Designing an accessible workflow for Rapid Prototyping on a homemade 3-axis CNC machine

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Abstract

This thesis gives insights into the capabilities of using a CNC machine for rapid prototyping as well as improving the accessibility of these capabilities for the users of the client. The software needed to design and manufacture parts has been selected according to the clients needs which are focussed on ease of use and safety. This resulted in the selection of Autodesk's Fusion 360 as the designated software. Next to the software the hardware which consists of a home-made CNC machine has been adapted to fit the same needs as the software, this resulted in an enclosure around the machine for safety and the implementation of additional safety mechanisms. To gain insight into the capabilities multiple experiments were executed and these resulted in the workflow presented in the result which ended up being a website with all the necessary information to start using the machine and the software. This website (millinator.com) has been proven to increase accessibility and ease of use by the lead user interviews and expert opinion.

Acknowledgement

I would like to take this opportunity to thank my primary supervisor Edwin Dertien as he and his projects inspired me to delve deeper into the field of hardware. I would also like to thank the Designlab for letting me build and operate the machine autonomously. Furthermore I thank Andrea Minuto for giving me valuable feedback on the design of the machine as well as motivating me to work harder. Also this would not have been possible without the great software made by the Autodesk team, Fusion 360 fulfilled the needs of the client perfectly. I also thank John from NYC CNC for making a set of great video's explaining the ins and outs of Fusion 360.

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Chapter 1

Introduction

Computer numeric control (CNC) machines are machines that are broadly used in industry to make metal parts. Milling is the term used to manufacture a part out of a larger piece of metal. Most CNC machines have a cutting head that is positionable on three or more axis. This allows for complex three dimensional parts to be made with good accuracy and precision [1].

CNC machines have been used since the 1970 to produce parts in various industries. It has enabled manufacturers to have a flexible manufacturing systems (FMS) that produces high quality parts according to tight tolerances. This has allowed for mass customization which gives the manufacturer a larger inventory of producible parts against minimal extra cost. These machines are also used in rapid prototyping, their flexibility is of great help in fine tuning a design.

With this flexibility in manufacturing comes complexity in the machine and in its operation. CNC machines are embedded systems, hardware and software have to work in tandem to accomplish the production of a part. With every production run the machine has to be programmed by a technician that has to set a multitude of parameters in order to get a well finished part. Without prior knowledge about machining setting these parameters and programming the machine can be a daunting task [2].

Design studies like Creative Technology and Industrial Design can benefit greatly from this rapid prototyping tool but the skills required are not included in their curriculum as of writing this thesis. Waggoner [3] highlights the advantages of having a 3D model when producing parts; “It gives the graphical representation of components appearing almost as photographs. Working with customers this allows for an up to date design review of a product that they are working with a vendor on.”. This has been included in the curriculum thus the step to using these models for CNC manufacturing is within the grasp of these students.

The clients both have CNC machines available, the Designlab has one built by Ibrahim Elfaramawy and Assortiments has a off the shelf machine. The inspiration for this thesis came after completing the construction of the machine, more knowledge was needed concerning operation and how to get the students to use the machine. For more information concerning the construction of the CNC machine see section 1.4 Background information.

The graduation project focusses on two aspects of the CNC machine; the capabilities and the implementations of these capabilities. Within a Rapid Prototyping setting the aim is to get the CNC machine integrated into the Rapid Prototyping environment that the students are familiar with at the clients.

1.1 Client 1 - The Designlab

The Designlab [30] is an area on the campus of the University of Twente where students of all design studies can come and work. From 3D design to sketching to usability testing to physical construction of prototypes, it's all possible in the Designlab. Two workshops are present in the Designlab one for electronics and one for mechanical work.

1.2 Client 2 - ASSortiMENS

ASSortiMENS [29] is a workplace for people with any form of autism. ASSortiMENS aims to provide daily activities that stimulate social and problem solving skills required to participate in society. Most of these activities are related to technical projects like retrofitting old radio's with bluetooth enabled electronics.

1.3 Challenge

As described in the introduction a CNC machine is a complex tool. This is the challenge for this research as it aims to increase accessibility. Since the users are not familiar with the tools the complete process needs to be explained and the capabilities shown. The margin of error when using a CNC machine are small as well, making a mistake usually produces a part that is not usable.

1.4 Background information

The construction of the CNC machine in the Designlab started in a 13 square meter dorm room on campus, it started out as a summer project unrelated to university or both clients. As the bits of parts started to look like a CNC machine as seen in figure 1.1, a job opened up at the Designlab as caretaker, upon a few weeks of working there it became apparent that the machine would have a very good home here. And so the Designlab acquired the home-made CNC machine from a student.

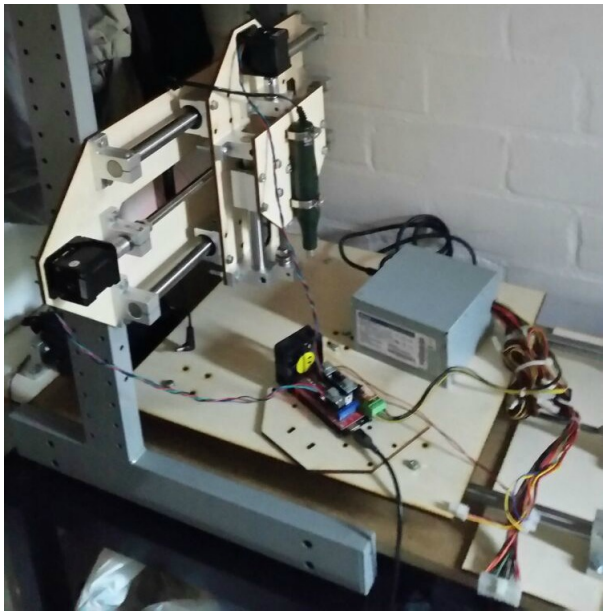


Figure 1.1: The early construction phase of the machine in the dorm room.

1.5 Research Questions

1. How can a CNC machine help in Rapid Prototyping in educational environments.
2. How can CNC Rapid Prototyping capabilities be made easily accessible to design study students.

Chapter 2

Problem Analysis

2.1 Literature Review

The field of CNC machining has been under continuous development since the 1970. However the marriage with Rapid Prototyping is a more recent development. Due to the popularity of the Rapid Prototyping method multiple researchers have employed this technique in tandem with a CNC machine and are thus relevant to the first research question.

As CNC's have an established role in industry there are university classes that teach the skill. From these cases valuable knowledge can be taken to shed more light onto the second part of the research question concerning accessibility.

2.1.1 Method of Literature Review

Search Engines

To find the articles required to form the literature review academic search engines were used with a selection of search terms. The search engine that was the most helpful seemed to be IEEexplore [4], this since all aspects of the research was in the field of engineering.

Search Terms

The search terms used can be seen in the list below. Most relevant were the Rapid Prototyping and CNC design.

1. Rapid Prototyping
2. CNC Design
3. Tinkering
4. CNC machine/Milling machine
5. Computer Aided Manufacturing
6. Computer Numeric Control
7. CNC Workflow

2.1.2 How can a CNC machine help in Rapid Prototyping in educational environments

Basic Operation

The most basic operation of a CNC machine is cutting a part out of a piece of stock. Like every other CNC operation it starts with a CAD model of the part that is to be made. The 3D model is then put into a CAM program so the paths can be generated for the CNC machine to cut the desired part out of a larger piece of material [7]. Frank compares the workflow of traditional CNC machines with a 3D printer, he states that in the case of the CNC machine there are more steps than with a 3D printer. The extra steps are; Fixing the stock and selecting the tool. According to Frank [7] the fixing to the stock, which is the process of securing the piece of material that the part is to machined out of, is a "difficult task that requires a significant amount of work from a highly skilled technician." [7]. Frank [7] gives three aspects of fixturing ; location, clamping and support. With harder material the clamping and support aspect of the fixturing become more critical.

Customized Molds

In Huang's [4] work is focussed on utilising the flexibility of a CNC machine to make custom parts for the end-user. Custom parts, in this case insoles for shoes, are especially suited for manufacturing on a CNC machine since the manufacturing setup does not need to change in order to produce different insoles, only the software. To make the custom insoles the process begins with a scan of the user's feet, this model is then exported to a CAD program for touch up and then exported to a CAM program to generate the paths for the CNC machine to make two halves of a resin mold. This mold can then be used to cast the silicon insole. Huang's method is suitable for the production of other silicone parts next to insoles as mentioned before, the only change is in the 3D CAD model used to produce the molds.

Molds for Injection Molding

Huang's method is similar to the method used by Fisher to produce injection molded plastic parts. Fisher [8] taught a class of 20 students how to make the aluminium molds needed to produce plastic parts. The difference between Fisher and Huang's method comes from the material that is cast into the mold. For injection molding a higher strength material is used to withstand the force of the injected plastic [8].

Printed Circuit Board

Printed Circuit Boards (PCB) are used in most electronic devices to mount the individual electronic parts and interconnect them. In industry these boards are made in production houses usually located in china [9]. For RP the time between design and manufacture is essential, it is called rapid for a reason. One way to achieve a shorter leadtime is by making the boards on a CNC machine, since this is never done in the industry no formal literature handles this. The website Technologystudent.com [10] describes a way to make PCB on a CNC macnhine. As usual the process starts with a CAD design of the board, this is put into a specialized CAM program to generate the paths for the CNC machine. The machine then mills the traces out of a copper clad board. According to Technologystudent.com the method of making PCB on a CNC is also safer, since no toxic chemicals are needed to etch the traces [11].

2.1.3 How can CNC Rapid Prototyping capabilities be made easily accessible to design study students

Accessibility can be split up into three subsets, visibility, ease of use and availability. These will be used to assess and improve the accessibility.

Visibility

The visibility aspect of the problem requires marketing methods to be applied properly. Since the machine will be located in a place that is visible and close to the users the barrier is low to start creating. First the users need to know what is possible, this can be accomplished by having a few sample projects that the future users can see. Videos showcasing high profile projects can be selected to maximize impact. No formal research was found on using videos with CNC machining, altough these do exsist as seen on the Udemy.com website [11].

Ease of Use

The ease of use aspect of making the machine more mainstream is by far the most complex. It requires the workflow, which are all the steps the user has to take to make a part to be easily executed in a fashion that minimizes errors and maximises safety. The term workflow will be used to describe the whole process of making a part on the machine, from Computer Aided Design (CAD) to having a finished part in our hands. Anderson [12] sums up the workflow on a CNC as follows CAD, followed by the CAM and the fixing of the stock and running the machine.

Anderson [12], and Fisher [8] both make the assumption that the user already knows CAD, this assumption cannot be made in the context of this research since most of the users of both clients do not know CAD. Fisher's work shows that students find CAM a difficult part of the workflow since they rate it low on the importance scale [8].

The prerequisite of knowing how to CNC machining are not essential in a Rapid Prototyping setting as Stephenson shows with the Fablab platform [13]. Stephenson mentions that working and learning as you go has multiple advantages; students learn faster from their mistakes and students that are less skilled in learning the traditional way are not undermined [13]. Although Anderson mentioned that students need to have experience in computer aided design before they attempt computer aided manufacturing [12] learning as you go has the upperhand as Stephenson illustrates; "By using accessible, relevant, creator technology and project based instruction methods, students do and build their way through various concepts, developing intimate experiences with theory and the modern tools for design, engineering and prototyping. In this environment, conceptual thinkers and practical doers can engage equally. " [13].

Availability

Availability of the machine is important since more accessibility will result in more users. For the most part the technician sets the hours when the machine can be used which are regular office hour times. Stamper [5] concludes that the capacity of CNC machines are not sufficient for a course of 20 students. This left the students in his class having to wait on the machine to finish.

Next to the availability of the hardware the availability of the software are paramount. A multitude of different software packages are available as pointed out by Fisher [8]. Anderson states that any software package chosen needs to have parametric modelling and seamless CAM integration [12]. The latter statement is in conflict with Fisher [8] since he used two different programs for CAD and CAM. Albeit having one software package to do all the work would be a better solution for students.

2.1.4 Conclusion Literature Review

The table 4.1 gives the results of the literature review concerning how a CNC machine can help in Rapid Prototyping. The operations listed are compiled out of a multitude of papers that have successfully completed the operation. The difficulty is based on the amount of steps that are needed to be performed to make a finished part.

Operation:	Difficulty:
Mold making (silicone, resin) [14][8]	Hard (5 steps)
Cutting hard materials (metals, composites)	Medium (4 steps)
Cutting soft materials (wood, plastics)	Easy (3 steps)
PCB manufacturing (one sided) [10][15]	Hard (6 steps)

Table 2.1: CNC operations useful in a Rapid Prototyping setting.

2.2 Methods and Techniques

Ideation

Here the idea is formed to solve a particular problem. The idea can be shaped by traditional ways like a order from a client or a product idea but also via more practical ways like Tinkering which has as a goal to identify novel applications for existing or new technology [15].

In the case of this study the ideation consist of experimentation with the machine in the form of diverse example projects that make use of all the different functionality of the machine. This practical knowledge gained from Tinkering is then used to develop the website that will make the machine easier to use for the students.

Specification

The idea is tested with the help of a repetitive prototyping cycle. After construction of a prototype it is tested and then improved or a new prototype is made in order to arrive at a better picture of what the solution should look like.

Realization

In this phase more traditional engineering methods are used like requirements engineering to build the product or application to specification. This consists of getting the hosting for the website and developing the content.

Evaluation

The product of the realization phase is tested and evaluated for its effectiveness and scope. This was done via a survey under the lead users and by checking the whether the requirements were met that were set by the client.

2.3 Specification

As a baseline the clients requests will be taken into account to ensure the product will suit the client. Secondly multiple user scenarios will be setup to get a clear picture of the users this will result in a list of user needs. Experts will be interviewed as well to gain insights into the caveats of the process. To conclude the specification phase a requirements list will be made according to the prior research, this list will be prioritised according to the MoSCoW [32] method.

2.3.1 Client Requests

To improve the in house prototyping capabilities of the Designlab a CNC machine was added to the selection of Rapid prototyping machines. Currently the Designlab posses an Ultimaker 2 , a Trotec laser cutter and a home made CNC machine. From the start safety was considered the most important aspect, this is why the enclosure was built around the CNC machine. After safety ease of use and maintainability have priority. The maintainability has been achieved through the use of cheap off the shelf parts and materials. Should a part fail a replacement part can easily be ordered or made since everything is homemade. To improve the ease of use a website will be created. From the interview with Andrea Minuto (see appendix 10.1) it became apparent that a website is the easiest method of delivering information to the users. The list below shows the ordered requests from the client the Designlab.

