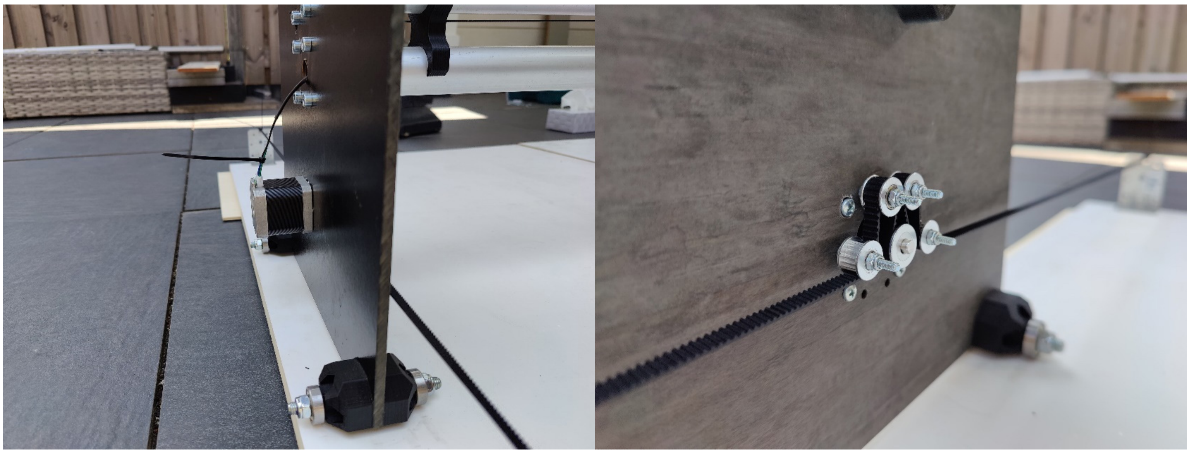


Figure 81: Second Y-Axis motor

As be seen in figure 81, adding a second Y-Axis motor with the same configuration of pulleys and at the same height of the original Y-Axis motor, also means that a second belt was necessary in order for the motion to be identical to the original motor.
In order for the belt to reach the right height and be able to be mounted/tightened, a temporary setup was created. Figure 82 shows the setup that was used in order for this iteration to be tested. With the help of two metal brackets that were screwed into the waste board, on which the machine was operating, the swinging motion of the X-Axis was successfully removed. Allowing both the end of the X-Axis and the Y-Axis carriage to move in parallel. Resulting in the successful operations mentioned chapter 7.3 Cutting operations. Figure 83 shows the fully assembled router with the implementation of the second Y-Axis motor and belt.

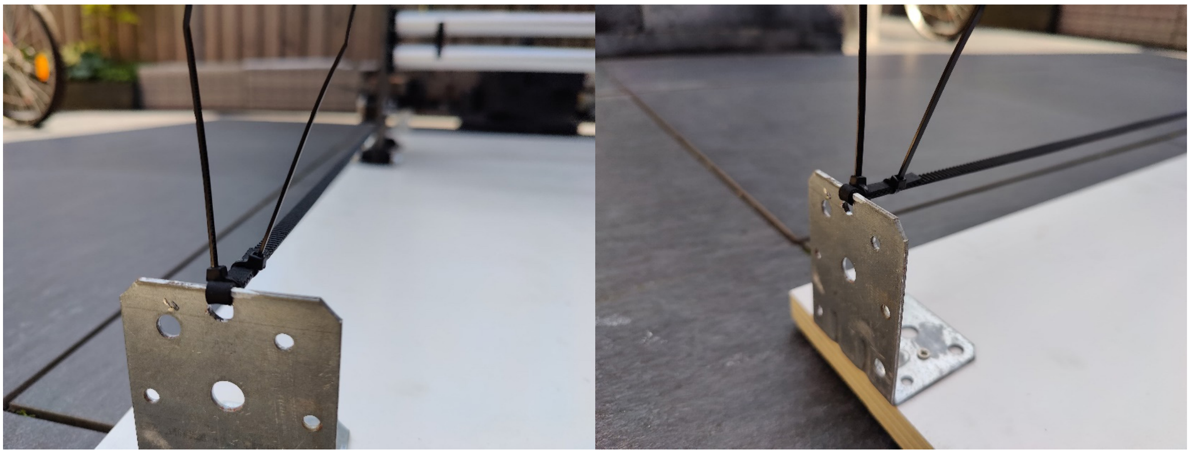


Figure 82: Second Y-Axis belt

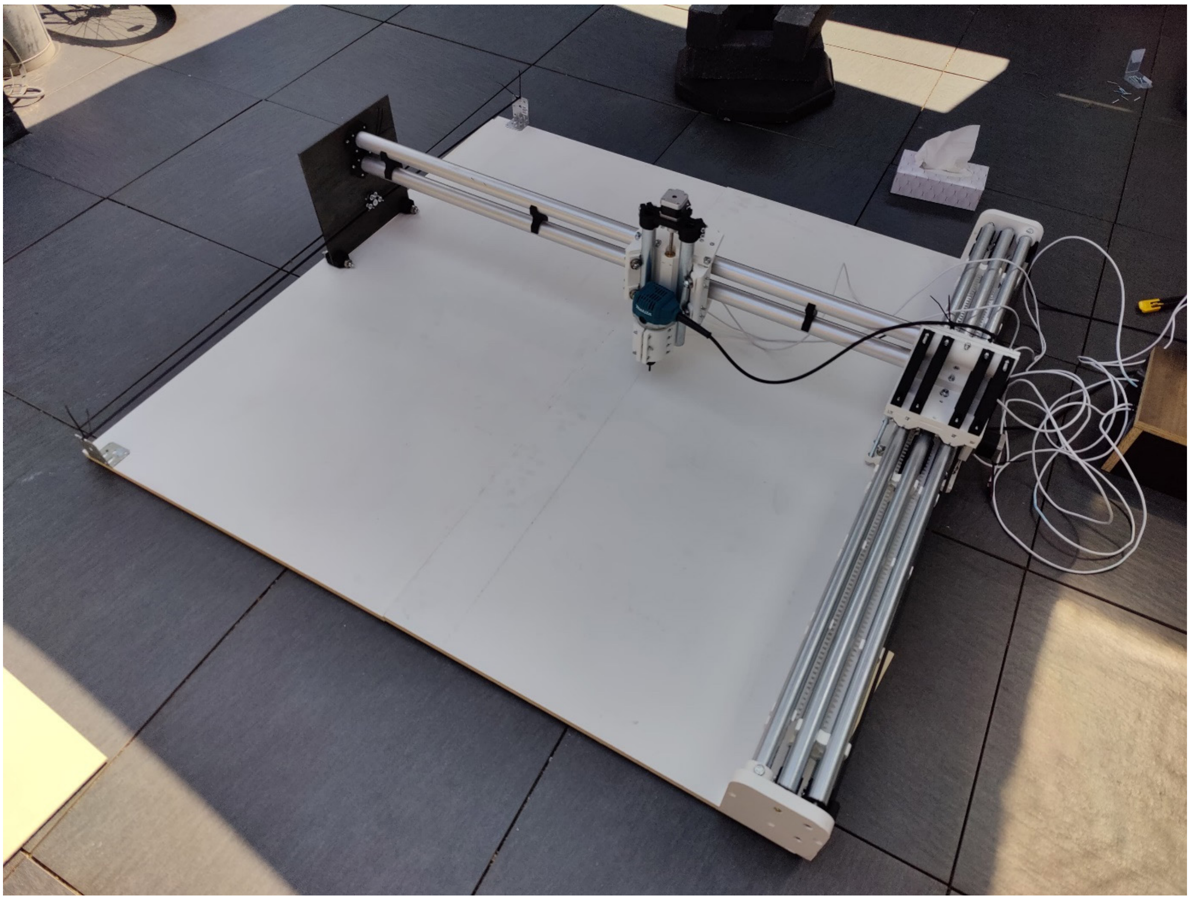


Figure 83: Fully assembled router

7.5 Max feedrate

In order to verify the requirement of the machine being capable to cut at a maximum feedrate of 3360 mm/min, another cutting operation test was conducted. This time the Delft University of Technology logo was machined from an 18mm thick sheet of poplar. Figure 84 shows the logo being machined from the sheet of poplar.
The logo was cut out at 3360mm/min with an RPM of 24000. This combination of feedrate and RPM along with the use of a 2 fluted, 6mm router bit provided the desired chipload of 0,07mm described in chapter 4.3 Resizability. The logo itself had a dimension of 500x500mm.

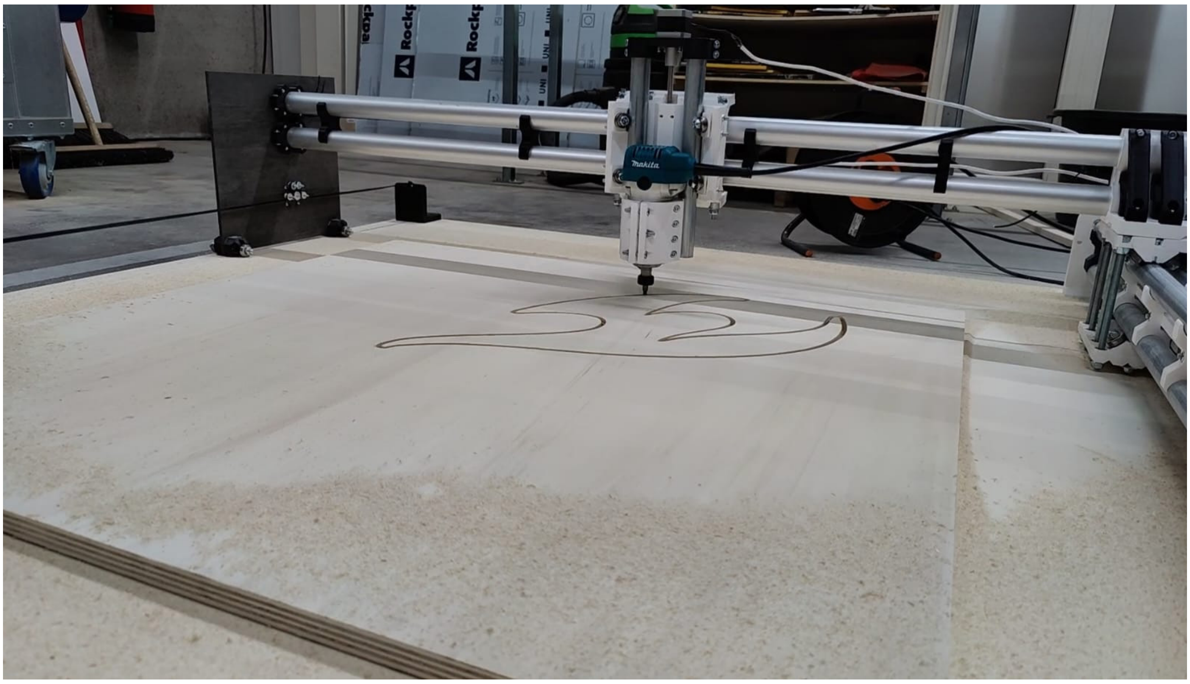


Figure 84: Delft University of Technology logo being machined from 18mm thick poplar

With this combination of feedrate and RPM providing the desired chipload, it became clear that the machine did not have any issues with cutting the material at this maximum feedrate providing a clean cut edge. Satisfying the stated requirement. Figure 85 shows the logo when the machine had finished its operation. Figures 86 and 87 show the sheet of poplar from which the logo was cut and the logo itself respectively.

Figure 85: Delft University of Technology logo finished operation

Figure 86: Cut sheet of poplar

Figure 87: Delft university of Technology logo removed from stock.

DISCUSSION

08

As was stated in the previous chapter, the machine is capable of performing dimensionally accurate cutting operations from the desired material (soft types of wood up to 18mm thickness). These cutting operations can be performed with a feedrate of up to 3360mm/min.
The Y-Axis of the machine can be extended in order to provide the user with a work dimension of between 1220mm and 2440mm.

8.1 Resizing Y-Axis

8.1.1 Resizing

The act of resizing the Y-Axis proved to be a little difficult. Which could be entirely related to the physical realization of the prototype.
As described in chapter 6.4 Y-Axis, the rack and pinion system that realized the resizing of the axis are clamped between the conduits. In order to connect the racks, the prototype made use of 3D printed parts for the rack system. Which were connected to each other through the brackets that were clamped between the conduits. However when building the prototype, the rack that was supposed to connect the assembly of the rack system to the end plate of the axis broke. Which meant that the rack system was secured to the conduits with nothing but friction.
Since the rack system was now held together with only friction limiting its degrees of freedom, this meant that when resizing the axis the rack system sometimes would slide across the conduits instead of providing the uniform motion.
Providing the rack system with a permanent connection to the conduits of the Y-Axis would solve this issue.
When this permanent connection is realised it still means that the user has to perform a number of steps prior to the machine being able to perform operations. These steps include;
The folding and securing of the X-Axis perpendicular to the Y-Axis and the tightening of the different belts. Since these steps only take a small amount of time to perform and the router is meant to be used by people that have some kind of technical background or familiarity with these types of machines, an extra step in the setup process should not be a problem.

8.1.2 Resized Guidance

When testing the guidance of the machine along the extended Y-Axis, an issue could be identified. When the Y-Axis carriage moved along the extended Y-Axis and approached the point where three guide conduits became two no issue was found(see figure 88). However when the carriage moved away from this point and therefore had to accept the third conduit the bearings that act as
the wheels on the carriage would sometimes get stuck behind the start of the conduit. Causing the carriage to stop moving and making the motor located on the carriage to lose steps. With the introduction of a second Y-Axis motor at the end of the X-Axis this loss of motion in the Y-Axis carriage meant that the end of the X-Axis would still move as expected. Causing the mounting plates that make up the connection between the Y-Axis carriage and the X-Axis to be forced apart(see figure 89). This could seriously damage the machine when left unattended.

