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Industrial Electrical Engineering and Automation

Design, Construction and Automation of Cutter for Styrofoam Insulation Material

Max Artursson
Simon Larsson

Division of Industrial Electrical Engineering and Automation
Faculty of Engineering, Lund University

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by Max Artursson, Simon Larsson

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Thesis for the degree of Master of Science
Faculty advisor: Erik Ottosson
Industrial advisor: Anders Löfgren
Examiner: Ulf Jeppsson

Sammanfattning

Reco Port AB är ett företag som bygger garagevikportar och är en del av ASSA ABLOY-koncernen. Reco använder Styrolit som isolering i sina portar, och deras nuvarande lösning för att skära Styroliten är att använda en sänksåg och ett specialbyggt bord för att hålla styroliten på plats. Lösningen är inte ergonomisk och sprider mycket styrolitrester runt arbetsstationen. En maskin som inte sprider rester av styrolit och som är ergonmisk att användas efterfrågas därför. Dessutom ska maskinen vara automatiserad och CE-märkt. För att verifiera om maskinen är tillräckligt bra för installation har en lista med tester tagits fram. Maskinen har designats, konstruerats och programmerats, alltid med säkertheten som största prioitet under utvecklingen. Vid examensarbetets slu kunde maskinen klara de flesta testerna, men vissa delar av maskinen är provisoriskt byggda och behöver ändras. Det största problemet med maskinen är robustheten och tillförlitligheten. Det finns fortfarande ett par dokument och tester som behöver slutföras innan CE-märkningen kan göras. Då maskinen inte var helt färdig har kunskapen och ansvaret för maskinen överlämnats till ASSA ABLOY, så att maskinen kan färdigställas så snart som möjligt.

Abstract

Reco Port AB is a company that builds folding garage doors and is a part of the ASSA ABLOY group. Reco uses Styrofoam as insulation in their doors and their current solution of cutting the Styrofoam is using a plunge saw and a custom built table to hold the Styrofoam in place. The solution is not ergonomic and spreads a lot of debris of Styrofoam around the workstation. Due to this it was requested for a machine that does not spread debris and is ergonomic to use to be installed at Reco instead. Additionally the machine is to be automated and the machine needs to be CE-certified. To verify if the machine is good enough for installment a list of tests were made. The machine was designed, constructed and programmed, always with safety as the main priority. By the end of the time for the thesis project the machine could pass most of the tests but some parts of the machine were provisionally built and will have to be changed. The biggest issue of the machine was the robustness and reliability. There are still some documents and tests to be made before the CE-certification can be set. Since the machine was not completely finished, the knowledge and responsibility of the machine was handed over to ASSA ABLOY so that the machine can be finished as soon as possible.

Acknowledgements

This degree project for the degree of Master of Science in Engineering has been conducted at the Department of Industrial Engineering and Automation, Faculty of Engineering, Lund University.

Supervisor at the Department of Energy Sciences was Erik Ottosson. Supervisor at ASSA ABLOY was Anders Löfgren. Examiner at Lund University was associate professor Ulf Jeppsson.

The project was carried out in cooperation with the IDDS R&D department at ASSA ABLOY.

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Finally we would like to thank both the industrial supervisor Anders Löfgren and the faculty supervisor Erik Ottosson for their help and patience during the project.

Division Of Work

During the project some natural division of work occurred between Max and Simon. Simon was responsible for the development of the linear drives and motors, the mounting of the wire, the PLC control logic and the electrical cabinet. Max was responsible of the ventilation system, the Styrofoam holder and the HMI. Help and knowledge was of course shared between each other to help with the respective areas.

Contents

Nomenclature

Abbreviations

ABS Acrylonitrile Butadiene Styrene

CAD Computer Assisted Design

CE Conformité Européenne

EMC Electromagnetic Compatibility

HMI Human Machine Interface

IDDS Industrial Door and Docking Systems

PET-G Polyethylene Terephthalate Glycol

PLC Programmable Logic Controller

PWM Pulse Width Modulation

R&D Research and Development

RCBO Residual current operated Circuit Breaker with Overcurrent protection

RoHS Restriction of Hazardous Substances

RTD Resistance Temperature Detector

RTU Remote Terminal Unit

TCP/IP Transmission Control Protocol/Internet Protocol

Chapter 1

Introduction

In this chapter a background to the problem that this project aims to solve is given. The aim of the project and the deliverables are also listed.

1.1 Background

Reco Port AB in Lidköping is a part of the ASSA ABLOY group and they produce folding garage doors. About 30 people work in the factory and about 10 work with sales and management. When creating the doors, sheets of Styrofoam are used as insulation. The current solution of cutting the sheets is a plunge saw, mounted on a custom table with a holding mechanism for the sheets that requires manual adjusting and is not ergonomically pleasing to use, as can be seen in figure 1.1. This solution also largely contributes to shredded Styrofoam debris being spread around the cutting station. The plunge saw is being used continuously throughout the day meaning that as often as the workers are available to cut the sheets, they will. Due to these reasons there is a request to substitute this solution for a new one that is easier for the operators to use.

Figure 1.1: The current solution at Reco for cutting Styrofoam

1.2 Aim

The aim of the project is to design and construct a machine that cuts sheets of Styrofoam automatically. This means that the operators should not have to do the actual cutting themselves, like the current solution requires. They will instead only load, unload and specify measurements for the cut sheets. The new cutting mechanism should be one that does not leave debris of Styrofoam behind after use. All of the components will be controlled by a PLC that will be programmed accordingly and interaction with the machine will be conducted trough an HMI-screen.

The machine will be designed, constructed, programmed, tested and CE-cerified at ASSA ABLOY in Landskrona and then transported to Reco Port AB in Lidköping for a final installation.

1.3 Deliverables

The machine is deemed complete when the following points have been completed:

- The machine is able to cut any sheet of Styrofoam being used at Reco into any dimensions smaller than 1200 mm x 1200 mm with a precision of ± 1 mm.
- The machine has been CE-certified or, in the case of insufficient time, an action plan for this to be completed has been developed.
- A user manual detailing the function and usage of the machine has been constructed and handed over to Reco Port.
- The machine should be built in a manner that minimizes the amount of non reusable Styrofoam.
- The machine should meet the requirements set up as target specifications.

Chapter 2

Theory

In this chapter, theory regarding areas where research and prior knowledge is needed to understand the corresponding parts and decisions in the project is presented.

2.1 CE-Certification

2.2 Requirements for CE-certification

In order to CE-certify a machine there are several steps set up by the European Commission and the machine must be compliant with an applicable EU directive in order to attain the certification.[1] The relevant EU directive, the machinery directive[2], is adapted and applied in Swedish law by the Swedish work environment agency (Arbetsmiljöverket) through their regulation ”AFS 2008:3”.[3] At the time of writing this report a new regulation exists, ”AFS 2023:4” but has not been put into effect. The new regulation will be activated on 1:st of January 2025, right before the machine is to be taken into operation.[4] For this reason the regulation used is the one that will be applicable when the machine is taken into operation.

In order to be able to take a machine into operation the steps that need to be taken according to the ”AFS 2023:4” regulation are[5]:

- Ensure that the machine fulfills basic health and safety criteria in regards to applicable standards
- Ensure that required technical documentation is available
- Ensure that a user manual, marking and other necessary information is available and supplied with the machine
- Ensure that an EU declaration of Conformity is drafted and supplied with the machine

- Affix CE-marking to the machine

The steps described above will be further explored and described in the following sections.

2.2.1 Health and Safety Criteria

The first step for attaining a CE-certification and being able to take the machine into operation the machine needs to fulfill the health and safety requirements defined in ”AFS 2023:4”[5]. By performing continuous risk assessments inherent with solutions and design decisions during the process of developing the machine, risks can be identified and taken into account for designing and constructing the final product.[5]

For the machine to be constructed in the scope of this project only the general guidelines of the machinery directive apply, none of the specific application areas given in ”AFS 2023:4” apply and thus should not be considered. Categories that fall outside general guidelines typically involve an inherent danger where tougher demands are in place, for example lifting devices etc.[5]

2.2.2 Technical Documentation

Another step for attaining a CE-certification is to ensure that proper technical documentation is present. The documentation should according to ”AFS 2023:4” contain the following points[5]:

- A general description of the machine
- A general drawing of the machine and control circuit diagrams
- Component drawings along with calculations and test results to prove that the machine fulfills the health and safety requirements
- Documentation of the risk assessment process detailing the applicable health and safety requirements and a description of the measures taken to remove risks. If some risks could not be removed then these should also be detailed
- A list of standards used along with the health and safety requirements associated with these
- Any technical reports containing results from tests performed by the manufacturer or their representative
- The user’s manual
- The declaration of conformity for the machine and for any products used in the

machine

2.2.3 User Manual

A user manual needs to be constructed according to the relevant ISO 20607 standard. This means, in short, that it needs to detail operation, risks present and a specification of how the machine is to be used.[6]

2.2.4 Declaration of Conformity

In order to declare that the product conforms to the norms required for CE-certification the EU Declaration of Conformity should be drawn up and must contain[7]:

- Number serving as a unique identification of the declaration
- Name and address of manufacturer
- A statement of responsibility for conformity by the manufacturer
- A description of the product that the declaration concerns. This could include pictures
- A list of legislation that the product conforms to
- References to standards used to ensure that conformity is achieved
- A signature by a representative of the manufacturer along with date and location

2.2.5 CE-Marking

The final step of the CE certification process is to physically attach the CE-marking to the machine.[5]

The CE-certification should be placed on the machine so that it is clearly visible, legible and does not come off. Further it should also be affixed using the same method as and in close proximity to the plaque containing the manufacturer's name and details.[5]

2.3 Hot Wire Cutting

In the application of hot wire cutting of Styrofoam a clear problem is that heat quickly leaves the wire when cutting begins[8]. In the article H.Brooks and D.Aitchinson research how heat distribution in a cutting hot wire changes by using the finite element method.

In the article, they used a moving hot wire but it is assumed that the same principles can be applied for a stationary wire with moving Styrofoam. It was found that after a while of cutting, the temperature in the wire stopped sinking and instead stagnated to a specific value. If one could estimate or perform tests to get the initial temperature right, so that the final temperature was the right cutting temperature, one could have the perfect cutting temperature for almost the whole duration of the cut. This could complicate things when multiple boards would be cut at the same time. The same experiment would then either have to be performed for each variance of number of boards, or a controller would be used to regulate the temperature to always be the correct value.

A third aspect that needs to be considered is how fast the feed-rate of the Styrofoam should be since this changes the rate of the temperature change [9]. In the paper, the authors discuss the kerf-width. The kerf-width is defined as the distance around the center of the wire with the heat of at least the evaporating temperature of the Styrofoam. To perform non-mechanical cutting, the temperature needs to be high enough so that the kerf-width is large enough for the Styrofoam to evaporate without actually touching the wire, meaning the kerf width being larger than the diameter of the wire. This action would be considered thermal cutting. Thermal cutting would result in the best possible cutting surface. On the other hand, if the kerf-width would be smaller than the diameter of the wire, thermo-mechanical cutting would occur instead. Since the kerf-width would become smaller with higher feed rate, thermo-mechanical cutting could result in faster cutting, though meanwhile perhaps shortening the lifespan of the wire due to bending and stress being applied to the wire.

There are ways to do a numerical estimate of the kerf width using methods displayed in article [10]. Here the authors use a method that with quite high precision can estimate the actual kerf width that occurs, however still with an error from 4% all the way up to 14%.

2.4 Temperature Measurement Method

For measuring temperature two different methods are touched upon in this report: thermocouples and resistance temperature detector (RTD). Their theory of operation and their strengths and weaknesses are presented in this section.

2.4.1 Thermocouples

The thermocouple principle of operation is that a probe is constructed from two different metallic materials connected together in a junction. When this happens a voltage difference can be measured between these two materials. The principle is shown in figure 2.1. When the temperature of the materials change, the measured voltage changes proportionally.[11]

Depending on what metals are used in the thermocouple the sensor is suitable for usage in different temperature regions.[11]

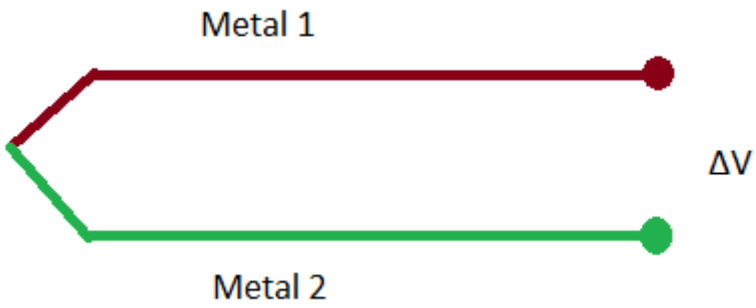

Figure 2.1: Principle of operation of the thermocouple

2.4.2 Resistance Temperature Detector

An RTD measures temperature using the phenomenon that the resistance of a metallic material changes depending on temperature. By either winding a wire or etching a path, depending on the probe geometry, a long piece of continuous metallic material is created. The length of this is created so that the resistance at 0°C is either 100 och 1000 ohms, depending on the type of probe, pt100 or pt1000. When the probe is heated, the resistance of the probe can be measured and can be converted to a temperature reading.[11]

2.4.3 Comparing the RTD and Thermocouple

RTDs have a good linear correspondence between resistance and temperature, giving it a typically larger operational temperature range compared to thermocouples. The method however tends to be slower than thermocouples and will be subject to self heating due to a current supply being needed for measuring.[11]

2.5 Fumes from Styrofoam

During hot wire cutting of Styrofoam a number of different substances are created. If full combustion was allowed to happen, the resulting substances would be limited to carbon dioxide, carbon monoxide and water. However, for lower temperatures incomplete combustion will occur resulting in mainly styrene but also with risk of lower levels of benzene, toluene, ethyl benzene and xylene. Some of these particles are known carcinogens and some are suspected carcinogens.[12]

In table 2.1 an overview is given for the odour thresholds, i.e. the point at which the particles cause a detectable odour when present in the air and the allowed threshold under Swedish law. In a study on the chemical composition of the smoke generated by combustion of Styrofoam styrene constituted around 22% of the measured fumes with the remaining components constituting only a few percent each.[13]

Hydrocarbon	odour Threshold(ppm)	Long Term Limit(ppm)	Short Term Limit(ppm)
Styrene	0.32[14]	10[15]	20[15]
Benzene	1.5[16]	0.3[15]	3[15]
Toluene	2.9[17]	50[15]	100[15]
Ethyl Benzene	2.3[18]	50[15]	200[15]
Xylene	1.1[19]	50[15]	100[15]

Table 2.1: odour threshold and exposure limits for different substances created during Styrofoam cutting with hot wire. Long term limit is defined as being the maximum exposure during an 8 hour work day and short term limit as maximum exposure during a period of less than 15 minutes

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Chapter 3

Defining Target Specifications

In this chapter an overview is given for the methodology of generating target specifications for the machine to be constructed. These specifications are then to be used as the basis for the construction of the machine

3.1 Identifying Customer Needs

The first step taken to determine the target specifications was to begin identifying the needs from the operators that are to use the machine and the needs of Reco Port AB, where the machine is to be installed. For this the methodology proposed by Ulrich and Eppinger in chapter five of ”Product Design and Development” was adapted.[20] Here the methods selected for gathering raw data was observing the current machine in use and conducting interviews with the operators and production manager.

When conducting the interviews hints proposed by Ulrich and Eppinger were regarded in order to try to extract as much information as possible and find latent needs.[20] Some of the tips included the use of visual stimuli, showing preliminary designs and concepts for the machine and watching for non-verbal information when observing the use of the current solution.

3.1.1 Observation of Current Solution

The current solution involves a metal frame mounted at a height so that a sheet of Styrofoam can be inserted between it and the table. The frame has stops on two sides of the table which can be adjusted by sliding the stops to desired positions and tightening them around the slide with a screw. The positioning of the stops are adjusted using measuring tapes fastened onto the table. The machine can be seen in figure 3.1 and the stops can be seen in figures 3.2 and 3.3.

Figure 3.1: The current cutting setup, difficult in operation and causes Styrofoam to be spread in the work area

Figure 3.2: Adjustable stop on existing machine where a measuring tape is used to set the cutting position along with an indicator on the machine

Figure 3.3: Adjustable stop on existing machine set by using the measuring tape to set the cutting position

Once the frame has been set to the desired position a plunge saw is used to cut the sheet along the support. A workshop vacuum is attached to the saw in order to help prevent the spread of Styrofoam around the work area. The cutting setup can be seen in figure 3.1.

The sheets have a tongue and groove construction so that the cutoff from a previous sheet can be reused along with a new sheet in order to minimize waste.

After observing the process some observations were made:

- Setting up the position of the stops seemed inexact in nature, relying on perspective to set correct measurements.
- Cutting the sheets seemed difficult for the operator, often resulting in the surface of the cut to be poor, especially when the operator has to stretch across an entire sheet and it often breaks off rather than being cut.

- The workshop vacuum fails to suck up most of the Styrofoam and this is then spread around the work area.
- The method used for cutting seemed dangerous with the exposed cutting blade, especially when the operator had to reach over the sheet to perform a cut.

3.1.2 Interviews with Operators

After observing the process informal interviews were conducted with the operators. Some predetermined questions were asked, but several more had also arisen when observing the process.

These discussions resulted in a few more insights:

- The size of the uncut sheets measured 1200 mm x 1200 mm x 50-54 mm depending on what doors were being manufactured.
- The side dimensions of the finished sheets were made to be between a few millimeters and 1200 mm. Typically cuts were not made to produce pieces of less than 10 mm for either side due to the difficulty of producing these. The current frame does not facilitate cutting of pieces this small and instead the sheets are placed into the holder with the desired piece sticking out rather than in and then aligning the sheet manually with a measuring tape. This procedure was not popular with the operators due to the difficulty of keeping the guide of the saw on the sheet and not slipping off. Instead typically small sheets were not cut but rather the expanding glue used for mounting the sheets in the door frame was used to fill gaps resulting from these missing pieces.
- The tongue and groove on the sheets are often not perfect, resulting in the fit sometimes being tight and sometimes being loose. In order to fit the sheets together when they were tight the frame played a vital part in preventing the sheets from folding upwards when they were thrust together. In order to keep the sheets together when they were loose, tape was used.
- Most often the sheets only need to be cut on one side. The width of a section in the folding door is never made to be larger than that one sheet manages to cover this entire width. The height is then achieved by stacking sheets on top of each other. This results in that only the width needs to be cut on most sheets. The only sheets that need to be cut twice are thus the ones that fit at the top or bottom of the door. For this reason typically a lot of sheets cut for a door are of the same size.
- Cutting the sheets were thought of as being difficult and not everyone could work at the machine since a person would have to be tall in order to reach the end of the sheet with the saw.
- The operators did not like the cutting method as it spread Styrofoam all over the

factory and was a hassle to clean up due to static charges.

After this the project was discussed with its end goal being to create a new automated machine. The operators were asked what they felt was important with the new machine. The points that were mentioned were:

- The new solution should not spread any Styrofoam that would need to be cleaned up.
- The new solution should facilitate easy removal of finished sheets and off cuttings.
- The new solution should facilitate easy insertion of sheets and provide some way of attaching sheets together with the tongue and groove.
- The HMI should be easy to understand and use, provide feedback of the current process and be placed in an easily accessible position.

3.1.3 Interview with Production Manager

Some discussions were also carried out with the production manager of Reco Port AB. From these discussions a few points could be noted that also had to be considered when setting target specifications for the machine.

Firstly, the machine would have to be CE-certified in order to take into operation

Secondly, several sheets of the same size were often needed and it would good if these could be cut at the same time. Typically due to the height of the doors and number of sections the amount of identical sheets needed were 4, 8 or 12.