1. Safe
2. Easy to use, every student should be able to get into CNC machining.
3. Maintainable, and easily upgradable.
4. Low sound pollution
5. Low cost

2.3.2 Machine Specifications

In this section the specification of the homemade CNC machine will be examined. These will be taken into account when the workflow is made and the example project will have to fit the capabilities of the machine as well. The table 4.1 shows the general specifications of the machine. Most important are the working area, and the maximum speed per axis. In this case since the mechanical parts and the motors are the same for each axis, all the speeds are the same as well.

Working Area	4000x3000x1000mm
Maximum Speed	300mm/min
Spindle RPM	5000 to 25000 RPM
Spindle Power	1050W
Spindle Collet Size	6mm and 3.175mm

Table 2.2: Specifications of the CNC machine.

The machine achieves these specifications with the parts listed in 12.6. Figure 2.1 shows the critical parts of the machine, these are the same for every axis, only their length differs.

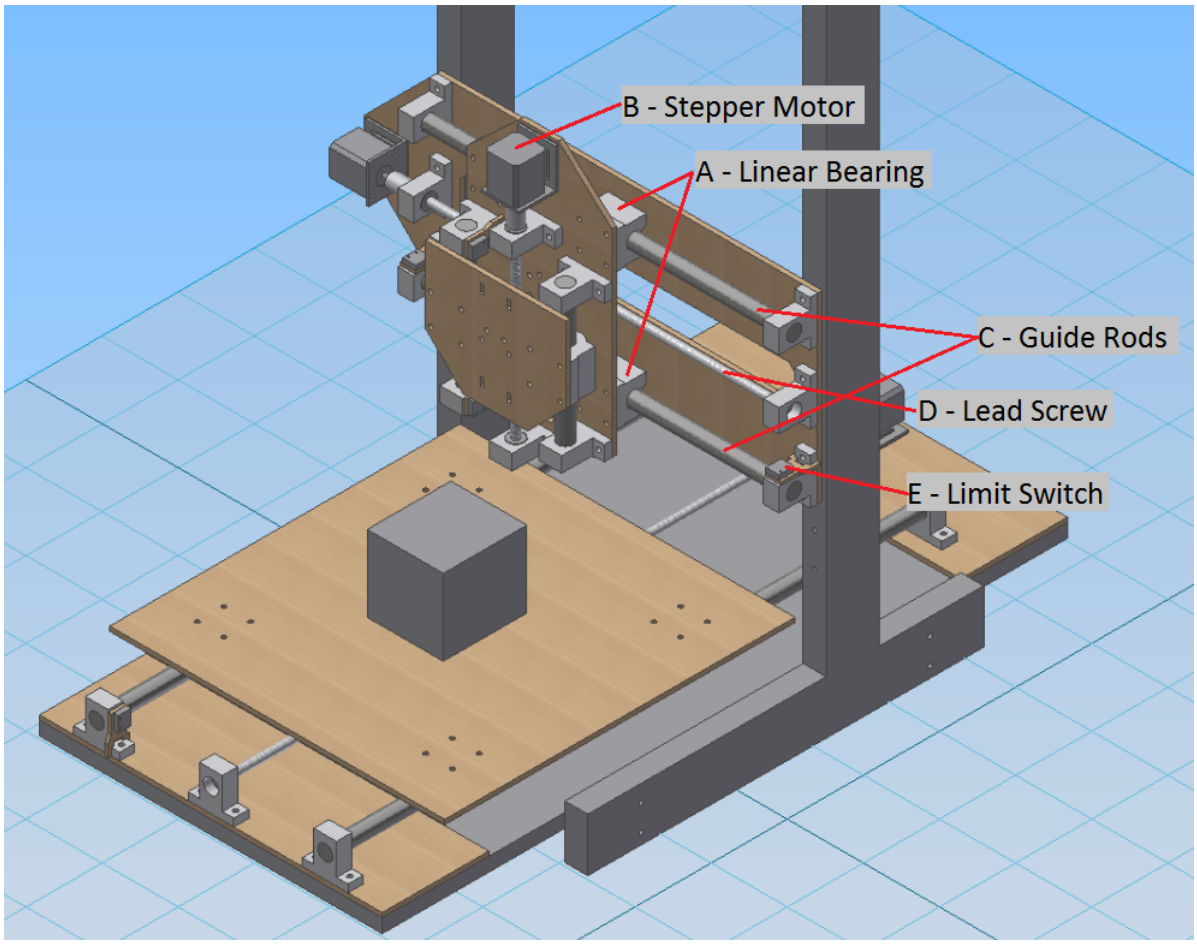


Figure 2.1: CAD model of the CNC machine with the critical parts highlighted.

The motors drive the lead screw, they are couples together with flexible aluminum coupler. The motors are standard NEMA 17 size, commonly found in 3D printers. The lead screw is a rod that had M10 thread on it, essentially a long bolt. On this leadscrew there exist a nylon wingnut, when the motor rotates the lead screw, the nut moves. The decision to go with a nylon wing nut versus a metal one is the buildup of metal grindings on the leadscrew if a metal nut was moving back and forth over an extended period of time.

The nylon nut with the leadscrew gives the machine good torque since the leadscrew act as a worm gear. The drawback is low speed, 300mm/min is slow compared to commercial machines, these usually operate at speeds in excess of 1000mm/min. The advantage is now smaller motors can be used and also smaller motor controllers, these parts are not cheap thus going for smaller versions saved a significant portion of the budget.

The electronics consist of Nema 17 Motors, operating at 12V. This is supplied by a regular computer power supply, which can output over 20 amps on the 12 volt rail, more than enough. Controlling the motors is done by a RAMPS 1.4 board as seen in figure 2.2.

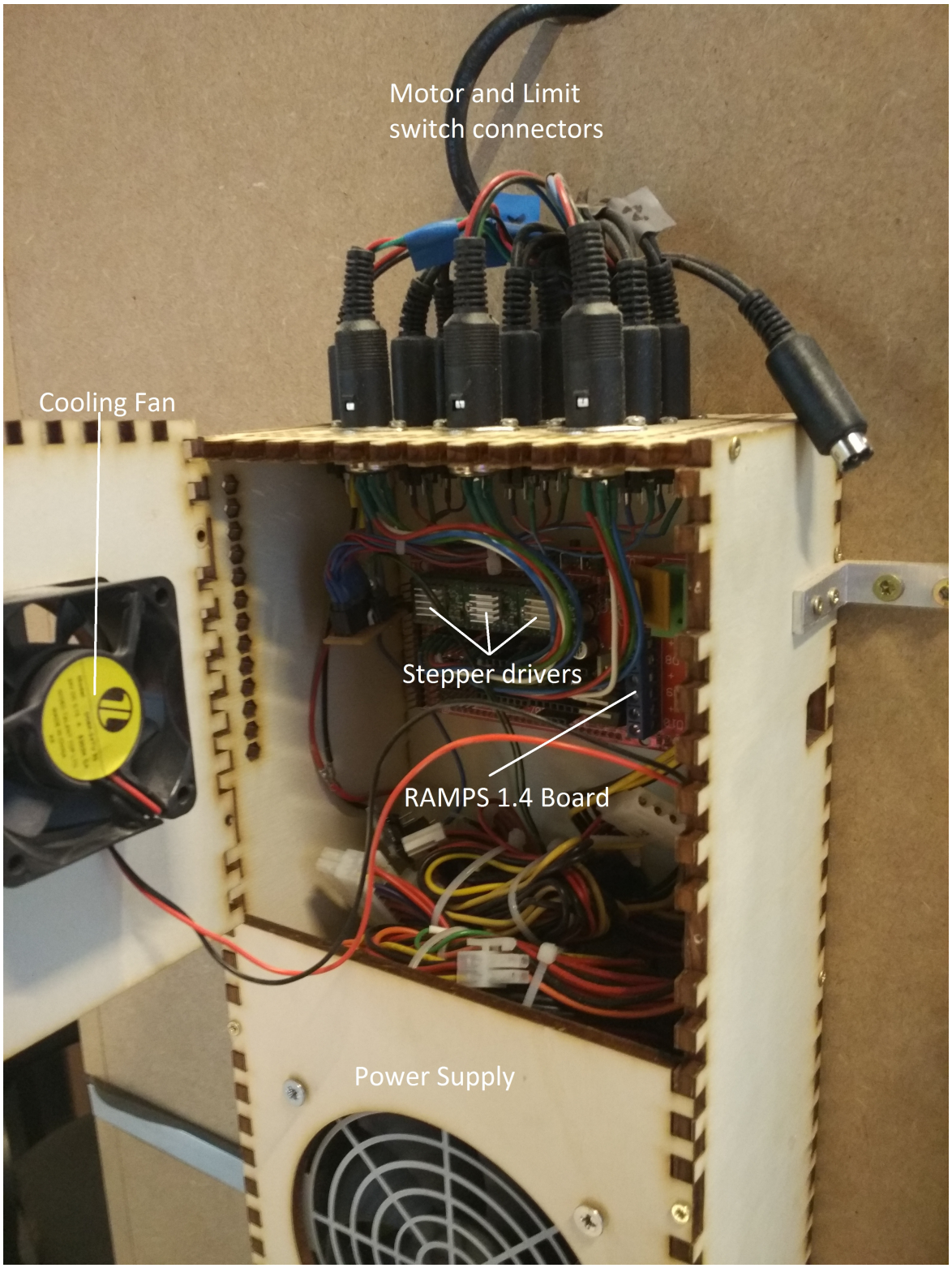


Figure 2.2: The electronics of the CNC machine, all in one enclosure.

On Top of the RAMPS 1.4 board there is room for 5 stepper controllers, since this board is originally designed for 3D printers. Only three are used on this machine. The board is loaded with GRBL firmware [], this firmware interprets the data coming over the USB connection and moves the motors accordingly.

2.3.3 User Scenarios

Different user are going to make use of the CNC machine and getting a clear picture of these users aids in the development of the website later on. Four key users groups have been established based on the popularity of the other Rapid Prototyping tools at the client.

Creative Technology Student

Simor, the creative technology students wants to make a prototype for the smart environment module. This requires him to design a wearable tracker that can locate the user within a building. The shape of the prototype needs to be round and lightweight to maximize the comfort of the wearer. After designing the part in Fusion 360 the student proceeds to visit the millinator.com website. Here the student reads the specifications of the machine and finds out that the curvature within the shape is too small for the CNC to cut. After a quick change in the design the student proceeds to the CAM phase. On the website the student sees that one should begin with the definition of the starting material. After completing the easy steps the student can't follow the website anymore since the example does not apply to his prototype anymore. The student who has scheduled working hours at the Client can now ask the technician for help. The technician points the student in the right direction and tells the student to use the 3D adaptive operation within Fusion 360 to create the 3D shape required. Now the student applies the operation and simulates it as described on the website and continues to the technician to manufacture the part on the machine.

The experience proved to be complex but as the students has multiple ways to get knowledge and advice the student should be able to make parts and use the machine in projects.

Industrial Design Student

Tanika, the industrial design students is familiar with CAD and should she choose the specialization also CNC manufacturing. This gives her the best background to use the machine. The student wants to make a mold for vacuum forming, the design has been made in Solidworks and after reading the millinator.com website [21] some design changes need to be made as the part is too big for the machine. The students splits up the mold into two parts and starts to CAM the part in fusion 360. After this is done and the checklist has been checked, the student proceeds to the Design Lab for analysis of the CAM by the technician and should it pass cut the part.

The machine gives the student a fast way to precisely make parts in house with a relatively low barrier of entry. It is likely that the student will come across CNC machines later in his or her career and this experience will be useful later.

Mechanical/Civil Engineering Student

Morty is more focussed on mechanical assemblies interacting with actuators and or sensors. Thus the precision and the possibility of making parts out of high strength materials is extra useful for him. The students wants to make a bracket out of carbon fiber for a quadcopter project. The bracket needs to

be strong and light as it is used in an aircraft. The students can already design parts in CAD and after inspection of the website proceeds to CAM in Fusion 360.

The experience gained and the ability to make high strength parts is useful as it opens doors to industrial machining and metal parts should the need arise. The ability to work with CNC maines is regarded as valuable for any engineer as these types of machines are ubiquitous in the manufacturing industry.

CNC Technician

Tycho the technician analyses the CAM done by the students and gives advice should it be necessary, after successful CAM the technician and the students can proceed to the machine. Here the technician fixes the stock in the machine and places the tool in the spindle. After a successful operation the students is asked to clean the machine. The technician also has the duty of fixing the machine should something break, and update the website should there be a gap in the process.

As the students access the website they are also required to make a quiz, the technician can see who made the quiz and who did not, should a students arrive at the technician without making the quiz it will result in the technician spending an excess amount of time explaining the ins and outs of the machine and the process of using it. Thus in these cases the technician kindly request the students to make the quiz and gain the required knowledge.

2.3.4 User needs

Based on the scenarios in section 2.3.3 and the client requests some user needs can be set. First and foremost the CAM section of the process needs to be explained in full, since no students has has this within the established curriculum. Secondly the website should be accessible at all times, this is ubiquitous and some websites are but in comparison to lectures or workshops it becomes apparent that a website fits the user needs best. Thirdly the website should be understood by any student technical or not. This since both Clients have user s that are not technical, leaving these user out would not meet the requirements set by the clients. A list of the points made can be seen below.

1. CAM process explained in full.
2. Website accessible at all times.
3. Website readable by any students, not only those with technical background.
4. Website should be maintainable by the technician.

2.3.5 Expert Interviews

To gain more insight into the workflows and the way machines are managed and used two experts in this field were interviewed in a semi structured way. The experts are: Wout Zweers from Wowlab and Jeroen Wolfs from Kast op Maat

Wout Zweers

Wout Zweers runs a workshop called the Wowlab [33] wherein he organises workshops and creates art and products. His use of the CNC machine is centered around making molds for silicone, cutting joints for wooden structures and intricate art patterns. The machine is located in the workshop with no enclosure but with a dust evacuation system. The base of the machine is a 2m by 1m metal table and since the machine is of a floating design big plates can be used. Only Wout Zweers operates the machine his skill was gained through manuals of the machine and practical experience. Concerning the workflow it's a combination of SolidWorks and the Proprietary software that came with the german CNC machine.