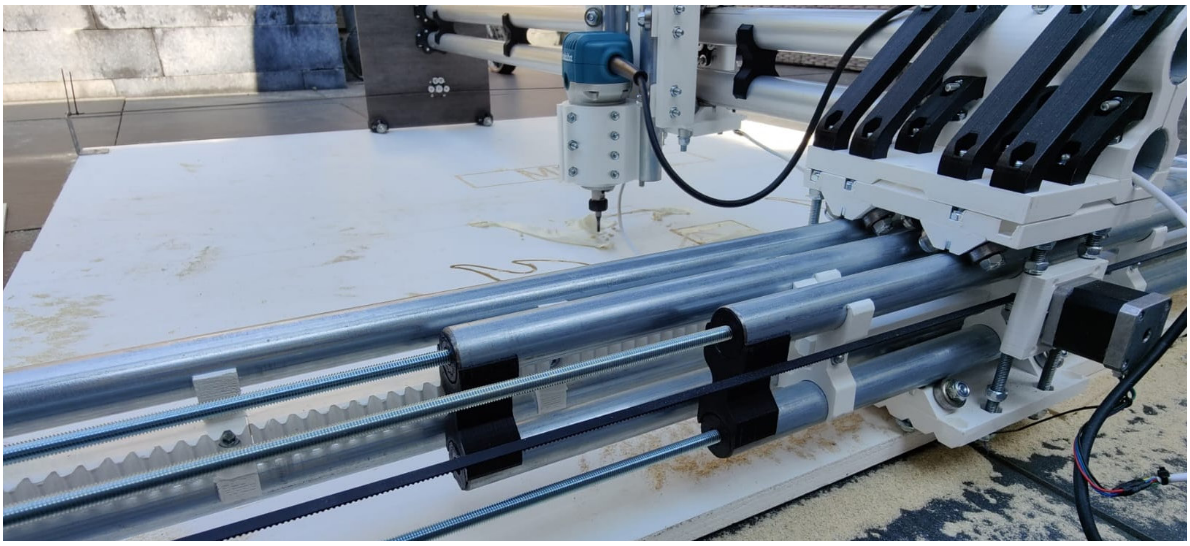


Figure 88: Carriage moving towards resize point

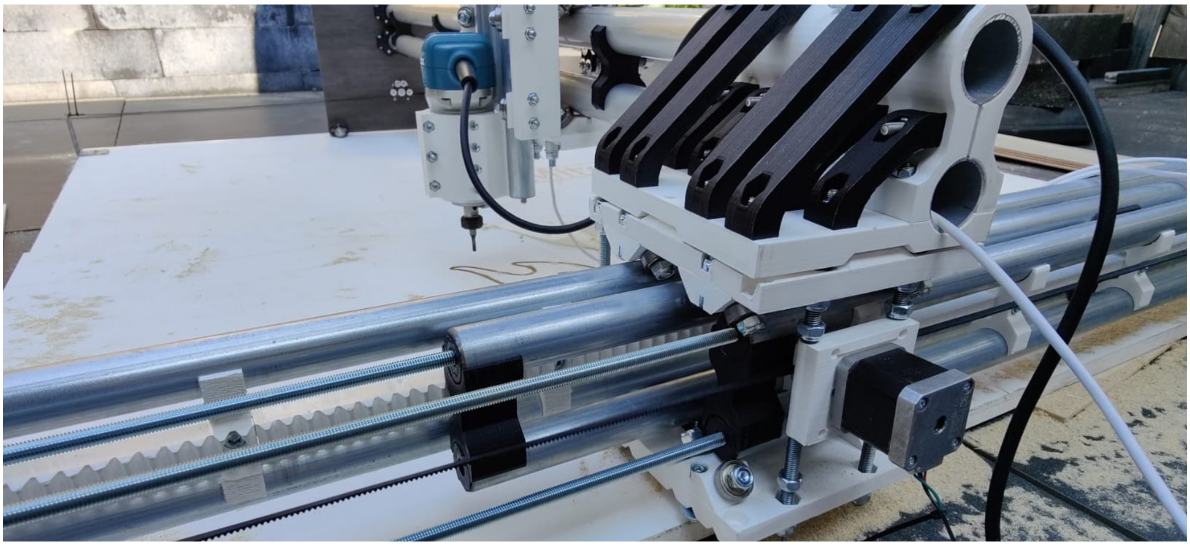


Figure 89: Mounting plates being forced apart because of loss of motion in Y-Axis carriage

RECOMMENDATIONS AND FUTURE WORK

This chapter focuses on possible recommendations and future work that could be done in order to bring the design to an even higher level of professionalism.

09

9.1 Recommendations

9.1.1 Dust Shoe

After finishing the prototype and running multiple engraving and cutting operations it became apparent that the wish for a dust shoe (as mentioned in Chapter 5 List of Requirements) was in fact a valid one. Figure 90 shows the aftermath of multiple engraving and cutting operations.

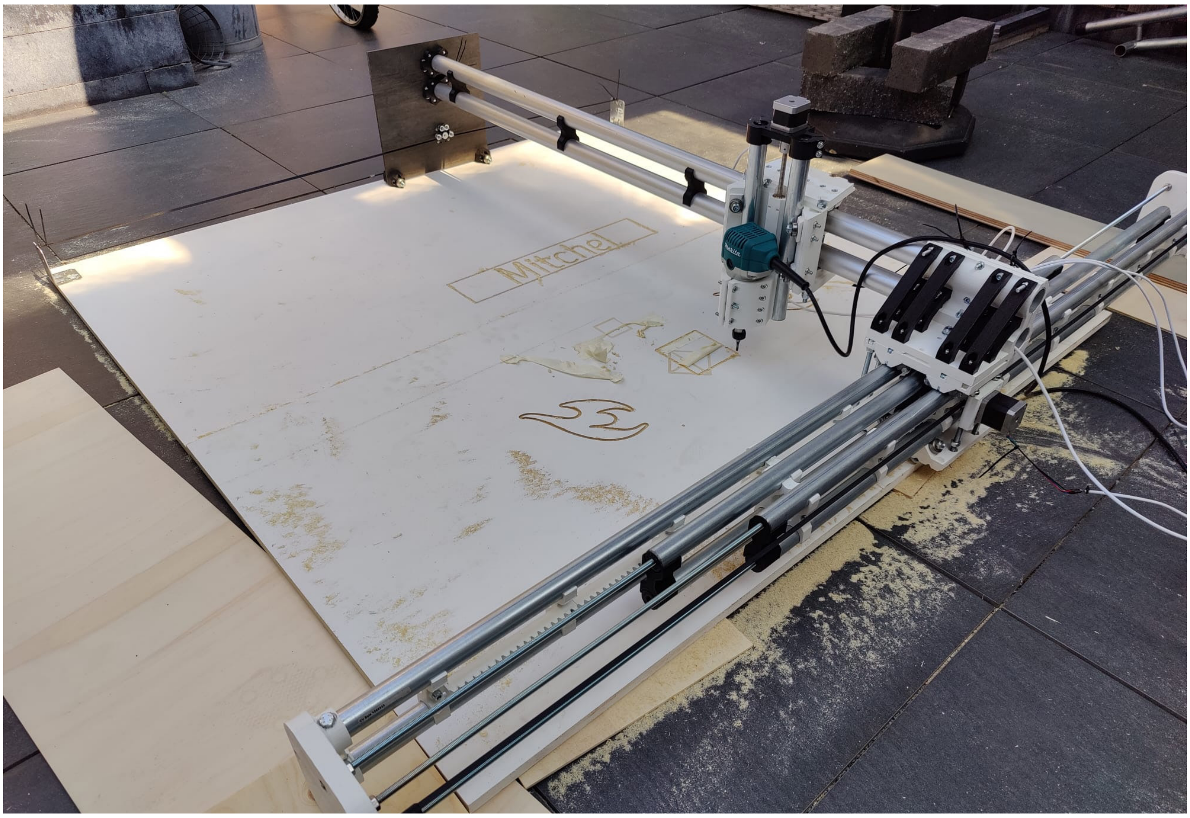


Figure 90: Aftermath of cutting operations

Not only did the dust make a rather large mess of the work area around the machine, it also affected the cutting operation itself. When milling, the machine created a cavity around the workpiece in which the dust could settle. This settled dust tended to clog together and form an obstacle for the milling tool when it reached the location of the clog again. When the cutting tool hit the clog of dust the clog would wrap around the router bit and occasionally introduce a small chatter in the cutting tool.
By introducing a dust shoe, which sits over the routing tool and removes all of the dust that is created immediately, no clogs can form and a smoother cutting operation can be realised.

9.1.2 Cable Management

Another wish stated in chapter 5 List of Requirements, involved the cables of the machine. This wish stated that the cables should be secured in such a way that they will not restrict the machine when in operation or that they could get damaged by the cutting tool. For the current prototype the cable management has been partially taken into account by creating a single electronics box that encases all of the electronics with only the USB connection to the computer, the power cable and the four motor cables coming out of it(see figure 91).

Figure 91: Electronics box

The only thing not satisfying the cable management wish are the motor cables. Currently the motor cables just hang loose across the machine itself leaving them exposed to the cutting tool and other external elements. With the introduction of a drag chain for the motor cables the cable management wish can be satisfied by giving the cables a place to safely be tucked away while providing the machine with the necessary flexibility.
Another option for keeping the cables away from the cutting surface of the machine could be to implement a type of suspension. Keeping the cables elevated, away from the cutting tool.
A final electronics recommendations would be the implementation of an emergency stop button. Providing the user with a way to halt the machine when necessary.

9.1.3 Size

Another recommendation for the design of this resizable CNC router could be to implement all the design principles in order to create a smaller version. When the current design of the router is folded up it still leaves the user with a rather long and big beam. This is not necessarily a bad thing since the machine does provide the user with a huge flexible work area of between 1220x1220mm and 1220x2440mm. However introducing a smaller version of, for example half the size of the original design, could possibly spark the interest of even more users. A version with a minimum work area of 600x600mm and a maximum work area of 600x1200mm still provides the user with a rather large work area while at the same time taking up a smaller footprint when the machine is not in operation and stored away. Since the machine will still be used in the same context and cut the same materials the only difference between the larger scaled machine will be the length of the axes.

9.1.4 Belt Holder

As described in chapter 7.4 Iteration Second Y-Axis motor, two temporary angle brackets were used to suspend the second Y belt. These brackets were screwed into the waste board onto which the router was placed.
In order to provide the user with an easier way of suspending this second Y-Axis belt a redesign was created in order to replace the angle brackets.
Figure 92 shows the redesign of the belt holders. This redesign made it possible to suspend the Y-Axis belt without the need of having to screw into the waste board. By placing weights on top of the belt holders on both sides of the belt the 2.8kg of tension that is required for the belt to function could be achieved (see Appendix K GT2 Belt Datasheet). Even though adding the weights to the belt holders did allow for the machine to function, it does require the user to keep an extra item(the weights) around in order to use the CNC router. When securing the belt holder directly to the waste board with the help of screws it means that the user can use equipment already at their disposal at the intended context.

Figure 92: Redesign of belt holders

9.1.5 Resizable Axis

As described in chapter 8.1.2 Resized Guidance, an issue was present when the Y-Axis carriage had to reaccept a third guide conduit. Upon closer inspection of the Y-Axis when extended it became clear that when the carriage moved along the 'resize point' and left the third conduit, this conduit would slope downwards ever so slightly. This slope was caused by the use of the threaded rod which would slide in and out of the conduits with the help of a sliding bearing as described in Chapter 6.4.1 Rack and Pinion System. Since the threaded rods only had a diameter of 7.85mm while the sliding bearing used were meant for rods with a diameter of 8mm a slack of 0.15mm was introduced to the axis. This slack apparently was enough for the conduit to slope downwards and catch the wheels of the Y-Axis carriage, causing the carriage to stop moving.

In order to solve this problem, linear rods with a diameter of 8mm could be used instead of the threaded rods. In order to mount this linear rod to the endplate of the Y-Axis the end of the rod could be threaded with M8 threads.

Another option to solve this issue could be to introduce a very large chamfer onto the end of the conduits(see figure 93). This way the wheel of the carriage would be guided onto the carriage like a funnel, centering the conduit.

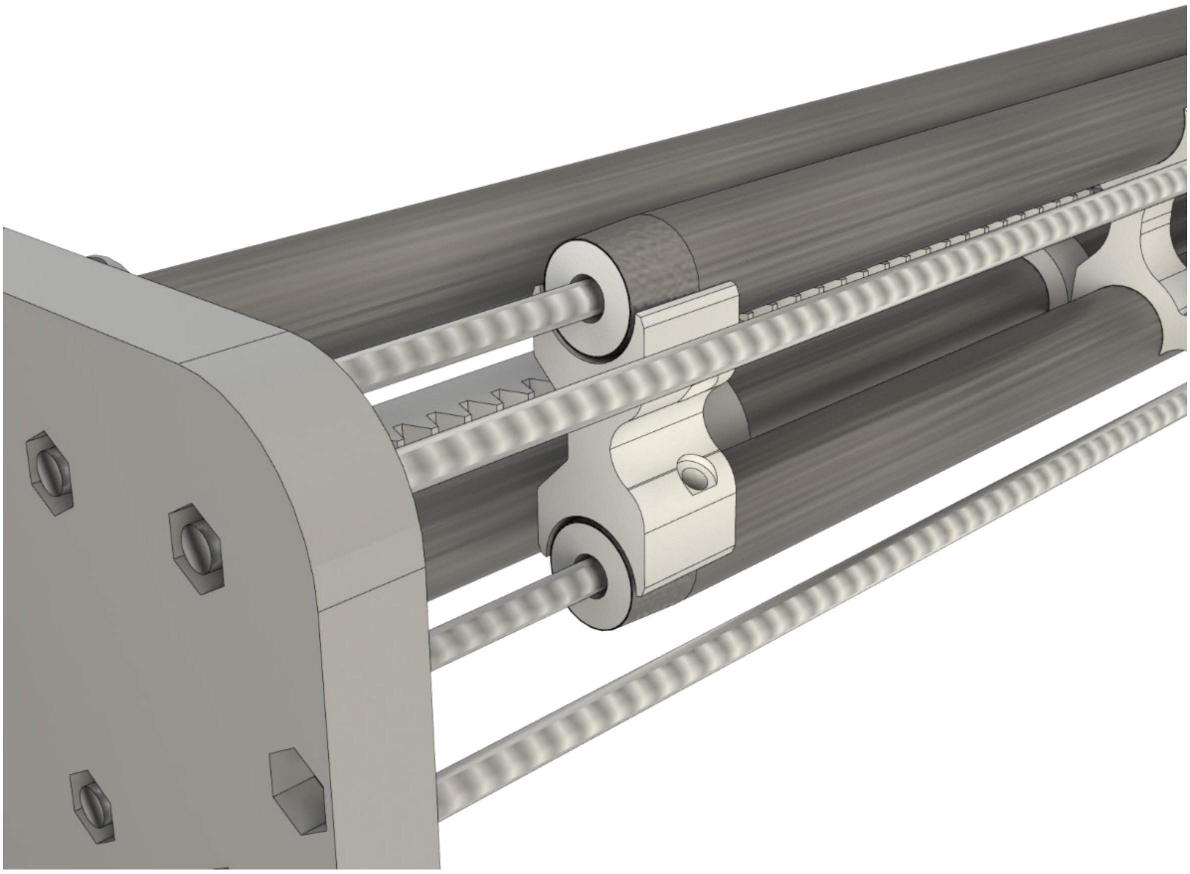


Figure 93: Conduit redesign Chamfer

CONCLUSION

10

The main goal of this project was to provide the user with a true flexibility in terms of work and build area. In order to achieve this, multiple design methods and tools were used in order to realize a fully functioning prototype of a resizable CNC router.
Providing flexibility in terms of build and work area was done by creating a resizable Y-Axis that could be extended. Allowing the user to choose between a work dimension between 1220mm and 2440mm. To provide the user with storage capabilities for the router the rigid X-Axis was made foldable. This foldable rigid axis folded parallel to the Y-Axis leaving the user with a single beam which could be stored when the machine was not in operation.
In order to evaluate the prototype multiple tests had been conducted. These tests included multiple cutting operations of various purposes, such as checking whether the machine was square, checking dimensional accuracy and feedrate capabilities.
Finally a set of recommendations have been created to lift the level of professionalism of the machine to an even higher level.