3.1.4 Determining Needs

After this a list of needs could be established. and categorized according to:

Using the Machine

- Inserting sheets into the machine is done easily
- Removing cut sheets from the machine is done easily
- Removing off cuttings from the machine is done easily
- The machine makes it easy to connect tongue and groove of sheets
- The machine is not sensitive to poor tongue and groove fit

Cutting

- The machine can cut sheets to a rectangle of needed size
- Sheets are cut to allow a good fit in the door frame while not leaving gaps
- Machine allows several sheets to be cut at the same time
- Cutting the sheets is easy and anyone working in the factory can do it

Interfacing ith the Machine

- Inputting cut data is easy
- The machine provides feedback on selected settings
- The machine provides feedback on how the process is progressing
- Feedback is clear and easily understood

Work Environment

- Machine does not pollute the work area
- Inserting sheets into the machine is done from a comfortable position
- Removing cut sheets from the machine is done easily from a comfortable position
- Removing off cutting from the machine is done form a comfortable position
- Inputting cut data is done from a comfortable position
- The machine is safe to use

CE-certification

- The machine should be CE-certified

3.2 Setting Specifications

With the needs defined it was time to determine exact specifications for the machine. For this help was once again taken from Product Design and Development by Ulrich and Eppinger. The main advice that were considered were the fact that each specification should have a corresponding metric and thus be measurable or answerable with a binary yes/no.[20] Another point taken from here was that each specification should be complete in the sense that every specification is rooted in the needs and every need is catered for.[20]

The final list of specifications was then assembled from the needs:

Using the Machine

- When inserting sheets into the machine the operator should not have to reach more than 600 mm in from the edge of the table to position the sheet
- When removing cut sheets from the machine the operator should not have to reach more than 600 mm in from the edge of the table
- The machine has a height so that loading and unloading is performed at 800-900 mm above floor level
- When removing off cuttings the operator should not have to reach more than 600 mm in from the edge of the table
- When inserting a sheet into the groove of a sheet in the machine the operator should have an overhang of 200 mm from the edge of the table for the new sheet
- When inserting a sheet into the groove of a sheet in the machine, the machine should support the sheet, so it does not fold upward
- The machine needs to hold the sheets together so to be able to cut sheets where the tongue-groove fit is loose

Cutting

- The machine can facilitate feeding in up to two sheets measuring 1200 mm x 1200 mm per level connected with the tongue and groove
- The machine can cut the sheets to any rectangular shape measuring 1200 mm x 1200 mm to 10 mm x 10 mm
- The machine can cut sheets to desired size with a tolerance of ± 1 mm
- The machine can be loaded with up to four sheets in height to be cut to the same dimensions at the same time

Interfacing with the Machine

- The desired cut dimensions can be input by the operator through the HMI
- The machine provides feedback by displaying the selected cut parameters

Work Environment

- The machine does not pollute the work area with debris or toxic gases
- The machine does not present any danger to the operator during cutting, loading or standby phases

CE-Certification

- The machine should be CE-certified. The overarching steps are presented here but every single document is not, this is instead discussed further in the relevant section of the report.
- The machine needs to conform to the requirements set by Arbetsmiljöverket in AFS 2023:4[5]
- Create a technical dossier according to the requirements set up by the European Comission[7], [21]
- Create and sign an EU declaration of conformity[21], [22]
- A user manual in Swedish is constructed and delivered along with the machine[22]
- A physical “CE”- mark is attached to the machine[21], [22]

Chapter 4

Method

Due to the requirements that were put on the machine in the beginning of the project, the machine had some standard rules concerning what major parts of the machine that were needed. In figure 4.1 these parts are visible.

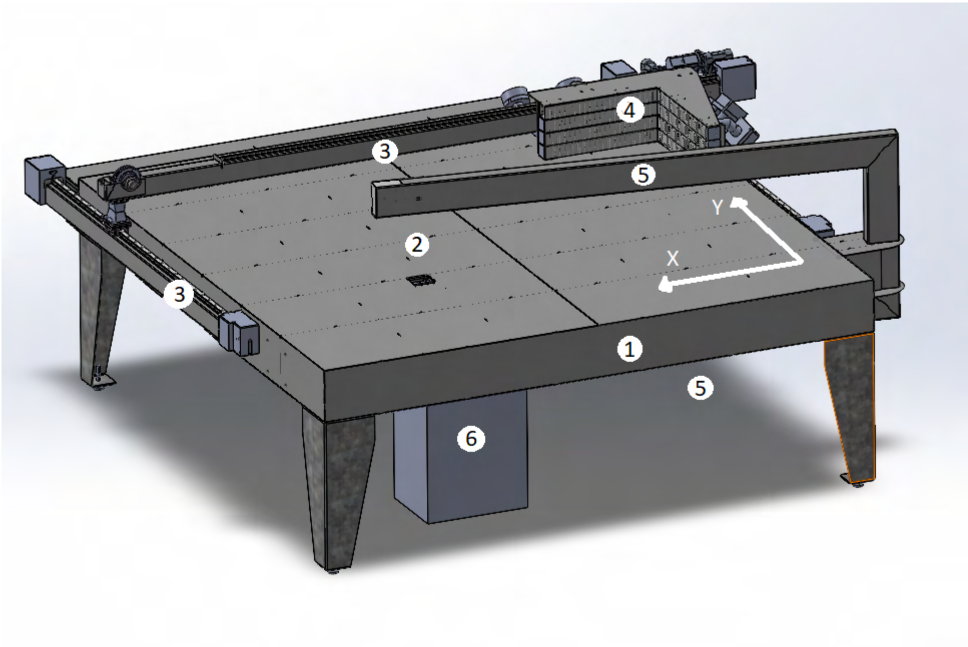

Figure 4.1: A CAD-model of the finished machine with numbering of its parts. 1. Table. 2. Cutting mechanism. 3. Mechanisms that allows movement. 4. Styrofoam holder. 5. Ventilation system. 6. Electrical cabinet.

Note that the parts in the picture were not designed or determined when the design process began and that the picture is only a visualization to understand the following steps that were taken when designing and constructing the machine.

When developing the machine, the usual way of progressing was to iterate through different versions of every solution until a solution that was good enough was found.

This means that there was a bigger emphasis on finding a solution and improving it over time instead of focusing on finding the perfect solution in the beginning. The reasoning behind this methodology was to minimize the time needed to find a solution that sufficed for the final product.

It is worth to mention that around halfway into the project, Reco made a decision to remove the tongue and groove and only use whole sheets. Since many decisions had already been taken with tongue and groove in consideration, some of the parts of the machine were dimensioned after the old specification of the machine.

4.1 Cutting Mechanism

The current solution at Reco, the plunge saw, spreads a lot of debris around the work station when cutting. Since one of the biggest reasons behind building this machine was to actually get rid of the debris, it is important to find a cutting mechanism that makes sure that this does not happen. Since the visit at Reco at week two the development of the ideas for the cutting mechanism began before a thorough introduction to the current machine. After a markets research of other solutions, it was clear that the mechanisms that seemed somewhat viable were either a hot knife or a hot wire.

A hot knife, much similar to an actual knife, has a sharp edge and a dull edge, meaning an edge were the cutting occurs and an edge where it does not. This means that if a machine was going to use a hot knife, after one dimension of cutting has been done, the knife would have to be rotated 90 degrees to cut the next dimension. Since a wire is round, it has no sharp and dull edge and can therefore, in theory, cut in any direction.

When the concept of hot wire had been selected, the concept of cutting was to be determined. The options that were considered, was either having a stationary wire, only having the Styrofoam moving, or having a hot wire moving around or in the table. An issue that needed considering was the fumes that are created when the Styrofoam is heated to its melting temperature. It is therefore important to make sure that the extraction system can always follow the wire to make sure that as much as possible of the fumes are extracted. In addition to this, the issue of having a wire moving on and through the table is problematic. The wire needs to be mounted both below and above the table and would therefore have to move through some kind slot in the table or at the edge of the table. Due to all of these considerations, it was determined to keep the wire stationary and only move the Styrofoam. Since both the wire and extraction system in this solution can stay stationary, the design of the machine becomes simpler.

Different sizes of resistance wire were bought and were tested briefly using the wooden prototype and the machine, see figure 4.2. The reason for the tests was to find the optimal wire considering durability, the amount of current needed and the quality of the cut. The wires that were tested had the dimensions 0.21 mm 0.3 mm 0.5 mm and 0.7 mm.

Figure 4.2: Wooden prototype used for testing the hot wire concept

Tests were performed with the wooden prototype to attempt to figure out a reasonable cutting temperature. First the temperature was raised until cutting was possible. After this the temperature was increased again until the kerf width was increased to an estimate of over one an millimeter at speed that was thought to be around the speed that would be the cutting speed.

4.2 Cutting Table

The design of the table top was made for cutting the sheets with tongue and groove as a joint, like the sheets that were already being used at Reco and was therefore optimized for this. The decision to remove the tongue and groove came later. In this specification, it is necessary to imagine the extreme scenario of wanting to connect two full sheets of Styrofoam to make sure that the table was never too small. The margins that were taken into account are visualized in figure 4.3.

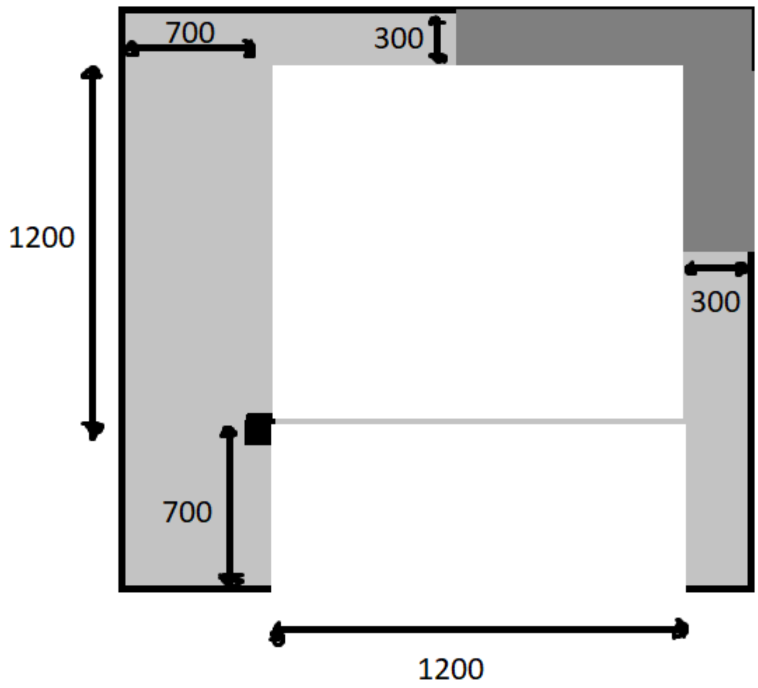

Figure 4.3: A visualization of the dimensions of the table. The figure illustrates the sheets resting on the table with a hypothetical holder. The measurements presented are the measurements of the holder, the Styrofoam and the margins needed for the Styrofoam to always rest on the table without falling off.

The table that was being used at Reco was elevated at 850 mm above ground and the operators were happy with this height. The legs of the table were designed to elevate the table top to the same height as the old to keep the working station ergonomically pleasing. Supports were added under the table to support its own weight to ensure that it will not fold on itself.

4.3 Linear Drives

In order to translate the rotational motion of the motors, intended to move the Styrofoam sheets, into linear motion some form of linear drives were required. In order to cut, the drives would need to be able to move the Styrofoam around in the plane of the table, i.e. allow for x and y movement.

The first step that was taken for this was to contact a few suppliers looking for a ready-made solution. It was quickly determined that these ready made solutions were outside of the budget allocated for the project and it was determined that large cost savings would be achieved by designing and building the system in house.

For the overall concept it was decided to go with a solution similar offered by suppliers with two linear drives mechanically connected with carriages onto which another drive was mounted to handle movements perpendicular to the other two drives. A CAD model of such a system is shown in figure 4.4. With this configuration it would be possible to move to any position on the plane of the table surface.

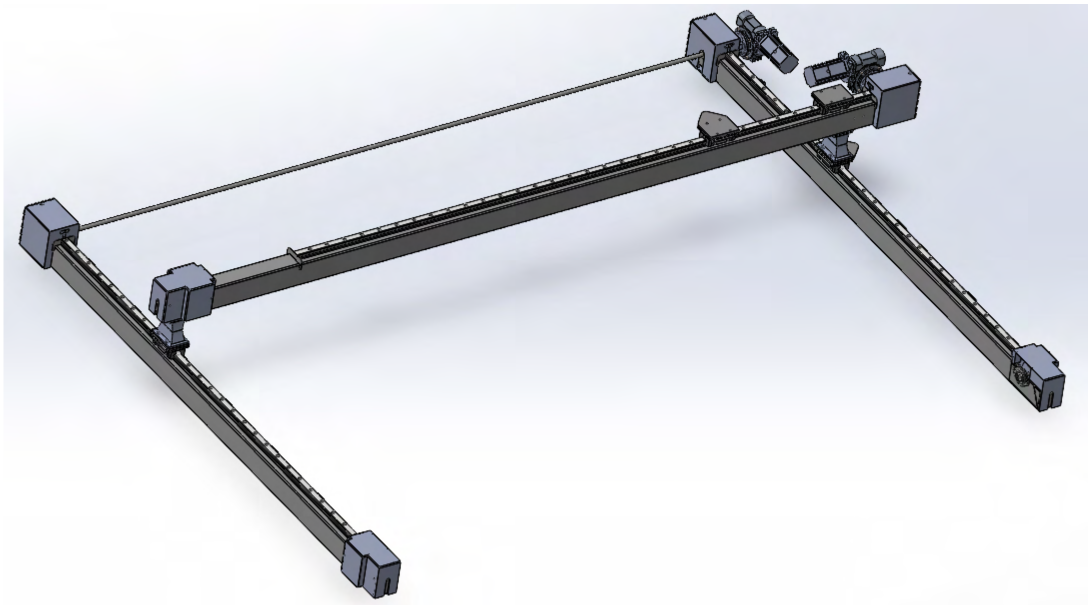

Figure 4.4: An example of the linear drive system needed

4.3.1 Rail Guides

For the linear motion a few different alternatives were considered such as telescopic rails, linear rails and ball screws. Ultimately linear rails were selected since they allow the rails to be supported along the entire length and not just an attachment point in one end like telescopic solutions do. This to ensure stability and provide precision when cutting. The rail systems were also more flexible in regards to available lengths.

With the selected concept appropriate rail sizes and carriages could be selected. For the smallest linear rail and carriage combination available, the maximum forces that could be applied according to manufacturer specifications were several factors of ten higher than the forces that would be acting upon them according to the mass of preliminary design at that time. The deciding factor for sizing was instead to give a rigid and wide base for mounting other components.

The rails and carriages were ordered from a supplier when the design had been finalized and lengths that would be adequate to give stroke lengths for moving the holder from the back or side of the table to just past the wire position.

4.3.2 Belt Drive, Pulleys and Axles

For driving the carriages of the linear rails the main concept explored was using toothed belts. The reasoning behind this was that the drives would not be subject to any backlash when moving or changing direction and be cost effective. Consideration was also taken to select a belt profile corse enough that teeth would be unlikely to slip out of position.

With a system like this some way of tightening the belt was also required. The main concept explored was mounting one of the pulleys on an assembly separate to the main linear drive structure. This assembly would then be constructed to fit into or around the linear drive and the belt tightened by using a screw.

The final step would be to attach the belt to the carriages of the linear drive and the main concept would be to use clamp plates with the belt profile tightened to grip on to the belt.

The pulleys were attached to axles that were to be mounted in bearings and in the case of the driving sides, also attached to the driving motor. For driving the two linear drives that were to run in parallel a long axle was decided to be used. Another solution would have been to use two separate motors but would have the complication of them having to run synchronized and would have increased the cost. The industrial advisor advised that an axle could be used without bending, even if the distance was long and for this reason a long axle was selected.

4.3.3 Mounting and Support Structure

With the subsystems of the linear drives created some form of mounting platform would be required. For this purpose good rigidity, stability and straightness would be important.

A hollow structural section was deemed to fit all of these criteria well and could be laser cut in order to give good precision for mounting holes and other cutouts required.

For other special mounting brackets and details 3d-printing was the main method used. This allowed for prototypes to be created and tried quickly and cheaply. For details that were not suitable for this method, i.e. containing threads or requiring welding instead sheet metal was used. Considerations here included some way of mounting the motor, physical stops on the rails to prevent the carriages from riding of the rails and holes to prepare for attaching cable chains and other mounting details.

4.4 Motors and Gearboxes

Using preliminary designs of the Styrofoam holder weights that the motors would need to drive could be estimated. Using this data dialogues were held with suppliers on what motors could be used. To allow for position control, a stepper motor was selected to be used. When selecting motors, care was also taken to select devices with drivers compatible with the communication protocols used by the PLC. Another consideration was that the motor shaft should be kept from rotation when external forces caused by inserting sheets were acting upon it.

By the time that the motors could be mounted onto the linear drive and tested, it was discovered that the motors did not generate enough torque to overcome the friction losses in the bearings and pulleys. For this reason a gearbox was required. A torque wrench was used to determine the driving force required for the linear drives and it was concluded that it was around two to three times the output of the motor.

The plan was to find suitable gearbox that would fit the motor and that could be attached using the same mounts that were used for the motor with a manufactured adapter. Since the gearboxes had a few weeks delivery time, another solution was devised, re-purposing a gearbox used in one of the garage ports produced by ASSA ABLOY. Using 3d-printed couplings and adapters this gearbox could be used as a substitute for testing and verification. This solution worked well enough that it was used moving forward. The adapter for attaching the motor to the gearbox provided difficult mounting geometry since the flanges intended for mounting had non aligning holes and the flanges of one pice would cover the holes of the other. This adapter was designed by a student worker att ASSA ABLOY.

For connecting the motors and gears to the axle, an axle coupling would be selected that would not introduce any backlash and be able to transfer the required amount of torque.

4.5 Wire Mounting

With the selected concept using a hot wire the wire would need to be mounted in two locations, above and below where the cutting was to take place. The positions had been selected to be in the top arm and under a hole in the table surface, both locations are described further in their own sections.

In general the wire would need to be easy to replace and not require any special adjustment to align when being replaced. These criteria come mainly from a guess that the life of the wire would be such that the operation of replacing it would occur, perhaps not daily but occasionally.

4.5.1 Top of Wire

In the early stages of the project when testing the hot wire cutting concept a wooden prototype was constructed. Here the wire was attached using two alligator clips, one in each end of the wire. One of the alligator clips were attached to a spring in order to compensate for thermal expansion and any other external forces. The wires were guided over ceramic corner isolators typically used in electric cattle fences.

This method was deemed to function well when full access to the clips and isolators was available and the concept was carried over to attaching the wire to the top arm.

4.5.2 Bottom Wire

For mounting the wire below the table, accessing the mounting point was more difficult since one would either have to access it trough the hole in the table where the wire would be run or from below the table. The concept selected for the top arm was thus deemed as being to difficult and some other form of clamp would have to be constructed.

To fasten the bottom of the wire it was deemed ergonomic to have the operator put the wire through the top of the table rather than from the bottom so that they would not have to get down on to the floor and under the table.

For the clamp to function it would have to grip the wire with sufficient force so that it does not slip out. Some way of operating the clamp easily would have to be devised. The clamp also had to be mounted, preferably in an adjustable manner, to the table.

For gripping the wire a few different concepts were tested with wedges, serrated surfaces etc. Some of the prototypes tested can be seen in figure 4.5. These different geometries were designed in CAD-software and 3d-printed in order to be tested. Ultimately the most promising concept was with rhomboid holes that when open would line up and allow the wire to be inserted and when closed would lock the wire into a reliable and predictable position. A prototype can be seen in figure 4.6.