Vision Wout Zweers

After stating the problem and possible solution in the form of a website the vision of Wout Zweers from the interview in A.2 was the following;

- The website would be useful even for people outside of the reach of the client.
- He would like to use the website.
- Checklists would be very effective in eliminating user errors.
- The user is safe when the machine is used with the lid closed.
- Fusion 360 seems like a good solution
- Using the machine and not succeeding the first time is a part of the process

Jeroen Wolfs

Jeroen Wolfs operates and own the company Wolfs and Meuleman [22] that also fulfills orders for Kastopmaat.nl [23]. The latter is a website for custom wooden furniture. The company Wolfs and Meuleman itself makes multiple products that are all from wooden multilayered boards. The CNC machine they operate is of an industrial type and can cut up to 3 by 2 meters. Jeroen Wolfs himself is a CNC enthusiast and the company was started because of his passion for the machines.

Vision Jeroen Wolfs

Jeroen Wolfs had the following to say in the interview in section A.3 about the problem and the solution produced by the ideation phase;

- The CNC work can be done by anybody with enough hours behind the machine.
- A website with all the steps laid out will help but a person will always be necessary.
- The size of the machine does not matter in the steps taken, if you know how to use a small machine you can easily upgrade to bigger one.
- The majority of the operations will be cutting plate material, since this is what the machine does best.

- The website will be useful for people outside the university as well.
- Video's will help with explaining difficult processes.

2.3.6 Stakeholder Analysis

Besides the obvious stakeholders like the client and users there are some groups that will be affected by the machine and the website that goes with it. In this section all the stakeholders and how they are influenced will be discussed. The stakeholders are listed below.

- Client 1 - The Designlab
- Client 2 - Assortiments
- The Users
- The University of Twente
- Companies with CNC personnel

The Clients

The two clients as discussed in section 1.1 and 1.2 will be affected in multiple ways. Hopefully foremost their users will have access to CNC machining and can develop their skills. A side effect will be that both clients will have projects rolling out of their workshop of higher quality. This will result in more impact on society and thus more interest in both clients.

As both clients will be familiar with CNC machining this will cause their users to be skilled in CNC machining. Should the clients coordinate this wisely by using an apprenticeship position for the technician job they can get skilled personnel operating their machines, and overtime their skill will only increase. In house made video's could increase this. The website will automatically generate more traffic on both websites of the clients as both are linked on the website. This might result in more users for both clients. The requirements of the website for the clients can be seen in the list below.

- Safety, in no way should the user be harmed by using the machine or the website.
- Easy to use, the website should be understandable by all.
- The clients should be reflected in a positive way on the website.
- Could have special video's catered to the user's and client needs.

The Users

The users of the clients will develop their CNC skills in house, this will result in skilled personnel that can use this experience in a position at a CNC related company. Furthermore the users can use this skill as a boost on their professional rapport. The users will visit the website any time it suits them to learn about CNC machining as they are most likely students working on their regular curriculum the website gives them flexibility in their learning. The complete workflow should be described, from explanation on what CNC machines are to the installation of the software to usage thereof.

Should the machine change or capabilities added the website can easily be updated to suit the user's needs. Based on this the following requirements can be listed for the users as seen in the list below.

- Website available at all times.
- Information on the website regularly updated to cater to the users.
- The website should reflect what the users have learned so companies can see the skills learned.
- The website should be lighthearted but still professional with condensed but accessible knowledge.
- The website should be readable within one hour since the users are like to be busy with more important things like studying.
- The installation of Fusion 360 software must be explained
- The what, how and why of CNC machines have to be explained.
- The website won't teach the user CAD.

The University of Twente

The education will increase in quality. Thus the impact will increase as well, this could cause more students or even companies to get familiar with the university. Based on this the following requirements can be set as seen in the list below.

- University logo clearly visible on the website to increase impact.
- Link to the website and related studies.

Companies with CNC personnel

As the CNC skill of the users of the clients will increase they will become more interesting to the companies employing personnel in that area. This might also result in more interest of those companies in the university itself or the clients. The requirements for these companies are listed in the list below.

- Accurate representation on the website of the knowledge gained.
- The requirements to fulfill the needs of the companies.

Website only users outside the university

As the website is available from anywhere in the world at any time some people might visit the website they have no relationship with the clients for even the university. These website only users can get interested in the clients or the university or just develop their skill for free. The image of the clients and the university will be boosted and the impact will increase. Based on this knowledge the requirements can be set as seen in the list below

- Knowledge on the website in in English to cater to the global users.

- This same knowledge can be grasped by anybody who has interest even with no technical background.
- The website is up to date with modern day CNC skills.

The CNC workshop in the Horst

The University of Twente has a workshop available for mechanical engineering students with a professional CNC machine, the usage of the machine minimal as the skills are not part of any curriculum. As the CNC at the clients are available for anybody to use these more experienced user might proceed to using the professional machine should the home-made one not be sufficient. Thus the unity of this workshop will increase and the skill of the users with it. The requirements can be set as seen in the list below.

- Website provides a solid foundation to progress into a more professional machine.
- The skills learned on the website are relevant even with operation of a different machine.
- The website resonated not only with student but also PhD, teachers and seasoned CNC experts.

2.4 Requirements

To chart the requirements of the stakeholders multiple tools were used. Starting with an interview with the client, a stakeholder analysis, user needs analysis and finally to prioritize everything the MOSCOW [32] method. Table 5 contains all the requirements from section 7.1 to 7.5. In the last column the MoSCoW method has been applied to classify the requirements into the four possible classifications:

- Must have
- Should have
- Could have
- Won't have

Using these classification the requirements can be formed as seen in the list below.

1. The website must be easy to use, every student should be able to get into CNC machining.
2. The website must be maintainable, and easily upgradable.
3. The website must explain the CAM process explained in full.
4. The website must be accessible at all times. To maximise accessibility.
5. The website must be readable within one hour since the users are like to be busy with more important things like studying.
6. The installation of Fusion 360 software must be explained. Since this is essential to using the machine.
7. The what, how and why of CNC machines must be explained. Most user will not know anything about these machines.
8. The website must be maintainable by the technician. Since the material is technical this fits the best.
9. The website must have a checklist for the design process, to minimise error.
10. The website must mention that failure is a part of the process, to minimise frustration.
11. The website must be in English to cater to the global users.
12. The website should be an accurate representation of the knowledge gained.
13. The website should have up to date skill set relevant to modern day industry.
14. The website should be be readable by user outside of the university. This increases the impact significantly.
15. The Website should take into account that a technician giving a helping hand is essential.
16. The clients should be reflected in a positive way on the website.

17. The website should be readable by any students, not only those with technical background.
18. Information on the website should be regularly updated to cater to the users.
19. The website should reflect what the users have learned so companies can see the skills learned.
20. The website should be lighthearted but still professional with condensed but accessible knowledge.
21. University logo clearly should be visible on the website to increase impact.
22. The website should have links to the website of the University and related studies.
23. The website should provide a solid foundation to progress into a more professional machine.
24. The website should resonated not only with student but also PhD, teachers and seasoned CNC experts.
25. The website could have special video's made to cater to the clients
26. The website won't teach the user CAD.
27. The website won't include PCB manufacturing.

Chapter 3

Implementation

In this chapter multiple experiments will be conducted with the machine in the form of example project, this will help gain insights into a possible workflow this is the ideation phase.

Conjointly a set of CAM software packages were analyzed to find the best workflow suited to the clients needs. The scope of the workflow is limited to CAM only. It is expected that the user can already design parts on the computer. This is done limit the scope of the project. As a result of this phase a product idea is presented which caters to the needs of the clients.

3.1 Ideation

To produce a workflow suitable for students the machine itself had to be made suitable for students first. This is the first step in the Ideation phase, the second step consists of experimenting with the machine to get a better understanding of the processes required to make parts.

3.1.1 Upgrading the CNC Machine

To make the machine more usable and safe 4 upgrades were implemented. Namely: full enclosure around the machine, a dust evacuation system, a reinforced subframe and firmware calibration.

The enclosure as seen in figure 3.1 is to prevent dust and noise from getting out and to protect the user in case a tool breaks. It is made out of MDF, aluminium square tubes and Polycarbonate Panels.

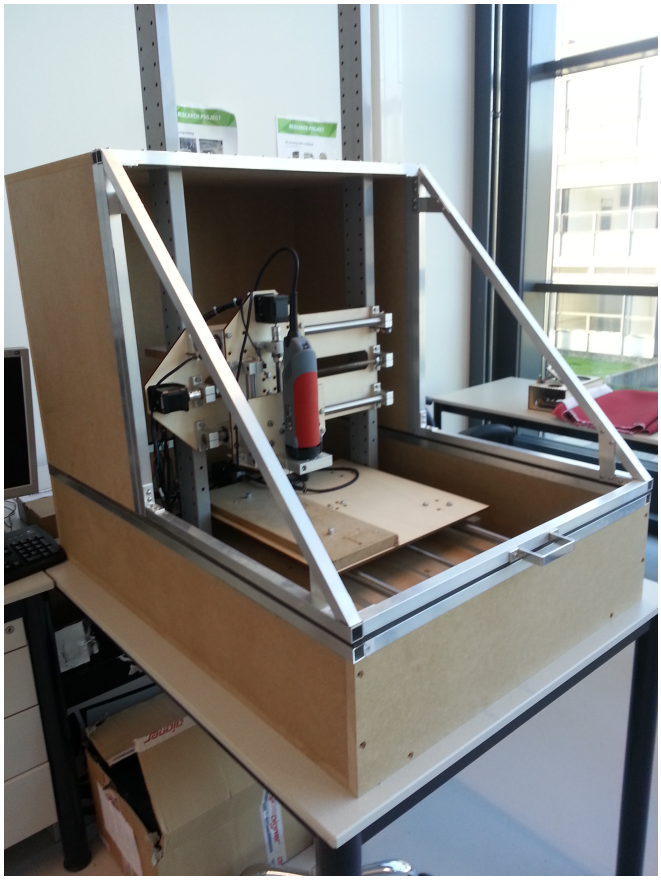


Figure 3.1: The enclosure that was built to increase safety as requested by the client.

Dust Evacuation System

The dust evacuation system consists of an industrial vacuum cleaner, a mounting bracket and the dust shoe as seen in figure 3.2. The tool can move in and out of the dust shoe, this is preferred to having the dust shoe move up and down with the tool since this would cause collisions with the material that is being cut. This has the disadvantage that the user now has to lower the dust shoe on top of the stock manually.

Figure 3.2: The dust shoe, where a vacuum cleaner can be attached.

Z-Axis Reinforcement

The reinforcement was necessary since initially the machine had a very light spindle that could only cut wood and other soft materials, in its place came the much heavier Kress 1050 which is capable of cutting hard materials like metals. This extra weight caused the 6mm Z-axis plate on which the Kress is mounted to bend and this caused imperfections on the parts produced. Therefore the z-axis plate was replaced with a 18mm MDF plate. This remedied the flexing during operation.

Firmware Adjustment

Whilst cutting carbon fiber for the first time the machine started to make a chattering sound, which indicated a stepper motor is skipping steps, this is catastrophic since then the machine loses its position. The firmware the machine uses is called GRBL, its job is to interpret the G-Code that comes from the serial port of the computer and control the stepper motors accordingly. GRBL allows the user to change a multitude of settings in this case the maximum speed had to be adjusted down to 300 mm/min to provide more torque when cutting harder materials like Carbon Fiber. In section A.5 in the appendix the settings of GRBL can be found.

3.1.2 Using the CNC machine

After the machine was made safe and usable the experimentation began. Three experimental projects were undertaken to gain the necessary experience to design a workflow. These projects were chosen to be as high profile as possible so they could also serve as example projects for the client to show to its users and for marketing purposes.

Carbon Fiber Quadcopter

The quadcopter is a recent technology that uses four propellers and software to stay aloft. Currently these type of aircraft are mostly used in the hobby industry but some are finding uses as aerial camera systems. The quadcopter is high profile because of the recent media attention. This factor is amplified since the camera footage is from a fresh new angle because it's a fast moving high altitude view, up until recently only doable by helicopter which requires much higher cost.

Currently most of the hobby grade quadcopters are made out of multiple carbon fiber plates that are CNC machined into a frame that can support four propellers, motors and controllers, the battery, the flight controller, and the video gear. The frame can be easily home made on the CNC machine.

Background Cutting carbon fiber by hand is no walk in the park, the plate can delaminate or not cut properly and the carbon dust irritates the skin furthermore the martial is so hard, even drilling a hole is a tedious job by hand. So why use carbon fiber when prototyping at all? It not a cheap material either.

Some products require a high strength rigid material, metals like aluminium can fill this void but have the disadvantage of being more difficult to machine due to bigger chips and having. a higher mass [31]. And since the designers at the client already use a laser cutter to produce parts out of wood, should the need arise to produce a stronger part the same CAD file can be used to make the part out of carbon fiber. This provides designers an efficient backup plan should the wooden construction be proven too weak. Figure 3.3 shows the first prototype for the Quadcopter frame, it broke after the first crash.

Figure 3.3: The wooden quadcopter frame was proven too weak.

Impact To illustrate this prototyping flow of replacing wooden parts with carbon fiber an example project was created. A quadcopter was chosen since it employs the lightweight properties and has good impact on the target group. This impact can be used in marketing campaigns to get more people to use the CNC machine and thus improve accessibility.

Result After the design was proven to be valid the frame was cut on the CNC machine out of 3mm 3K Carbon Fiber (CF). The result can be seen in figure 3.4. The CAD files for the quadcopter stayed unchanged during the transition between wood to CF.

Figure 3.4: The first full CF version of the quadcopter.

Foam Prototype

Prototyping with foam is done in many industries since it cuts easily and is inexpensive. It is also useful for making molds for vacuum forming and rough shaping for later manual sculpting. The goal was to show the 3D capabilities that a laser cutter lacks.

Background AER is a throwable dart that houses a GoPro to get similar footage a with a video drone. The head of the dart is a special shape to not interfere with the viewing angle of the GoPro as seen in figure 6. Producing this part out of foam is difficult to do by hand thus the team from AER approached the Designlab for the manufacturing of the head on the CNC machine. This turned out to be a success as seen in figure 6.