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APPENDIXES

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Appendix P Design Renders

Appendix A
Project Brief

Personal Project Brief - IDE Master Graduation

TU Delft

Design of a Resizable Computer Numerical Control Router — project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 01 - 11 - 2022 — 31 - 03 - 2023 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

Computer numerical control (CNC) routers, mills and lasers have enabled engineers, designers and hobbyists to create various complex forms and designs through the process of subtractive manufacturing. Whereas CNC-routers and -lasers are generally used to machine flat 2D shapes out of stock sheets of various kinds of materials, CNC mills are used to create full 3D designs.
Even though the machines are capable of creating very intricate and detailed parts, the machines themselves are very large and rigid contraptions. Owning a CNC machine often involves making the decision of either giving up a large amount of workspace, simply to be able to house the machine itself and manufacture large parts. Or saving space by choosing a desktop style CNC machine which comes at the cost of a smaller build area (see figure 1).

Generally speaking there are two types of users of CNC machines; The professional user and the more casual user. The professional users are people with a technical background and profession, often employed in fields such as for example; the automotive-, aerospace- and timber and building industry(RapidDirect, 2022). These users often operate in large work areas such as factories or lumber mills. The more casual users are people that are simply enthusiastic about the technology and use it to manufacture their own parts. They operate in smaller work areas such as workshops, sheds and even attics. These users include people such as hobbyists, model builders and makers (CNCZone, 2017). A third group of users actually also exists; the 'semi-professional' users. This type of user could be described as a mix of the two previously mentioned users. This type of users are people that use the machine in a professional setting but simply do not have the space available to house a full-on professional machine (think of, for example, contractors, small architectural firms or small timber and building supply shops). They often settle for a smaller mid-range machine or decide to outsource their CNC work (Jongeneel, personal communication 2022).
All three types of users have a desire for flexibility in terms of work area in common. When more work area can be utilized, more parts can be manufactured or other projects can be realized. For the casual and semi-professional users this could mean more available space for different types of side-projects. While for the professional user this could mean an increase in production.

The main opportunity that becomes apparent when looking at the users of CNC machines is the desire for flexibility when working with these machines.
Providing a solution in order to offer a grip on true flexibility in terms of work area when owning or working with a CNC machine.

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Personal Project Brief - IDE Master Graduation

introduction (continued): space for images

image / figure 1: Size comparison of a professional CNC machine (left) and a desktop CNC machine (right)

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

The desire to have a grip on true flexibility in terms of work area is not something new. Different users (engineers, designers, makers and technical personnel) have tried to tackle this desire to save space when owning a CNC machine. A more recent development in this field is the mounting of the entire machine to a wall or foldable workbench(see figure 2). Both 'solutions' do in fact provide a way to save work area on the literal work floor by moving the machine to a wall or folding it out of the way for storage purposes. However for both scenarios the user is still limited and constricted to the dimensions of the mounted CNC in question. This limits the user in gaining a true flexibility in terms of work area in the workshop as well as build area of the machine itself.

Providing an all-in-one and 'one size fits all' solution to the previously mentioned problems will be the goal of this graduation project. Being able to manipulate the X-, Y- (and Z-) axes of the machine to every desired dimension, at every given moment, enables users to resize the entire machine to the (at that time) available space.
The ability to resize the router to every desirable dimension enables the user to decide how much workspace the router will occupy and for how long. The user could resize the router to its largest dimensions to be provided with a very large build area. While resizing the router to its smallest dimension will provide an easy way of storing the machine when the operations are complete. This provides the user with true flexibility in terms of work area in the workshop as well as build area of the machine itself.
Because of the flexibility of the machine a 'on size fits all' style of designing can be achieved when looking at the target groups. Even though the context of the machine will be more targeted towards the 'casual' users and the 'semi-professional' users, the flexibility and versatility of the machine enables it to be implemented in a lot of different contexts and work environments.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

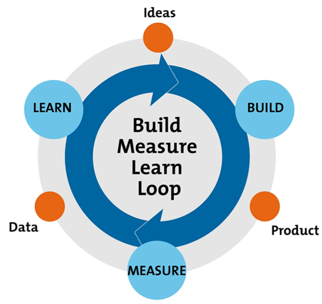
Designing a 'one size fits all' resizable CNC router to enable designers, engineers and hobbyists to manufacture (large) parts without the need to compromise valuable workspace. Providing true flexibility to the user in terms of work- and build area.

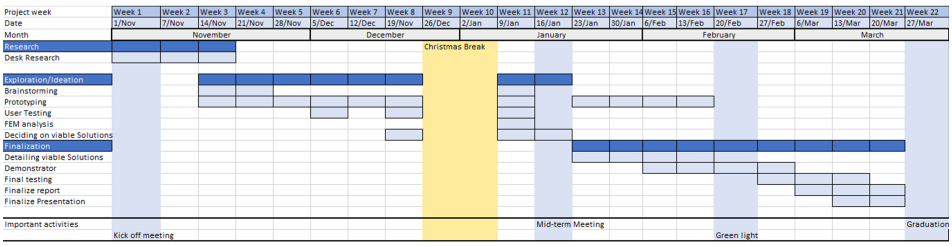
For this project a CNC router will be used as case study.
The biggest challenge that will be addressed during this project will be the mechanical aspect of the machine. Creating resizable axes while maintaining a stiff construction for the router to function, will be the main concern. Manipulating the X-, Y- (and Z-) axes at every moment to the desired dimension is a key element to this design.
Another large aspect of the machine that will be addressed during this project will be that of the 'ease of use'. Enabling users to resize the machine to their liking will only be beneficial when designed with the ease of use in mind. When resizing the router will prove either too difficult (which mostly relates to the casual users and users without a technical background), or too time consuming(which relates to the professional users, such as engineers and other technical personnel, for whom time is money), users will disregard this aspect of the machine.
To limit the scope of this project the router will be limited to cutting softer types of wood such as spruce and poplar, instead of (soft)metals such as aluminium. Reason being that to be able to machine metals, a much stiffer construction is required in comparison to machining wood.
The design of the CNC router will be delivered in the form of a prototype to illustrate the outcomes of the project. This prototype can be used as a demonstrator during the final presentation.
In order to successfully deliver a prototype of the router the main design method that will be used during the project will be the Build Measure Learn method (Ries, E. (2011)). This method illustrates a loop that can used to quickly generate, test and validate prototypes (see Planning And Approach).

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 1 - 11 - 2022   31 - 3 - 2023 end date





According to the proposed planning the start date of this graduation project will be 1-11-2022, with the end date being 31-03-2023. With a two week Christmas break in between which will help gain a fresh perspective for the final stages of the project.
The project will be started with a research phase. This research phase will be used to gain a better understanding of the context and working principles of the CNC machines themselves through desk research and possible interviews/visits to CNC workplaces. The outcomes of this research phase will be used to start the exploration and ideation phase. During this phase the Build Measure Learn (BML) method (Ries , E. (2011)) will play an important role. This method describes a loop that can be used to quickly generate, test and validate prototypes. Constantly creating prototypes to generate ideas and designs in order to validate concepts and reiterate these will be the main focus during this phase(see the figure above).
To accumulate and validate the 'ease of use' of (aspects of) the machine, user testing will also be a valuable part of the design process during this project. Week 6, week 8 and week 11 will be used to test (parts of) iterations/prototypes in terms of 'ease of use'. The outcomes of these user tests as well as outcomes of prototyping sessions and the FEM analysis in week 11 will be used to decide on viable solutions to be presented during the Mid-term Meeting.
During the Mid-term Meeting a solution will be chosen to be detailed in the Finalization phase of the project. The detailing of this most viable solution will again be done using the BML loop as reference in order to successfully create a demonstrator. This demonstrator will be used to illustrate the outcomes of the project during the final presentation.
To provide the project with the needed adaptation to the outside world in terms of professionalism and realism, the project will moved through a (growing) network of stakeholders. These stakeholders range from e.g. robotics engineers to ergonomic experts as well as end users of CNC routers. The moving of the project through the group of stakeholders will be done in three different, small scale, forms; interviews, brainstorming and user testing.

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

The main motivation to set up this project is directly linked to my personal ambitions, interests and hobby's. In my free time I have worked on, and with, CNC-machines such as 3D-Printers and laser engravers. In the past I have designed and built both types of machines from scratch, however building a CNC router is something that I have not gotten around to but have been meaning to tackle.
More in depth knowledge on the field of CNC- routers and -machines in general is one of my main goals. As well as working on the embodiment of yet another mechatronic device which has gotten my interest during the elective spaces of both my Bachelors and Masters studies.

Another motivational factor originates from my weekend job in a timber and building supply shop. Here the issue that I have chosen to solve is very prominent. Over the years a lot of costumers(contractors, construction workers etc.) have stated to be interested in owning a CNC router but they simply do not have the space to house the machine. Even within the timber and building supply shop itself the issue has been discussed. Currently customers have to order their CNC machined parts, which will then be produced at the main mill which is located in Utrecht. Making the production of parts rather expensive and time consuming due to transportation costs and time. This is currently the only option since the shop simply does not have the space to sacrifice a permanent space for a CNC router. This issue would however be solved by a resizable machine which only takes up the space when the machine is in operation.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

Appendix B
Design Approach

The process can be categorized into three different phases; The Research/Analysis Phase, The Idea Generation Phase and the Embodiment/Materialisation Phase.

Research/Analysis Phase

Within the Research and Analysis phase two main analyses are illustrated; The Context Analysis and the 'Function Analysis'.
The context analysis will be performed in order to gain a better understanding about the core and essence of the context. The users within this context are at the front. With the help of personas, 'costumer journeys' and/or storyboards, the user's needs, concerns and behaviours will be captured.

The 'Function Analysis' describes a method for analysing a function structure of an existing product or new product concept. *"It helps you to describe the intended functions of the product and relate them to its parts and 'organs'. A good analysis can help you find and explore new possibilities to embody certain functions in a product or product concept."(Delft Design Guide, 2020).*
This method consists of four steps:

- Describing the main function of the product in the form of a black box.
- Making a list of sub-functions. The use of a Process Tree will result in a good starting point.
- Creating a function structure. Ordering the functions in a way that seems fitting.
- Elaborating on the function structure.

Since this method for analysing can be used on existing products and on new product concepts/ideas it makes it an ideal choice to be used to create structure and boundaries within the research phase.

When applying this method to existing solutions the results will fill in the gaps and provide the depth and reasoning that has been lacking up till now. A Process Tree and component overview will be the result of this part of the analysis. As well as other outcomes that were missing but were in fact needed from the current research that has been done. For example calculations about the speeds, forces and accuracies of existing solutions.

Applying the Function Analysis method to analyse the assignment and solution space of the project will *'Force me from known products and components in considering the question: What is the new product intended to do and how could it do that?' (Delft Design Guide, 2020)*. Which is exactly one of issues and culprits I need to overcome/avoid during the project, since being stuck in researching 'known products' was one of my main issues up till now.
Combining the outcomes of the analyses will result in an updated and more elaborate List of Requirements and a so-called Function Structure. Which will both be the starting point of the 'Fish Trap Model'.

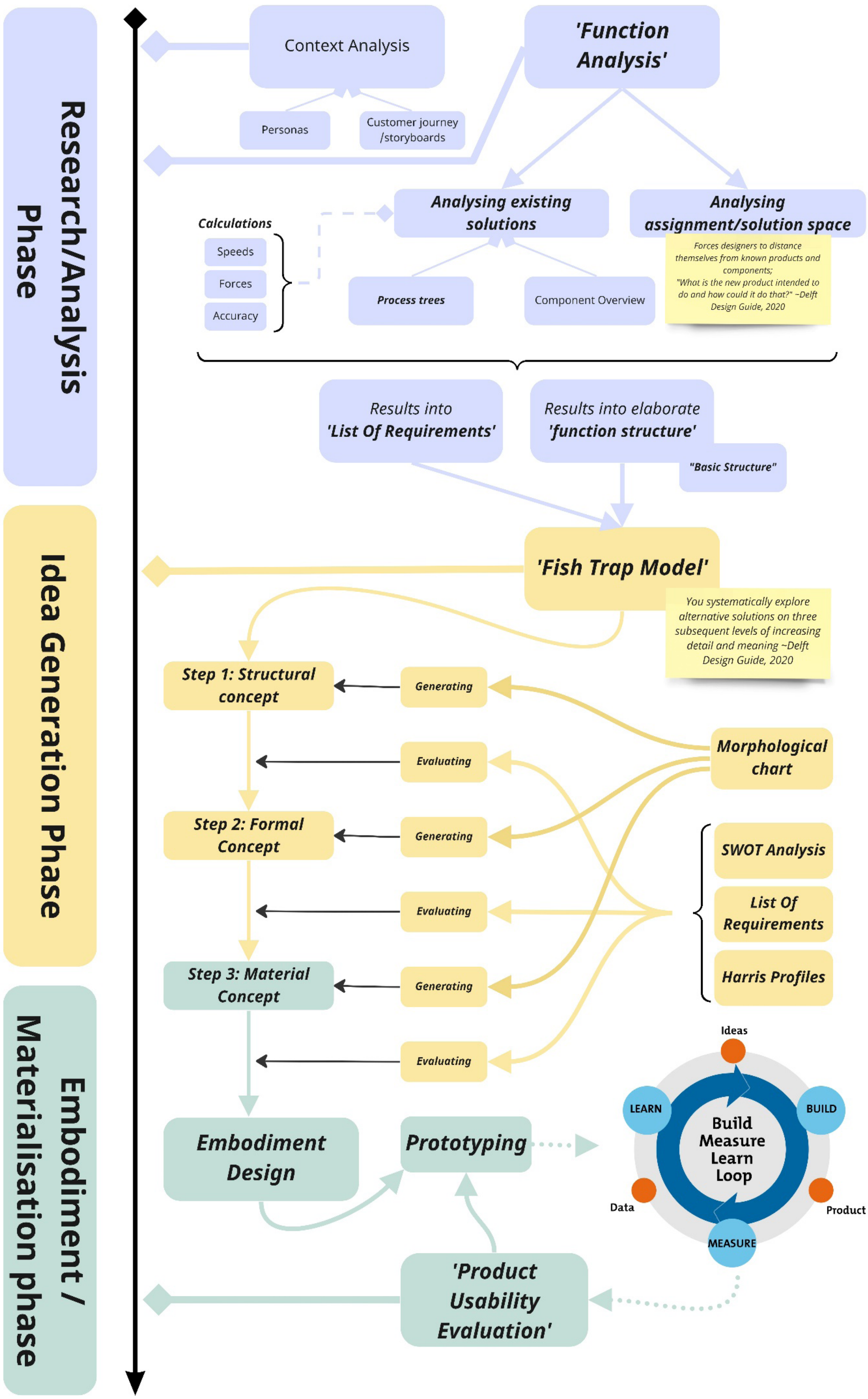
Idea Generation Phase

'The Fish Trap Model helps you in generating and developing material concepts. It prescribes a process of converging, diverging and categorising, metaphorically referring to a 'fish trap" (Delft Design Guide, 2020).
In short this model uses the Function Structures, generated during the Analysis phase, and allows you to systematically explore solutions on three subsequent levels of increasing detail and meaning(Delft Design Guide, 2020). The way I intend to use the Fish