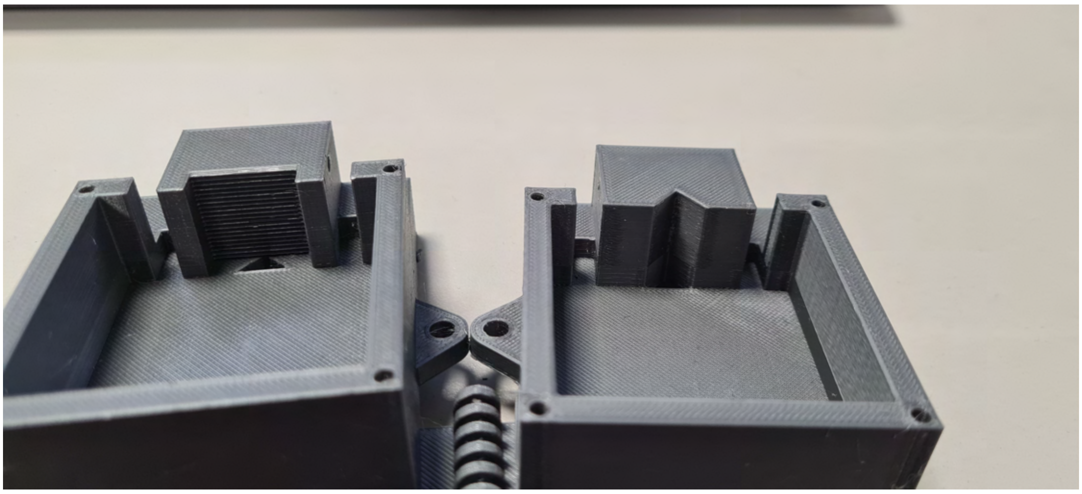

Figure 4.5: Two of the prototype clams for holding the bottom of the cutting wire

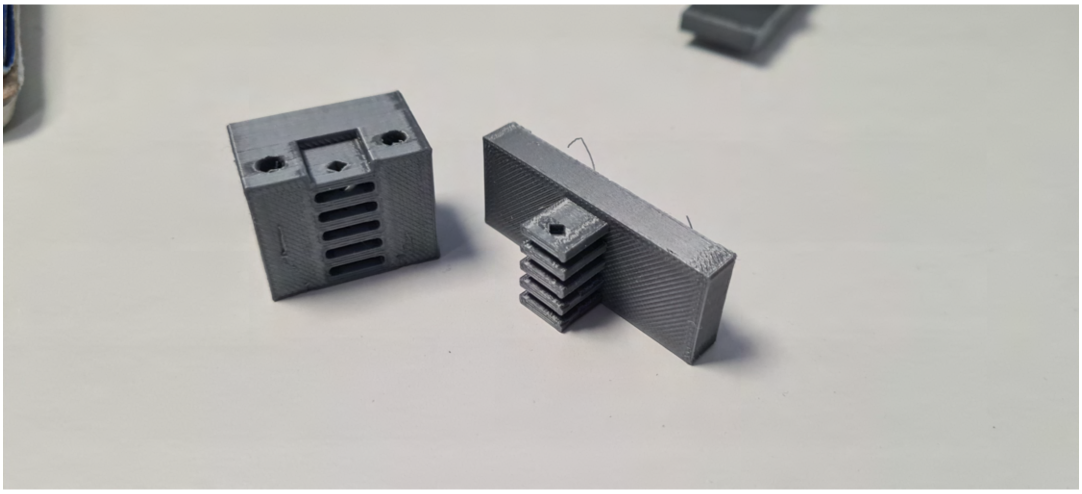

Figure 4.6: A prototype used for testing the rhomboid clamp concept

When testing the different concepts, a spring was used to provide the clamping force. A few springs that were available at ASSA ABLOY were tested until one that provided adequate gripping force was found. Pulling the wire out by hand was difficult with the selected components and this was deemed adequate since the spring on the top mount would not exert nearly as much force.

A lever to push the clamp open would be designed. For this, different lever angles, lengths and shapes were tested by creating them in CAD-software and 3d-printing them. After a few iterations a few points were noted for creating a final design. Firstly by incorporating an over-center mechanism the lever would allow the lever to be held open and thus making the insertion of the wire much easier. By having the lever be bent 90° upwards it would be easily accessible from the operator's position from above the table. A late prototype can be seen in figure 4.7.

Figure 4.7: A late prototype of the lever used in the clamp for the bottom wire

Care was taken to design the lever as long as possible to make it easy to grab from above and the throw distance as short as possible to allow easy operation. The lever was decided to be 3d-printed in ABS plastic, since this had the highest hardness of the available filaments to provide good wear strength [23].

Finally, a housing for the clamping mechanism would be designed so that the clamp could be attached to the table. In this housing considerations for mounting a temperature probe and an attachment for supplying the current to heat the wire were made. As with the other components of the clamp several iterations were made and 3d-printed so that they could be tested.

4.6 Ventilation System

As mentioned before, the fumes created when cutting Styrofoam with a hot element can be dangerous to inhale. It is therefore necessary to have some kind of ventilation system that extracts the fumes from the work station to keep the operators safe. Since the wire is stationary, it is possible to also have the extraction system stationary. An issue that arises however is that if fumes are only extracted from above, the fumes created from the bottom sheet, when cutting four sheets, might not be extracted. It was therefore determined to also extract the fumes from below the table, through the same hole that the wire runs through in the table.

From table 2.1 it is possible to see that all dangerous particles created are detectable by smell before their threshold values is reached, except for benzene. Since the main particle produced is styrene [13] with a very low odour detection threshold, this will be the first indication of fumes not being extracted, well before any other particle becomes detectable or dangerous.

4.7 Styrofoam Holder

The Styrofoam holder's main function is of course to hold the sheets of Styrofoam. It must do this in a way that does not damage the sheets, and it is important that the holder does not get damaged by the wire either. The holder also needs to keep holding the part of the Styrofoam that is being cut, after a piece of the Styrofoam has been severed, but needs to let go of the severed piece. The holder needs to adapt to how many sheets that are going to be cut in one operation so that the operator does not have to set up the machine for this this every time. In addition to this, the sheets vary from being 50 mm to 54 mm thick, meaning that the holder needed to handle this as well. After studying the data of the dimensions that were cut at Reco last year it was clear that a large majority of the cuts being made had at least one dimension over 500 mm, the dimension being smaller usually being the height. This can be used when designing the dimensions of the holder and taking advantage of the fact that it is not needed to solve the cutting of the smaller dimensions.

Many different ideas to solve these issues were iterated. Ideas like holding the Styrofoam using pneumatic cylinders were examined but the issue of maybe running into the cylinders, hence not being able to cut the whole way through remained. Another solution tried was suction cups. This idea seemed to work fine but since the suction cups had a maximum temperature that they could handle, there was a risk of damaging the mechanism if the dimension being cut would end up at the exact position of where the cups were positioned.

Accidentally, when trying to solve another issue that the old specification with the tongue and groove had presented, a specialist in pneumatics from Festo had an idea of drilling and countersinking holes in metal profiles. The idea meant that airflow needed to be generated through the small holes, which in turn would lead to a pressure being created, making the sheet stick to the wall of the profile. The specialist tested his theory with a prebuilt test mechanism and it seemed to work well.

The next step was to create the actual mechanism for the holder to see if it was a viable strategy in practice and to see what kind of flow and pressure that needed to be created to hold the sheets reliably. The tests were performed by firstly, actually drilling and countersinking a lot of holes in one 50 x 50 mm aluminum profile. A vacuum cleaner was then attached to the profile and tests were done to see how well the Styrofoam was being held. When this seemed to work, a flow meter was connected between the profile and the vacuum cleaner to determine how much flow and pressure that were needed to be generated in the finished version of the holder.

When it was clear that this would work, the actual design of the holder was required, specifically the orientation and position of the holes to make sure that the holder can adapt to every thickness of the sheets. To solve this, models of the holder and the different sheets were created in CAD and compared to each other to find the optimal solution of dispersing the holes on the wall of the profile.

4.8 Temperature Regulation

For regulating the temperature of the wire there were a few main points that needed to be addressed. Firstly, some form of indication of the wire temperature would be needed, such as a temperature reading or similar. Secondly, some physical way of mounting this is needed and finally a way of acting upon the given information is needed in order to heat the wire. This section shows the methodology for creation of these subsystems.

4.8.1 Temperature Measurement

A few initial concepts were developed for measuring the temperature of the wire. The first concept was to use a simple temperature probe directly in contact with the wire to measure its temperature. The second concept was to utilize the principle component of the RTD concept by measuring the resistance of the cutting wire and using this as the basis for regulation, since the resistance of a metallic material depends on temperature according to a temperature coefficient [24]. Ultimately the first concept was selected to be further explored since it was deemed as being easier to implement with ready made components.

For temperature probes two different technologies were initially explored: thermocouples and RTDs. RTDs were selected for initial testing due to a wide range of different probe sizes and shapes being available, and the more appropriate temperature ranges that were found from suppliers. A few different varieties were selected and purchased for evaluation. The main area of interest here was how shape, i.e. flat and cylindrical types, different sizes and different sensor types, i.e. Pt-100 and Pt-1000 where the number indicates the resistance of the probe at 0°C, impacted the temperature sensing. A few of the probes tested can be seen in figure 4.8.

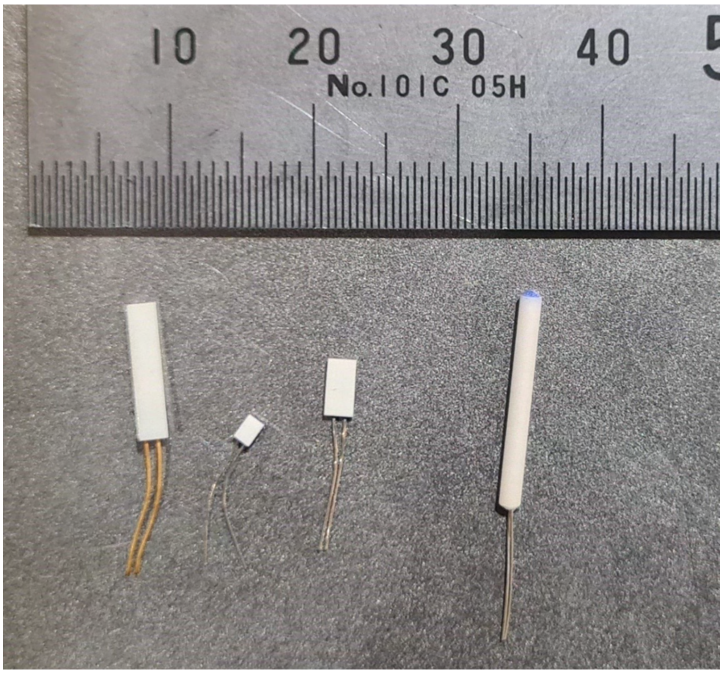

Figure 4.8: A selection of the different geometries and sizes of the probes tested

For reading the values a signal converter handling both Pt-100 and Pt-1000 probes at tunable temperature intervals was purchased with the intent of also using it in the final product. It could then be connected to the PLC and providing an output signal of 4-20mA. By scaling the signal in the PLC to an appropriate range a wide variety of sensors could easily be connected and evaluated.

When evaluating the different sensors they were attached to the wooden prototype and put into contact with the wire which was then heated up. Here the response times where observed. By performing this experiment it could be observed that the flat type probes were the fastest to respond, probably because most of the sensing was in contact with or near the wire. The smaller the probe, the faster the response time, probably since it has less thermal mass. In regards to the Pt-100 versus Pt-1000, the technology used did not seem to impact the measurement. With the Pt-1000 probes resolution would theoretically be better but in the situation at hand with typically a few hundred degrees interval it did not seem to matter.

The most promising probes were also used in an attempt to regulate the temperature of the wire using a PID-controller implemented in the PLC and then attempting to tune the controller accordingly.

During the experiments a controller configuration with the smallest flat type probe could regulate the temperature of the wire with an accuracy of about 2-3°C with minimal oscillations and what was deemed as an adequate response time in the range of a few seconds.

4.8.2 Mounting of Temperature Probe

For mounting the temperature probe two main issues were faced. The first issue was that when the wooden prototype was used to test the cutting mechanism it was discovered that cutting the Styrofoam would cause a very local temperature drop, as observed by the change of the red glow of the wire to its normal metallic color. This was also supported by the study conducted by H.Brooks and D.Aitchinson [8]. The second issue was that the probe would have to be mounted so that it was in contact with the wire and to somehow create a holder tolerant to the heat. For reference the temperature probe that would have to be mounted would be of the flat type and as small as possible as seen the second probe from the left in figure 4.8.

The desired position of the temperature probe was decided to be placed as close to the cutting as possible. This to ensure that the temperature dip in the wire would be observed as good as possible. The best place for the probe to be mounted was deemed to be at the bottom clamping assembly since it would place the probe near to the cut and allow the probe to be reliably in contact with the wire due to the mounting mechanism, as described in section 4.5.

For the actual mounting of the probe no mounting points were available on the probe so the main concept to be explored was decided to be to cast it into some material. Two different products that would handle the heat from the cutting wire were tested for this.

The first product was an exhaust repair gum from CRC with glass fiber reinforcement. The motivation behind this was that it would be able to be cast into a brick and thanks to the reinforcement hold its shape well.

The second product was a heat resistant joint compound called Heat 1500°C from Casco, typically used in fireplaces and other high heat applications. This was selected since it had a more liquid texture than the repair gum and thus might be easier to mold.

Using 3d-printed molds, attempts were made to cast these into bricks containing the temperature probe. These tests showed that due to the size of the bricks both materials would crumble despite what was advertised, even when hardened according to specifications.

The next attempt was to make a 3d-printed holder that would contain a smaller amount of compound cast in place to hold the probe and protect the plastic holder. Attempts were made with ABS plastic, which was the plastic with the highest glass transition temperature available at ASSA ABLOY, so that the products could be oven hardened just below the glass transition point. The holders were tested using a soldering iron hotter than typical wire temperatures in contact with the holder at the point where the probe would be for several minutes, resulting in harsher conditions than would be seen in cutting situations and the glass transition temperature for the plastics were never reached. Thus this was deemed a reliable and satisfying concept.

Out of the two different products tested the addition of glass fiber reinforcement ultimately did not seem to make an impact on the end result and thus the easier to handle material would be used.

4.8.3 Temperature Regulation Controller

For temperature regulation of the hot-wire a pre-made PID-function block was available.

4.9 Electrical Design

The electrical design of this project mainly included selection of various parts to be used and their physical implementation. This section shows the methodology for performing these tasks.

4.9.1 PLC and HMI Selection

For selecting a PLC recommendations were given by the industrial supervisor to select a Crouzet product. The development software is freeware and it is function block based. This was decided to be an advantage for when the machine was to be handed over to make it easy for any future improvements or fixes to be implemented by someone without a background in PLC programming.

A supplier was contacted and discussions were held. Some features that were known to be needed were a PWM output to drive the cutting wire, an analogue input for temperature measurement and the PLC would need to act as master in modbus RTU communications with the motor drivers. Only one option existed, the em4-E. Apart from the analogue input and analogue output a number of digital inputs and outputs would be needed, however the exact amount was not known. Extensions were available for the model suggested and could be purchased if needed.

An HMI was also suggested from the same manufacturer to allow for compatibility and ease of integration. A 7" display was deemed sufficient to allow for clear legibility for the application at hand.

4.9.2 Proximity Sensor Selection

Sensors were needed in the Styrofoam holder in order to determine how many layers of Styrofoam were in the machine to control the holding fans accordingly. These would be mounted on the end of the Styrofoam holder and thus an appropriate sensing distance was deemed to be a few millimeters to a few centimeters. The types available were inductive, capacitive, optical and supersonic. Both inductive and capacitive were disregarded since they would not interact with the Styrofoam sheets. Some quick research on pricing from supplier shops showed that the optical sensors were cheaper and thus this concept was selected. Since the environment around the machine would be free of debris and obstructions, using an optical sensor was deemed appropriate. With optical sensors it was also important to select a sensor that would be safe to the operators by not causing eye damage. This could be done by selecting a class 1 laser as these are safe even when exposure is prolonged.[25]

4.9.3 PWM-signal Current Amplification

Since the PWM output from the PLC was not rated for the current that would be required in order to heat the cutting wire, a current amplifier was needed. An amplifier of unknown origin was available to be used in proof of concept testing. If the amplifier performed well, the plan was to perform EMC-tests to determine if it would be compatible with the requirements for CE-certification on these points. Another option would be to find a new replacement component from a trusted supplier.

4.9.4 Physical Implementation

During the course of the project different components and subsystems were delivered or completed at different times. Whenever such a system or component was tested it was noted how these would be connected to the complete system, i.e. the PLC, power supplies etc.

When a good understanding of all subsystems existed an electrical cabinet was found and components could be installed and connected. Components like power supplies could be selected based on the current drawn from the other components selected.

Wires that needed to go outside the electrical cabinet were then installed under the table through cutouts in the support structure using cable pipes to desired locations.

The final step was to create documentation in the form of an electrical diagram.

4.10 Software

Within the project some form of control system would need to be implemented using the Crouzet-soft environment for the selected PLC. Software would also need to be created for an HMI-screen with the supplied software Crouzet-touch-soft that would serve as an interface between the PLC and the operator. This section shows the methods for creating these programs.

4.10.1 Control and PLC Logic

The first step for creating the control logic was to create a state machine that would represent the different steps that the control would be based upon. The chart created would then be updated several times whenever new functions were needed or misses were discovered.

For implementing control and PLC logic the development sofware Crouzet-soft, shipped with the selected PLC, was used. This environment allows setting up state machines using SFC, implementing logic using gates, performing calculations and implementing ready made PID-controllers.

For the main logic of the state machine SFC was used and appropriate input signals were combined with logic gates to create transition conditions. For outputs from these states a single output bit was available. This could be used, again with logic gates, to set outputs, for example turning on the extraction fan. However, other more complicated operations were also required to be performed, such as writing to registers in the motor drivers an passing data back to the HMI screen.

Communication with the HMI was done using TCP/IP. Communication with the motor drivers was done using Modbus RTU. For these communications function blocks were available where target registers could be set up. A spreadsheet was made to coordinate the use of what registers were used in communications.

4.10.2 HMI

When designing the HMI it was deemed important to listen to the operators' opinions of what the HMI should look like. Their biggest concern was that the HMI would be too complicated to use and that the buttons would be too small. In addition to this, the HMI of course needs to have all of the functions that are needed for the complete functionality of the machine. It should also be easy to tune and change the parameters of the machine from the HMI. Maybe the most important aspect in designing the HMI, however, is making sure that wrong handling of the HMI can not break the machine or putting the machine in states that are not handled by the HMI.

The method for developing the HMI was based on implementing the functions that were needed to test the different systems in the machine when it was time for implementing that specific system. Most of the functionalities were already considered early in the project and could therefore be added early but other functions were invented later which then required implementing them in the HMI. In the later part of the process the design was reworked to handle the concerns of the operators.

4.11 CE-Certification

With the previously researched information about CE-certification, as presented in chapter 2, a meeting was set up with a product safety engineer at ASSA ABLOY. At this meeting an introduction was given for the internal implementation of steps required for CE-certification. The steps required depended on the applicable standards and these in turn on the product. The path was thus not apparent from the start but would depend on design decisions or component choices. A technical file template, that in the end is one of the documents required for CE-certification, was filled in with documentation as it became apparent and needed. Nonetheless a list of a few items that would be required could be set up:

- An initial concept risk assessment early in the project where potential risks could be identified and worked with during the project. This risk assessment was constructed according to the SS-EN-ISO 12100:2010 document.
- If the risk assessment showed that emergency stops were required, an additional document detailing these had to be compiled, according to SS-EN-ISO 13850-2015.
- An electrical diagram
- A user's manual
- A final risk assessment when the machine is finished needs to be made in order to ensure that no remaining risks are present
- A declaration of conformity

The product safety engineer also assisted in selecting the relevant applicable standards for the risk assessment to the following:

- Machinery directive
- Low Voltage directive
- EMC directive
- RoHS directive
- SS EN 60204-1:2018 Electrical Equipment of machines - General Requirements
- SS EN ISO 12100:2010 Safety of machinery - General principles for design - Risk assessment and risk reduction for guidelines

- SS EN ISO 13849-1:2015 Safety-related parts of control systems - Part 1: General principles for design
- SS EN ISO 13854:2019 Safety of machinery - Minimum gaps to avoid crushing parts of the human body

The internal documents pointed toward emergency stops being required. For cutting the power in conjunction with the emergency stop a device with a large amount of breakage cycles would need to be selected. For this a safety relay was used for supervision along with a contactor to break the current.

The main component to be cut from power were the motors. It was decided that all other components and subsystems would also be turned off when the emergency stop button was pushed, however not through the safety relay but through logic in the PLC. There was some initial ideas of the extraction fan still remaining operational in this state to extract any possible fumes, however it was ultimately deemed inappropriate since it might prove to be unexpected behavior.

Other risks that were identified with the machine was with extraction of fumes created from cutting and the temperature of the wire. Elimination of these risks were to be implemented by design and are described in their respective sections.

The risks concerning the low voltage directive were fire hazards and electrocution hazards from mains power.[26] This had to be considered in conjunction with the power supplies and extraction fan used. In order to satisfy this appropriate wire gauges had to be selected, cables protected and competent installation preformed.[27]

The remaining RoHS and EMC directives could be achieved by using already CE-certified components, since if the component is CE-certified it does not contain any material prohibited by RoHS and would be tested according the EMC directive.[28][29].

4.12 Result Verification

With the target specifications set up in chapter 3.2, tests would need to be set up. Certain points here can be answered with a yes or a no by taking measurements, while some points require testing before a definite answer can be given.

For the CE-certification points, the points set up as target specifications will be achieved by conforming to the relevant directives and standards. The relevant standards have previously been discussed, but are listed in table 4.1 also. If these standards are met all points presented in the specifications will be fulfilled.

Under the ”Using the Machine” all points are directly answerable by taking a measurement. As previously discussed the tongue and groove method of connecting sheets together currently in use will be be removed in favor of using only full sheets, all specifications regarding connecting sheets could be removed.

For ”Cutting” a similar situation with the tongue and groove is observed, where the specifications regarding connected sheets were replaced with only handling a single sheet measuring 1200mmx1200mm. For the specifications here more extensive testing would need to take place than taking a single measurement.