Impact The aim was to showcase the 3D capabilities of the CNC machine and increase the awareness. Since AER is a startup that heavily relies on content marketing to raise awareness for its product that can now be used to expose the CNC machine to the public. Next to that the University tries to promote the startups in any way possible, students of the University of Twente already know of AER and knowing that it is made on the CNC at the client resonates with the user group.

Result Figure 3.5 shows the final prototype of the foam bumper. This bumper is designed to protect the GoPro that resided in the blue 3D printed housing. The part started out as a 2cm thick disk with a diameter of 15cm. AER can now prototype with these bumpers to see if the dimensions are right and if it is enough to protect the GoPro.

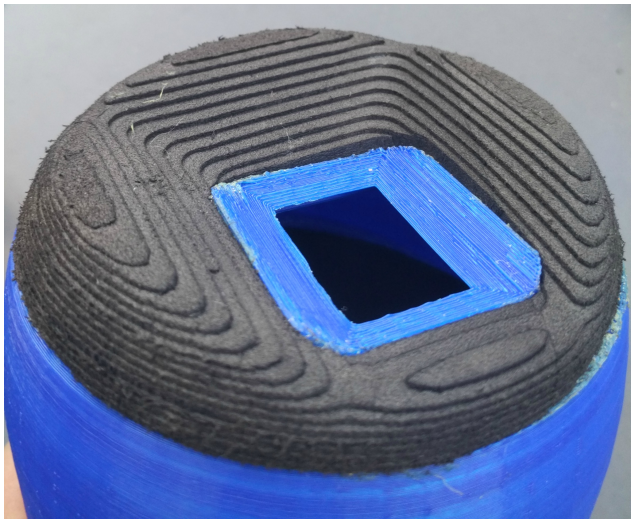


Figure 3.5: The foam bumper prototype on top of a 3D printed housing.

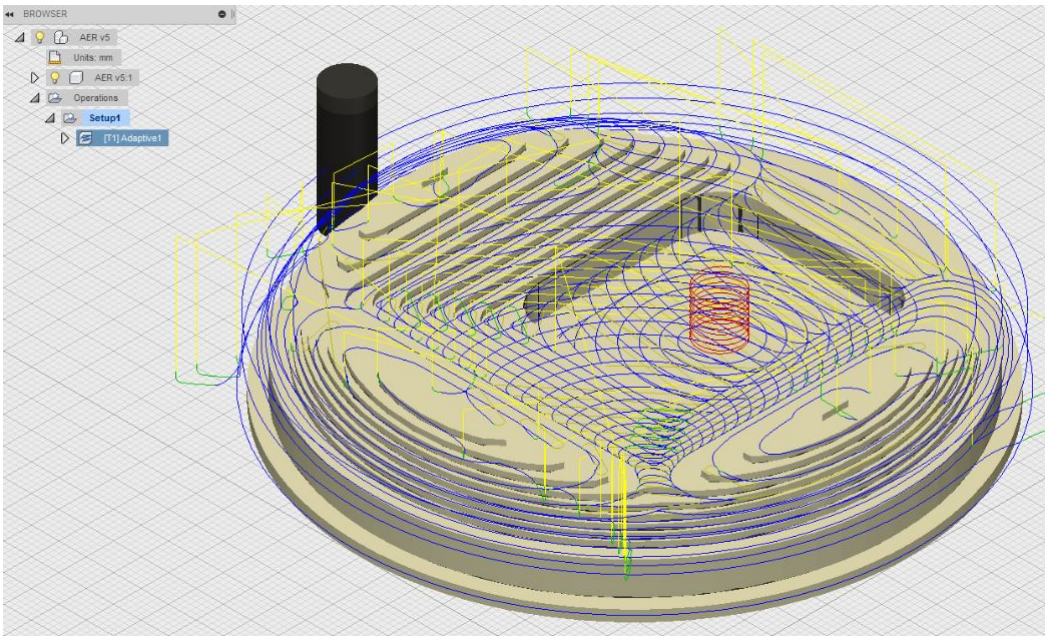


Figure 3.6: CAM simulation of the foam bumper.

Figure 3.8 shows the toolpaths created by Fusion 360 using the 3D Adaptive method. This method can be applied to most 3D shapes and is extremely useful since it requires minimal setup.

Vacuum Form Molds

To illustrate the mold making capabilities and the tandem use of the CNC machine to produce molds for the vacuum form machine a conjoint project was done with Estis Design. This design bureau consisting of industrial design students at the University of Twente wanted a plastic shell around a prototype they were developing for a client.

Background The prototype Estis is developing is an electric cheese slicer that had a plastic shell covering the electronics. The shell would be vacuum formed with two molds being made on the CNC machine out of engineering foam. One for the top and one for the bottom.

Impact The prototype ended up being showcased at one of the convention of Industrial Design at the University of Twente. The visitors inquired about the production process and three students have since contacted the client for help with projects concerning CNC machines. Furthermore this gave Estis the ability to come up with an aesthetically pleasing prototype within three weeks.

Result The result can be seen in figure 8, this is the foam mold ready for vacuum forming. Figure 9 shows the finished prototype.

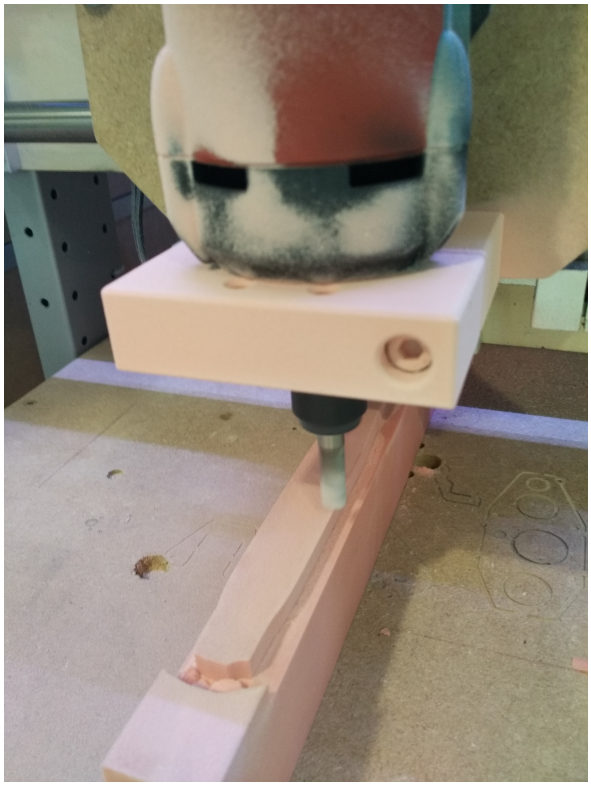


Figure 3.7: The foam mold for vacuum forming made for Estis design.

Figure 3.8: The finished prototype of the electric cheese grater.

3.1.3 Computer Aided Manufacturing software package comparison

After the design of a part in whatever CAD software the user uses it is time for Computer Aided Manufacturing (CAM). Here the user sets different settings like what the dimensions of the cutting tool are, the size of the stock and speeds and feeds of the operations. These settings are then used by the CAM software package to generate the toolpaths to create the designed part out of a piece of stock. Table 4.1 shows the comparison.

-	Fusion 360	Easel	Chillipeppr	Meshcam	Mastercam
Price	FREE (non commercial)	FREE	FREE	200 euro	>1000 euro
3D	YES	NO	YES	YES	YES
Nr. of operations	13	4	4	10	12
Installer	YES	NO	NO	YES	YES
Opensource	NO	NO	YES	NO	NO
Toolpath Simulation	YES	YES	YES	YES	YES
Stock simulation	YES	NO	NO	NO	YES
Uses Wizards	NO	YES	NO	NO	NO

Table 3.1: Comparison of a selection of CAM software packages.

Easel

Easel [16] is a online CAM solution but is limited to 2D operations, so no 3D features can be done via this software. The ease of use is very good, the user does not need to install anything and wizards guide the user to the right settings. The software comes standard with the Shapeoko CNC machine and is completely free.

Chilipeppr

Chilipeppr [17] is an online environment for CAM and is opensource. It supports 3D features and can also simulate the paths created. The ease of use is good since the layout is logical and the simulation helps with finding errors.

Meshcam

Meshcam [18] is a CAM tool that supports 3D features but lack the simulation although this can also be done in chilipeppr. The software is easy to use, wizard are available. The software is also relatively cheap with a price of 200 euros. Unfortunately no simulation is included.

Mastercam

Mastercam [19] is currently the market leader in CAM and thus the licence costs 3500 euros. It supports 3D features and has the best optimization options, this will lead to faster production times and a better finished part. Toolpath simulation is included, and is the most advanced.

Fusion 360

Fusion 360 [20] from Autodesk is a fully integrated solution, it facilitates full 3D CAD and CAM with an exporter for the G-code. The ease of use is medium, user needs to install it and since there are a multitude of options available it can overwhelm the user. A free educational licence is available for the University of Twente. It also features the most operations which makes for a more optimal CAM experience since the best operation can be used for a particular need. The best selling point however is the Stock Simulation, a feature that is usually reserved for more professional CAM packages. This feature lets the user see what part is left over when the machine is done. This is invaluable for checking for errors.

CAM Conclusion

For both clients the cost of a licence cannot exceed the 300 euro mark. Fusion 360 seems to be the best option, it supports 3D operations and is free for students or non-commercial use. It is the only free software (non commercial) that includes stock simulation. This feature is especially useful for inexperienced users since it completely visualizes the process of making the part on the machine in real time as seen in figure 3.9.

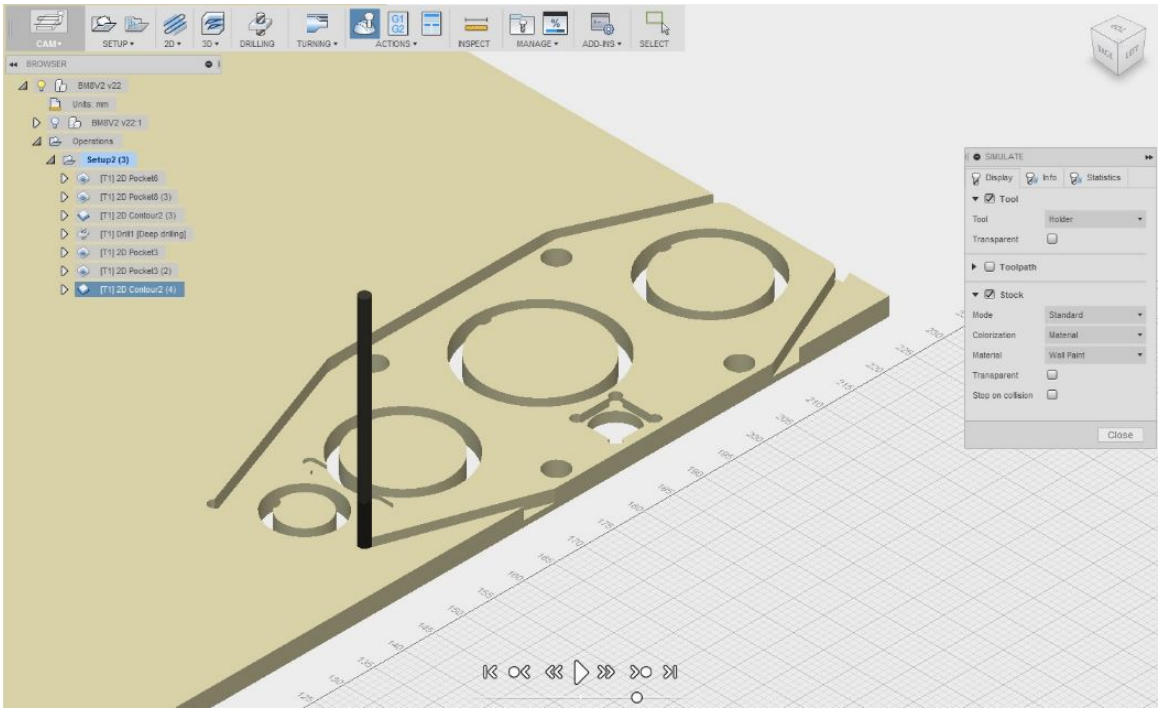


Figure 3.9: Stock simulation of all the CAM operations in Fusion 360.

3.1.4 Product Idea

From the conclusion of the literature review (section 3.3) the difficulty of manufacturing PCB's could exceed the easy of use requirement set by the client in section 2.3.1, thus the product should focus on increasing accessibility for cutting soft to hard materials since these are easier, and for which Fusion 360 has native support following out of the CAM analysis in section 3.1.3.

To maximise the accessibility, upgradability, visibility and ease of use a website with video content catered to the users is the best option. The alternatives like workshops, online courses, and physical literature all have less accessibility than a website. Furthermore the website can be updated easily and maintained to always best suit the needs of the user with ease. The integration of different forms of media is allowed and the users are all already familiar with accessing websites for project purposes.

Chapter 4

Results

In this chapter the result of the implementation will be assessed.

4.1 The Product, Millinator.com

To make it as easy for the user as possible all the information required to start with the CNC machine is located at millinator.com [21]. The complete workflow is described there accompanied by all the machine settings and limitations. A step by step video is also available on that same website that explains the process of design and manufacture of a part. The intention is to let users that want to get started first visit the website, download the software, design the part and CAM the part autonomously. After the CAM is complete or the user hits a snag he or she can ask for the technician to continue. The technician then checks the work and the user and the technician can start making the part on the machine.

The answers on both research questions can be answered by the website that is found at millinator.com [21] which showcases the possibilities and limitations of the machine through video and step by step instructions. Both the how, what and why are answered on the website. The flow of the website can be seen in the list below.

1. What are CNC machines
2. Why use the CNC machine of the client
3. What not to do when using the CNC machine
4. How to design for CNC machining
5. How to use the CAM features of Fusion 360
6. What to do to get the part made
7. Quiz of the gained knowledge

Thus the result is a one stop shop for any prospective CNC user. And upon finishing the quiz the user should have a baseline of skills sufficient to start designing parts. Although it would be best for the website to encompass the whole process including the actual manufacturing of the part on the machine it has been chosen to keep this step for the technician at the client. Since the margin of error is small.

Figure 4.1 shows a screen shot of the front page of the website, with the introductory information of user with no prior knowledge. A complete snapshot of the website can be found in the Appendix, section A.8.