Trap Model during this project will be to overarch it and stretch it out over this phase and the next.
The way this model works is by taking in the Function Structures, in order to generate Structural Concepts. Which focuses on the structural aspects of the concepts and the spatial layout of the design. The Function Structures will be defined as components, parts or even subassemblies that embody the working principles of the context. By combining these components with the help of a Morphological Chart or even making use of the SCAMPER tool (Substitute, Combine, Adapt, Modify, Put to other use, Eliminate and Reverse) a large variety of ideas/concepts can be realised. This collection of ideas/concepts will be evaluated and a predetermined number will be selected to be used in order to create a Formal Concept. Which focuses on the actual form of the concept. The evaluation of the concepts/ideas will be done using a number of tools; A SWOT analysis to help identify the positive aspects of the concepts, as well as the negative. The list of requirements will be used in combination with Harris Profiles in order to weigh the concepts/ideas against each other after the SWOT analyses have been conducted.
The same process of generating concepts/ideas and evaluating them is applied in the next step which will result in Material Concepts. Which focuses on the actual embodiment of the concept. The concepts will be materialised in a very detailed manner, including aspects such as assembly specification of material/components and overall embodiment.

The Embodiment/Materialisation Phase

The final step of the Fish Trap Model leads to Material Concepts that will be evaluated and turned into an Embodiment Design. This design will be the start of the Embodiment and Materialisation Phase of the project. Within this project I intend to make use of the Build, Measure, Learn loop(BML) that has been described in my project brief. The BML loop will be used to generate and evaluate the to be created prototypes in a fast paced manner. In order to successfully validate and improve on the usability of prototypes/aspects of the design a Product Usability Evaluation can be conducted. This Evaluation is used to help understand the quality of designs in the actual context by user testing them. By possibly conducting this loop a number of times I hope to evaluate and improve on the final embodiment of the design.



Research/Analysis Phase
Context Analysis
Personas
Customer journey /storyboards
'Function Analysis'
Analysing existing solutions
Analysing assignment/solution space
Forces designers to distance themselves from known products and components; "What is the new product intended to do and how could it do that?" ~Delft Design Guide, 2020
Calculations
Speeds
Forces
Accuracy
Process trees
Component Overview
Results into 'List Of Requirements'
Results into elaborate 'function structure'
"Basic Structure"
Idea Generation Phase
'Fish Trap Model'
You systematically explore alternative solutions on three subsequent levels of increasing detail and meaning ~Delft Design Guide, 2020
Step 1: Structural concept
Generating
Evaluating
Step 2: Formal Concept
Generating
Evaluating
Step 3: Material Concept
Generating
Evaluating
Morphological chart
SWOT Analysis
List Of Requirements
Harris Profiles
Embodiment / Materialisation phase
Embodiment Design
Prototyping
Ideas
LEARN
BUILD
Build Measure Learn Loop
Data
Product
MEASURE
'Product Usability Evaluation'

Appendix C
Overview of components used in CNC routers

Couplers

Are used to connect the shaft of a motor to a (long) rigid entity such as e.g. a lead/ball screw. They are often made from aluminium (Acassis, 2017). Couplers come in a lot of different varieties depending on the application;

Rigid Couplings are used to transfer torque between two shafts. This coupling does not allow for misalignment. Also does not allow for backlash(imperfection of translation of movement which can be caused by play. Also called non-movement (Machinetoolhelp, 2010).

Flexible Coupling are couplings with a helical cut out which allows for some flexibility in the coupling. This however does also allow/introduces backlash. (Acassis, 2017)

Oldham Coupling are couplings consisting of a three piece assembly -> two aluminium discs with a polymer disc in the middle. Allows for a large misalignment between the shafts connected. And allows for almost no backlash. (Ruland, 2023).

Jaw Coupling are couplings consisting of again a three piece assembly -> two aluminium discs and an elastomer disc in the middle. These coupling are used for torque transfer and dampening but do allow for some backlash.(Acassis, 2017)

Screws

Are often connected through a coupler directly to the motor, or by a belt that connects through geared pulleys(often used in the Z-axis). A lead/ball screw have a lead and a pitch. The pitch describes the distance between screw threads while the lead describes the linear distance a nut travels per one screw revolution. For a single start thread, lead equals the pitch. For multi-start threads the lead can be found by multiplying the pitch by the number of starts (ThomsonLinear, 2022). There are two types of screws that are generally use in CNC routers:
Lead screws is a screw that relies on a literal screw connection, thread to thread. Allows for backlash

Ball screws -> Ball bearing connection, tiny metal balls guide the linear bearing smoothly across the screw. No backlash.

Belts

Connected to the motor through pulleys. Belts are a very popular option for linear motion since they can be quite inexpensive and are readily available. They are also available in a number of different dimensions. The most popular type of belt used in CNC routers is the GT Belt;

GT Belts are belts with a rounded tooth profile. Belts are a lightweight option for linear motion. However belts can stretch over time and can start to sag, which can lead to slipping of the belt which in turn leads to skipping of steps. The longer the belt, the more sag is introduced. Unless idler pulleys are installed to make the belt support itself. (RepRap, 2015).

Guidance of linear motion

Guiding the movement created by the motor across an axis is often done in three different ways in CNC routers(RS-online, 2022);

Through linear rails. Which provide a high precision and are included with a bearing style carriage. They can be more load bearing because of a beefier setup and mounting method.

Linear rods are the cheaper alternative and are prone to bending when a load is applied to the rod. These rods are to be used with linear bearings.

V-slot rails are the third type. This style of rail works by a carriage. Which is mounted, by bearings acting as wheel, to aluminium extrusions. The bearing wheels tend to wear over time when created from a polymer.

Rack and pinion drive

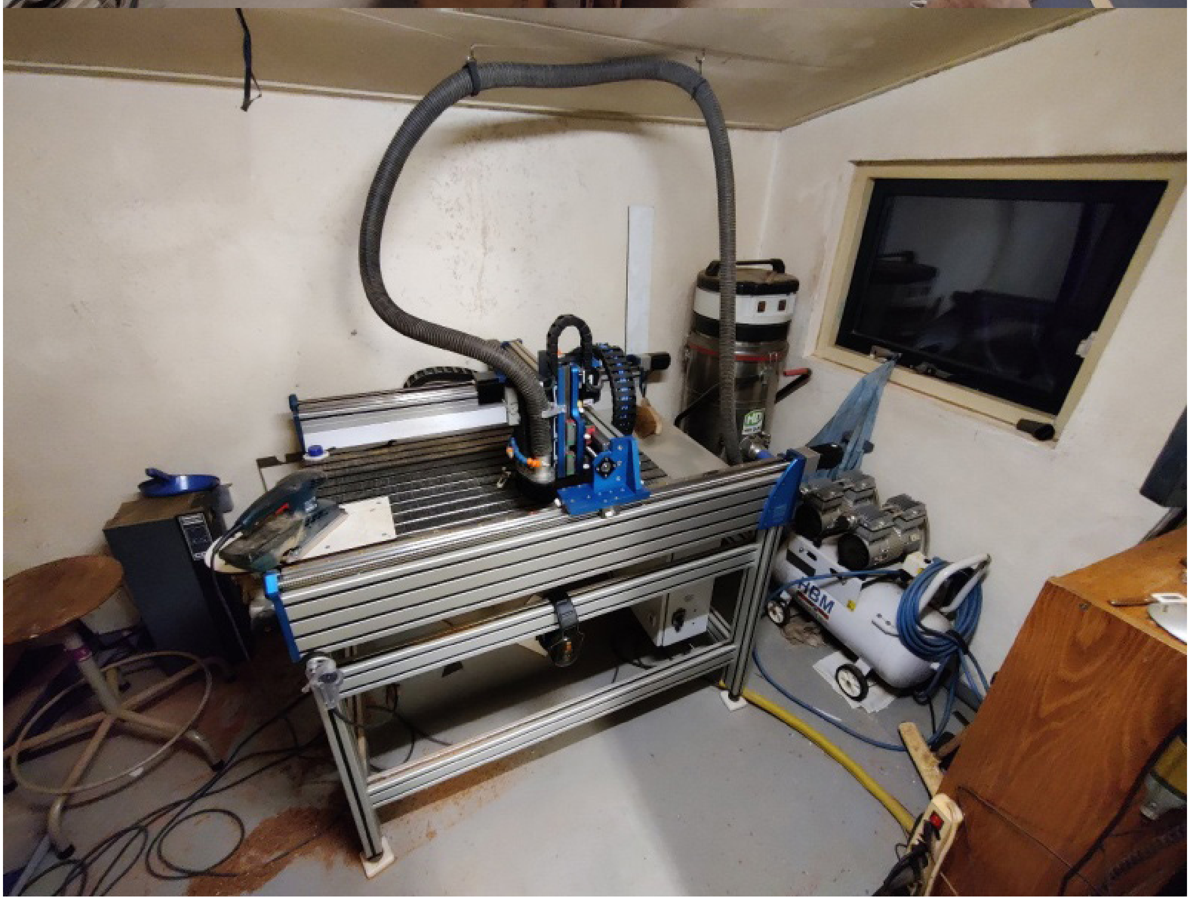
A rack and pinion drive consist of a gear track (rack) and a pinion(gear) that can be used to create a linear movement across the track. They are available in a large number of dimensions. This system does allow for backlash because of tolerance inaccuracies. Lubrication is essential with this type of system since it is a metal on metal construction (Budimir, M. (2017)).

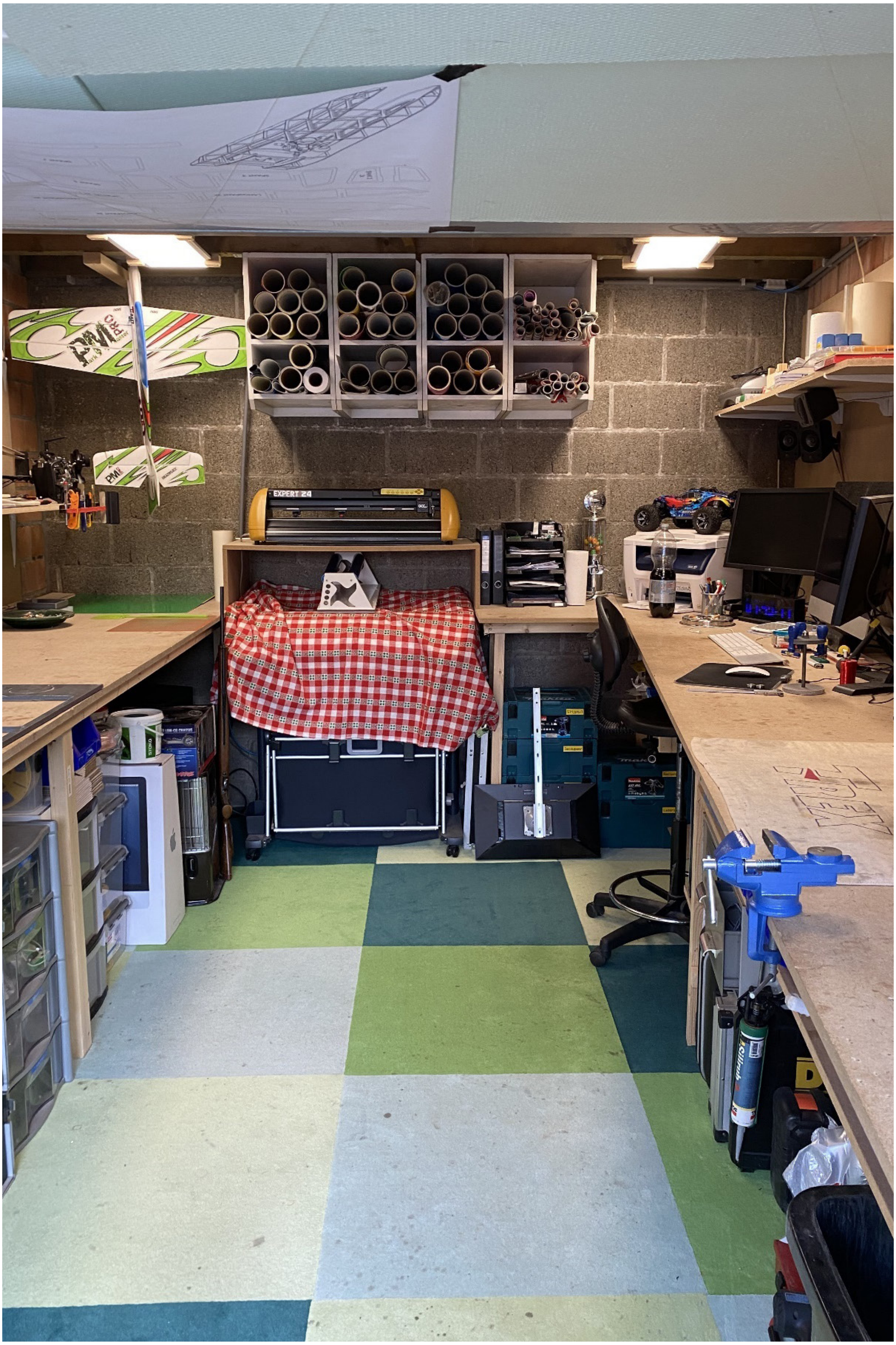
Appendix D
Context pictures

The following pictures have been collected from the open forum CNCZone (CNCZone, 2021).