For ”Interfacing With the Machine” the points are a simple yes or no regarding implemented features in the HMI.

For ”Work Environment” some tests have to be devised to find if the points are fulfilled.

Since the concept of hot-wire cutting had not been determined when the target specifications were determined and agreed upon, no specification relates to how long the machine should be able to operate before the wire needs to be replaced. This was deemed as an important factor so this and the ease of replacement were included as testing points after consultation with the industrial supervisor.

In order to verify that the machine and this project is finished, a document for verifying the machine's functions was created. These are different tests that are performed on the machine when it is deemed finished to verify that the machine is ready to be installed at Reco. The tests were also constructed in a way that fulfills the demands that were set in deliverables as well as in the setting specifications. If the tests are passed, the demands are deemed as if they are completed. The validation of these tests varies from actual objective results to subjective reasoning ultimately judged by supervisor Anders Löfgren. In order to complete the CE-certification of the machine, certain directives and standards need to be met. When they are completed, the machine is ready to be installed at Reco where it will be used during a trial period to make sure that it works as intended. The tests and the standards can be seen in table 4.1.

Testing Category	**Test**	**Comment**
Cutting precision	Cutting 10 sheets several times reducing the dimension by 50 mm after every cut and measuring at 5 points of the sheet after each cut in both cutting directions without homing between cuts. If cuts are made with a precision of ± 1 mm, the accuracy is deemed approved. This should be tested with one, two, three and four sheets in the machine	This will address the points under ”Cutting” in the specification list
Wire longevity	Wire survives performing the precision cutting test. This serves as a stress test of the wire testing amount of heating cycles it can survive before needing replacement.	No specification correlates to this, however was deemed important

Testing Category	Test	Comment
Styrofoam holding	The Styrofoam holder can reliably hold one to four sheets of Styrofoam while performing cuts. By performing the cutting precision tests and noting if the sheets are reliably held in place this test can be passed.	This will address the points under ”Cutting” in the specification list
Fumes and debris	Performing 10 cuts with four sheets. Observations are made if any fumes can be smelled or if any debris is spread in the work area. If no debris is spread and no fumes can be smelled this test is passed.	While a direct correlation between this point and a specification set up exist, this specification requires more testing than taking a simple measurement and for this reason it is mentioned here
Replacing wire	If the cutting wire can reliably be replaced in less than five minutes this test is passed.	No specification correlates to this, however was deemed important
Ergonomics	Having five people performing 10 cuts each using the machine with unloading and loading of several sheets, the machine is deemed comfortable to use if the people find it comfortable.	While specifications exist for exact measurements the operator has to reach, it was deemed appropriate to verify that these did in fact result in an ergonomic solution
CE-certification	Machine adheres to MD, 2006/42/EC	
CE-certification	Machine adheres to LVD, 2014/35/EU	
CE-certification	Machine adheres to EMCD, 2014/30/EU	
CE-certification	Machine adheres to RoHS, 2011/65/EU	
CE-certification	Machine adheres to EN 60204-1:2018 (Electrical equipment of machines)	
CE-certification	Machine adheres to EN ISO 12100:2010 (Risk assessment and risk reduction)	
CE-certification	Machine adheres to EN ISO 13849-1:2015 (Safety of machinery)	
CE-certification	Machine adheres to EN ISO 13854:2019 (Minimum gaps to avoid crushing of parts of the human body)	

Testing Category	Test	Comment
CE-certification	Emergency stops break power to all components that it should when pressed	Test to ensure that connections have been made correctly for the safety related systems
CE-certification	Stopping the system in all program states and starting up to make sure that there is no unexpected startup	Test to ensure that connections have been made correctly for the safety related systems

Table 4.1: Tests devised for verification points

Chapter 5

Results

In this chapter the finished solutions to the machine will presented and how well the machine can pass the tests that it has gone through.

5.1 Cutting Mechanism

As mentioned previously the machine cuts the Styrofoam using a stationary hot wire. This means that the wire does not move but the Styrofoam does. The wire size chosen from the test was 0.21 mm.

From the tests conducted using different wire gauges, the 0.21 mm wire was sufficient for cutting one sheet of Styrofoam as discovered with the wooden prototype. Cutting of one sheet could be conducted at a pace that was deemed to be at around that of the final machine. Due to the limitations of the prototype, it was only possible to test with one sheet. However, when several sheets were to be cut the resistance was to high to provide adequate power and thus the wire was cooled too rapidly.

The cutting tests showed that cutting was possible at temperatures as low as around 150-200 °C and at around 400°C the kerf width was over one millimeter. The cutting temperature was thus deemed to be within this span of temperatures.

5.2 Cutting Table

The tabletop has the dimensions 2200 x 2200 x 200 mm and was designed this way due to the initial intensions of continuing using the tongues and the spare parts of the Styrofoam. This would allow for loading two 1200 x 1200 sheets before cutting. The legs of the table are designed so that the tabletop is at a height of 850 mm which allows for ergonomic loading and unloading of the sheets. The height is slightly adjustable due to the adjustable feet at the bottom of the legs but their main function is helping getting the table into level position. At 660 x 660 mm from the edges closest to the operators starting position and the side to the left of the operator, a 80 x 80 mm quadratic hole is cut through the table top. It is through this hole, the wire is mounted. To support the weight of the table, support structures under the table has been designed so that the table is sturdy enough. Strategically placed holes are made in the sides of the table to allow for mounting of the features which can be seen in figure 5.1.

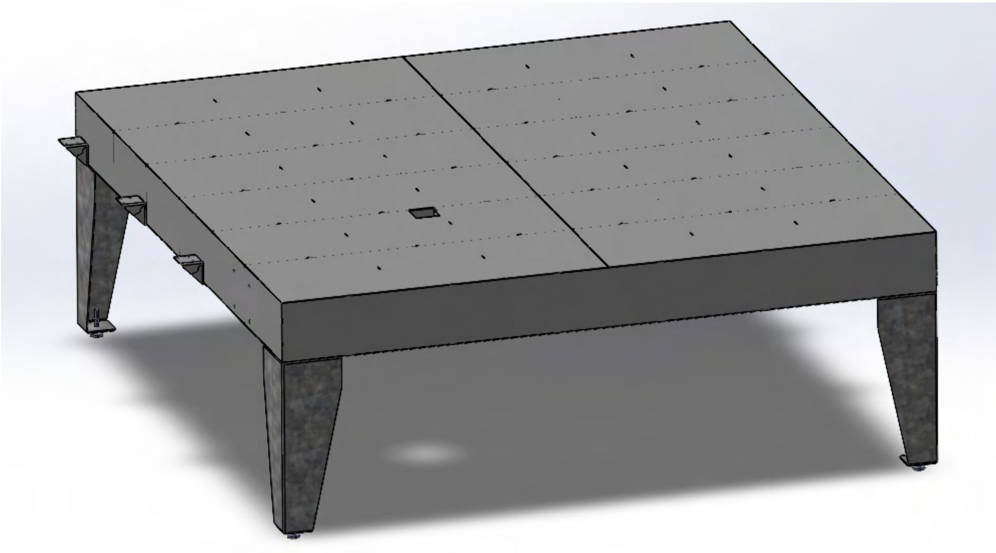

Figure 5.1: CAD model of the table

5.3 Linear Drives

The final linear drives consist of linear rails mounted onto a hollow structural section. Two pulleys are attached at each end of each drive and a belt is run inside and above the structural section and clamped to the carriage with a clamp plate. A CAD model of a mounted linear drive can be seen in figure 5.2. The different parts of the linear drive are described in further detail in the following subsections.

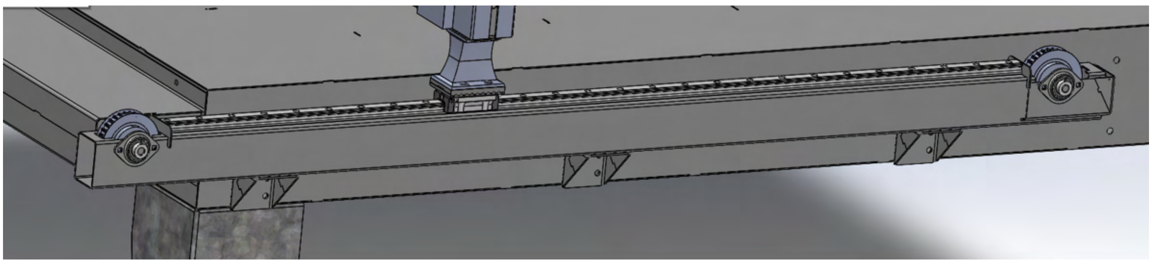

Figure 5.2: An image showing a CAD model of a mounted linear drive

5.3.1 Rail Guides

The rail guides and carriages that were ultimately selected were manufactured by NTN Europe in a 25mm rail configuration. The deciding factor for the dimensions were, as mentioned, the mounting base each carriage had available and the 25 mm configuration gave what was considered an adequate plate for mounting. The lengths of the rails were decided to be 1590 mm and 1990 mm respectively in order to provide the desired stroke lengths adequate for cutting and loading sheets.

5.3.2 Belt Drive, Pulleys and Axles

For driving the carriages of the linear drives a toothed belt was used. A tooth-to-tooth distance of 10 mm was deemed adequate to prevent slipping, especially since the belts were designed for larger loads than would be experienced in driving the linear drives. A pulley designed to be as large as possible for the structural hollow section without hitting the bottom was also ordered from the same supplier and manufactured to fit onto the 12 mm axles that were used for driving. The principle for pulley mounting can be seen in figure 5.3.

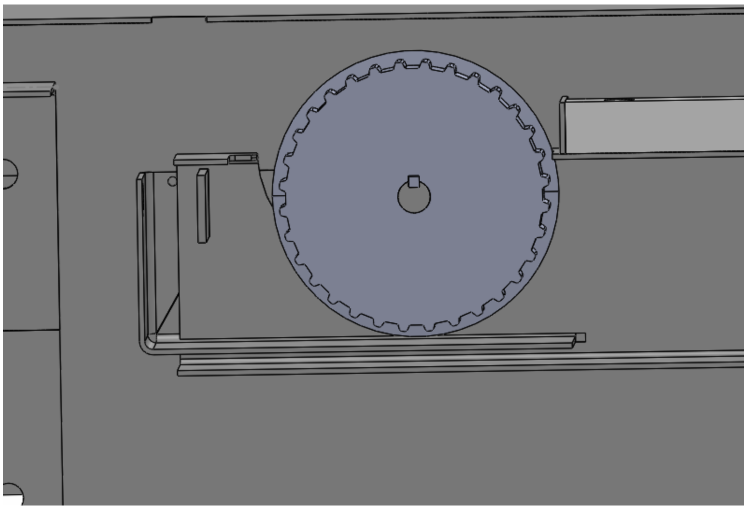

Figure 5.3: Cut view of a linear drive illustrating the principle of the pulley mounting

Tightening the belt was done by mounting one pulley of each drive on a separate assembly than the rest of the hollow section that was the base of the drives and slotting it into a cut out groove. This assembly was manufactured out of sheet metal and bent into position and welded. A nut was welded to the assembly and by using a screw the assembly is pushed away from a plate and thus tightens the belt. A second nut is then used to lock the screw into position. The mounted assembly can be seen in figure 5.4.

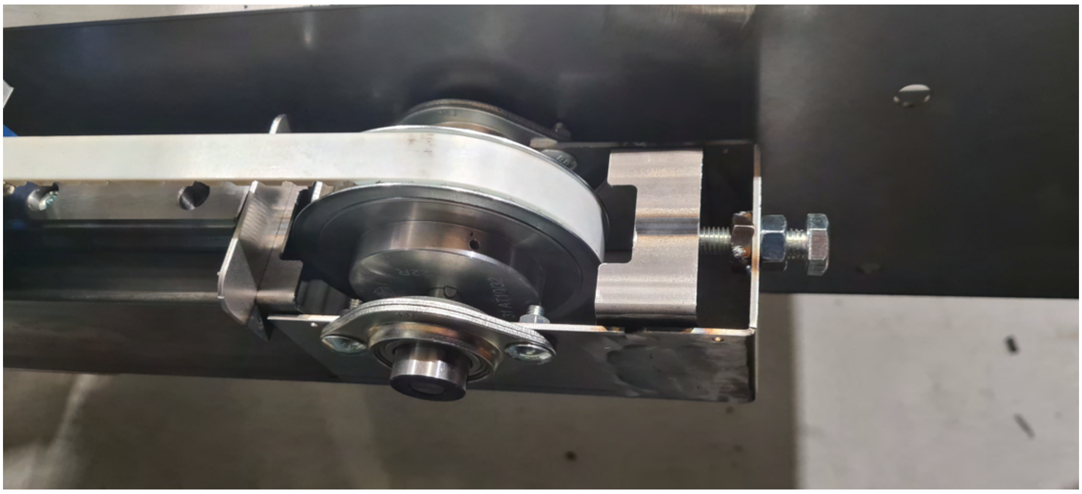

Figure 5.4: The adjustable pulley assembly

The clamp plates attaching the carriages to the drive could be created in CAD-software to match the given belt and 3d-printed. These were then screwed onto the rail carriages and clamp the belt. The mounted clamp plates can be seen in figure 5.5.

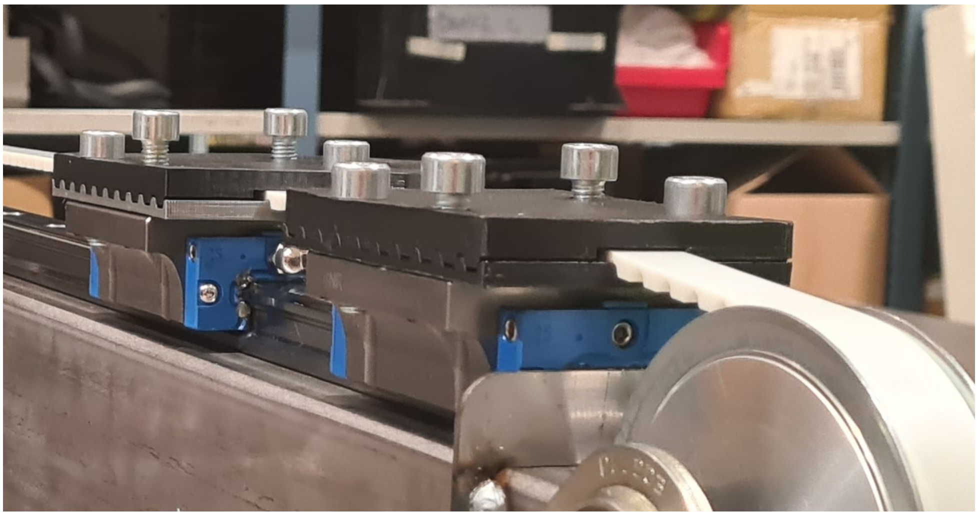

Figure 5.5: Mounting of clamp plate on the linear drive

The axles used for driving were dimensioned to be 12mm. This decision was made after consultation with the industrial supervisor, since he deemed this appropriate for the long length of the axle on the back side. Appropriate bearings were selected with a flange mount so that easy and compact installation with carriage bolts could be performed with square holes cut in the structural section. A mounted bearing can be seen in figure 5.6.

Figure 5.6: Picture of a mounted bearing

5.3.3 Mounting and Support Structure

The mounting structure for the linear drives consists of a main hollow structural section manufactured using laser cutting with appropriate cutouts for pulleys, axles, adjustment assemblies and holes to facilitate mounting of the rail guides and cable chain attachment points using thread pressing screws.

Onto the section are welded stops for the rails as seen in figure 5.7 and mounts made for the motors, that later instead would be used for the gearboxes.

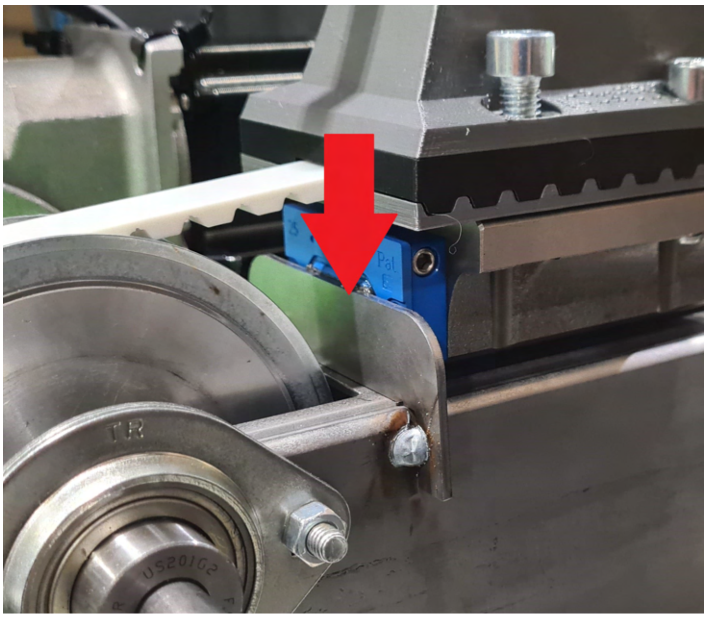

Figure 5.7: Rail stops mounted on drives indicated by the arrow

The connection between the lower linear drives and the upper drive consist of a 3d-printed block as seen in figure 5.8.

Figure 5.8: Connection block between upper and lower linear drives

5.4 Motors and Gearboxes

The motors selected were of the type CS-M22313B manufactured by Leadshine. This is a closed loop stepper motor, meaning that a certain position can be set and the accompanying drivers, CS2RS-D507, along with an encoder in the motor ensure that the position is reached or it indicates an error. The motors also include breaks to be used in holding the motor stationary when movement is not desired.

The gearbox that was used was a worm gear type gearbox, purpose built to attach to a different motor so, as mentioned before, some adaptions had to be made. For attaching the gearbox to the mount plate originally intended for the motor an adapter was designed and 3d-printed using ABS. The attachment adapter between the motor and gearbox was a plate 3d-printed in ABS where the attachments were staggered from each other by 45° and threaded inserts were melted into the plastic to allow for fastening from both sides of the mount. The mounts can be seen laid out in figure 5.9.

When coupling the driving mechanism the first item to look at was the coupling from the axles to what was first the motor and later the gearbox. For axle coupling an appropriate friction coupling was used. The holes for axles in this coupling were designed based on the 12 mm driving axle and the 8 mm motor axle as seen in figure 5.9. For this reason when a gearbox was later required, the gearbox's outgoing axle used with the gearbox was machined down to fit the 8 mm and slotted into the gearbox using key and keyway.

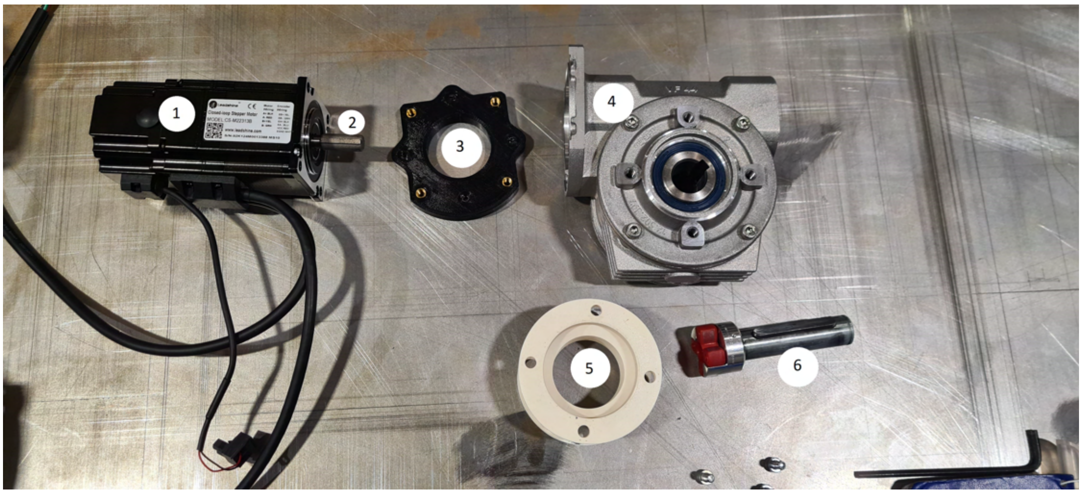

Figure 5.9: Parts of the driving assembly laid out with parts marked by number: 1) Stepper motor 2) Motor-gearbox axle adapter 3) Motor-gearbox mount adapter 4) Gearbox 5) Gearbox mounting adapter 6) Outgoing gearbox axle with axle coupling mounted

The final coupling was between the motor and the gearbox and here the model used when 3d-printing plastic test pieces was used and a 3d-print was made in stainless steel to be rigid and durable. The part was 3d-printed since the geometry required to fit on top of the axle and into the gearbox did not lend itself to conventional machining methods and the price of the printed parts was low. The piece can be seen in figure 5.10 and a CAD model showing a cut view can be seen in figure 5.11.