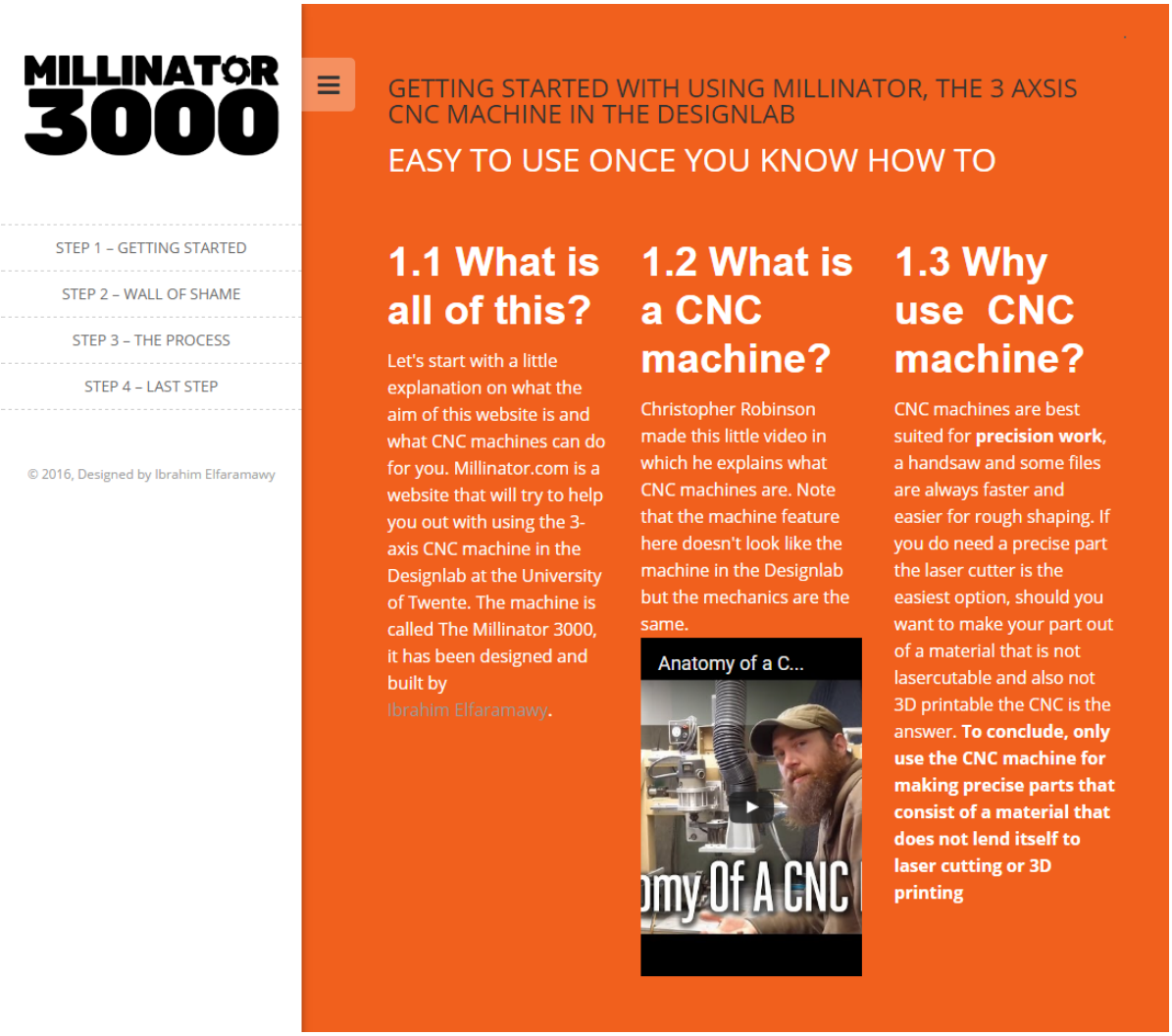


Figure 4.1: Screenshot of the front page of the website.

4.1.1 Maintenance

The maintenance of the website will primarily be done by the technician that also manages the machine, as of now that job lies with Ibrahim Elfaramawy and his colleagues at the Designlab. The changes that need to be made are likely to be small since the workflow is likely to stay the same for at least a couple of years. The decision to go with a Content Management System like Wordpress makes making these changes easy and fast.

It is expected that the technician has to spend two hour per month to add or change some content. Should the decision be made to move to a different software suite a more substantial overhaul will be needed.

4.1.2 Lifetime

Most websites dont live forever, millinator.com will sta usefull as long as the machine is used at the client. Should the machine be neglected the use for the website will go with it. It is likely that the machine will stay in operation for more than a year.

Should the website become superfluous a possibility of hosting it under a private sub-domain exists so users could still access it albeit not in relation to the machine at the client.

4.2 Constuction of Millinator.com

The millinator.com website consists of a domain coupeled with a webshosting package both at TransIP [24]. The web hosting includes 10 gigabytes of space and one MySQL database. The Wordpress [28] content managements system (CMS) is installed on the web hosting package and requires one MySQL database. The decision to go for a CMS instead of a from the ground up approach is apparent as maintainability and upgradability are paramount.

4.2.1 Hosting and Domain

The Hosting and domain name registration have been handled by Trans IP [24]. In the future the website can be hosted on the University servers but this can be done at any time. The specifications of the hosting package can be seen in table 4.1.

Specification:	Package:	Used:
Storage	10 GB	345 Mb
Database(s)	1	1
Data Traffic	Unimited	0.5 GB/month (august 2016)

Table 4.1: Specification of the hosting package of Millinator.com

4.2.2 Wordpress

Wordpress [28] is a CMS that has maintainability and ease of use as the core aspects. The CMS lends itself to being upgraded easily and since it's immense popularity the support is exceptional. The version of Wordpress running as of august is 4.5.3. The Wordpress administration panel makes changing the website a breeze, there is also an option to do it via a phone app.

4.2.3 Layout

Wordpress uses themes to set the layout of the website, the theme chosen for Millinator.com is One Page Scroll [25] version 1.1.9. This theme has a one page layout, meaning there are no individual pages but only one and the scrolling navigates the user to the area of interest. This fits the step by step concept of the CNC process perfectly as the user has to scroll over the required information to get to the next step. Furthermore it keeps the website simple and navigation easy.

4.2.4 Quiz

Wordpress also has the advantage of having plugins that can be installed easily onto the website. These plugin bring extra features or functionality, in this case a front end and back end quiz system. The plugin is called WP-Pro-Quiz [26] version 0.34. It features the ability to; make multiple quizzes but Millinator.com only uses one, see who and how the users made the quiz and modify the quiz with ease through the Wordpress administration panel.

4.2.5 Google Analytics

To make the job of analysing the users and getting useful data from them Google Analytics [27] has been installed on the Millinator.com website. This allows for the web administrator to see multiple demographics like origin of the users, amount of users, time spent on the site, area of interest and more.

4.3 Limitations and Assumptions

In this realization only the technician operates the machine this is a result of the inflexibility in the steps required to make a well finished part. Should one of the steps be done in a mediocre manner or skipped the chance of getting the part the user expects are slim at best. Yet it is superfluous to say that a completely autonomous solution would be best for all parties this can be achieved only when the technician has confidence in the user to operate the machine on his or her own. Furthermore this implementation assumes the user knows how to design parts on the computer (CAD), this assumption is purely made to limit the scope of the project. Another limitation is the Use of Fusion 360, albeit the best choice for new users some intermediate users at both clients use different software

Chapter 5

Evaluation

The evaluation has been split in two parts, the effective evaluation of the produced product (Millinator.com) and an ethical evaluation. The latter is aimed at exposing any ethical issues the stakeholders could have with the produced product.

5.1 Evaluation Setup

To evaluate Millinator.com three methods were used, firstly; 9 students were asked to CAM an already finsihed CAD model in Fusion 360 on a supplied computer. After the student autonomously CAM's the part and validates using the Stock Simulation the student proceeds to cutting the part on the machine with the supervision of the technician. The stock is already fixed in the machine and the tool is already placed in the spindle. After a final check by the technician the cutting can begin. After the cutting the user can proceed with taking out the part and filling out the survey which is listed in the appendix section 10.5.

Secondly a Google Analytics [23] report has been compiled which shows a detailed view of the amount of users and their characteristics on the website. The setup here is a piece of Javascript code supplied by Google that logs the required data and synchronises this with the Google server, the data is then compiled and viewable through the Google Analytics website.

Thirdly the list of requirements are checked with the current product, should the product fulfill the most important requirements its is deemed a success.

5.2 Evaluation Millinator.com

The evaluation of the website was done with nine Lead Users and the data collected from the Google Analytics tool. These two combined provided valuable data used to both tweak the product and prove its effectiveness.

5.2.1 Survey Lead Users

In this section the result of the survey will be analysed. Starting with the assumption of the user knowing CAD before any usage of the website. Figure 5.1 shows the majority of the lead users (6) already knowing CAD.

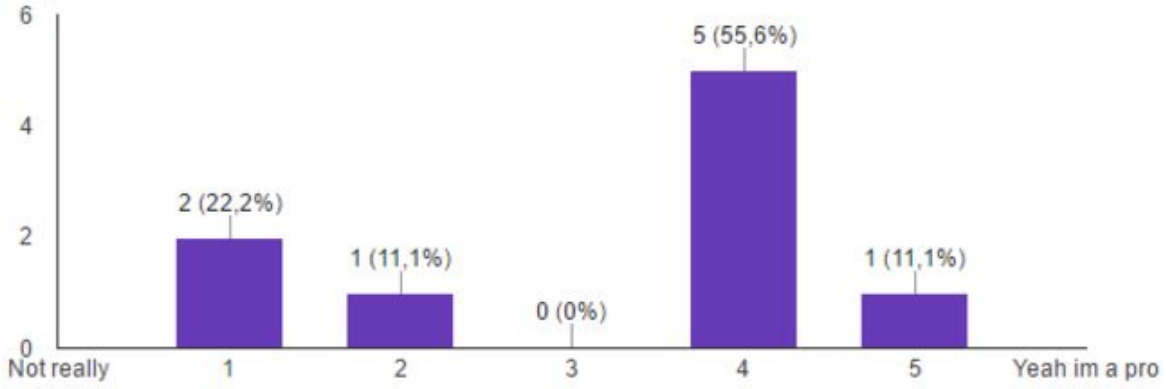


Figure 5.1: The results on the question ”Do you know how to design part on the computer (CAD)”. Five being a professional.

The assumption of the user already knowing CAD is confirmed when the amount of designed parts is queried. On average the lead user have designed more than 17 parts in 2016. The reason the lead user know CAD is due to the background of the users. Most of the lead users have studied either Creative Technology or Industrial Design Engineering. After reading the website most users know what a CNC machine does although there are some gaps as seen in figure 5.2. This is a point of improvement.

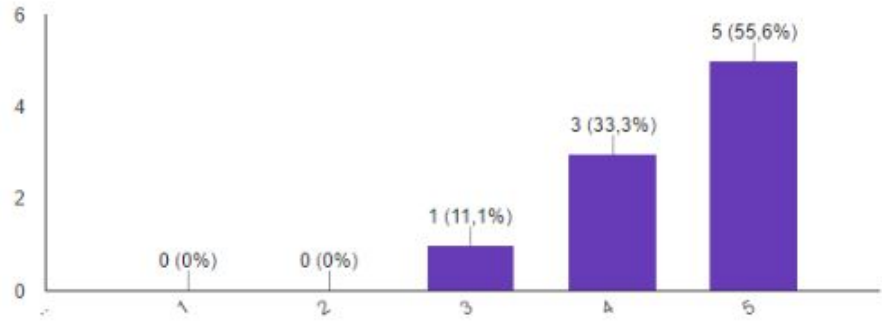


Figure 5.2: The result on the question “Do you know what a CNC machine does?”. Five being fully understood.

Surprisingly 55.6% of the lead user have used CNC machines before. This can be explained by the industrial engineering students having some courses where these machines are mentioned.

Furthermore 89.9% of the lead user have used the laser cutter before, this tool also required CAD although in a simpler form. The usage of the 3D printer is significantly less, only 55.6% of the lead user have used the 3D printer before.

The lead users found the website useful although not extremely as seen in figure 5.3, this could be improved as well as the knowledge should be new to all.

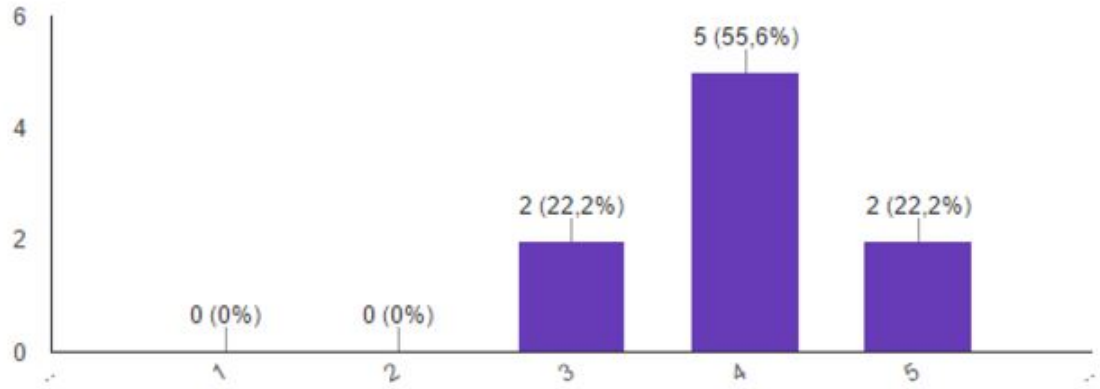


Figure 5.3: The result on the question “How helpful did you find the website?”. Five being very helpful.

The majority of the lead user sees the advantage of using a CNC machine versus a laser cutter or 3D printer in some applications. Furthermore a stunning 88.9% would consider using the CNC machine in their next project. The quiz is considered a medium cool idea as seen in figure 5.4 which is to be expected since it is a fairly classical approach to testing knowledge.