Casual users


TECH Graphix


HBM


EXPERT 24


STEPCRAFT 840

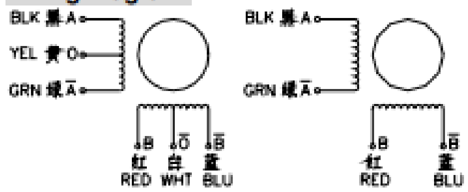
Semi-Professional users

Appendix E
Stepper Motors

The most common type of motor used in CNC machines in general is the stepper motor. Because of their high precision, high availability and their versatility they have become a very popular option for CNC machines and CNC routers in particular. As can be seen in the figure below, stepper motors are available in a wide range of varieties each with its own application.

2 Phase Hybrid Stepper Motor
17HS series-Size 42mm(1.8 degree)

Wiring Diagram:



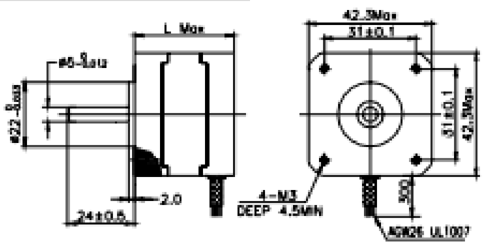
UNI-POLAR(6 LEADS) BI-POLAR(4LEADS)

Electrical Specifications:

Series Model	Step Angle (deg)	Motor Length (mm)	Rated Current (A)	Phase Resistance (ohm)	Phase Inductance (mH)	Holding Torque (N.cm Min)	Detent Torque (N.cm Max)	Rotor Inertia (g.cm²)	Lead Wire (No.)	Motor Weight (g)
17HS2408	1.8	28	0.6	8	10	12	1.6	34	4	150
17HS3401	1.8	34	1.3	2.4	2.8	28	1.6	34	4	220
17HS3410	1.8	34	1.7	1.2	1.8	28	1.6	34	4	220
17HS3430	1.8	34	0.4	30	35	28	1.6	34	4	220
17HS3630	1.8	34	0.4	30	18	21	1.6	34	6	220
17HS3616	1.8	34	0.16	75	40	14	1.6	34	6	220
17HS4401	1.8	40	1.7	1.5	2.8	40	2.2	54	4	280
17HS4402	1.8	40	1.3	2.5	5.0	40	2.2	54	4	280
17HS4602	1.8	40	1.2	3.2	2.8	28	2.2	54	6	280
17HS4630	1.8	40	0.4	30	28	28	2.2	54	6	280
17HS8401	1.8	48	1.7	1.8	3.2	52	2.6	68	4	350
17HS8402	1.8	48	1.3	3.2	5.5	52	2.6	68	4	350
17HS8403	1.8	48	2.3	1.2	1.6	46	2.6	68	4	350
17HS8630	1.8	48	0.4	30	38	34	2.6	68	6	350

*Note: We can manufacture products according to customer's requirements.

Dimensions: unit=mm



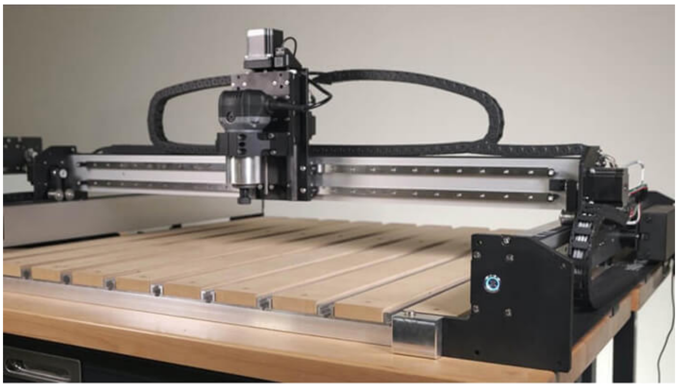
Motor Length:

Model	Length
17HS2XXX	28 mm
17HS3XXX	34 mm
16HS4XXX	40 mm
16HS8XXX	48 mm

Appendix F
CNC Router Comparison

To gain an even better understanding and get an overview of existing CNC routers that share similarities/requirements that the to-be-designed system should possess the following comparison has been conducted.

For this comparison six different CNC routers that possess qualities that the to-be-designed system should possess have been analysed. These six machines included; The ShapeOko, The X-Carve, The MPCNC (mostly printed CNC), The Stepcraft, The AVIDCNC and finally BOBSCNC.



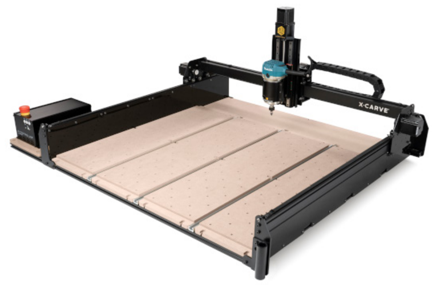


Figure 94: ShapeOko(left) VS X-Carve(right)

The first two machines(see figure 94) are the ShapeOko(Shapeoko Enthusiasts, 2022) and the X-Carve(X-Carve, 2022). These machines are very similar in terms of build area and overall capabilities.

Build area ShapeOko: 790mm x 790mm

Build area X-Carve: 750mm x 750mm

Since both machines use the same hardware they are capable of the same cutting varieties. Generally speaking the Makita RT0700 router is used as the cutting tool. This router is capable of providing an RPM range of 10000 – 30000 RPM and has 710 Watts.

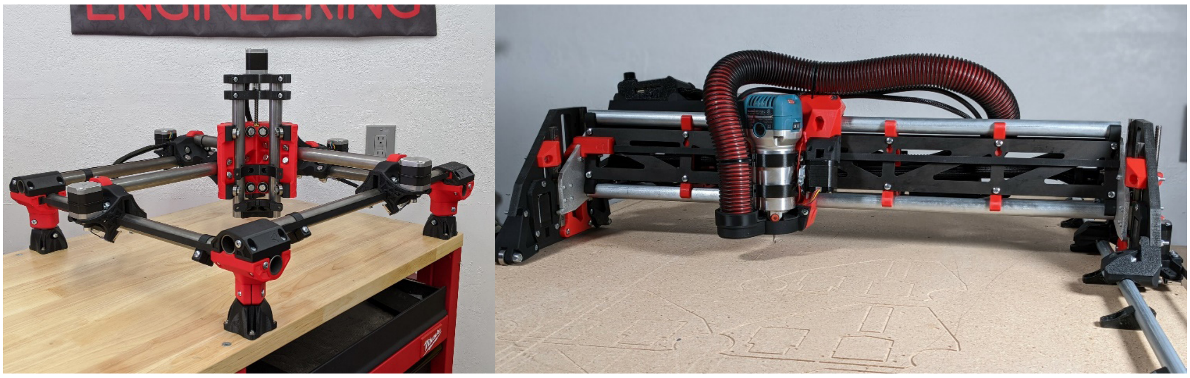


Figure 95: MPCNC(left) and Lowrider MPCNC(right)

The following machine is the MPCNC or Mostly Printed CNC(MPCNC, 2022). This machine is a DIY kit makers can build themselves using a 3D printer. Figure 95 shows the regular MPCNC on the left side which can be mounted on a table. The lowrider MPCNC on the right side of the figure can be mounted to any workbench, workpiece are table and provides better storage capabilities.

Since the machine is a DIY kit it is up to the user how strong/large they want the machine to be. Generally speaking again the Makita RT0700 router is used as the cutting tool.

Figure 96: StepCraft(left) and AvidCNC(right)

Both the following machines(figure 96) are machines that can be found in a professional setting. In case of the StepCraft machine this is mostly because it is available in a wide range of varieties in terms of build area and is capable of machining a large number of materials. Which provides an option for almost every professional.(STEPCRAFT, 2023)

The AvidCNC is a largescale and very powerful professional machine (AvidCNC, 2023). This machine is available in two different options; the NEMA 23 version and the even stronger NEMA 34 version. The latter being used to cut thick sheet of metal.

Figure 97: BOBSCNC

The final CNC machine that will be discussed is BOBSCNC. This machine again is a DIY kit. The machine can be acquired in two ways. By purchasing it as a ready to assemble kit or by purchasing the build files and creating it yourself. Since the machine is constructed out of plywood it is a cost effective and accessible machine. The design of the machine is parametric, leaving the capabilities of the machine again up to the user to decide. (BOBSCNC, 2023).

Appendix G
Chipload

MATERIAL	CHIP LOAD FOR VARIOUS TOOL DIAMETERS		
	3mm	6mm	8mm
MDF	0,05	0,08	0,10
Soft Wood, Plywood	0,035	0,07	0,09
Hard Wood	0,03	0,06	0,08
Soft Plastics (PE, PP, PLA,...)	0,035	0,09	0,11
Hard Plastics (PVC, PA, PMMA,..)	0,025	0,08	0,10
Aluminium	0,02	0,05	0,07
Carbon Steel	0,01	0,04	0,06

Appendix H
Idea generation

'The Fish Trap Model helps you in generating and developing material concepts. It prescribes a process of converging, diverging and categorising, metaphorically referring to a 'fish trap" (Delft Design Guide, 2020).

In short this model uses the Function Structures, generated during the Analysis phase, and allows you to systematically explore solutions on three subsequent levels of increasing detail and meaning(Delft Design Guide, 2020).
During this idea generation the three steps of the Fish Trap Model will be executed.

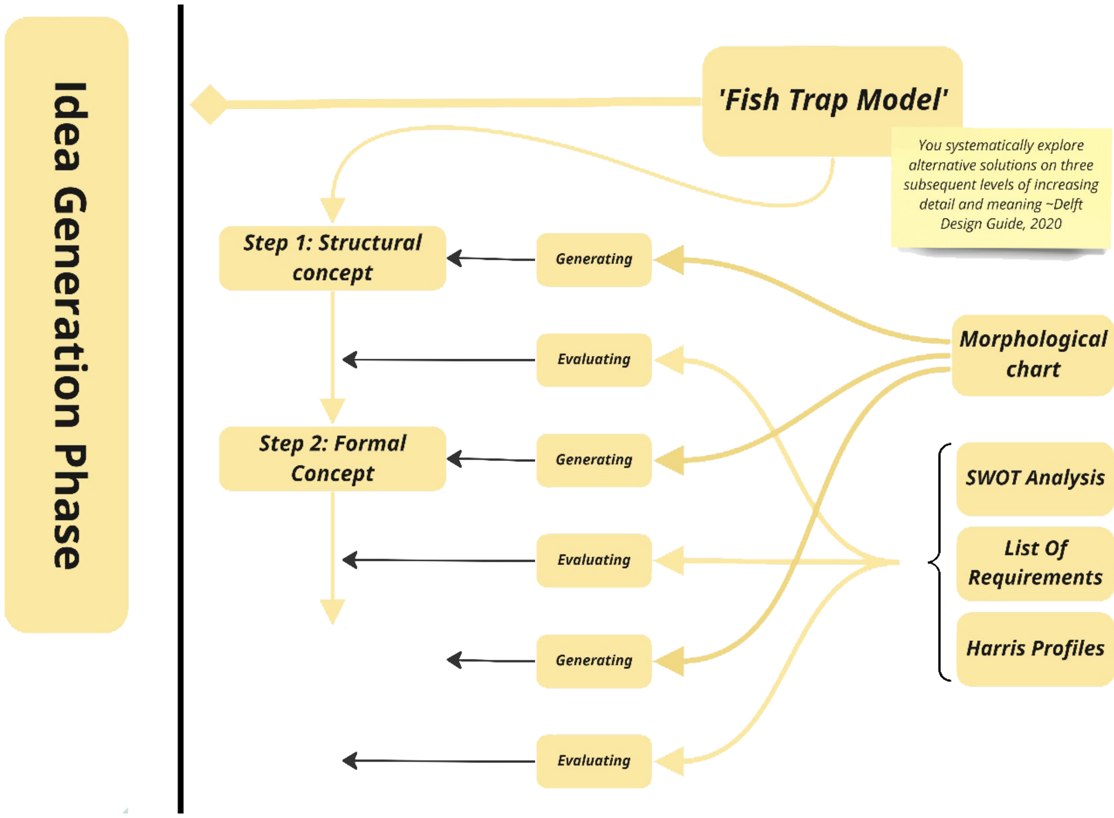
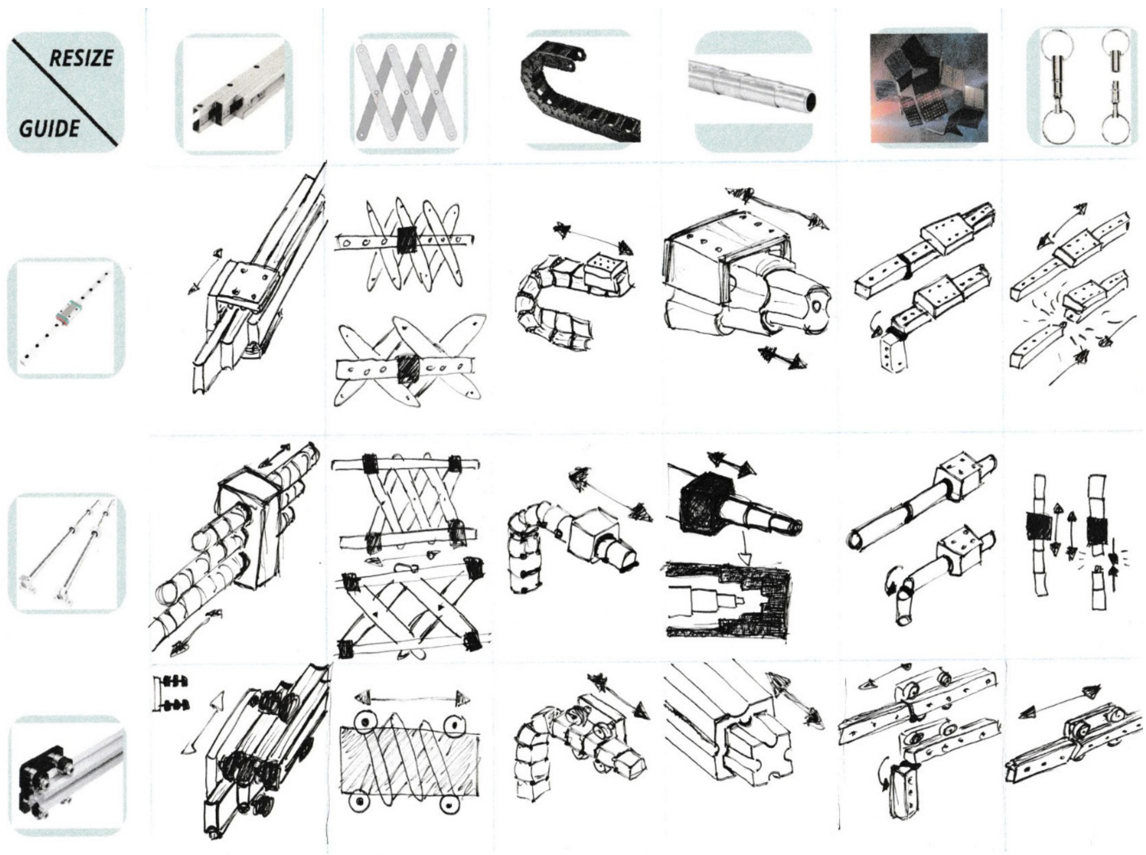
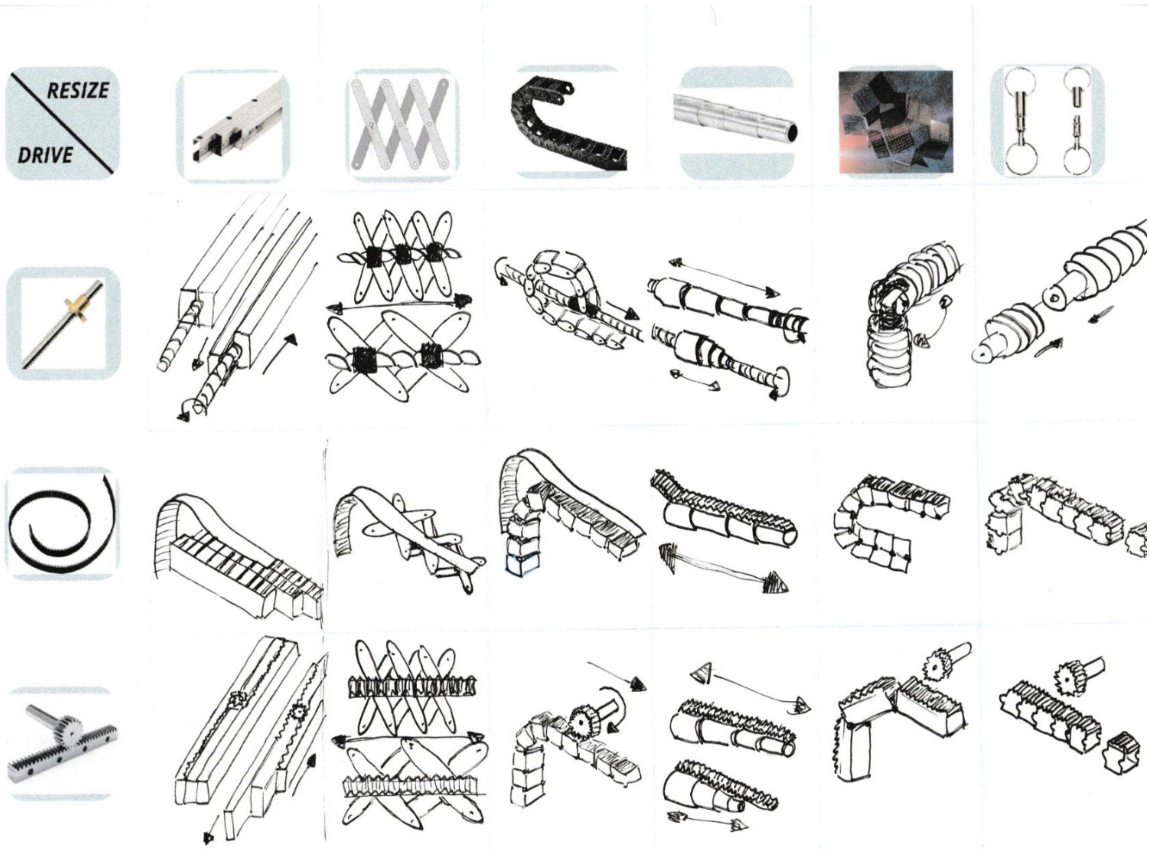