Figure 5.10: Stainless steel 3d-printed adapter for fitting the motor into the gearbox

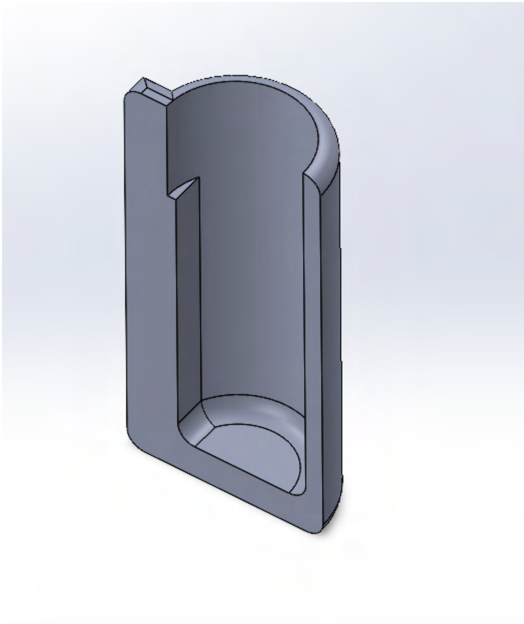

Figure 5.11: Cad model showing geometry of the motor-gearbox adapter

5.5 Wire Mount

In this section the results regarding the mounting of the cutting wire are given.

5.5.1 Top of Wire

The mounting top of the wire was, as mentioned, handled using an alligator clip mounted on a spring. The force exerted on the wire of the spring would not need to be large, it would only need to handle keeping the wire taught during thermal expansion experienced when the wire is heated. A large selection of springs were available at ASSA ABLOY and thus one that fit these criteria was selected. Markings were added to the mount to indicate how far the spring should be extended when mounting the wire. The wire is then run over a porcelain corner isolator to position it and current is supplied to the wire using another alligator clip. The screw onto which the spring is attached has a plastic piece 3d-printed collet with a groove for the spring to sit into in order to isolate it from the top arm. An image of the setup can be seen in figure 5.12.

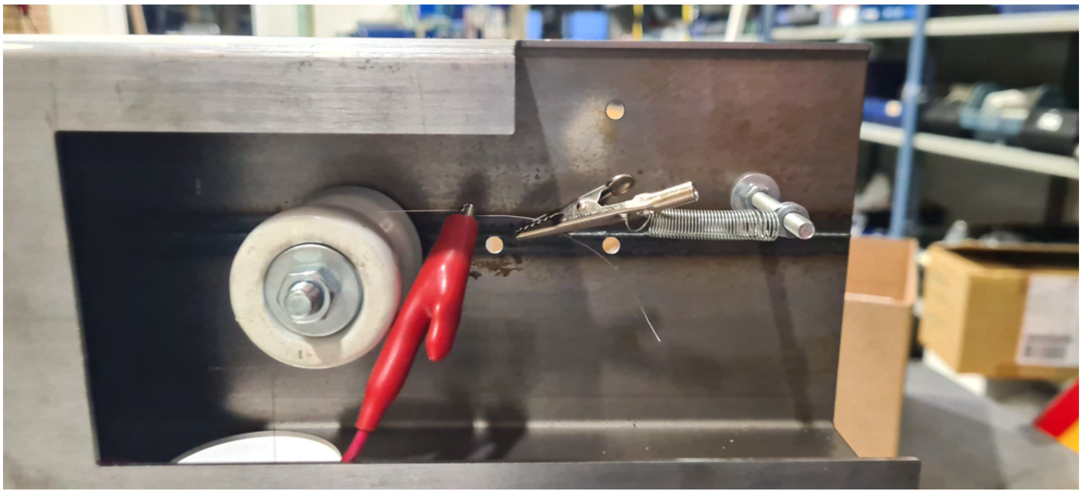

Figure 5.12: Compartment in top arm where wire is held and connected to current. The clip attached to the spring holds the wire and the isolated clip supplies the current

5.5.2 Bottom of Wire

For the bottom clamp the final concept of overlapping rhomboids was used and metal plates were ordered to be laser cut for this purpose. These plates were then inserted into 3d-printed holders that could be mounted to the housing. The mechanism can be seen in a CAD model in figure 5.13.

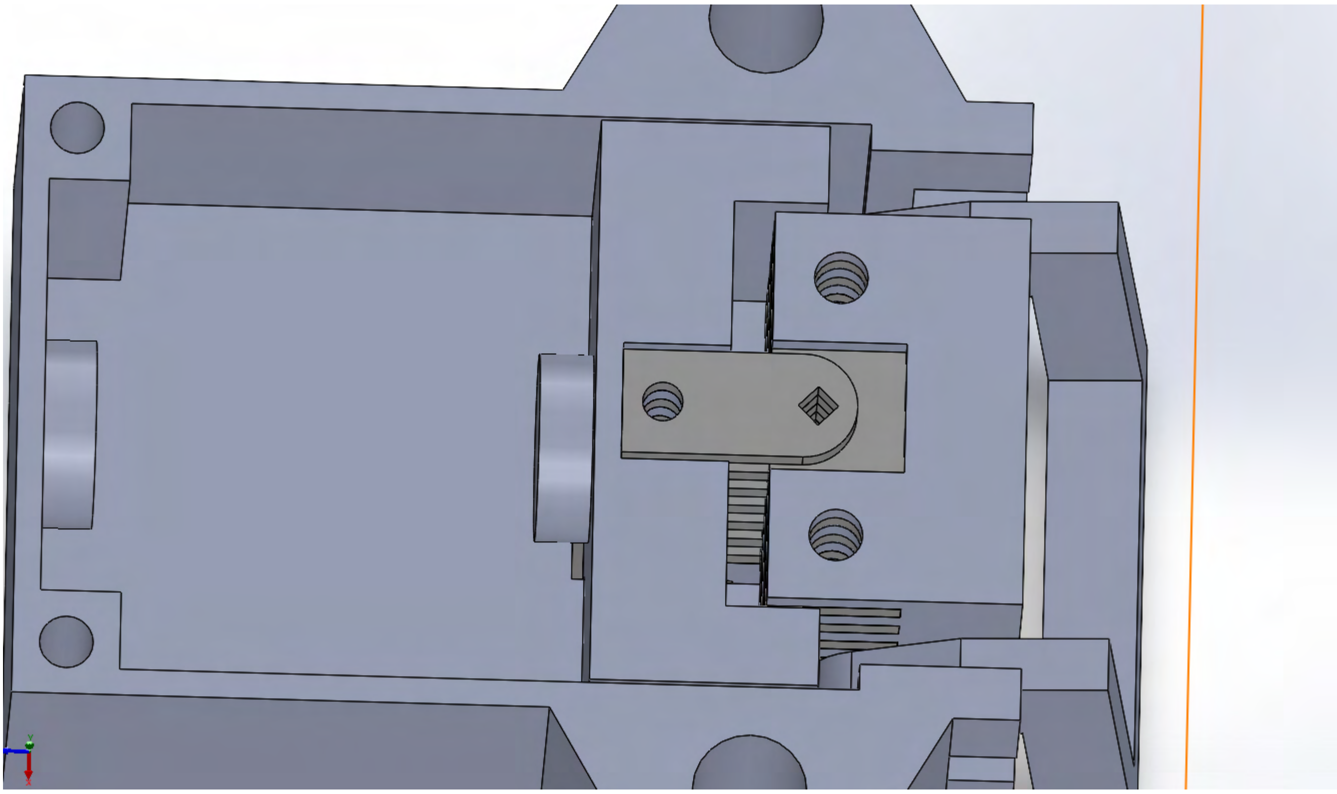

Figure 5.13: The clamping mechanism assembly as seen in CAD software

The lever to be used was based on the over-center principle to hold the clamp open. The exact length and shape of the final lever can be seen in figure 5.14.

The decision to print the lever in ABS plastic was not enough to provide the wear resistance desired and after some use it was observed that the clamp sometimes would slip into the closed position by itself.

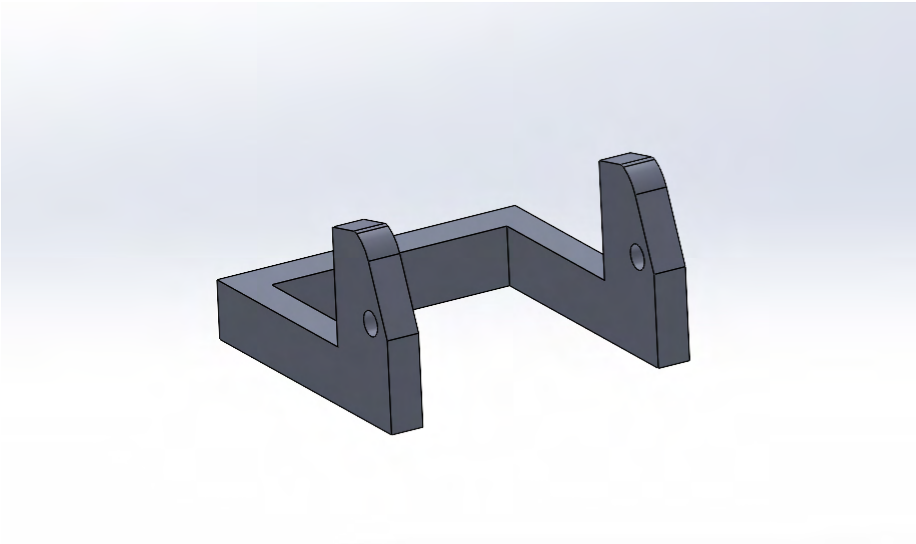

Figure 5.14: The lever used for holding the clamp open

A large variety of springs were available so a spring that held the wire comfortably while still allowing the lever to be operated was found by testing and selected.

The clamp housing was mounted to the table by use of a special laser cut mounting plate welded to the bottom of the table. It was designed so that by pushing it against the supports of the table it would be positioned to align with the mount in the top arm. Some adjustment were still made possible by having slotted cutouts where carriage bolts with their heads machined down would be used for mounting the housing trough mounting holes as seen in figure 5.15. A mount slot was created for the temperature probe holder to slot into. The mounted probe holder can also be seen in figure 5.15.

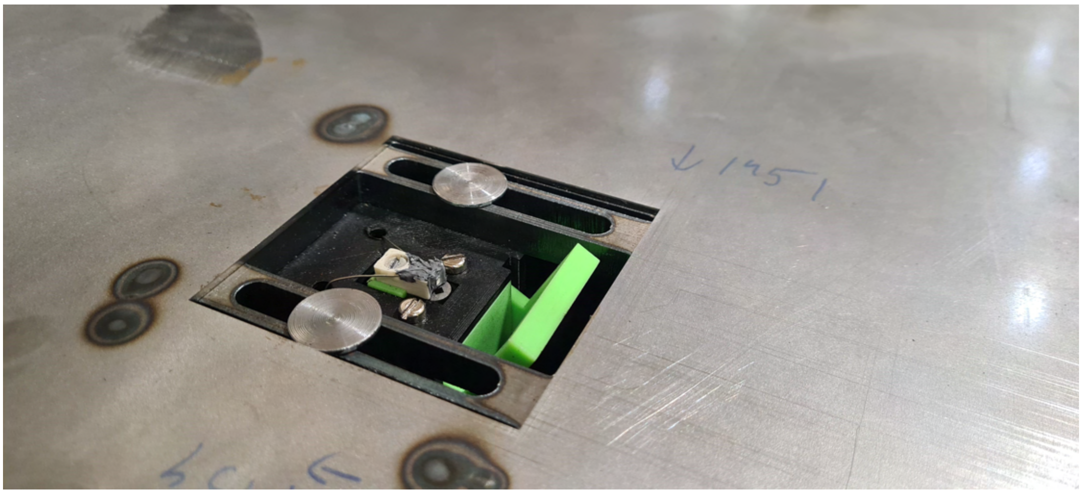

Figure 5.15: Bottom clamp mounted into position on the table

By utilizing the sheet metal parts of the clamping mechanism the current supply for the wire could be attached directly to these using a nut as seen in figure 5.16.

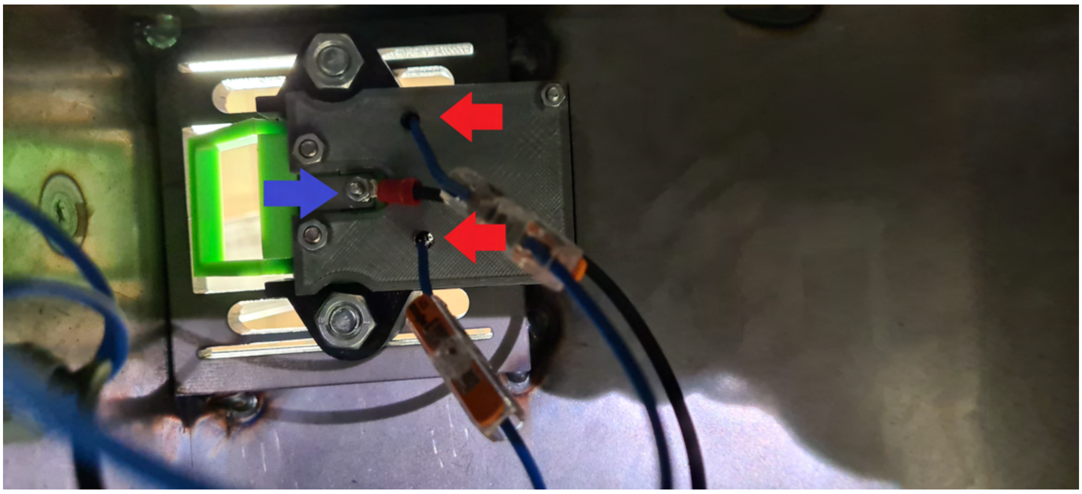

Figure 5.16: Bottom of clamp with current supply for wire indicated by the blue center arrow and RTD connections indicated by the two red arrows

5.6 Ventilation System

In order to have a working ventilation system a 62 l/s fan is mounted below the table. This fan is connected to a flexible plastic tube that in its turn is connected to a T-cross, see figure 5.17.

Figure 5.17: The T-connection of the ventilation system. The left pipe after the T-cross leads into the arm that the wire is mounted on. The right pipe leads to the box below the table.

This allows for only one fan being used for both extraction points. Since an end cap is put on the end of the steel profile to direct the flow to the 50 mm hole where the wire runs through so that the fumes are removed upwards into the steel profile, as figure 5.18 shows.

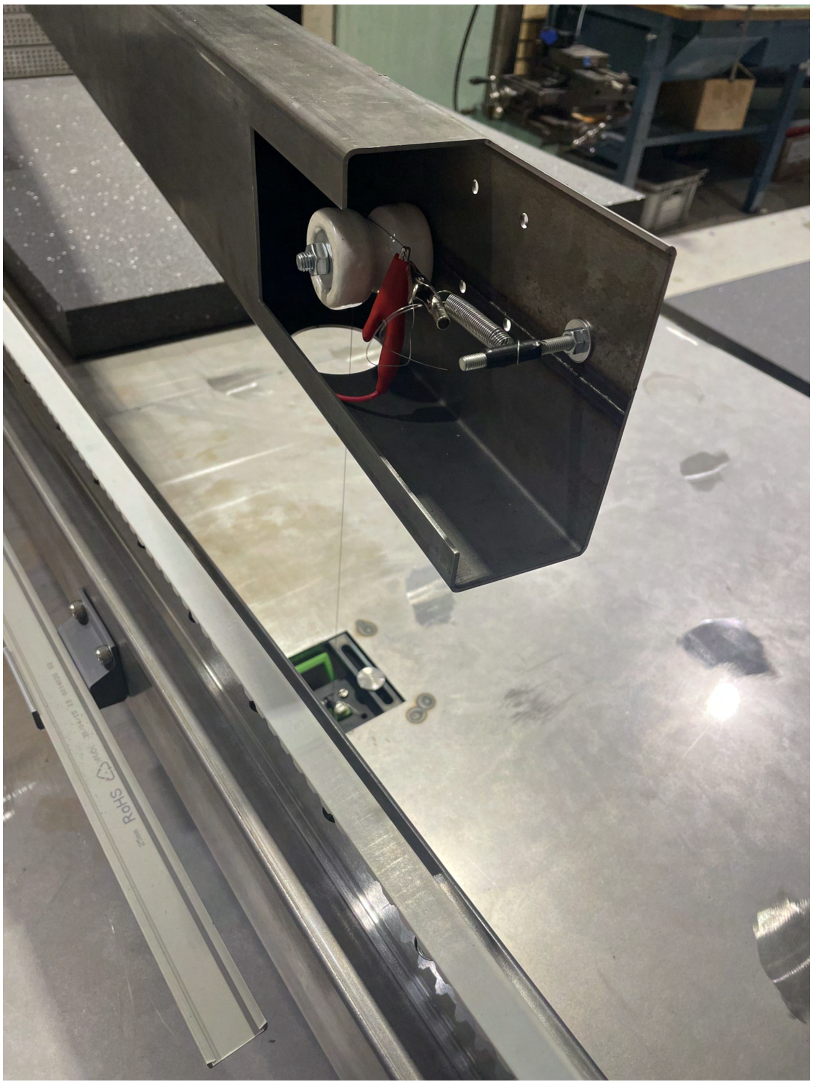

Figure 5.18: The ventilation hole in the arm

The mount of the arm rotates the arm 9° to make sure that the hole is placed directly above the hole in the table. The fact that the arm is a steel profile is taken advantage of since the profile acts as the ventilation pipe. On the other side of the T-cross the pipe leads into a box that is created by sheets of metal being welded to the supports under the table, see figure 5.19.

Figure 5.19: The box below the table. The red arrows point to the magnets

In order to seal the box the sheets of metal are bent and magnets are screwed to the bends. The magnets will hold the bottom metal sheet in place. The bottom has insulation tape mounted on it. The tape is pressed up against the supports under the table, creating a seal. 3d-printed handles are placed on the bottom metal sheet to be able to remove the bottom if maintenance on the bottom wire holder is needed, see figures 5.20 and 5.21.

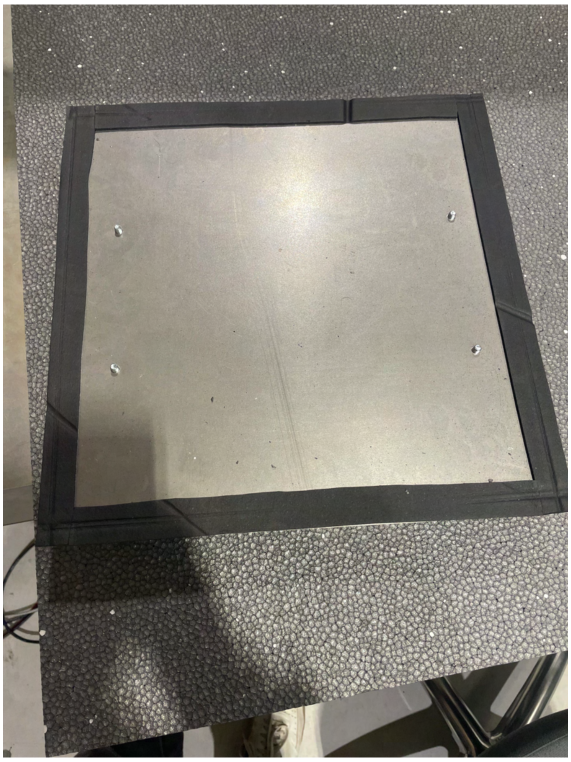

Figure 5.20: The insulation tape in the bottom sheet of the box

Figure 5.21: The handles on the bottom of the box

On the other side of the fan another pipe is connected and this pipe will, when the machine is installed in Lidköping, be mounted through a hole in the wall, making sure that the fumes leave the building.

When cutting with the machines extraction running no fumes could be smelled, indicating that no dangerous particles remained according to the previously mentioned thresholds for odor compared to the allowed limits.

5.7 Styrofoam Holder

The holding of the Styrofoam when being cut is done by sucking a large volume of air through small countersunk holes in the aluminum profiles, which work like pipes for the airflow, whilst supporting the Styrofoam on both axis as can be seen in figure 5.22. Since most of the sheets that are being cut are larger than 500 mm on at least one axis the pipes are 450 mm long which means that in most cases the wire will never interfere with the pipes. To allow for 4 sheets of Styrofoam being cut at the same time there are 4 pipes on each axis. The aluminum profiles are screwed together to a corner that is 3d-printed. This corner allows for air to flow between axis X and Y in each level of the holder separately. To allow the intake into a level, an optic sensor has to give an output telling the valve that there is a sheet present at that level.