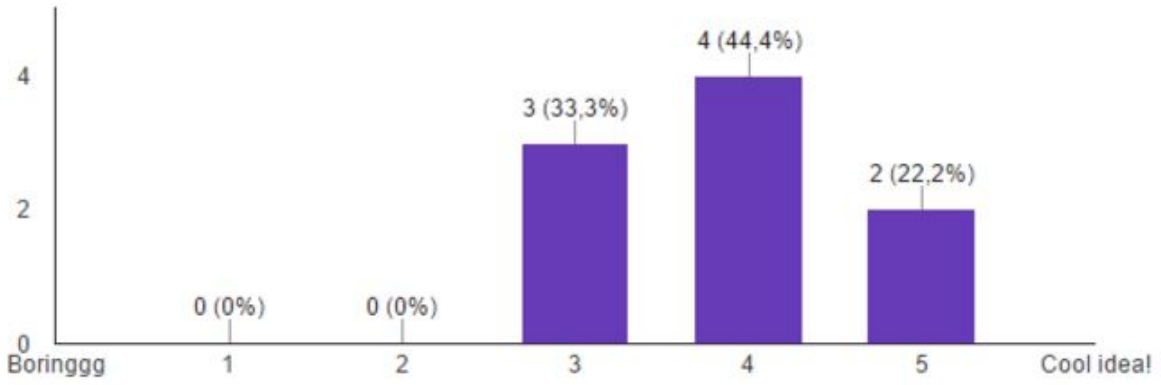


Figure 5.4: The result of the question “What do you think of making a online quiz to be able to start using the CNC machine”.

In total the lead users found the experience not hard, thus the website did its job to a sufficient extent as seen in figure 5.5.

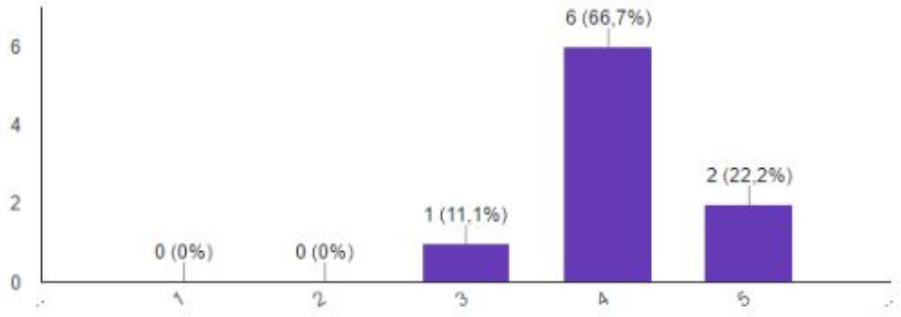


Figure 5.5: The result on the question “How easy did you find the experience?”

The open question at the end of the survey resulted in some useful tips on the website:

- Visit the video's for more information on the possible danger.
- Introduction video "what is a cnc machine?"
- Videos/pictures illustrating the steps and also in the beginning maybe an overview of the whole procedure.
- Some basic design rules that you should follow to be able to make stuff on the cnc.

All these tips have been implemented in the final product.

5.2.2 Google Analytics Report

From the report as seen in appendix section A.7 161 users have visited the website from 15-06-2016 to 17-08-2016. Surprisingly most users are outside of the Netherlands, meaning outside of the University. Only 18.36% of the users (38) are from the Netherlands. This amount of users within two months is low, but considering no marketing has been applied the results are to be expected. The Google Analytics information will prove to be useful in determining the effectiveness of the marketing campaigns.

The time spent on the website on average is only 2:15 minutes, this shows that most users just click through the website quickly and don't spend the time to make the quiz or watch the videos.

5.3 Ethical Evaluation

This section provides insights into the ethical aspects of the machine and the accompanied website. The evaluation starts with plausible ethical scenarios based on the stakeholders, these scenarios are then assessed by likelihood of happening and severity. Furthermore critical ethical issues like safety, intellectual property, laws and regulation, client and user expectations are discussed.

5.3.1 Ethical Scenarios and Analysis

As a method of analysing possible ethical issues multiple fictional scenarios are assessed on likelihood and severity or importance in case of positive scenarios. Figure 5.6 shows both the positive and negative scenarios that have significant likelihood of happening. Figure 5.7 shows the full analysis per scenario.

Negative Scenario's:	Positive Scenario's:
Z - Use the machine to make parts for weapons	A - Use the machine to produce better prototypes
Y - Over-use the machine	B - Use the machine to produce parts that are impossible to produce otherwise like PCB's, castings.
X - User getting harmed by the machine	C - Re-use scrap material
W - User breaks (a part of the) machine	D - Provide insight into CNC programming
V - User don't know how to make parts by hand anymore	E - Learn a more technical approach to designing prototypes.
U - Only one group of people uses the machine	F - Learn cartesian coordinate system
T - Only user from the UT using it	G - User makes parts faster than by hand.
S - User stealing parts of the machine	H - Make multiple copies without much extra work.
R - User unable to use the machine due to lack of skill	
Q - Machine destroys user's material due to bad programming by user.	
P - User hacks the machine	
O - User copies the design of the machine and sells it	

Figure 5.6: Possible Positive and Negative scenarios.

The estimation of the likelihood of the scenario happening is indicated by the first number, a grade from 1 to 5, 5 being completely certain of this scenario happening, 1 being unlikely but possible. The second number is the severity or importance in case of a positive scenario. 5 being extremely severe or important, 1 being severe but manageable.

Stakeholders:	A	B	C	D	E	F	G	H	Z	Y	X	W	V	U	T	S	R	Q	P	O
1. Creative Technology Students	5 5	4 2	3 4	4 4	4 5	4 3	5 5	4 5	1 5	3 3	2 5	3 3	3 2	4 1	5 1	1 3	3 4	3 1	2 1	2 1
2. Industrial Design Students	3 5	4 2	3 4	4 4	4 2	4 3	5 5	3 5	1 5	3 3	2 5	3 3	2 2	3 1	5 1	1 3	3 4	3 1	1 1	2 1
3. Electrical Engineering Students	3 4	5 2	3 4	4 4	4 2	1 3	5 5	3 5	2 5	2 3	2 5	3 3	3 2	3 1	1 5	1 3	2 4	3 1	2 1	2 1
4. PhD Students of all design studies	2 3	2 2	3 4	2 4	1 3	1 1	5 5	4 5	1 5	1 3	2 5	2 3	2 2	2 1	1 5	1 3	3 4	3 1	1 1	1 1
5. Designlab Visitors	1 3	1 2	3 4	3 4	2 3	3 3	5 5	2 5	1 5	2 3	3 5	3 3	2 2	2 1	1 4	1 3	4 4	3 1	1 1	1 1
6. Students who are developing a prototype for a startup	4 5	4 2	3 4	2 4	1 3	2 3	5 5	2 5	1 5	1 3	2 5	3 3	2 2	2 1	1 4	1 3	4 4	3 1	1 1	1 1
7. Technicians of the Designlab	5 5	5 2	3 4	1 1	1 1	1 1	5 5	5 5	1 5	1 3	1 5	1 3	1 2	2 1	1 5	1 3	2 5	3 1	1 1	1 1
8. Management of the Designlab	1 1	1 2	3 4	1 1	1 2	1 1	5 5	3 5	1 5	1 3	1 5	1 3	2 2	2 1	1 5	1 3	4 2	4 1	1 1	1 1
9. Artists of Studio 13 with Autism	5 4	5 2	3 4	3 4	4 4	4 3	5 5	2 5	1 5	1 3	2 5	3 3	2 2	2 1	1 1	1 3	2 4	3 1	1 1	1 1
10. Participants of the workshops at the Vrijhof	2 2	2 2	3 4	2 4	3 4	4 3	5 4	2 5	1 5	1 3	3 5	3 3	2 2	2 1	5 1	1 3	4 4	3 1	1 1	1 1
11. Prospective students (promotional purposes)	2 3	2 2	3 4	1 4	2 4	4 4	5 4	3 5	1 5	1 3	3 5	3 3	2 2	2 1	1 1	3 3	5 3	5 1	1 1	1 1
12. Teachers of all studies named above	3 2	3 2	3 4	1 4	2 4	1 3	5 5	2 5	1 5	1 3	1 5	1 3	1 2	2 1	3 1	1 3	2 5	2 1	1 1	1 1

Figure 5.7: Scenario analysis per stakeholder.

Based on the analysis in figure 5.7 some conclusions can be drawn:

1. Harm to the user is possible and severe.
2. Users lacking skill are going to try to use the machine.
3. Users copying the machine is no problem since it's open source anyway
4. Hacking the machine is unlikely and not severe
5. Users stealing parts of the machine is unlikely

5.3.2 Wasted material

The first issue counts for all stakeholders that use the machine. They will have to buy their own materials to put under the CNC machine, should the machine not work accordingly due to a mechanical, electrical or human error the raw materials could be wasted. This provides both the user and the client with a significant problem since no parts were produced but money was still spent.

The problem stated above can lead to disappointment with the user and have negative consequences for the client in the form of a bad reputation. Possible solutions are;

- Doing a test run on a cheap piece of material first, before cutting the more expensive material bought by the user. The higher the price of the material the more appealing this option becomes.

- Requiring the user to buy extra material so when an error occurs there is still enough material to try again. This costs the user more money buy will increase the chance of getting a good part out of the machine.

- Making it clear of the user that things can go wrong. As every tool breaks so does a CNC machine, making this clear to the user brings disappointment down when it happens.

5.3.3 False User expectation

The goal of the product is to make the relatively complex skill of CNC maching more accessible to any who is interested. Should this goal not be met it will not only result in a failure of the product but also frustration with the users. This is an ethical problem as it puts the users in a position where he or she can feel bad due to failure.

The website mentions multiple times that failure is a part of the process, next to that the technician handles these cases with a good teaching attitude that supports any students that has trouble following the relatively complex process. Nect to this the website can also be tweaked and updated to suit the users needs better.

5.3.4 False Client expectation

The client has to be aware that running a CNC machine requires more effort than a laser cutter or even a 3D printer. The personnel required to effectively run the machine have a set of specific skills that require experience to sharpen. As stated in the introduction (section 1), the machine has a set of parameters that need to be changed according to the specific job at hand. Should one of these parameters be set incorrectly the result will likely not come out as expected. Therefore the return on investment is lower that with a laser cutter, this fundamental idea is important to grasp for the clients as when this is not the case disappointment is a result.

In order to fulfill the client's expectations of having a CNC machine that is used frequently to cater to the diverse needs of the users skilled personnel is essential. To achieve this at minimum cost and effort an apprenticeship can be created for the next CNC operator. The current operator of the CNC machine at the client (Ibrahim Elfaramawy) would train the next operator so the skill of the operator is guaranteed.

5.3.5 Safety

Albeit the foremost requirement set by the clients accidents do happen and therefore the technician operating the machine is the final responsible person for the machine and it's users. The process of using the machine is left to the technician for this reason. The enclosure eliminates most chance of somebody getting hurt but the clients needs to make sure that the technician knows that he or she is responsible.

Only clear rules followed by all parties can make the usage of this relatively safe machine more safe. Although standard workshop rules apply like eye protection and ear protection the technician should always have to opportunity to shutdown the machine instantly.

5.3.6 Intellectual Property

The complete design of the machine and all of its software is opensource, thus IP protection is not required. Should someone choose to copy the design of the machine, the website or its software it would be no issue under the current law.

5.3.7 Law and regulations

The Designlab has, like every public place, some regulation that will have to be met, like noise levels, air pollution and safety. As of now the machine fulfills all these requirements and is thus deemed legal. The technicians are responsible for the users and the machine. This guarantees the safety of the users and other people working in the workshop.

5.4 Evaluation Results

From the lead user survey and the Google Analytics report the following became apparent:

- Users know CAD enough to start using the CNC machine.
- The explanation on what a CNC machine is needs to be improved
- Most users will have used the laser cutter prior to using the CNC machine.
- The usefulness of the website is good but can be improved.
- Users will consider using the CNC machine for their next project.
- The website will be visited frequently by users outside of the university.

5.5 Future Work

As discussed a completely autonomous workflow is beneficial for all parties, yet this is not possible in a learning environment since none of the users are experts (yet). A possible solution is to implement a points system where users can accumulate points after successful operation of the machine, to chart the progress per user. After a certain number of points the technician can assess if the user is skilled enough to machine autonomously.

As of now Millinator.com does not touch on the CAD side of the process. Should this be implemented as well on Millinator.com. This would make it a one stop shop for the whole process. And as Andrea Minuto pointed out in the interview, most time is spent making and helping with the CAD file.

5.6 Conclusion

From the lead user survey it became apparent that the website does what it's supposed to do, the clients now has a place to direct people that are interested in using the CNC machine. These people will get sufficient knowledge to start on their journey of making parts with great precision. Furthermore multiple example projects have been carried out so the client has material to show to its users and for marketing purposes.

The ways CNC machines can help with rapid prototyping are diverse, the focus was put on making parts out of plate material, and mold making for various methods. The PCB manufacturing was proven to be too tedious for novice users and thus dropped. The accessibility has been improved by facilitating marketing with projects to showcase and the ease of use increased with millinator.com. Furthermore a complete workflow has been laid out for the students to try out and experiment with and the barrier to entry lowered to the absolute minimum as everybody can access the website and start learning.

To conclude this thesis a summary of the whole process will be given. It all started with the construction of the CNC machine in the Designlab, after this multiple example projects were undertaken to increase the knowledge about the operation of such machines. The machine was also upgraded to suit the safety needs to the client. After the example projects and expert feedback it became apparent that a website would solve most problems concerning accessibility and ease of use. A list f requirements was made and the website built using Wordpress. The website guides the user from start to finish and the knowledge is split up into easily understandable steps. The website was then evaluated using lead users, Google Analytics, and requirements check. This resulted in a positive evaluation. As of now the website is generating more traffic to the machine and the client has experienced an increase in users wanting to use the machine.

5.6.1 Requirements Check

For this evaluation the requirements table is copied form section 7.6 and every requirement is checked against the current product which is the Millinator.com website. The result can be seen in figure 5.8

Requirement:	Check:
The website must be easy to use, every student should be able to get into CNC machining.	Pass, with a one page layout and a simple web address everybody can read it.
The website must be maintainable, and easily upgradable.	Pass, Wordpress is releasing new versions every quartile, and the ease of use is exceptional.
The website must explain the CAM process explained in full.	Partial pass, the video used to explain the process goes through the whole process but this can change according to the users needs, since every part is different.
The website must be accessible at all times	Pass, the uptime of TransIP is over 99%
The website must be readable within one hour since the users are like to be busy with more important things like studying.	Pass, the lead users spent 23 minutes on average to read through the website.
The installation of Fusion 360 software must be explained	Pass, this is done in Step 3 on the website.
The what, how and why of CNC machines must be explained.	Pass, this is the first Step on the millinator.com website.
The website must be maintainable by the technician.	Pass, Wordpress can be maintained by anyone who can open a webpage.
The website must have a checklist for the design process	Pass, a checklist containing over 15 entries is presented in Step 3 on the website.
The website must mention that failure is a part of the process	Pass, in Step 3 in the checklist it stated that the user is to expect failure, especially in the first operations.
The website must be in English to cater to the global users.	Pass, the website is in English
The website should be an accurate representation of the knowledge gained.	Partial pass, a full list of capabilities can be presented, the steps now function as an alternative.