Figure 98: Fish Trap Model Idea Generation

With the help of this model multiple morphological charts will be created. These will form the foundation of the three different concept phases; The structural concept, the formal concept and the material concept. These concepts will all be evaluated with the help of multiple design methods/techniques such as e.g. a SWOT Analysis or a Harris Profile. The List of Requirements will form the final decision in the analysis of an idea and whether it will advance onto the next concept phase.

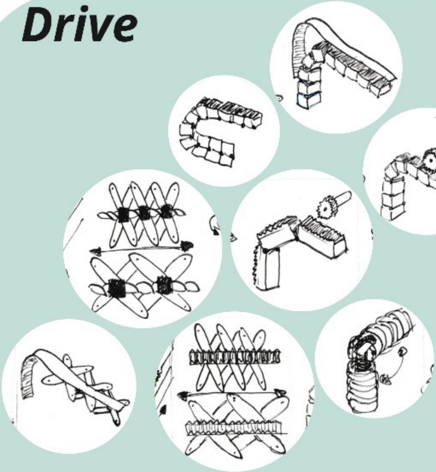
The figures on the next pages show the Morphological charts for the idea generation. These have formed the foundation for the final concept design. The ideas from the morphological charts have been clustered multiple times and afterwards eliminated with the help of multiple requirements. After elimination a single cluster remained which formed the foundation for the concept.


RESIZE
GUIDE

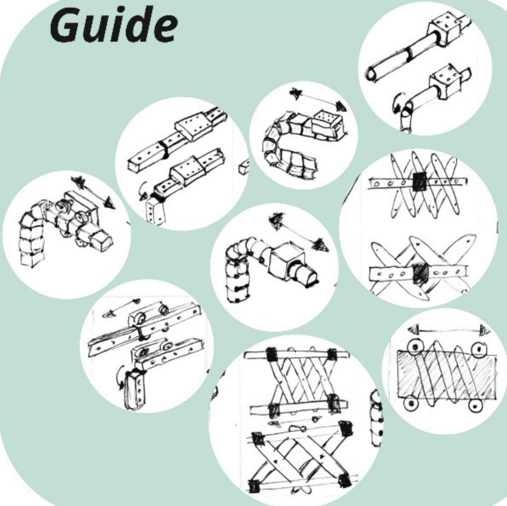

RESIZE
DRIVE

FOLDING

Drive

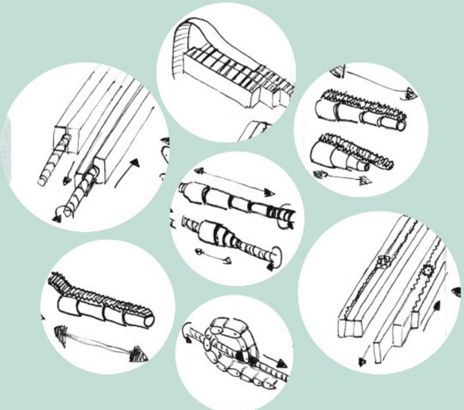


Guide

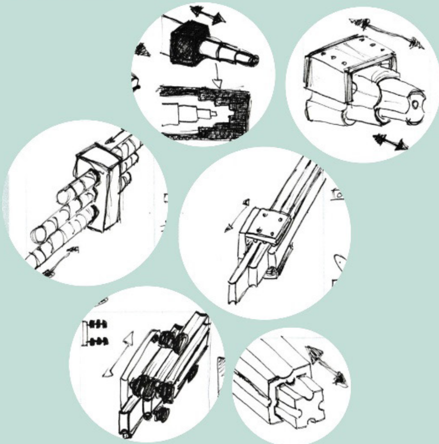


EXTENDING

Drive

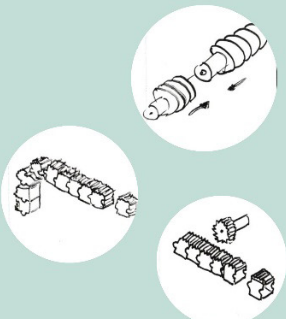


Guide

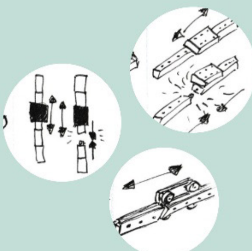


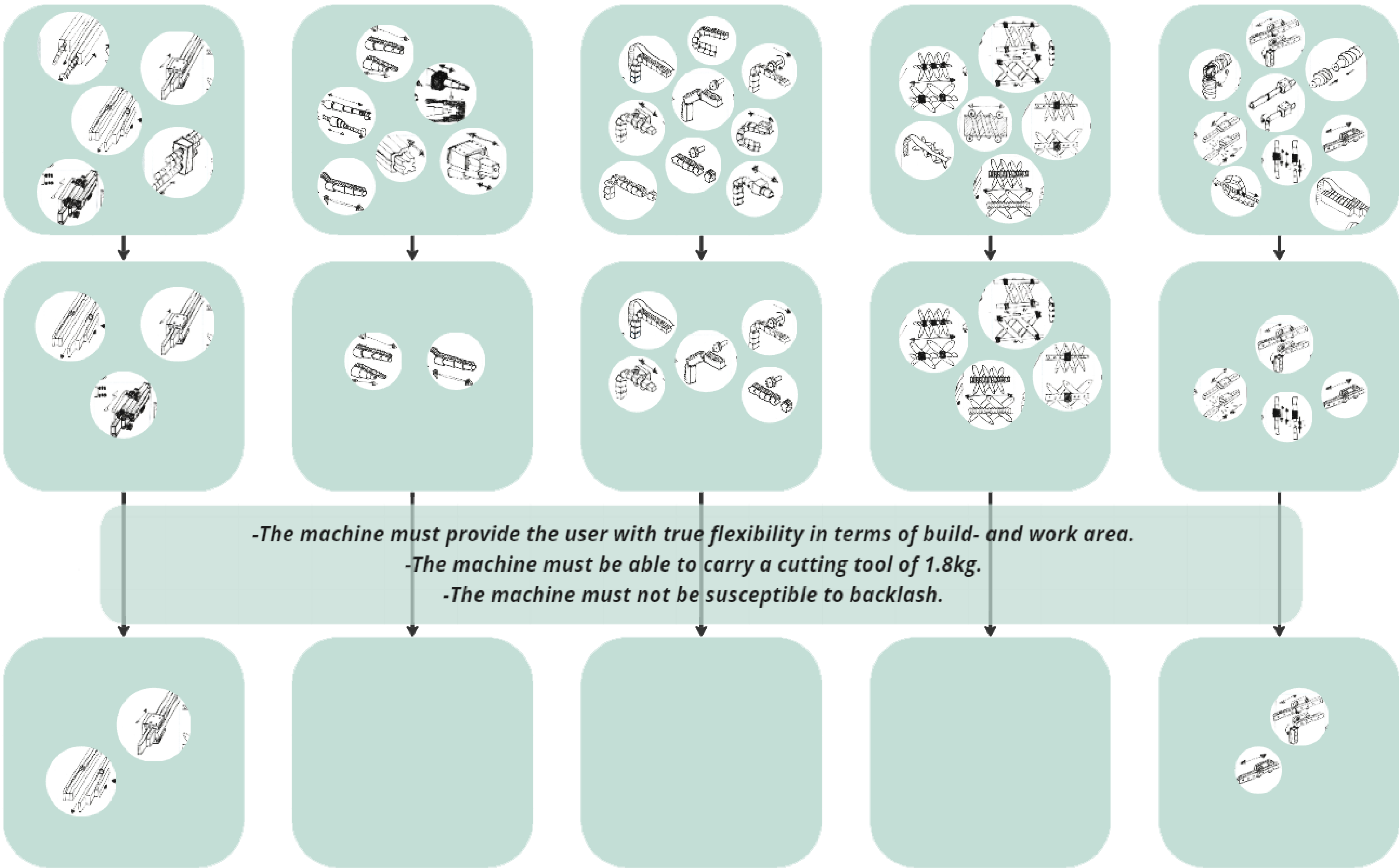
MODULAR

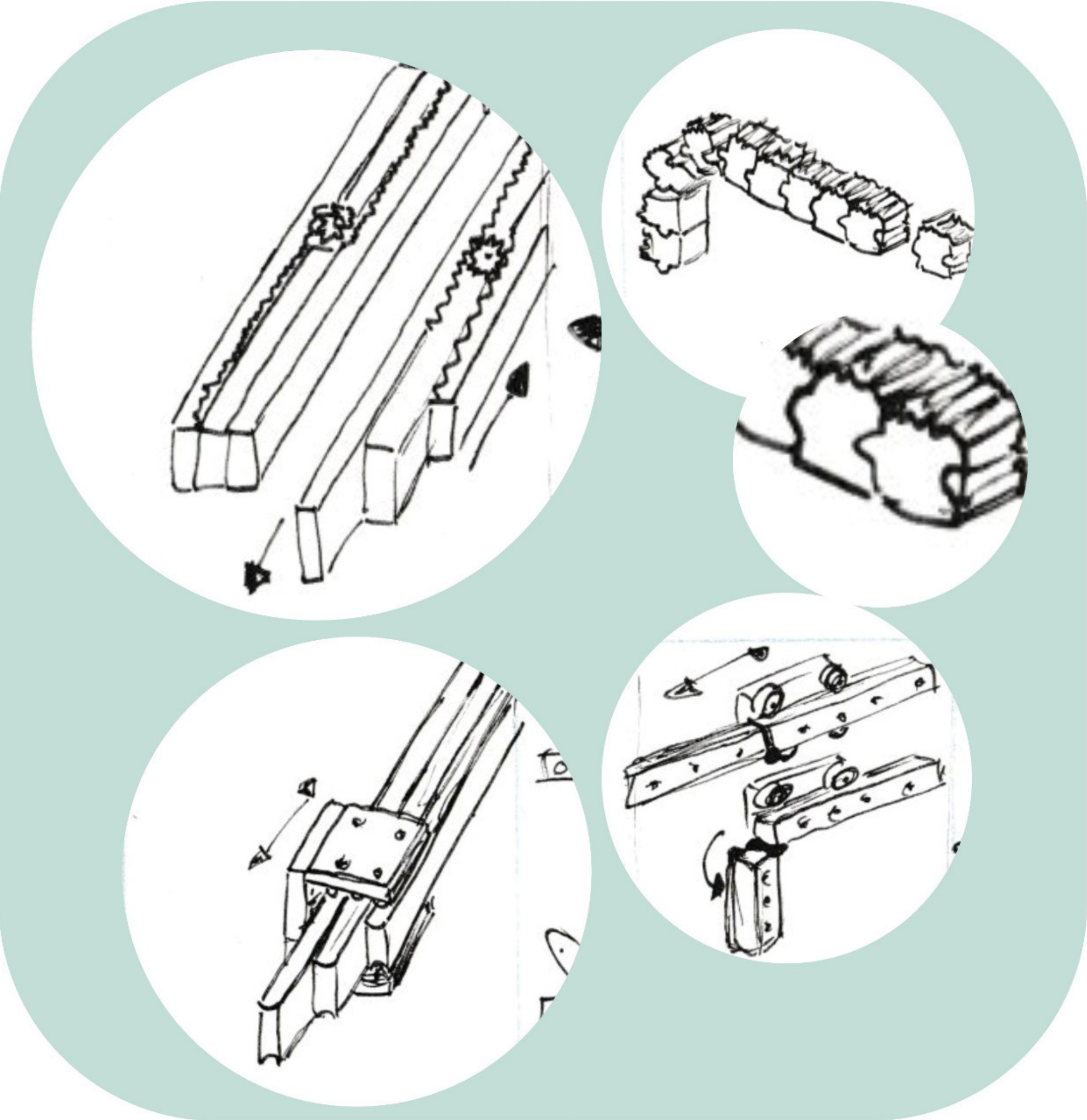
Drive



Guide




-The machine must provide the user with true flexibility in terms of build- and work area.
-The machine must be able to carry a cutting tool of 1.8kg.
-The machine must not be susceptible to backlash.