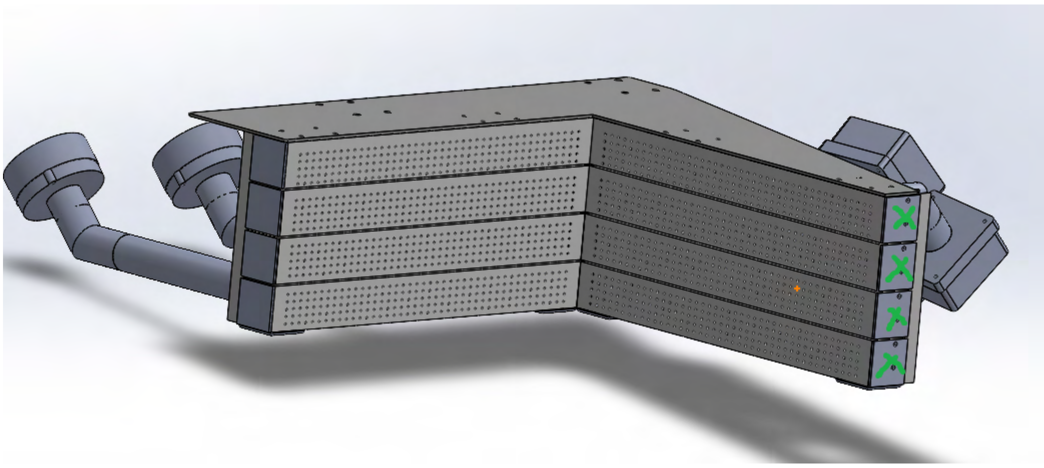

Figure 5.22: A CAD model of the Styrofoam holder. The placement of the sensors are marked with green X:es

The bottom of the holder is placed on 4 low friction blocks to allow for easier movement of the holder. The top of the holder on the other hand is attached to a laser cut sheet of steel that both makes sure that the x-axis and y-axis creates a right angle and is the attachment point for the trolleys that are controlled by the motors. Since the corners of the sheets are not always at a right angle, the sheets do not always connect with both of the sides of the holder, causing a lot of air to leak through the holes not being covered. To counter this, a separation of the two axis in the bottom pipe was added. In addition to this, each axis on the bottom level has two fans connected to them. The reason for having more fans in the bottom is due to the added friction to the table after having more sheets placed on top of the first one. If the bottom level is strong enough, the rest of the levels are as well. Therefore the rest of the levels only have one fan per level with both their axes still being connected.

5.8 Temperature Regulation

While testing of the individual subsections of the temperature regulation seemed promising, certain difficulties were experienced when they were put together resulting in less than optimal temperature control of the wire. This section includes a detailed description of the difficulties and how they affected the temperature regulation.

5.8.1 Temperature Measurement

Using the result from the testing conducted with different RTD sensors the probe RND 410-00029 was selected due to it being a flat type and its small size. This sensor also had a maximum rated temperature of 500°C, being well above what tests had shown would be necessary to cut.

This probe was used along with the signal converter purchased for testing, INOR APAQ-R130 RTD, to be able to measure the temperature and communicate it to the PLC.

According to the specification sheet for the temperature probe a maximal deviation of around 1.5°C for the measuring interval that would be used, 0°C-300°C. The signal transmitter reported a maximum deviation of 0.15°C. These values were deemed to result in a temperature measurement with tolerances good enough to use for basis for regulation.

When testing the probe with the wooden prototype the temperature reported remained steady in steady state without fluctuations that would indicate any noise or disturbances in the temperature reading.

5.8.2 Temperature Probe Mount

For mounting the temperature probe into the position where the probe would be in contact with the wire a mount was 3d printed where a void intentionally was left to be filled with the Casco heat 1500 °C product being the easiest to handle during testing.

This mount was created so that the void would be filled with the casting medium and then the probe would be inserted. By using a flat object the probe is then pushed up to the walls of the mount. By doing this the probe will be positioned to come in contact with the wire when mounted. More casting medium was then put into place to cover the probe legs to fasten them and protect them from shortening. The temperature probe mount without casting medium and the final mount can be seen in figure 5.23.

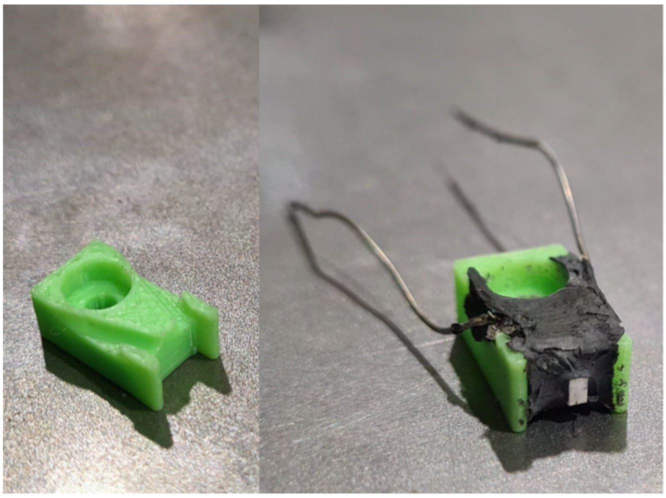

Figure 5.23: Temperature probe mount without the probe molded into position (left) and finished with the probe (right)

5.8.3 Temperature Regulation Controller

A PID-block was available in the software and could be used to regulate the wire temperature. Tuning of this block was done using an automatic tune feature in the software where values were selected based on time constant of the system. The time constant of the wire was thus deemed to be within the $<$1s category available in software due to the fast heating time. The parameters suggested were tested and deemed to work well. For this regulation the desired temperature was read from the HMI and the measured temperature was received from an analogue input on the PLC. The signal converter was tunable to a selectable temperature interval, where the lowest and highest output corresponded to these temperatures. By scaling the input on the PLC to the same interval the temperature could easily be read.

5.9 Electrical Design

In this section the selected electrical components and their implementation are given.

5.9.1 PLC and HMI selection

The PLC selected was the Crouzet em4-E. This model of PLC had all the required traits as described in the method section. The option of adding I/O extensions to the PLC was never needed since the inputs and outputs available in the base model were sufficient.

The HMI selected was the CTP-107-E with a 7” screen. After mocking up a few versions of the HMI software this size was confirmed to be legible and clear enough to be used in the machine.

5.9.2 Proximity Sensor Selection

The proximity sensor that was picked was LD30ETBI10BPA2IO manufactured by Carlo Gavazzi. The sensor was installed on the Styrofoam holder and could be tuned to detect when a Styrofoam sheet was in position in front of the holder. The sensors were also certified class 1 lasers, making them harmless[25]. Sensing distance by these sensors was tunable and could be tuned to detect if Styrofoam sheets had been inserted properly into the holder. The mounted sensor can be seen in figure 5.24.

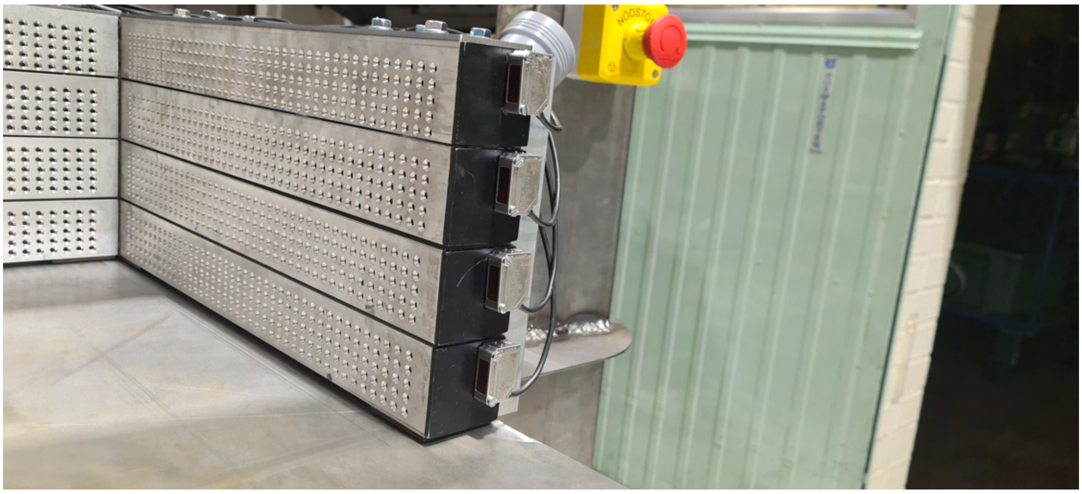

Figure 5.24: Proximity sensors mounted on the end of the Styrofoam holder

5.9.3 PWM Current Amplification

The amplifier used for concept proving showed that such a component could be used to provide current to the wire in order to heat it. Due to time constraints, further steps for determining if this could be used in the final product or research into finding a replacement from a trusted supplier was not conducted. Reasoning and the implications of this is left for the discussion part of this report.

5.9.4 Physical Implementation

Components in the electrical cabinet were mounted on DIN-Rails and logic and power connections were made according to how the subsystems had been connected when testing. For components outside the electrical cabinet, each connection was given a number and a corresponding terminal block so that the electrical cabinet would be easily removable for painting or moving etc. An image of the electrical cabinet can be seen in figure 5.25.

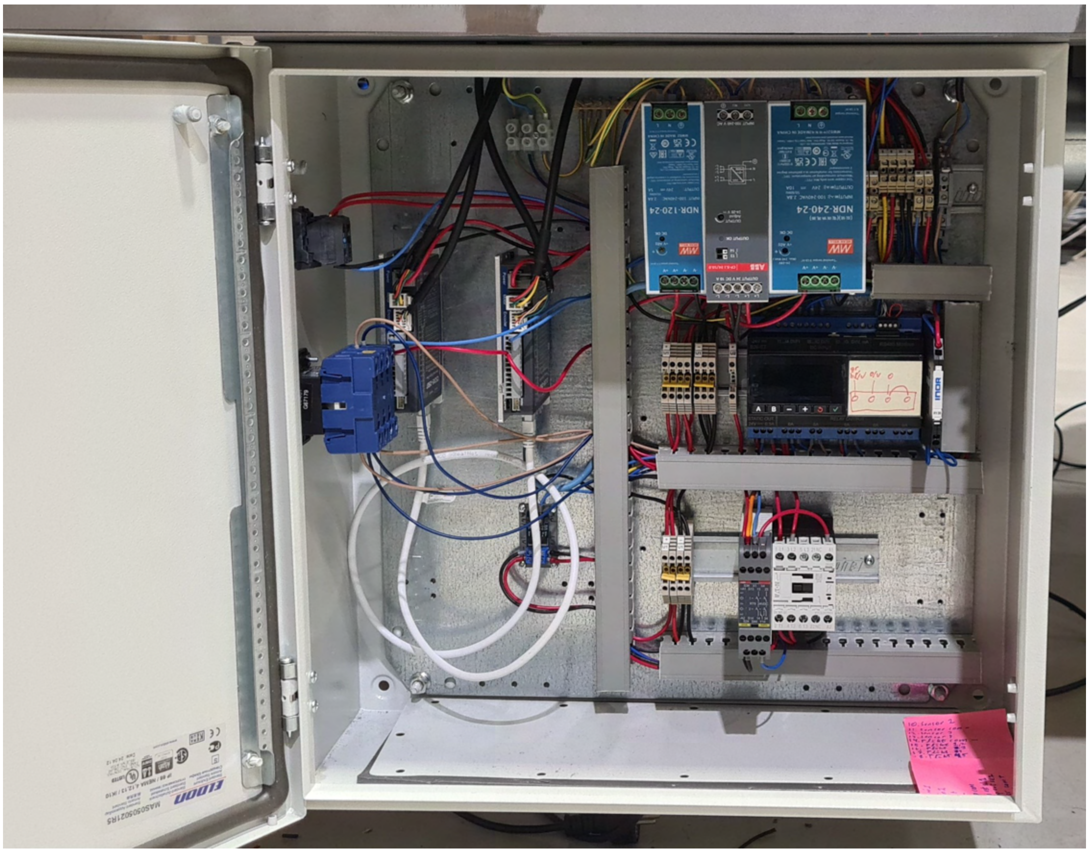

Figure 5.25: The electrical cabinet

Ultimately three different power supplies were needed, one for the motors, one for the holding fans and one for the cutting wire, PLC and logic signals. These were selected according to the rated current use of the components connected.

The wires needed to be drawn to other components outside the table were drawn in cable channels going through the support structure of the table. This was to minimize risk of the wires being damaged during transportation and general use.

A bill of materials for all electrical components can be found in appendix A.

5.10 Software

In this section the software created for the PLC and HMI are given and their functions explained.

5.10.1 Control and PLC Logic

The logic of the automatic cutting consists of a few main steps. The first cut is the width of the sheet. The Styrofoam holder drags the sheet of Styrofoam to the correct position on the Y-axis, figure 5.26, before moving the sheet straight in the x-direction towards the wire, figure 5.27. When the whole sheet has passed the wire along the x-axis, the machine will perform the same action but for the height direction, figures 5.28 and 5.29, or in the case of the height has been inserted to be the height when the sheet, 1200 mm, this step is skipped.

The machine will then move the sheet to an unload position, figure 5.30, where it can be retrieved, figure 5.31.

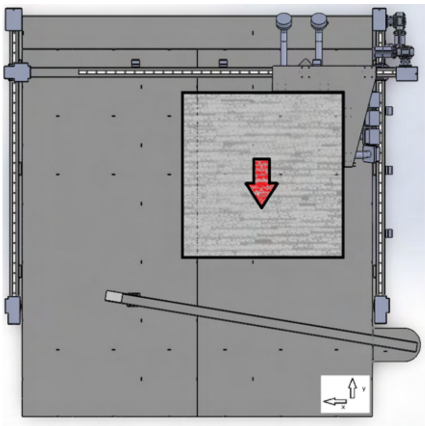

Figure 5.26: Moving the sheet to prepare for the width cut

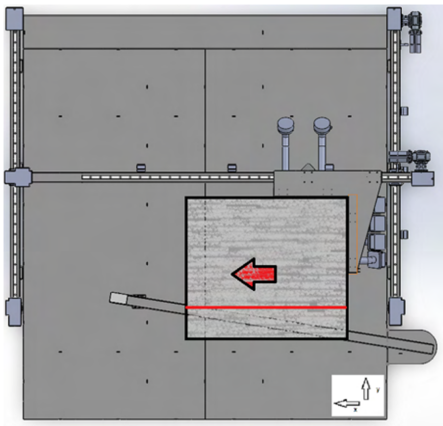

Figure 5.27: Performing the width cut

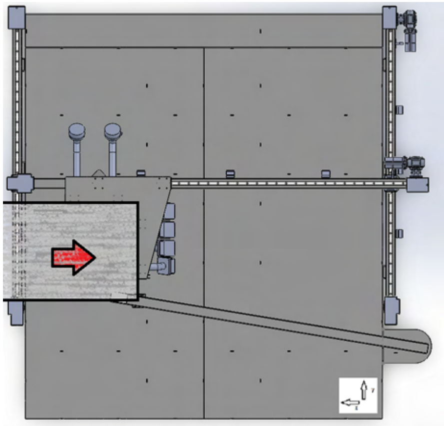

Figure 5.28: Moving the sheet to prepare for the height cut

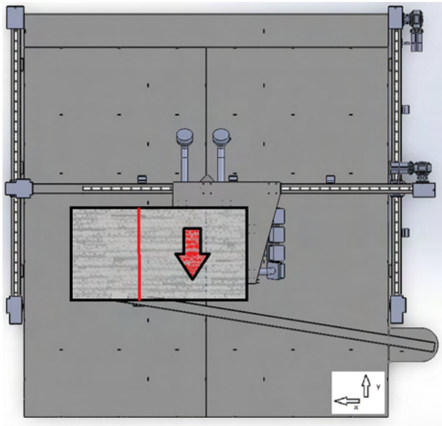

Figure 5.29: Performing the height cut

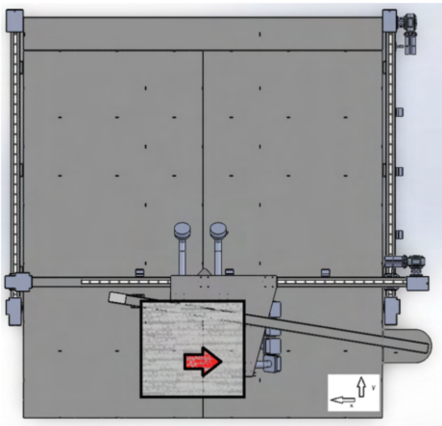

Figure 5.30: Moving the sheet to unload position

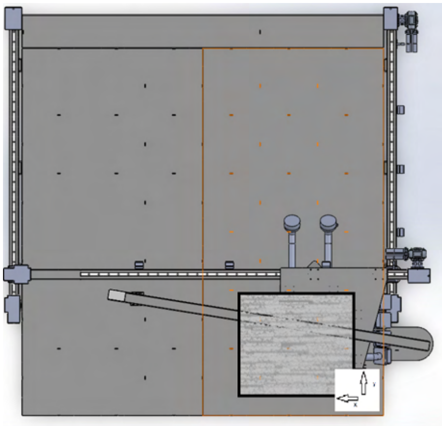

Figure 5.31: Sheet has been moved to a retrievable position

The machine can also be set to a manual mode. In this mode the operator controls the Y-distance to the wire and can use the Styrofoam holder as a guide for manual cutting or free-hand the cutting if desired. The manual cut procedure is presented in figure 5.32.

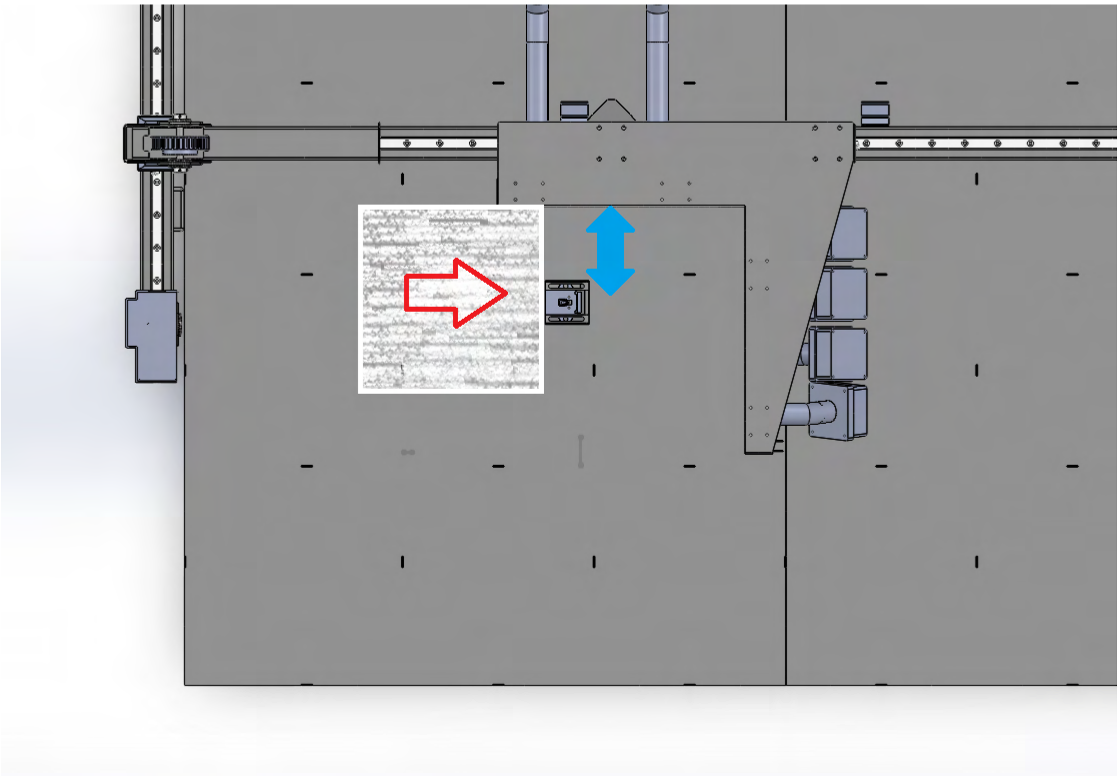

Figure 5.32: Illustration of how the adjustable support is used in manual cutting mode. The red arrow indicates the direction that the sheet should be moved when cutting and the blue arrow indicates the distance that the operator can set through the HMI

A final mode of operation is included in the form of a wire tune mode. In this mode the Styrofoam holder moves so that the inner corner is positioned exactly where the wire is supposed to go. This allows for adjusting the wire so that it is in the position that the machine expects.