Figure 5.8: The requirements check for Millinator.com.

From figure 5.8 7 of the 25 requirements set 17 get a pass, 5 get a partial pass and 3 get a fail. Of the must have requirements, which are the most critical ones , not one gets a fail or even a partial pass.

Appendix A

Appendix

A.1 Interview Andrea Minuto from Designlab

1. Why does the Designlab need a CNC machine? 3D printing has some shortcomings. On a CNC you can make flat faces and use stronger materials useful for making prototypes.
2. What type of materials do the users want to work with but can't due to limitations of current rapid prototyping machines? Thicker stronger materials.
3. Do the designlab visitors know CAD? In general no, currently I help students with their design prior to 3D printing or laser cutting. Which subsequently is the largest portion of time I spend helping them.
4. Do you think autonomous operation is feasible? No the students aren't skilled enough to do that.
5. What do you think of the website as a teaching tool? Good, it will help but won't solve all problems. A helping hand is always necessary.
6. Do you think the designlab needs a more professional machine? Yes, we can do more things and in less time
7. How many user per week do you expect? Only a few, but like the Laser Cutter and 3D Printer it will increase overtime as it becomes more known under the potential users. Marketing will improve this.
8. What studies do you think will make use of the machine the most? Industrial Design since they are already familiar with CNC's
9. Are you interested in giving/receiving CNC workshops? Yes i'd like to receive one.
10. Should the users buy their own End Mills? No, should the project be for university we can supply them since they aren't too expensive
11. Do you think a video would help with getting user up to speed? Yes it will help some users but not all.
12. What do you think of the name Millinator.com? Yes it's an amazing name (could not place if sarcastic or not)

13. How much time do you think a inexperienced user needs to learn CAM? Don’t know.

A.2 Interview Wout Zweers from Wowlab

1. What does the Wowlab use the CNC machine for? Intricate shapes for artistic purposes, silicone molds, and wooden parts for furniture.
2. What is the workflow for the machine? CAD is done in Solidworks, CAM is done in RhinoCAM a proprietary piece of software that came with the german CNC machine.
3. What is the frequency of use of the machine of average? Since I am the only one that uses the machine the frequency is quite low, only thrice a week on average.
4. What materials are used most often? Wood and engineering foam are my favorite on the machine.
5. What do you think of a website as a method of educating novice CNC users? I think it will speak to the current generation, the added benefit of having anyone in the world have access to the website is fantastic. I would also like to use the website.
6. The website will try to educate the user from what a CNC machine is to making their first part, do you think it's feasible if not why not? It is feasible although probably the user will not be successful the first time, this should be stated on the website as well.
7. How much time do you think the users needs to learn CNC? Given that the users already know CAD the CAM part should be understood in a day's work.
8. What do you think is essential for having a successful website for the education of CNC machines? A checklist would be very beneficial, especially since the process is unforgiving.
9. Do you think the user is safe enough when using the machine with the lid closed? Yes, especially since the lid of polycarbonate, the most dangerous scenario is the tool shattering, this happend to me multiple times. With the lid the shrapnel is contained and the user kept safe.
10. What do you think of the name Millinator.com? I think is is an OK name, although the user will not directly get that it is a CNC machine.
11. Do you think a video would help with getting user up to speed? Yes definitely, I see the current generation consuming a great amount of video.
12. Any recommendations for the website? As I said a checklist and of course a collection of useful tips and tricks.

A.3 Interview Jeroen Wolfs from Kast op Maat

1. What is the main usage of the CNC machine here? The machine cuts shapes from plates of multiplex wood, these are used in custom pieces of furniture.

2. What education does the CNC operator have? We educated the CNC operator inhouse, no extra education was necessary.

3. Does the machine run all day every day? Yes the machines runs about 40 hours per week.

4. What is the most useful extra function of the machine? For commercial use the tool changer is a must, this decreases the time between operations and provides tremendous flexibility. Furthermore the machine has an upgraded bed with suction cups to hold the plates in the machine during the operation.

5. What is the workflow of the machine? The CAD is done automatically via our website, which has a custom interface so the user can design the furniture. The CAM is also automated with some tweaks here and there by the operator.

6. What do you think of a website as a method of educating novice CNC users? Useful and accessible but not official, it would make attaching any certificate to the skills learned difficult.

7. The website will try to educate the user from what a CNC machine is to making their first part, do you think it's feasible is not why not? Yes although I think the parts made will be simple in the beginning.

8. How much time do you think the users needs to learn CNC? Not much, I would guess two days given a simple part.

9. What do you think is essential for having a successful website for the education of CNC machines? A clean interface would make learning about CNC easier, nowadays most CNC operator use software to set the parameters correctly and here in a commercial setting they don't change often.

10. Do you think the user is safe enough when using the machine with the lid closed? Absolutely, we use a cord that limits any person of coming to close to the machine, when the cord is tripped the machine shuts down automatically, no lid or enclosure is needed.

11. What do you think of the name Millinator.com? Fits the CNC machine well, although milling is more focused on metal.

12. Do you think a video would help with getting user up to speed? Absolutely videos can contain way more information is little time spent.

13. Any recommendations for the website? If done correctly the website would be useful for anybody involved with CNC, thus making is in eglish would increase the user base tremendously.

A.4 Survey Lead Users

Questions:

1. Do you know how to design part on the computer (CAD). (Likert scale)
2. How many parts did you design on the computer? (number)
3. Age? (number)
4. Study and year?
5. Do you know what a CNC machine does? (Likert scale)
6. Have you used a CNC machine before? (yes/no)
7. Have you used the Laser Cutter? (yes/no)
8. Have you used the 3D printer? (yes/no)
9. How helpful did you find the website? (Likert scale)
10. Do you feel you know more about CNC's after viewing the website? (Likert scale)
11. Do you feel you could make something on your own now? (Likert scale)
12. Do you see the advantages with a CNC versus a 3D printer or laser cutter? (Likert scale)
13. Would you consider using the CNC machine for you next project? (Likert scale)
14. What do you think of making a online quiz to be able to start using the CNC machine (Likert scale)
15. How easy did you find the experience? (Likert scale)
16. What should be added to make the website more clear? (Open)

A.5 GRBL Settings

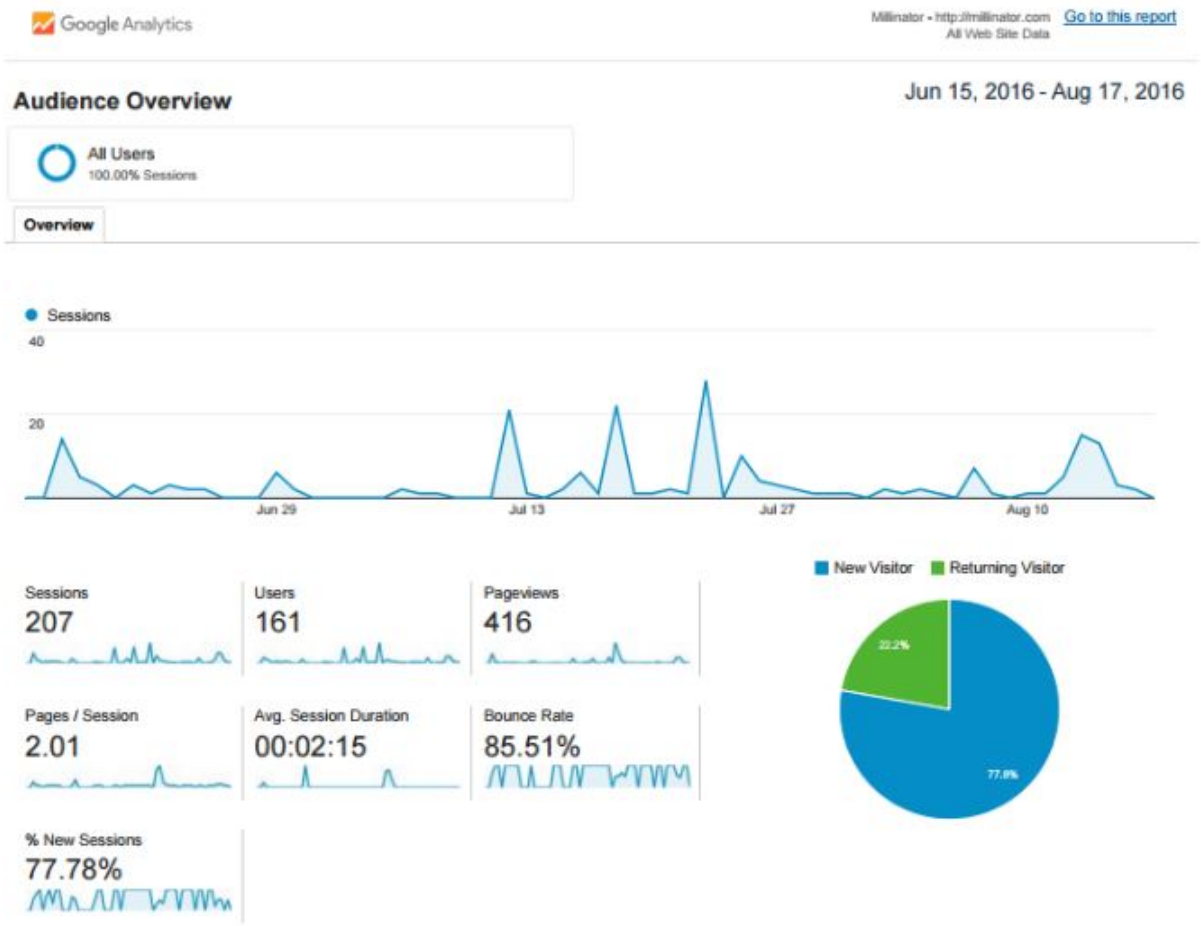
- $0=30 (step pulse, usec)
- $1=255 (step idle delay, msec)
- $2=0 (step port invert mask:00000000)
- $3=2 (dir port invert mask:00000010)
- $4=0 (step enable invert, bool)
- $5=0 (limit pins invert, bool)
- $6=0 (probe pin invert, bool)
- $10=17 (status report mask:00010001)
- $11=17.000 (junction deviation, mm)
- $12=0.002 (arc tolerance, mm)
- $13=0 (report inches, bool)
- $14=1 (auto start, bool)
- $20=0 (soft limits, bool)
- $21=1 (hard limits, bool)
- $22=1 (homing cycle, bool)
- $23=3
- $24=800.000 (homing feed, mm/min)
- $25=700.000 (homing seek, mm/min)

A.6 Bill Of Materials Millinator CNC

The full bill of material of the CNC machine including its upgrades are listed below. The currency is in Euro's.

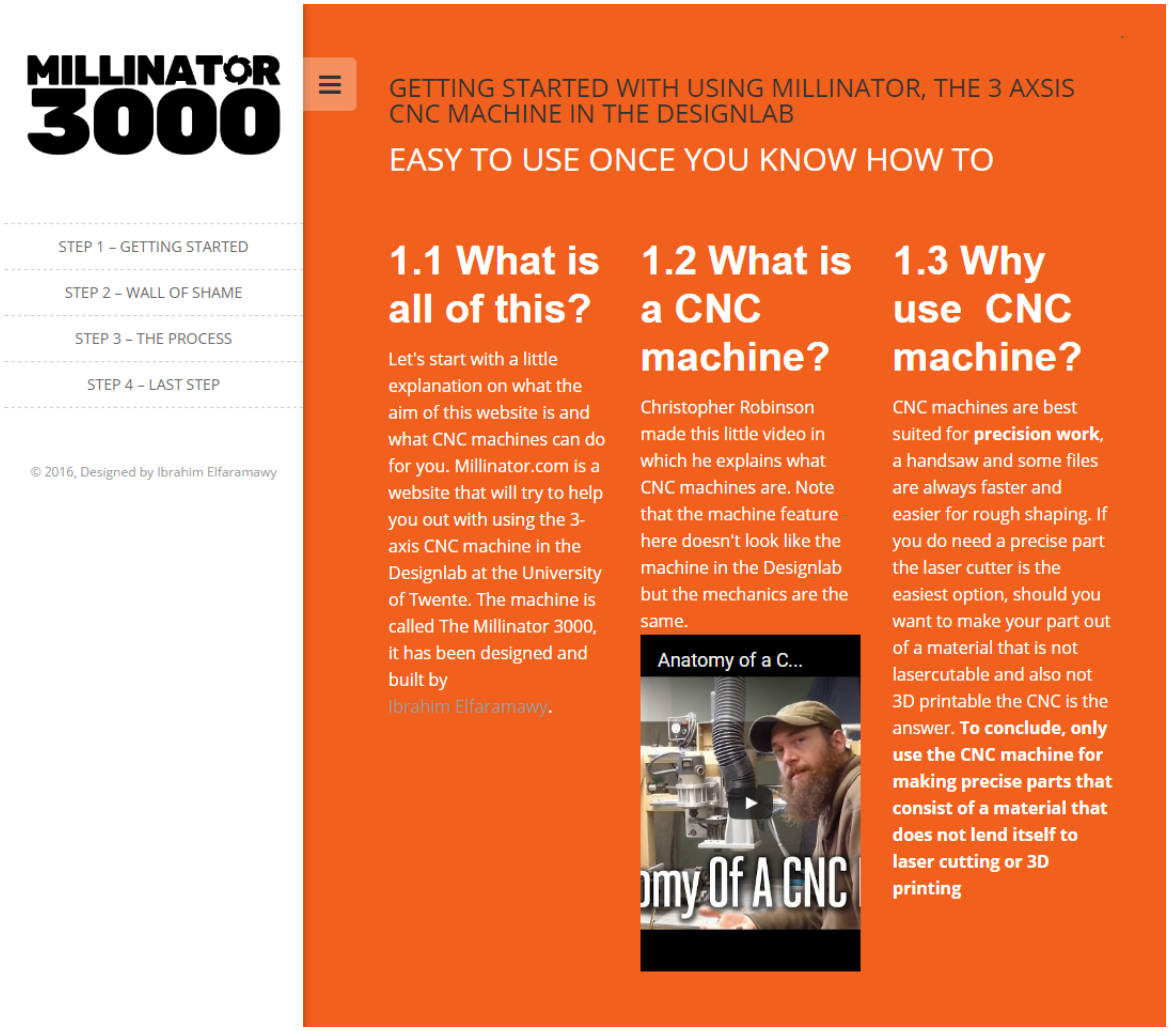
TOTAL COST:	755.67			
Part:	Qty:	Assembly:	Total Price:	Source:
Guide Rods	6	CNC	65.59	THN
Endmill 8mm	1	CNC	1.37	EBAY
Limit Switches	10	CNC	4.06	EBAY
Stepper Motors	3	CNC	48.2	EBAY
Linear Bearing SBR20UU	8	CNC	41.6	EBAY
Rod Support SK20	10	CNC	48.12	EBAY
Motor Mount	3	CNC	9.3	EBAY
Control Board RAMPS 1.4	1	CNC	24.77	EBAY
Nylon Wing Nut	10	CNC	15.37	EBAY
Axial Ball Bearing	10	CNC	7.05	EBAY
Ball Bearing Flanged	10	CNC	8.85	EBAY
Ball Bearing Deep Groove	10	CNC	5.7	EBAY
Linear Bearing SC20UU	2	CNC	14.11	EBAY
M10 Nyloc Nut	2	CNC	9.15	EBAY
Dust Shoe Bristles	1	CNC	7.99	BLOKKER
Kress Mounting Block	1	CNC	171.7179	DAMEN CNC
Kress 3.175 Clamping Nut	1	CNC	38.6179	DAMEN CNC
Kress FME 1050-1	1	CNC	27.7279	DAMEN CNC
Couplers	3	CNC	4.1	ALIEXPRESS
M6 Nyloc Nut	100	CNC	5.95	TOOLSTATION
M6 Bolts 20mm	10	CNC	2.32	TOOLSTATION
M6 Washer	100	CNC	0.62	TOOLSTATION
Threaded Rod	2	CNC	17	TOOLSTATION
Female Connector Mini-DIN	10	Electronics	6.77	ALIEXPRESS
Male Connector Mini-DIN	10	Electronics	4.55	ALIEXPRESS
Female Connector DIN	6	Electronics	3.39	ALIEXPRESS
Male Connector DIN	6	Electronics	3.39	ALIEXPRESS
Flexible Nozzle	1	Electronics	0.95	ALIEXPRESS
Adjustable Handle	2	Electronics	3.46	ALIEXPRESS
Plastic End Caps	20	Enclosure	5.78	ALIEXPRESS
MDF	1	Enclosure	40.98	PRAXSIS
Aluminium	1	Enclosure	37.96	PRAXSIS
Hinge	1	Enclosure	3.29	PRAXSIS
LEDstrip (used 1 of 5m)	0.2	Enclosure	5.866	ALIEXPRESS
Polycarbonate Panels	1	Enclosure	60	RESTSTUKKEN.NL