Appendix I
Datasheet Makita RT0700C

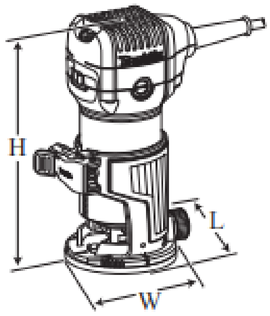
TECHNICAL INFORMATION

makita

PRODUCT
P 1/ 13

Models No. ► RT0700C

Description ► Trimmer



CONCEPT AND MAIN APPLICATIONS

Model RT0700C is a high power, durable and accurate Trimmer with the following main features:

- Aluminum housing and base for higher durability and accuracy
- 4 different base assemblies for added versatility

This product is available in the following variations.

Standard equip. \ Model No.	RT0700C	RT0700CX1	RT0700CX2	RT0700CX3
Trimmer base assembly	Yes	Yes	Yes	Yes
Tilt base assembly	No	Yes	Yes	Yes
Offset base assembly	No	Yes	No	Yes
Plunge base assembly	No	No	Yes	Yes
Tool bag	No	Yes	Yes	Yes
Side grip	No	Yes	Yes	Yes
Grip attachment	No	Yes	No	Yes

Dimensions: mm (")	
Length (L)	89 (3-1/2)
Width (W)	89 (3-1/2)
Height (H)	200 (7-7/8)

► Specification

Voltage (V)	Current (A)	Cycle (Hz)	Continuous Rating (W)		Max. Output (W)
			Input	Output	
110	6.8	50/60	710	230	850
120	6.5	50/60	---	230	850
220	3.4	50/60	710	230	850
230	3.2	50/60	710	230	850
240	3.1	50/60	710	230	850

No load speed: rpm = min.$^{-1}$		10,000 - 30,000
Collet capacity*		6.0mm, 8.0mm, 1/4" (6.35mm), 3/8" (9.53mm)
Plunge capacity: mm (")	w/ Trimmer base	0 - 40 (0 - 1-9/16)
	w/ Plunge base	0 - 35 (0 - 1-3/8)
Switch type		Rocker type on/off switch
Variable speed control by dial		Yes
Electronic control	Soft start	Yes
	Constant speed	Yes
Protection against electric shock		Double insulation
Power supply cord: m (ft)		European countries: 4.0 (13.1), Brazil, Australia: 2.0 (6.6) Other countries: 2.5 (8.2)
Weight according to EPTA-Procedure 01/2003: kg (lbs)		1.8 (3.9)

* Collet capacity may vary by country.

► Standard equipment

For all countries

Trimmer base ass'y 1
Straight guide 1
Wrench 13 1
Wrench 22 1

For some countries only

Tilt base ass'y 1
Offset base ass'y 1
Plunge base ass'y 1
Trimmer guide 1

Collet cone 6mm or 1/4" 1
Collet cone 8mm or 3/8" 1
Dust nozzle (for Plunge base) 1
Dust nozzle (for Trimmer base) 1

Grip attachment 1
Side grip 1
Straight bit 1
Tool bag 1

Note: The standard equipment for the tool shown may vary by country.

► Optional accessories

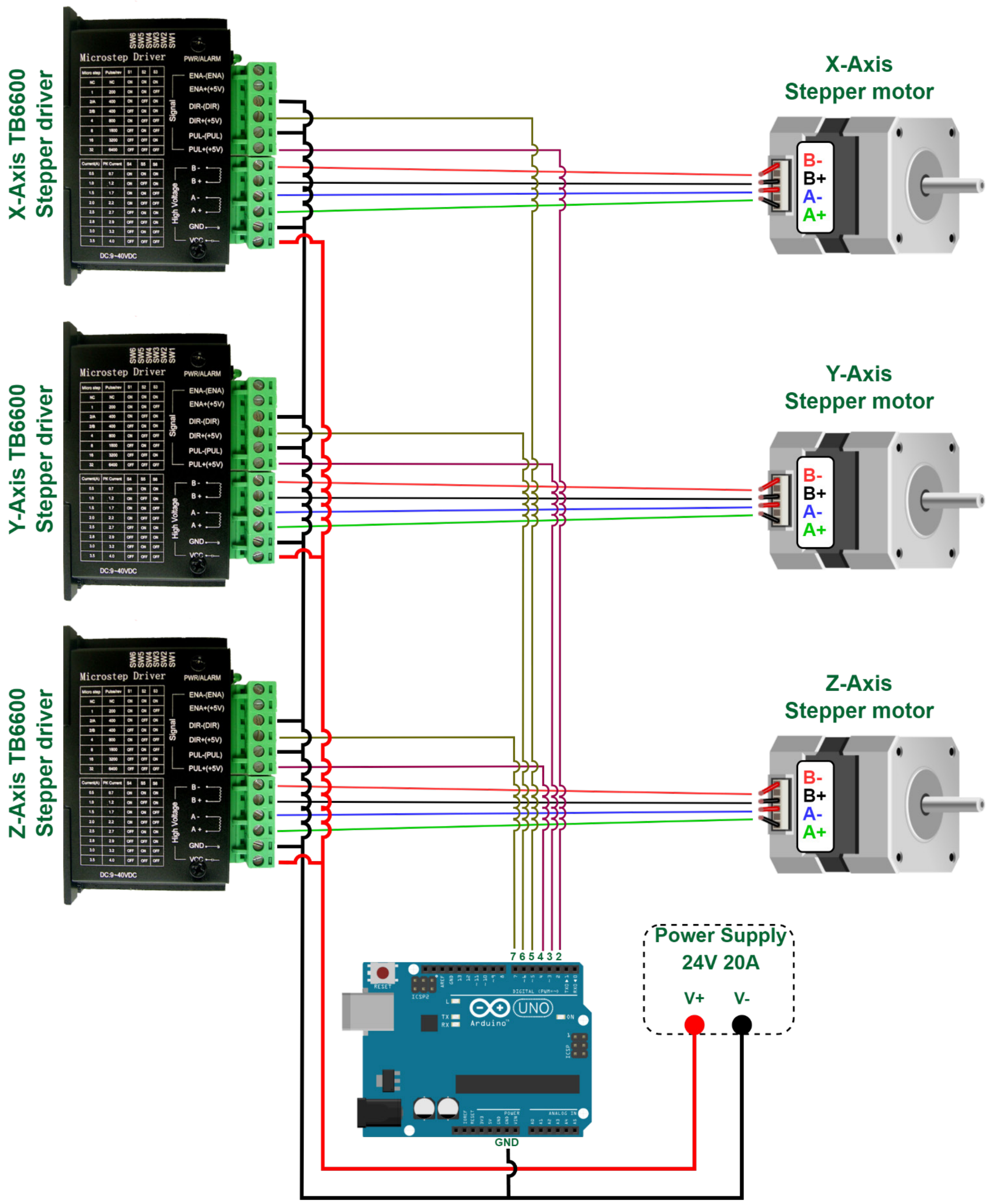
Router bits
Templet guides
Side grip
Dust nozzles

Trimmer guide
Straight guide
Tool bag
Guide rails

Guide rail adapter set
Straight guide with micro adjustment
Grip attachment
Trimmer base assembly

Tilt base assembly
Offset base assembly
Plunge base assembly

Appendix J
Wiring Diagram



Appendix K
GT2 Belt Datasheet

Handson Technology

Datasheet

GT2 Timing Belt - Open Ended

The GT2 series of belts are designed specifically for linear motion. They use a rounded tooth profile, with 2mm pitch, that guarantees that the belt tooth fits smoothly and accurately in the pulley groove, so when you reverse the pulley direction, there is no room for the belt to move in the groove. Belts are supplied as one length which is easily cut to the required length. Work with GT2 pulley for most variants of 3D printer, CNC machine, robotics and other linear motion designs. Reinforcing Cords are Fiberglass (belting can be easily cut with regular scissors)

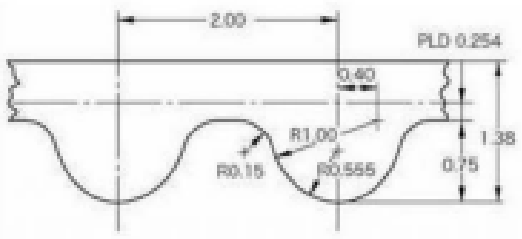
SKU: MCH-1123

Brief Data:

- Belt Pitch: 2mm.
- Belt Width: 6mm.
- Length: 1 meter.
- Shape: Open-Ended Timing Belt.
- Belt Height: 1.38mm.
- Tooth Height: 0.75mm.
- Breaking Strength: 124 lb / 56kg.
- Working Tension: 6.25 lb / 2.8kg.

Mechanical Dimension:

Unit: mm



GT 2 Timing Belt - 2 mm Pitch

6 mm Wide

Material: Rubber
Reinforcement: Fibre Glass
Colour: Black

REFERENCE	Mat/ Finish	Type	Pitch	R_1	R_2	R_3	b	H	h	i	PLD
HT-GT2-06	R/FG/B	GT2	2	0.15	1	0.555	0.4	1.39	0.75	0.63	0.254

Appendix L
T8X2 Lead screw Datasheet

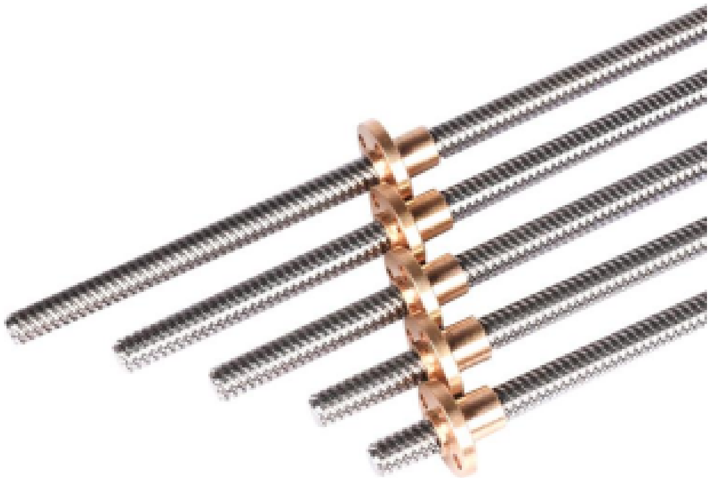
HT Handson Technology

Data Specs

Ø8mm Trapezoidal Precision Lead Screw

Our lead screws offer an excellent way to turn rotational motion into linear motion. This screw fits the bill for most machine designs and will quickly become a standard on Maker store for 3D printer , CNC Machine and robotics DIY community. The 2~4mm pitch offers a good trade-off between torques required to drive the screw and linear speed created. Each rotation of the lead screw will drive the mating nut precisely 2~8mm, depending on the pitch. The OD of our lead-screws is precise 8mm to ensure proper fitment in an 8mm ID bearing or clamp. It's a great power transmission choice for your DIY build!

An example steps settings for your control software would be 200 steps per millimeter if you are running the common 1.8° degree stepper motor and your stepper driver is set to 1/8 step mode.



SKU: MCH-1095

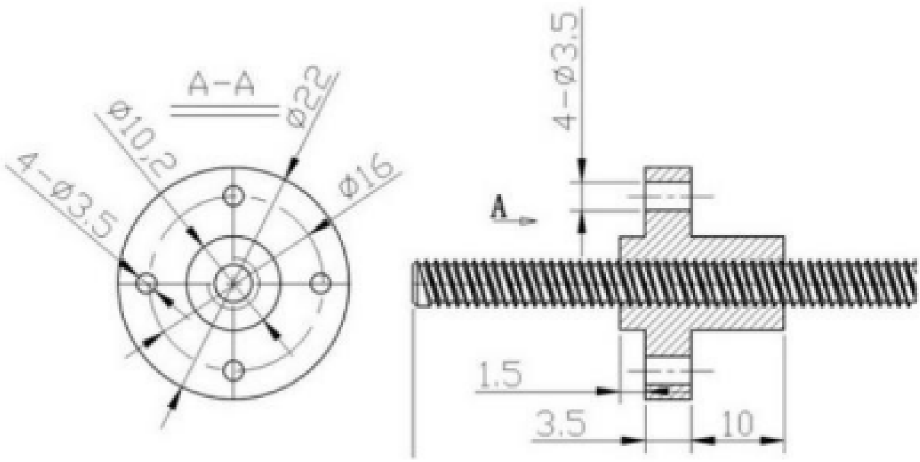
Brief Data:

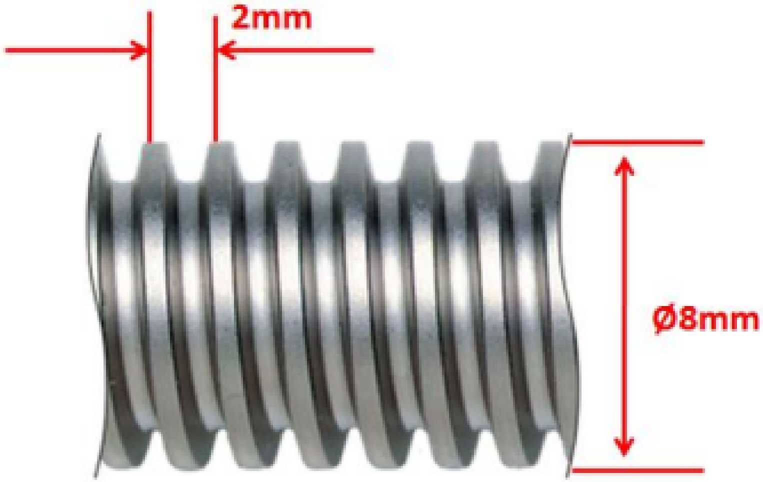
- Model No: THSL-3xx-8D
- Tread: Tr8*8-2p (4 starts)
- Lead Pitch: 2mm.
- Lead Distance: 8mm (8mm/rotation).
- Number of Start: 4.
- Lead Screw Outer Diameter: Ø8mm.
- Lead Screw Length: 300~750mm.
- Structure: Trapezoidal Spindle Screw.
- Material: Stainless Steel.