The main structure of the control program was based around motor control. Sending instructions to the motors was a multi-step process and the parameters for moving, setting parameters, starting and waiting for the motors to complete an action had to be individual steps. An example of how this was handled is shown in figure 5.33. This is stared by entering a state where the parameters can be set by ensuring that the motors are not busy. The parameters for movement, position and speed can be set in this state. Once these parameters have been set, the next state starts the motors and transitions when they are showing up as running. The next state then waits until the motors are showing as not busy and the next action can take place. Some details used in the software can be found in appendix B.

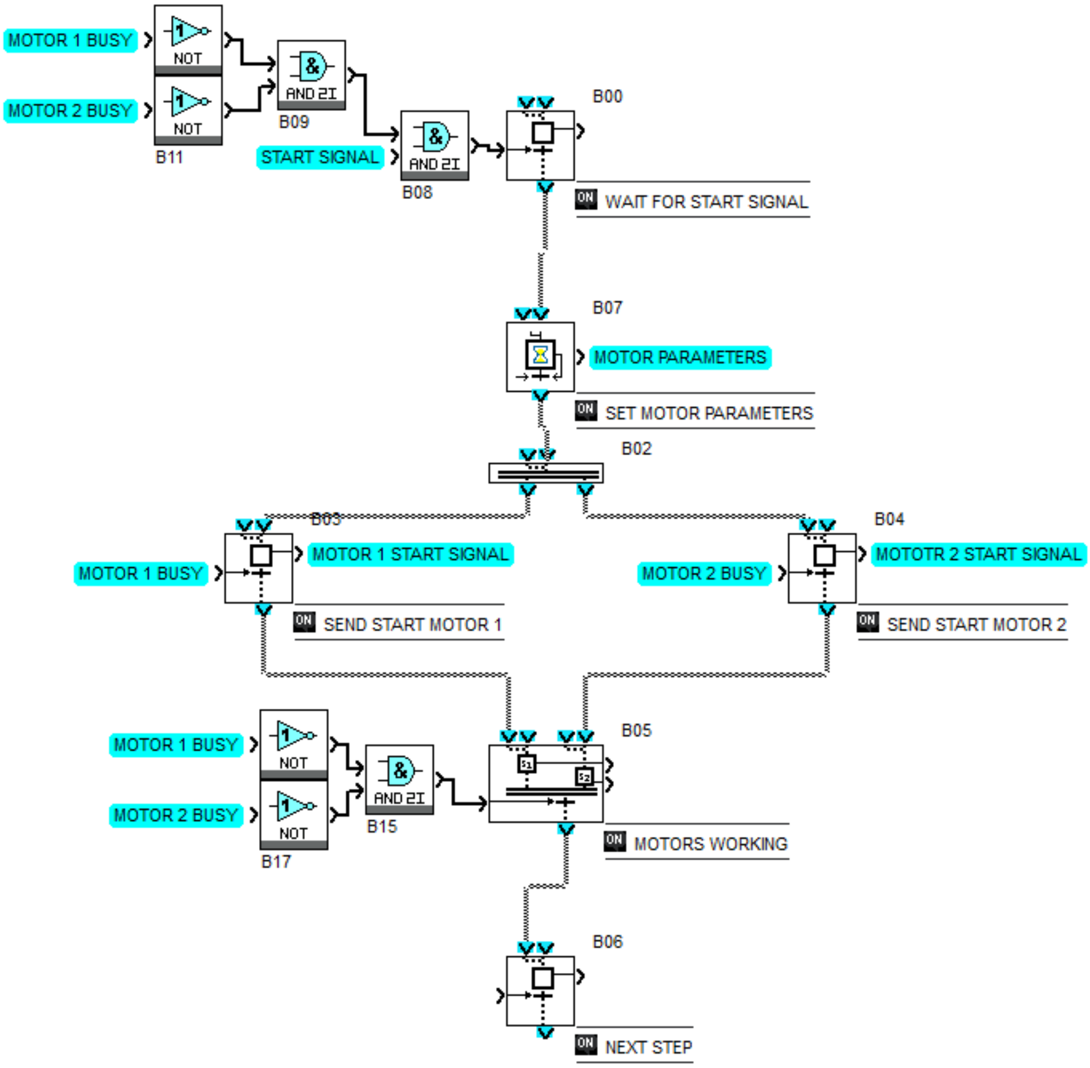

Figure 5.33: Example of how the control logic was built around the motors. Note that the actual motor communication is not present in this figure, but only the structure used

Four main programs were used in conjunction with this methodology: an absolute move, a relative move, a homing function and a stop function. These programs can be selected by writing a value corresponding to the program to a specified register in the motor driver.

The gearboxes used included a certain amount of backlash, as mentioned in more detail in the discussion section of this report, and this was compensated for in software. By keeping track of the direction that the motors have moved, an offset can be added or removed to the absolute position that is sent to the motor. Since the start position is in the home position, an offset is added to the absolute value when the motors move forward, and that same offset is removed when moving backwards. It is only when the direction of movement is changed that compensation for backlash needs to be considered. An image illustrating the logic is presented in figure 5.34.

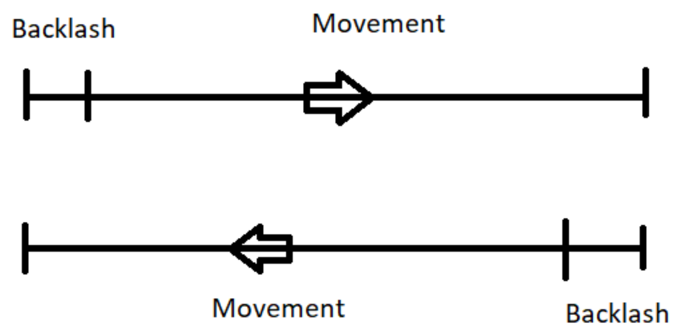

Figure 5.34: Illustration of how the rotational movement of the motor axle can be regarded as linear to show how backlash in the gearbox can be compensated for

Communications from the PLC to other devices are handled using communication blocks in the development software where registers can be written to or read from different communication ports using different protocols, i.e. TCP/IP to HMI screen and Modbus RTU to motor drivers can be set up.

Transitions between states were implemented using logic gates and input signals such as sensors, buttons in the HMI and values. Care was also taken to create mutual exclusion when faced with diverging branches.

5.10.2 HMI

Figure 5.35: The calibration window

When the user starts the machine, figure 5.35 is the first screen they will see. In this window they will press the big yellow button to make the motors perform the homing program. When homing has been done they can leave this screen by pressing the orange button. The stop button can be used to stop the motors. Whenever the stop button is pressed, regardless of what state the machine is in, the HMI returns to the calibration screen and forces the user to perform the homing once again. Throughout the buttons in the HMI, the text on the buttons will be gray if it is not possible to press the button and white if it is possible.

Figure 5.36: The automatic cutting window

The automatic cutting window is where the operator will spend the most time and can be seen in figure 5.36. It is referred to as the home screen in the user manual. In this window they will have the opportunity to set the desired dimensions of the Styrofoam that is going to be cut. There is also a button that is labeled 1200 that directly puts the desired height to 1200 mm. This is a feature since a large number of the sheets being cut has this height dimension. The operator also has the opportunity to decide the position of the holder during the event of loading sheets into the machine. Every number that is to be entered in a text field is entered by pressing the numbers on the numpad and can be seen in figure 5.37. The numpad has an enter button and a delete button that removes the last entered digit.

Figure 5.37: Numpad

In addition to this, it is possible to move to the loading position, to start the holder, starting the cutting, stopping the machine and changing to manual cutting via pressing the buttons on the right. The blue and green lamp in the bottom can be used as a feedback for the user as a confirmation that the machine is doing what it is supposed to. If the user wants to change any parameters of the machine, they can do so by pressing the settings button in the bottom left.

Figure 5.38: Manual cutting window

If the machine is put into manual cutting mode by pressing the orange button in the home screen the manual cutting window will appear to the user. From this window, the user can set the distance the holder should be placed from the wire to support manual cutting. The other buttons have the same purpose as in the home screen with the difference being that the start button only starts the wire and the ventilation system. The orange button will also put the machine into automatic mode and change the screen to the home screen again.

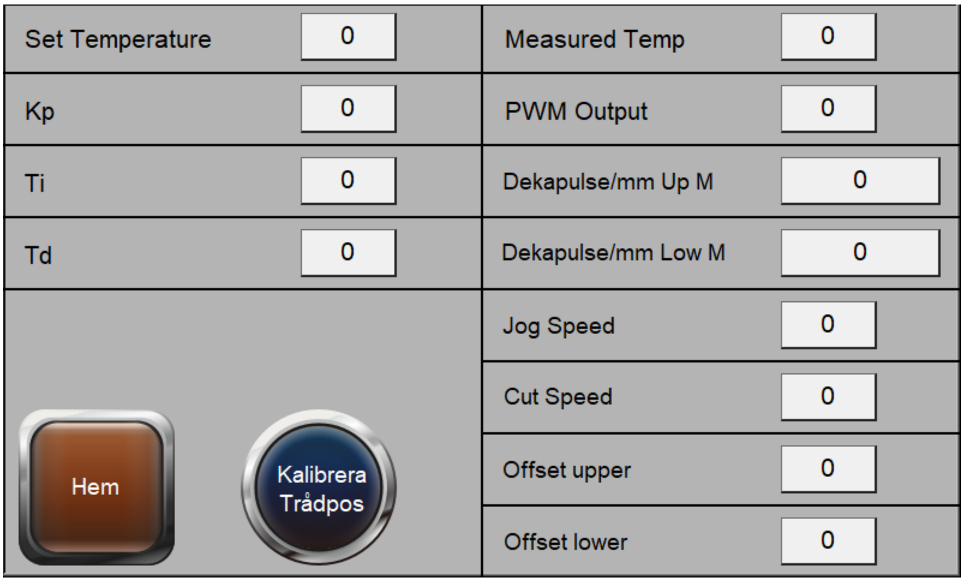

Figure 5.39: Settings window

In the settings window the user has the opportunity to change some of the parameters that control the machines behavior, see figure 5.39. The blue button can be used when changing the wire and can be pressed whenever. Pressing the orange button will take the user back to the screen where they came from and the machine will remain in that mode for the whole duration of being in the settings window.

5.11 CE-Certification

From the initial risk assessment conducted early in the project it was concluded that safety functions were required due to the Styrofoam holder posing as a crushing hazard. Following the internal document based on the SS-EN-ISO 13850-2015 standard a 2 channel emergency stop would need to be implemented. These stops would cut the power to the stepper motors and signal the PLC so that necessary steps could be taken to reset the state machine controlling the cutting logic.[30]

It was decided to place two emergency stop buttons on the machine, one readily available for the operator to push from the loading position and one available to push when standing near the machine in the walking isle next to where the machine would be placed. This was decided to ensure that the machine could be stopped by anyone in a possibly dangerous position.

The documentation that was created for the CE-certification included:

- Functional description

- Initial risk assessment
- A performance level calculation for the safety related components
- A wiring diagram
- A user manual
- A bill of materials of all electrical components
- A technical file detailing all documentation regarding CE-certification of the product and how they can be obtained was begun but not finalized

As mentioned, due to time constraints, the CE-certification process was not fully completed, however, by having conducted prior research, design decisions could be made that were in accordance to the process and the standards that would need to be fulfilled.

5.12 Result Verification

Since the machine is not completely finished, all the verification points have not been met yet. Table 5.1 shows the tests that were created for verification and their status of completeness.

Testing Category	**Test**	**Completed**
Cutting precision	Cutting 10 sheets several times reducing the dimension by 50 mm after every cut and measuring at 5 points of the sheet after each cut in both cutting directions without homing between cuts. If cuts are made with a precision of ± 1 mm, the accuracy is deemed approved. This should be tested with one, two, three and four sheets in the machine	No, test has not been completed since the machine cannot reliably hold more than one sheet while cutting
Wire longevity	Wire survives performing the precision cutting test. This serves as a stress test of the wire testing amount of heating cycles it can survive before needing replacement.	No, test has not been completed since the machine cannot reliably hold more than one sheet while cutting, however during testing the wire used has experienced similar conditions to what would be observed during this test

Testing Category	Test	Completed
Styrofoam holding	The Styrofoam holder can reliably hold one to four sheets of Styrofoam while performing cuts. By performing the cutting precision tests and noting if the sheets are reliably held in place this test can be passed.	No, the Styrofoam holder does not hold more than one of the Styrofoam sheets reliably
Fumes and debris	Performing 10 cuts with four sheets observations are made if any fumes can be smelled or if any debris is spread in the work area. If no debris is spread and no fumes can be smelled this test is passed.	Yes
Replacing wire	If the cutting wire can reliably be replaced in less than five minutes this test is passed.	Yes
Ergonomics	Having five people performing 10 cuts each using the machine with unloading and loading of several sheets, the machine is deemed comfortable to use if the people find it comfortable.	No, the machine is not in a state where this would be possible
CE-certification	Machine adheres to MD, 2006/42/EC	No, see CE-certification section
CE-certification	Machine adheres to LVD, 2014/35/EU	No, see CE-certification section
CE-certification	Machine adheres to EMCD, 2014/30/EU	No, see CE-certification section
CE-certification	Machine adheres to RoHS, 2011/65/EU	No, see CE-certification section
CE-certification	Machine adheres to EN 60204-1:2018 (Electrical equipment of machines)	No, see CE-certification section
CE-certification	Machine adheres to EN ISO 12100:2010 (Risk assessment and risk reduction)	No, see CE-certification section
CE-certification	Machine adheres to EN ISO 13849-1:2015 (Safety of machinery)	No, see CE-certification section
CE-certification	Machine adheres to EN ISO 13854:2019 (Minimum gaps to avoid crushing of parts of the human body)	No, see CE-certification section
CE-certification	Emergency stops break power to all components that it should when pressed	Yes

Testing Category	Test	Completed
CE-certification	Stopping the system in all program states and starting up to make sure that there is no unexpected startup	Yes

Table 5.1: Tests devised for verification points

The machine can pass most of the tests if only one sheet is being cut, meaning that the machine works as intended, apart from the holder.

Chapter 6

Discussion

In this chapter discussions will be held regarding how well the machine performs and how well the different parts perform. The future work of the parts will also be discussed with tips and pointers in what direction the project should continue.

6.1 Cutting Mechanism

In some regards it might have been an advantage to not have seen the current machine and solution before beginning designing the Styrofoam cutter. This is proven by the skepticism from the operators of the current solution when the concept behind the new machine was introduced during the first visit to Lidköping. It is important to remember that the operators had worked there for at least a decade, some more, and they were a bit hesitant of changing their machine into something that is so different. Since this project began before seeing how the old station operated, it made it easier to think outside the box. Even though the concept that was developed before the first visit solved many old problems, it had not solved some problems that the old solution actually already had. Therefore the visit to Lidköping to view the current cutting solution was vital for the project. It allowed for a first draft outside the box before iterating over the draft and drawing inspiration from the old solution to solve the problems that were not introduced before the visit. If the cutting mechanism would have looked differently, meaning a wire that would have been moving, the complexity of the machine as a whole would have been much larger with at least double the amount of motors to move the wire as well.

6.1.1 Future Work

Initial tests were conducted with larger diameter wires, however due to time constrains no detailed results were had. More evaluation of which wire is optimal is a must in making sure the machine works.

6.2 Cutting Table

Due to the fact that the parts of the table were ordered before the decision of removing the tongue and groove, the dimensions of the table were made with the presumption that the machine would have to be able to support 2 sheets that are both 1200 mm long. In this sense, the machine is a lot larger than it would have been ideally. At the same time, there is a lot of space at Reco at the area where the machine will be placed and it does not take up much more space than the old setup already does. There is also a discussion at Reco about changing the dimensions of the Styrofoam sheets to 1800 x 1200 mm instead of 1200 mm x 1200 mm. This is because the most common dimensions in width that Reco cuts is 874 mm to 908 mm. With some smart dividing of the order of the cuts, Reco would then be able to cut two sheets per original sheet of 1800 mm with minimal waste of Styrofoam. It was therefore somewhat lucky that the table was designed in the way that it was, since the table would have been too small to support the new sheets if dimensioned for 1200 mm.

6.3 Linear Drives

The initial idea of purchasing a ready made linear drive system for the x-y-motion of the table stemmed from discussions with a supplier where ”low cost implementation” was interpreted differently by the supplier and the authors of this paper. This miscommunication led to the thought that such a system would be viable for use in this particular situation and thus when it was discovered that this was not the case some time had gone.

Ultimately there were points in the project, especially during the construction phase, where work stood still due to linear drive components not having been delivered. Had this work begun earlier, the linear drives would have been complete earlier and challenges further ahead would have been discovered earlier.

Design and construction took time that had not been planned for and the project was delayed accordingly.

From an economic point of view, the decision did make sense. The total cost of the ready made units would have been around 100 000 SEK while the constructed drives ended up at around 30 000 SEK.

6.4 Motors and Gearboxes

When the linear drives had been installed and the motors were to be tested, it was discovered that some form of gearbox would be needed. The decision not to purchase gearboxes initially was according to supplier recommendation, where the supplier having seen the concept said that the motor would have sufficient torque for driving.

Thanks to gearboxes being available at ASSA ABLOY, the time loss due to this was fairly short, but not negligible. Adapters had to be made for the gearbox and motor to be mounted and connected to the driving shafts.

The gearboxes available were not particularly suited for the application. The gear ratio was higher than needed and included non negligible backlash. These were issues to overcome, however, it was deemed appropriate to do since delivery times for better suitable gearboxes would make them available at around the time that the project would come to an end. By using the available gearboxes testing and some form of verification could still be conducted within the time frame of the project.

6.4.1 Future Work

The backlash present in the gearboxes was attempted to be compensated for in software, something that the limited testing performed seemed to work well enough that it was deemed that tuning the machine to cut with an accuracy specified in the target specification was possible. Further tuning and final verification of this was due to time constraints left as future work.

6.5 Wire Mounting

In this section discussions regarding the mounting of the wire are carried out concerning how well the current solutions would work in the final product.

6.5.1 Top Wire Mount

The final design for mounting the top of the wire was deemed functional but not ideal. While the wire is being held firmly, the isolation of the clamp to the rest of the table is done using a 3d-printed plastic piece deemed fragile.

The clamp for connecting the wire to supply current was also deemed as non-optimal since care must be taken to place this wire so that it does not contact the wire and melts the wire isolation.

Due to time constraints none of these points were addressed since they were deemed as functional, even if suboptimal.

6.5.2 Bottom Wire Mount

The design for mounting the bottom of the wire was deemed as very functional, making the wire fast and easy to replace. The only problem being that the 3d-printed lever wore down with use being the main issue. Nonetheless it is still fully possible and not difficult to insert the wire by using two hands and holding the clamp open.

6.5.3 Future Work

It is suggested that a more robust isolation is implemented for the top attachment point. It is also recommended that the current supply wire is mounted inside the top arm so that the plastic insulation will not contact the cutting wire and risk melting it.

For the bottom attachment point, a recommendation is left to consider alternative materials for the lever components. Manufacturing this out of a more durable material and inserting a sheet on the surface upon which it acts would greatly improve the durability of the clamp and improve its ability to hold itself open.

6.6 Ventilation System

While the ventilation was deemed to work well and no smell was detected during any cutting there is still the issue of benzene, however very unlikely, existing in the environment without being detected by smell. Measurements could be made where the operator stands during operation to ensure that the threshold value is not passed.

If the extraction system is blocked this would become apparent due to the principle component being styrene and this being the first to be detected by smell. In this case the machine can be stopped and the problem investigated before presenting a danger to the operator.

6.6.1 Future Work

Right now the fan is held up by 3d-printed mounts that do not provide dependable mounting. This will most likely be changed into some bent sheet metal. In addition to this, the pipe that will be mounted through the wall is currently attached by a number of cable ties. This will also change into a similar solution in the manner that the T-cross was mounted with a hose clamp.

A funnel could be placed on the top arm in order to collect more fumes and avoid them being spread outside the area where the fan can extract. Several mounting holes for components no longer used also exist in the top arm that should be sealed.

6.7 Styrofoam Holder

Before the decision to remove the tongues from the sheets was made the design of the holder needed to be a lot more complicated. In this situation the holder would not just have to hold close to the corner of the sheets, like the solution in the machine currently does, but would have to be designed to always hold at least a small portion of the second sheet inserted as well. In addition to this it would be a problem to handle and completely remove the part of the sheet that has been severed. This is due to the fact that it is not possible to predict where the cut will occur and design sections of the holes to counter the problem that almost all holes need to be covered in order to grab the sheets. This means that in some cases the severed piece would still be held by the holder and would follow along the rest of the cutting. Another issue that could occur is that the cut occurs closely after the connection between the old and new sheet as seen in figure 6.1. In this case, if the machine manages to remove the severed part of the sheet, it might be impossible to hold the small part of the new sheet if the cut occurred in the middle of a section of holes, since almost all holes need to be covered in order to grab the sheets.