A.7 Google Analytics Report



Language	Sessions	% Sessions
1. (not set)	84	40.58%
2. en-us	48	23.19%
3. nl	38	18.36%
4. en	31	14.98%
5. en-gb	3	1.45%
6. ru	2	0.97%
7. es	1	0.48%

A.8 Snapshot Millinator.com



WALL OF SHAME, WHAT YOU SHOULDN'T DO

ALOT OF THING CAN GO WRONG, AND THE PROCESS IS NOT FORGIVING AT ALL :(

2.1 Not being safe

The most shameful things to do are:

- **Opening the lid** CNC machine when the machine is running.
- Not wearing **eye protection**.
- No wearing a **gas mask** when working with carbon fiber (source)
- Not wearing **latex gloves** when working with carbon fiber (its a bad idea)
- Not **fixing your material** securely in the machine, it will fly out and slap you (see video)

2. 2 Bad CAD (Design)

Bad design will result in a bad part, and will waste your time, the technicians time, and the material. To get you design right here are some tips:

- Laser-cut first if possible, to check if you're on the right track. Especially useful when working with expensive material like Carbon Fiber.
- No overhang, like a 3D printer the CNC is incapable of making parts with overhang. To simplify, imagine looking down on your part from the top, can you touch all features of the part, if so you don't have overhang, YAY!
- Keep in mind the inner radii of any features. Imagine a part that has a hole of 0.1 mm, how are you going to make that hole if the smallest tool is 3.175mm?

2.3 Bad CAM

Bad camming can result in:

- Not getting the part you designed but getting a paperweight (see video below)

- Wasting material
- Getting a part that flies out to kill you, this happens when you forget to add tabs. Imagine cutting a circle from a plate, what happens to the disk when you're removing the last few millimeter of material to complete the full circle?
- Getting bad finish on your part, results in a lot of sanding an manual labor : (
- Breaking the tool and we have no tool tree ;).

FROM CAD TO CAM TO MILL, THATS THE ORDER

The software we are going to use to design and cam the part is **Fusion 360** by Autodesk. It is free for students and non-commercial use.

AUTODESK® **FUSION 360**™

3.1 CAD

Fusion 360 is capable of doing the CAD as well as the CAM. We are assuming that you already have a 3D design for your part, should you not watch the video below for a good starting point. If you do have your design ready albeit in a different CAD program (like Solid Works) continue with the following steps:

1. Create a new Project, give it a descriptive name.
2. Open your new project.
3. Import your design, you can import:
   - .stl
   - .obj
   - .iges
   - .skp (Sketchup)
   - and more
4. Be sure your part fits in a box that is 40 cm wide, 30 cm long and 10 cm high.
5. You are now ready to CAM.

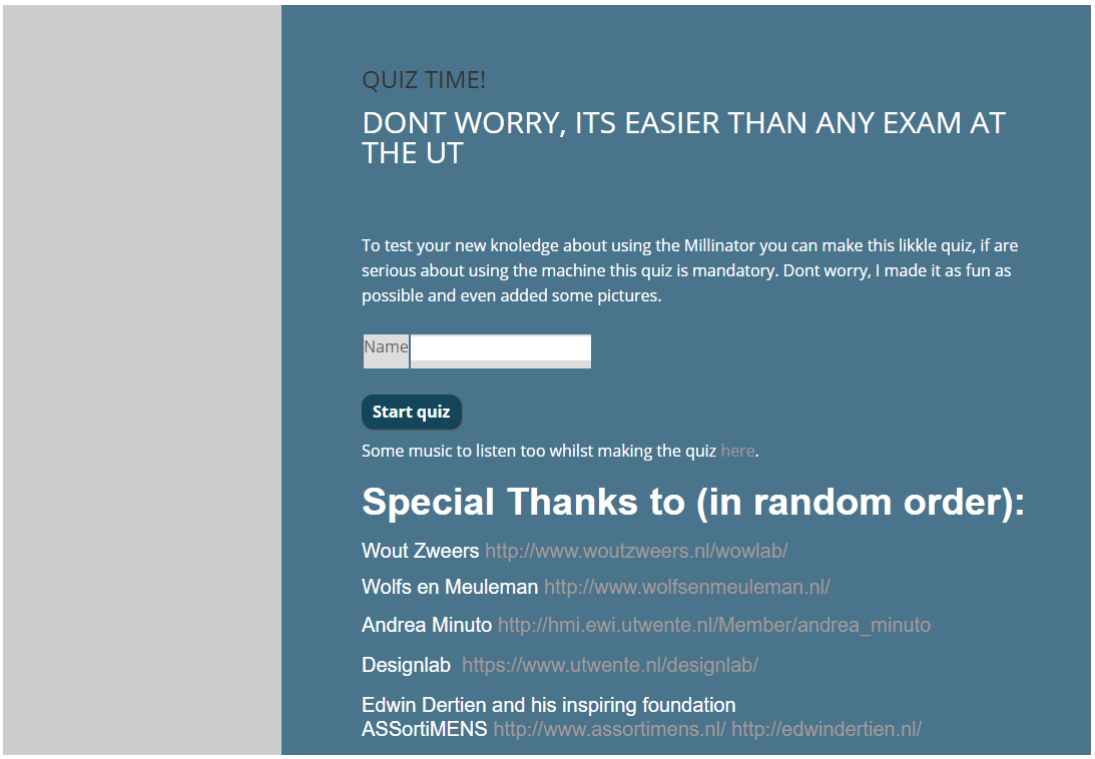
3.2 CAM

In the CAM section of Fusion 360 you define all the parameters needed for the generation of the tool paths, these are the paths the machine should take to make your part. In the video below John from NYC CNC gives a great explanation on how to start camming in Fusion 360. Note John uses inches, stick with millimeters.

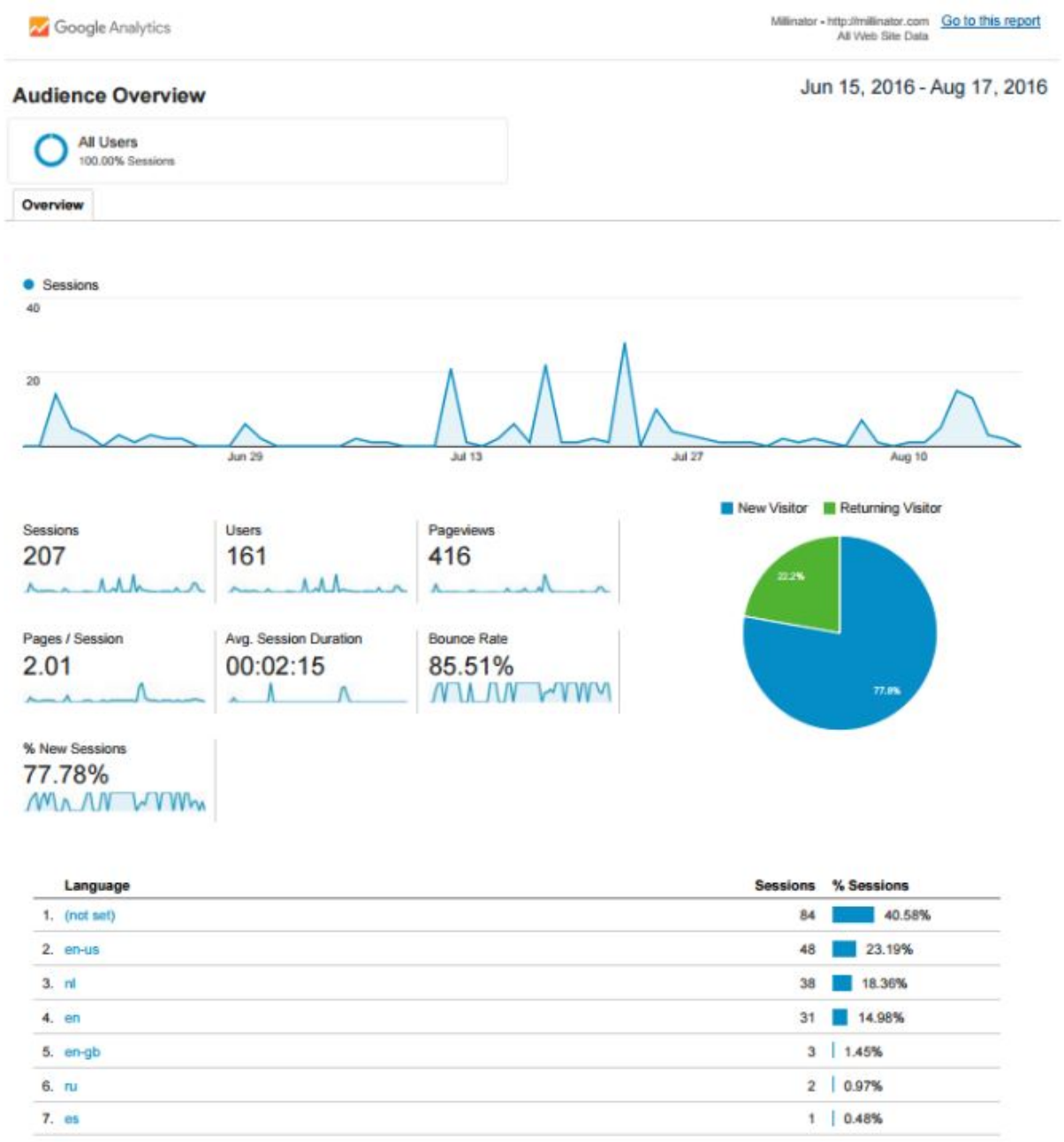
3.3 Checklist

To minimize the chance of failing here's a checklist for you to check **before** you ask the technician to CNC your part.

- ☐ Part is fits in box of 40x30x10cm.
- ☐ No overhang in model.
- ☑ Enough material to cut twice.
- ☑ Units set to millimeters.
- ☑ Right orientation of model.
- ☑ Right orientation of the setup.
- ☑ Operation type in setup set to milling.
- ☑ Stock set to right dimensions.
- ☑ Origin set on top of stock in right orientation.
- ☑ Right operation type for features.
- ☑ Correct tool specified per operation.
- ☐ Correct speed set per operation.
- ☑ Correct contours selected per operation.
- ☑ Negative stock to leave so part is cut all the way through.
- ☑ Tabs correctly placed and sized if necessary.
- ☑ Simulated produced correct part.
- ☑ Simulated time under 30 minutes.
- ☐ Expect failure, its a part of the process.


QUIZ TIME!
DONT WORRY, ITS EASIER THAN ANY EXAM AT THE UT
To test your new knoledge about using the Millinator you can make this likkle quiz, if are serious about using the machine this quiz is mandatory. Dont worry, I made it as fun as possible and even added some pictures.
Name
Start quiz
Some music to listen too whilst making the quiz here.
Special Thanks to (in random order):
Wout Zweers http://www.woutzweers.nl/wowlab/
Wolfs en Meuleman http://www.wolfsenmeuleman.nl/
Andrea Minuto http://hmi.ewi.utwente.nl/Member/andrea_minuto
Designlab https://www.utwente.nl/designlab/
Edwin Dertien and his inspiring foundation ASSortiMENS http://www.assortimens.nl/ http://edwindertien.nl/

A.9 Google Analytics Report



Language	Sessions	% Sessions
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3. nl	38	18.36%
4. en	31	14.98%
5. en-gb	3	1.45%
6. ru	2	0.97%
7. es	1	0.48%

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