Application:

- 3D Printer
- CNC Machine
- Robotics
- Linear Motion

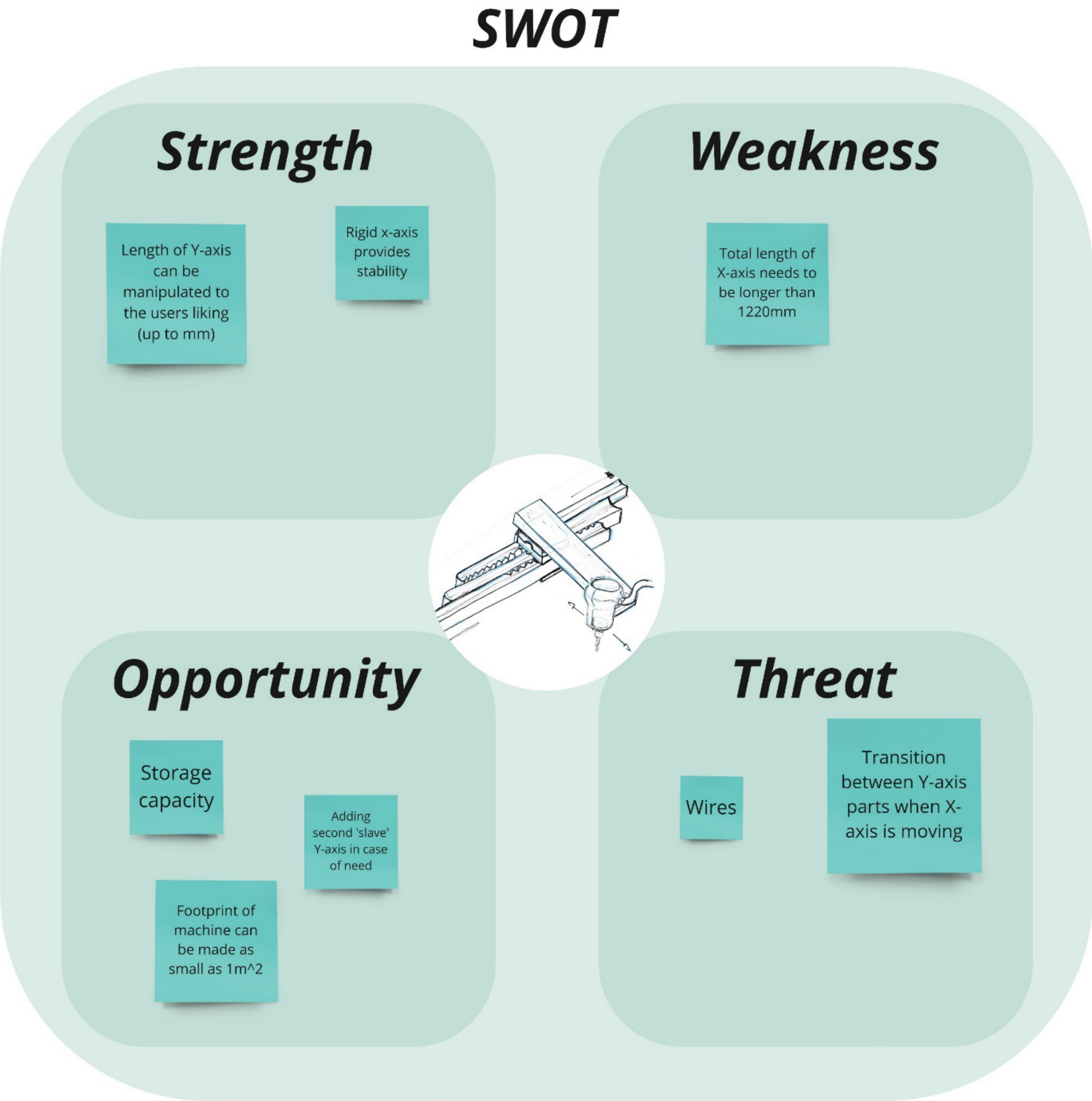
Mechanical Dimension:





What is Number of Starts, Pitch and Lead of Lead/Ball Screw?

Appendix M
SWOT Analysis of Concept

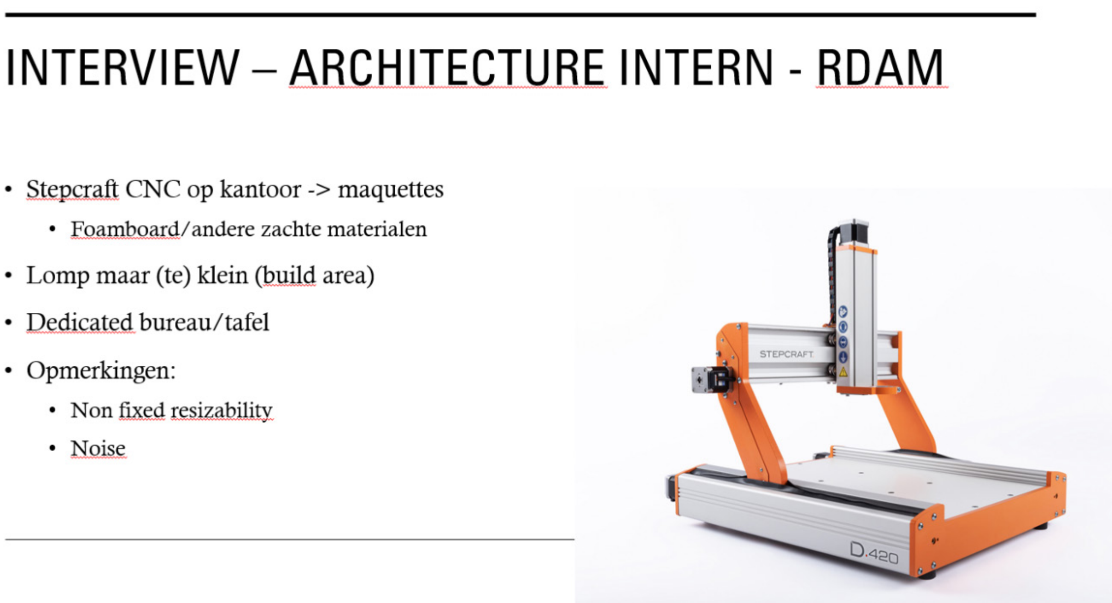


Appendix N
Take Aways interview Architecture Intern

To conduct a user research, I interviewed an architecture intern in Rotterdam. I was searching specifically for someone who was working at a smaller-scale office. This way I had a comparison of 2 different types of users. The professional, which I interviewed at Jongeneel Utrecht and a semi-professional user, which in this case was an architecture intern.

I first started of asking which brand of CNC-router they used and what they used it for. This came out to be the Stepcraft CNC, which was put together by one of her colleagues. They typically used the machines to create models and experiment with different materials. These materials were often 5mm plywood or foamboard.

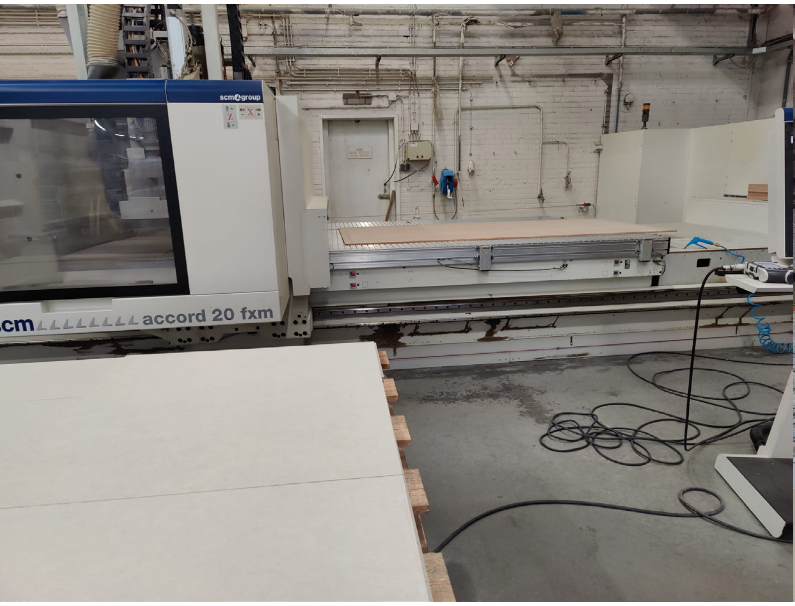
Most architecture firms work in a specific scale when making a model. The scale often differs depending on the project which in turn requires a flexibility in operating size. The Stepcraft CNC is a machine with a fixed work area which created a limit in which they could experiment and create. This specific CNC also had a small build area with a bulky, overall footprint making it difficult for them to use it with ease. Also, the machine was situated in the middle of their office, this created too much noise, and they therefore were required to use it at night or after office hours. She stated that the machine had a dedicated table in the office, but it often created an uneasiness with her colleagues since they couldn't use it freely. Which made them not use the machine that often.
She stated that the biggest struggle was the fact that the machine did not have the flexibility which they often were looking for.



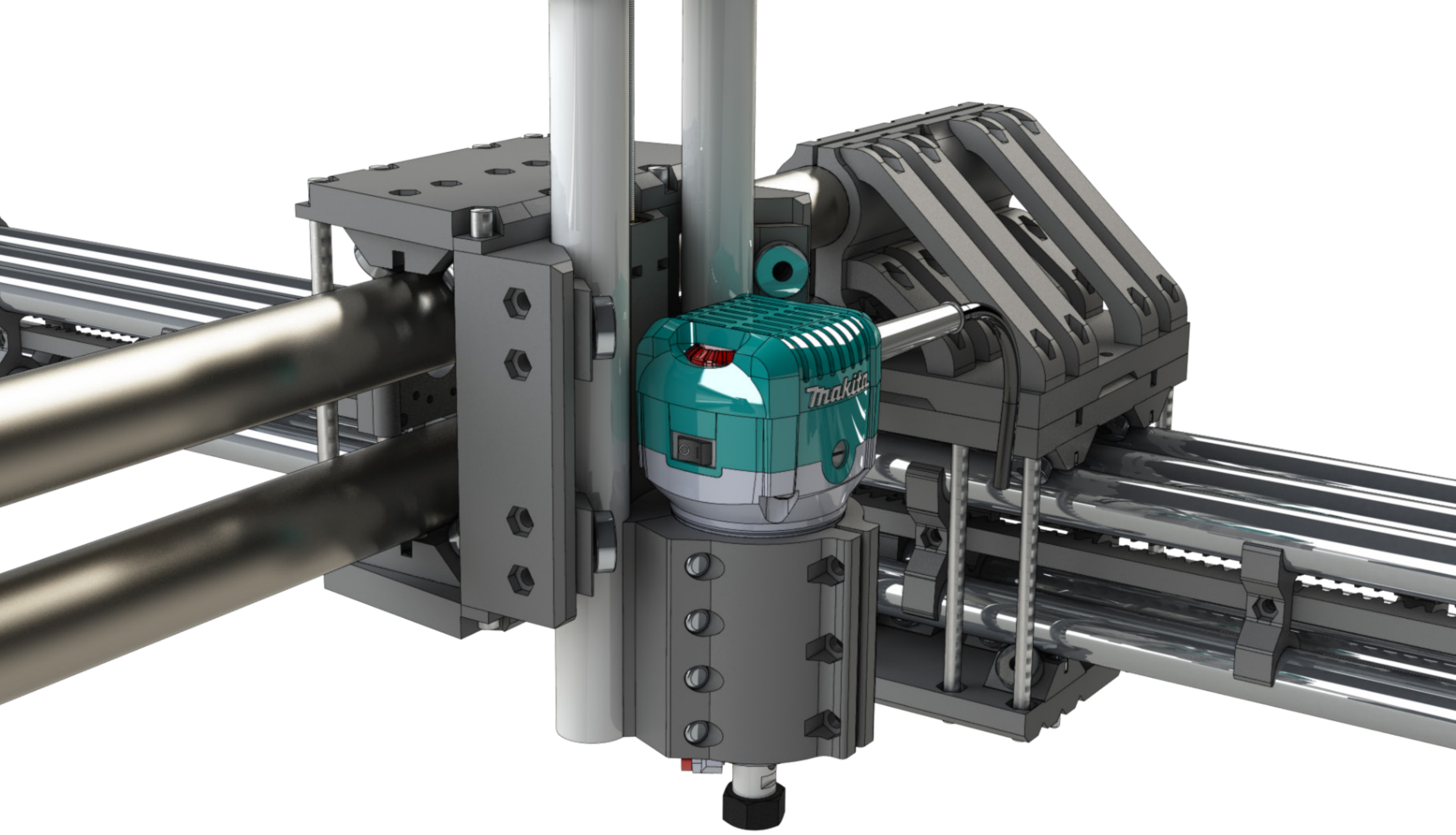
Appendix O
Timber and Building supply mill visit Utrecht

On 9 December 2022 I got the opportunity to visit the main location of one of the largest processors of wood of the Benelux. I received a tour of the entire location and explanations of the operations executed there. I was able to ask a number of questions regarding the operations and machines which were operated. And got to see one of two professional CNC routers in action.

Currently they operated 2 large CNC routers at the location, which would be 5 in 2023. These machines are operating constantly.
The main process of receiving a machining job is the following;
Request at one of the many locations across the country, which is then translated into a technical drawing. This technical drawing is later translated to G-Code by a CNC programmer. The CNC programmer sends the G-Code to the CNC operator who operates the CNC router itself and machines the requested material.



Appendix P Design Renders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