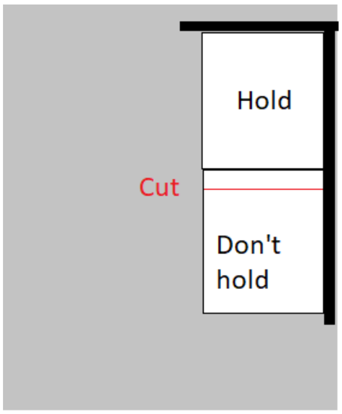

Figure 6.1: Visualization of issue with tongue and groove

No solution had been found for these issues when the decision to remove the tongues came and there is no saying that a solution would have been found either. The decision might have been vital for the project to progress on. Unfortunately a few weeks were spent on this issue, however, meaning that the project could have been further along if this decision would have been taken earlier, not to speak of other functions that was needed for the sheets with the tongues.

Regardless of how the holder could have been designed to solve the issues, there were more functions that would have been needed on the machine if the tongues remained. Firstly, some mechanism was needed to hold down the old sheet when the new sheet was to be inserted. This is due to the fact that the tongues and grooves are not perfect and sometimes need a bit of force to be properly inserted. The solution that was chosen was a pneumatic cylinder that would lower down when the sheet was in the correct position.

The correct position would be found by the machine using an optical sensor mounted at the bottom of the table. The holder would back up the sheets until the sensor was no longer covered. To ensure the removal of the severed piece of the sheet from the one being cut, another pneumatic cylinder would have been placed on the outside of the top arm next to the mount for the wire. This device would lower itself after the cut in the X-direction, grab the severed sheet and hold it in place when the sheet being cut continues being moved by the holder.

Since these functions are not needed anymore, but the order had already been placed on the cylinders and all of their attachments, this was an unnecessary cost for the project, even though the devices are stored at ASSA ABLOY for future projects. The removed functions does not impact the function of the machine more than a small inconvenience in that of replacing the wire. Since the second cylinder would be placed next to the wire, the steel profile was cut with the left side open (standing to the left of the machine), to allow for the cylinder to be placed on the right. This is not a big issue but replacing the wire would have been easier if the right side of the steel profile had been open instead so that the operator would not have to lean over the table when performing maintenance.

6.7.1 Future Work

The Styrofoam holder is not finished as it is right now. Firstly, even though the current holder is sometimes strong enough to hold four sheets, the results are not always perfectly reliable. More tests need to be done to see if it works better if all of the levels in the holder are separated and more fans mounted. When that is finished, all of the cables need to be redrawn and a small junction box will be used instead to get all of the components in the holder the correct signals and currents. This is mainly due to having two pole cables which make the cable chain way too heavy, and it will become even heavier if more fans are introduced to the holder. When fixing this problem, the cable chain will also be replaced to an open one, at least the lower cable chain, since the motor cable can not fit into a closed cable chain.

If it is found, however, that the current idea does not work it would be reasonable to go back to the old idea of having pneumatic cylinders as the holders of the Styrofoam. This idea was previously abandoned before the decision of removing the tongue and groove since it was not possible to design the mounting of the cylinders in a way that could always hold both the groove sheet and the tongue sheet. The cylinders idea might work if they are only placed on the y-axis part of the holder so that the wire never interfere with one of the cylinders. Having them on the y-axis is safe since the width almost never is smaller than 500 mm whilst the height frequently is. The issue that needs to be considered with this idea ,however, is if the cylinders can fit under the top arm and if not, if the holder should be prohibited from getting that close to the operator. The operator will then be forced to lean more over the table when operating the machine than intended. Suction cups on the y-axis would also be a reasonable solution based on the same idea.

If the suction cups work well enough, this would even be better than the cylinders since the holder now definitively can fit under the top arm.

Another big issue with the holder is the low friction blocks. Even though the blocks have low friction and allows for easy transportation of the holder, it is easy for small debris to be stuck under the holder which in turn scratches the table and makes the holder more difficult to move around as visible in figure 6.2.

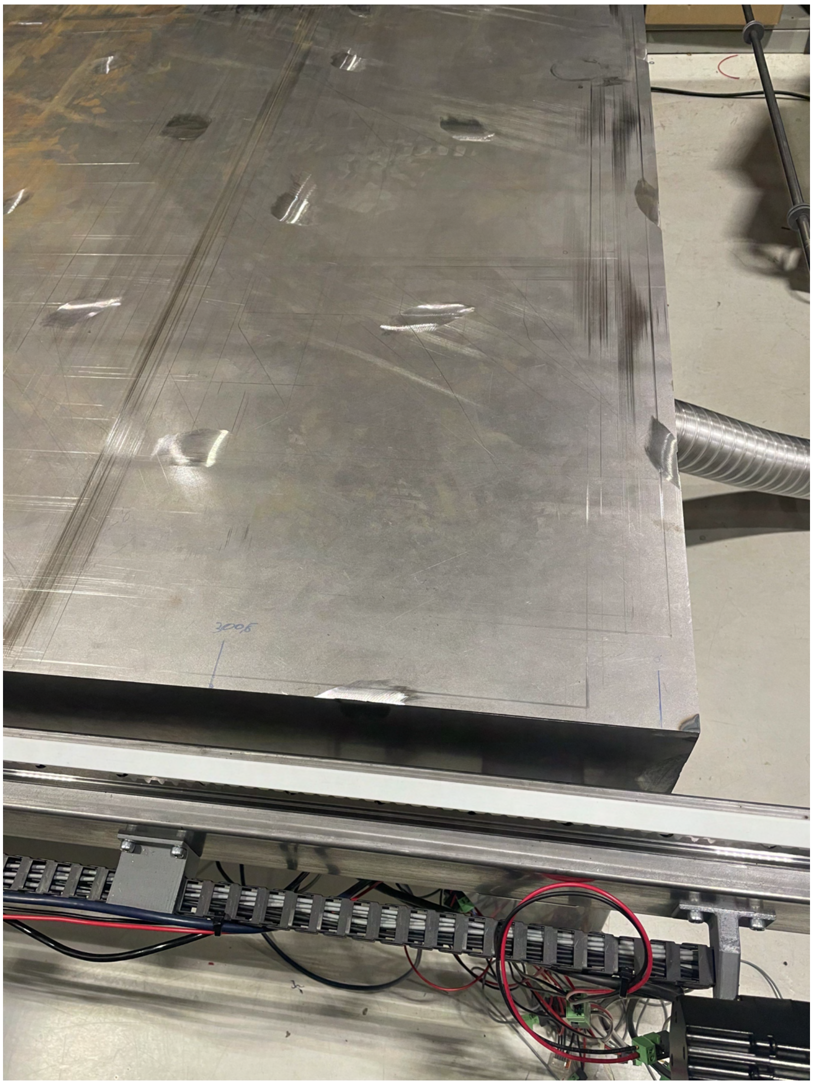

Figure 6.2: Scratches on the table surface caused by movement of the holder over the table

The prevailing solution for this issue right now is mounting a ball roller so that the holder can still move freely but at the same time eliminating the risk of debris and grains getting stuck under the holder.

6.8 Temperature Regulation

In this section discussions are carried out in regard to how well the final temperature regulation was. probe selection, mounting and software is discussed here.

6.8.1 Temperature Measurement

The temperature measurement was in the end not as accurate as initial experiments had shown. The prediction that the wire temperature would be measurable where the probe was mounted and that regulation could be based on this proved incorrect, so it was not possible to directly influence the temperature of the cutting. The mount and clamp did in the end act as a large heat sink, cooling the wire in proximity of the temperature probe substantially compared to where the cutting would take place. Despite this, and as is described in more detail later on, it was still possible to perform cutting by overshooting the set temperature.

6.8.2 Temperature Probe Mount

The temperature probe mounting turned out to hold the probe in a rigid way, providing reliable contact with the cutting wire. The manufacture of the holder is one point of complaint. Applying the molding medium is somewhat difficult and accidentally covering the temperature probe is easy when mounting it into position. Ultimately it is possible to achieve a good result with some practice. however, since the probe has a very long life it will very rarely need to be replaced. If several probe mounts are manufactured in a batch it is likely that a batch will last for several years, depending on how the plastics and casting medium hold up over extended periods of time.

6.8.3 Temperature Regulation Controller

With the points mentioned above the final temperature regulation proves difficult. The parameter ideally regulated upon would be the cutting temperature, i.e. the temperature. As previously researched this temperature would correlate with the temperature measured in the wire outside of the cutting zone. However, another dynamic is added when, as mentioned, the temperature probe is mounted close to the clamp and it acts as a thermal sink. While this is easily tunable to function while cutting, a correspondence with the target value and the parameter that is desired to be controlled is very much lost and the excessive heat in the wire may impact the life of the wire.

6.8.4 Future Work

While functional, the dynamics of the current regulation loop is difficult to understand. The question should be asked if regulation instead should based on the current or voltage. Since the measured temperature is in no way representative of the actual cutting temperature, the current solution is already indirectly implementing exactly this, however in a more convoluted way, since depending on the set temperature a specific PWM-signal value output is achieved in steady state.

6.9 Electrical Design

In this section the selected electrical components and their implementation are discussed.

6.9.1 PLC and HMI selection

The selection of the PLC and HMI devices proved to fulfill all needs set up and are thus deemed as good choices appropriate for the task at hand.

The development software for the PLC was, as mentioned, purely function block based. Signal handling proved difficult since more complex entry conditions for states or output signals often required large chains of logic blocks, quickly making the program difficult to follow when troubleshooting or adjusting functionality. Ultimately this software was used so that at the end of the project the code could be handed over to be maintained by someone without much prior knowledge in PLC-programming. From this perspective, while at times being difficult to follow, the overall structure and logic might be easier to understand than if it was implemented in some, for example, structured text program.

6.9.2 Proximity Sensor

The proximity sensors used for detecting sheets proved satisfactory and were tunable to the desired distance. Sheets could be detected reliably, and since no pollution is generated or exists in the vicinity of the machine, the sensor selection is deemed to be a correct decision.

6.9.3 PWM Current Amplifier

The amplifier used with the PWM signal for the wire was, as mentioned, not from a known supplier and no data sheet could be found. As such, even though performance was deemed satisfactory, it is lacking documentation regarding EMC emissions and a RoHS declaration, which is required in order for it to be directly implemented in a CE-certified product.[29][28]

A replacement product from a known supplier was looked for but a substitute proved difficult to find.

The product could still be used if tested according to the required values set up for EMC emission[29] and, since the RoSH directive states thresholds for substances, if assumed the worst case scenario, the amount of potentially banned materials is less than the allowed percentage of the electrical equipment weight.[28]

The initial plan was to have these tests and calculations performed by competent personnel at ASSA ABLOY, however the decision for moving forward with this is left as future work.

6.9.4 Physical Implementation

For the physical implementation the method used was very functional. As the components and systems were to be mounted on the machine or in the electrical cabinet a good understanding was had, making the work easy.

6.9.5 Future Work

While wires are drawn and the electrical cabinet at the end of the project are working, there is still more work to be done for these. Firstly, the wires drawn outside of the electrical cabinets are drawn in temporary cable channels. When the table has been painted, more work needs to be done regarding this. Permanent cable channels need to be installed and many of the wires drawn could be combined into multi conductor-cables. A general ”tidying” needs to be performed when the design of the Styrofoam holder has been completed and the amount of connections in regards to this has been determined.

Inside the electrical cabinet, some changes, such as an RCBO (Residual current operated Circuit Breaker with Overcurrent protection) should be installed when the machine has been tested and an appropriate trip current for a breaker has been determined. Further changes mainly regarding the temperature regulation and PWM-amplification may also result in further changes being needed.

For PWM signal current amplification the future work that needs to be done is to make a decision on whether the existing component is to be used or if a replacement component should be researched and tested. If the component is to be kept, tests would need to be conducted according to the discussion above.

6.10 Software

In this section the created software for the PLC and HMI is discussed in regards to how well control and interfacing with the machine are.

6.10.1 Control and PLC logic

The control logic is written with the intent of implementing mutual exclusion in the state machine and the creation of a robust system. Transition condition between states that have multiple exits are mutually exclusive and when controlling the motors they are always checked to be marked as not busy before a command to run is sent. Likewise they are always checked to be marked free again before transition to the subsequent state is allowed.

The only thing that is not checked before moving forward are parameters for movements sent to the motor drivers. This is due to the fact that reading these values in the drivers from the PLC is only available by polling. This overloads the communications and noticeable delays were observed when this was tried. While checking the values before continuing would be the optimal solution, if the values were not received some form of communication disruption would be present and most likely the motors would not be able to be triggered anyway. If, by any reason, values were not written to the drivers and they were sent a trigger signal, this would at worst result in old parameters being used and result in incorrectly cut Styrofoam sheets but never be a safety concern.

6.10.2 HMI

The HMI does follow the guidelines that were given from the operators in Lidköping. Whether they agree or not and if they find it intuitive to use will be apparent when they start using it.

6.10.3 Future Work

One improvement to the HMI that could be interesting to develop is to force the user to insert a password when wanting to enter the settings window. Right now this is replaced with an extra text box asking if the user is sure that they want to enter the settings. The password would have been implemented already if a way of doing this had been found.

If the operators are not pleased with any of the names or colors of the buttons that were selected in the HMI, it is not difficult to change the naming and coloring in the development software for the HMI by connecting it to a computer.

6.11 CE-Certification

Ultimately, due to time constrains all necessary steps had not been taken to complete the CE-certification process. Time has however been spent to research the requirements for achieving the certification and the internal documentation implementing the relevant standards. By doing this, design decisions could be based on what would result in an end product compatible with these directives.

6.11.1 Future Work

The finalization of the CE-certification is left as future work. According to the internal documentation, the final steps for completing the CE-certification were:

- A final risk assessment when the machine is completed to determine if any remaining risks are present
- A declaration of conformity
- An electrical safety test report according to EN 60204-1
- An EMC compatibility test report, if the amplifier of unknown origin is to be used.
- A RoSH declaration

Apart from creating these documents, other documentation will also have to be updated if any changes are made to the machine.

6.12 Verification Points

Clearly the machine is not ready right now to be put into use but the project has still come very far even if there are more points to solve. The additions that are required are quite time consuming however, meaning that more time will have to be spent on the machine before it is finished. The biggest problem in the machine right now is the robustness and precision. The machine will pass all tests set up if future work is carried out as suggested. Regardless if all of the tests could not be completed, the machine can run reliably with one and two sheets and works as intended.

The list of the specifications set up in the project and their status of completeness are presented below along with comments.

Using the Machine

- When inserting sheets into the machine the operator should not have to reach more than 600 mm in from the edge of the table to position the sheet - Passed by having the operator select the loading position on the HMI.
- When removing cut sheets from the machine the operator should not have reach more than 600 mm in from the edge of the table - Passed by having the machine go to an unload position after the cut has been performed.
- The machine has a height so that loading and unloading is performed at 800-900 mm above floor level - Passed by designing the table to stand at this height.
- When removing off cuttings the operator should not have to reach more than 600 mm in from the edge of the table - Passed by the off cuttings being left at the edge of the table and then being pushed out of the way by the sheet during continued cutting.
- When inserting a sheet into the groove of a sheet in the machine the operator should have an overhang of 200 mm from the edge of the table for the new sheet - Removed from specification due to tongue and groove being removed.
- When inserting a sheet into the groove of a sheet in the machine the machine should support the sheet, so it does not fold upward - Removed from specification due to tongue and groove being removed.
- The machine needs to hold the sheets together so to be able to cut sheets where the tongue-groove fit is loose - Removed from specification due to tongue and groove being removed.

Cutting

- The machine can facilitate feeding in up to two sheets measuring 1200 mm x 1200 mm per level connected with the tongue and groove - Removed from specification due to tongue and groove being removed
- The machine can cut the sheets to any rectangular shape measuring 1200 mm x 1200 mm to 10 mm x 10 mm - Not passed, testing is conducted using tests in table 5.1.
- The machine can cut sheets to desired size with a tolerance of 1 mm - Not passed, testing is conducted using tests in table 5.1.
- The machine can be loaded with up to four sheets in height to be cut to the same dimensions at the same time - Passed, clearance is left for four sheets to be cut at one time

Interfacing With the Machine

- The desired cut dimensions can be input by the operator trough the HMI -

Passed by implementing this feature in software

- The machine provides feedback by displaying the selected cut parameters - Passed by implementing this feature in software

Work Environment

- The machine does not pollute the work area with debris or toxic gases - Passed by having inspected the work area for debris and smelling to see if any fumes are present
- The machine does not present any danger to the operator during cutting, loading or standby phases - Not passed, even though this has been a main point of concern in the design this point will be marked as passed only when the final risk assessment has been performed

CE-Certification

- All points under this headline will be passed once the work described in the CE-certification section has been passed and are not repeated here.

The replacement frequency and replacement time of the wire, while not set up as specifications are also relevant. The informal results achieved during testing indicate that both these points will not be an issue for the final machine.

Chapter 7

Conclusion

All of the goals that were set before the start of the project were not met. The biggest reason for this, however, was the lack of time in the project, alternatively the extent of the project was simply too large for the amount of time that was available. Looking back at the deliverables from the start it is clear that the machine can cut any sheet of Styrofoam into any dimension smaller than 1200 mm, but the precision is at this moment not as good as ± 1 mm. One of the goals was the CE-certification however and even though the machine was designed with safety as the main priority and most of the forms and standards were filled in, the machine still has some tests to go through and more documents to be evaluated against. A user manual has been created and will be used for supporting the operators when learning to use the machine. The machine is, when comparing to the old solution, comfortable to use and the reaching distance is customizable. The machine has been constructed to minimize the amount of non reusable Styrofoam and Reco has the opportunity to use the machine in ways that does not waste Styrofoam. The machine requires next to no physical effort and in contrast from the old solution no part of the Styrofoam gets damaged from the cutting. The machine runs as intended and functions well when one and two sheets are being cut.

Nevertheless the machine has been built, although a bit provisionally to some parts, and can complete most of the tests that were set in order to verify if the machine is ready to be installed at Reco or not. The machine has been passed on to ASSA ABLOY and a finished machine that can be installed at Reco in order to begin an evaluation process with the operators will soon be completed outside of this project.

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Appendices

Appendix A - Bill of Materials for Electronic Coponents

Component	Manufacturer	Amount	Comment
EM4 B26 ET	Crouzet	1	PLC
Modbus RS485 interface	Crouzet	1	Modbus RS485 interface extension for PLC for communication with motor drivers
CTP107-E	Crouzet	1	HMI-screen
LD30ETBI10BPA2IO	Carlo Gavazzi	4	Proximity sensor for detecting Styrofoam sheets
CS-M22313B	Leadshine	2	Stepper motors
CS2RS-D507	Leadshine	2	Driver for stepper motor
410-00029	RND	1	Pt-1000 RTD temperature sensor
R130	INOR	1	Signal converter for use with RTD temperature sensors
RT9 2TLA010029R0000	ABB	1	Safety Relay
DIL M7-01	Eaton	1	Contactor
ZBE-102	Schneider Electric	4	NC push button
ZBE-101	Schneider Electric	1	NO push button
ZBE-B6	Schneider Electric	1	LED for emergency stop button reset
CK 100 A	Östberg		Extraction Fan
B97 9BMB24P2K01	San Ace	5	Fans used for creating vacuum and holding Styrofoam sheets
unknown	unknown	1	PWM-amp
NDR-120-24	Mean Well	1	24v, 5A PSU For logic, PWM-amp
NDR-240-24	Mean Well	1	24v, 10A PSU for Extraction Fans
CP-S.1 24/10.0	ABB	1	24v, 10A PSU for Motors
KG41B	Kraus & Naimer	1	Pole isolation switch

Table 1: Component List with Manufacturers, Amounts, and Comments

Appendix B - Programming Details

Values Depending on State

When an output value from something in the control program depends on states, number blocks are used along with multiplexers in order to select a value to send as parameter or select a program to be used as seen in figure E.1.

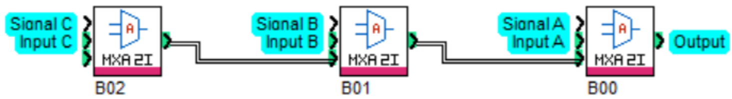

Figure E.1: Example of how multiplexers are chained to select parameters. When a signal is active, the output is equal to corresponding input