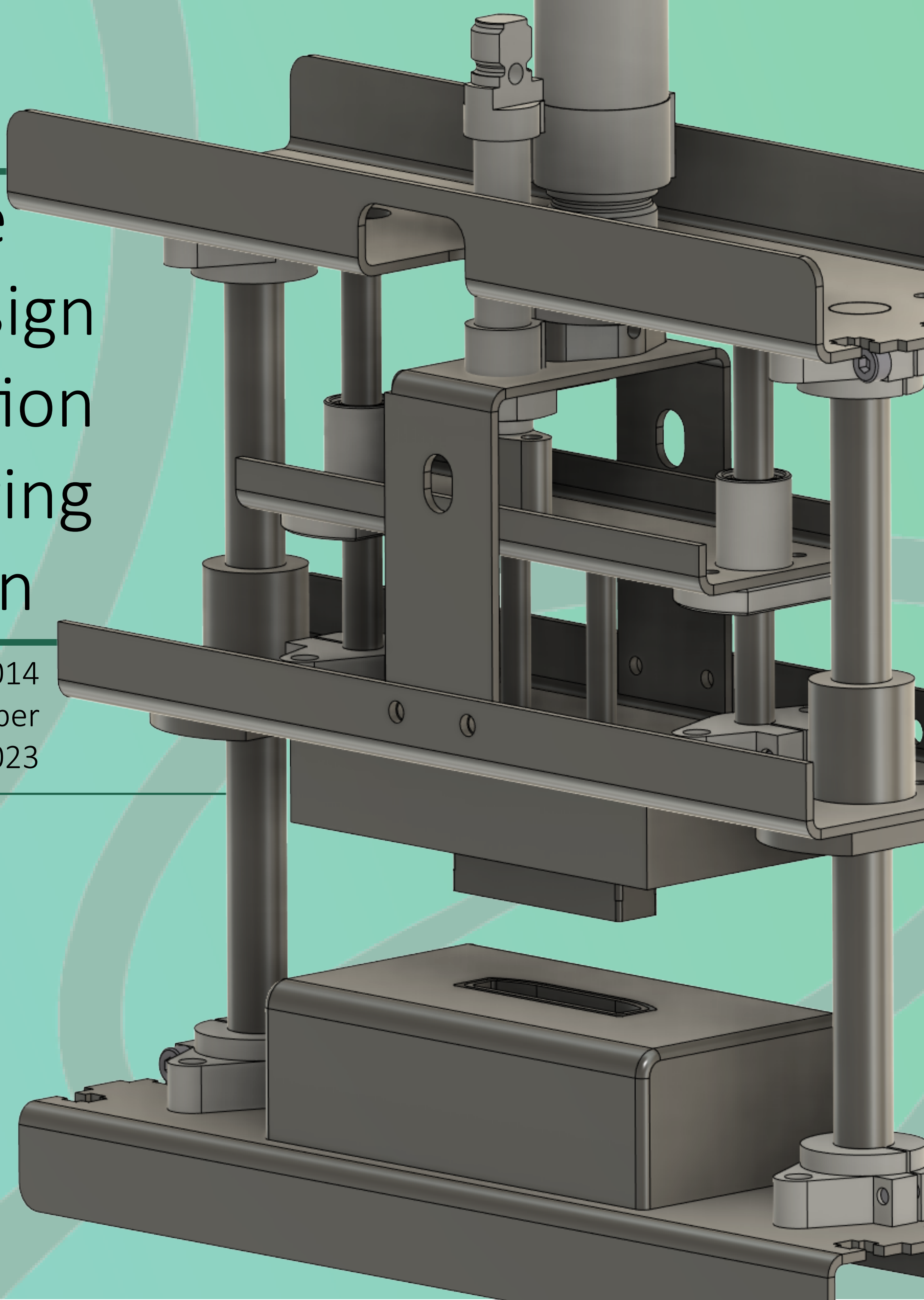
MASTER THESIS

Improvements in the development and redesign of a tea infuser production machine at TeaWall during continuous production

DPM-2014
Brian Schipper

15th of June, 2023



TEAWALL

UNIVERSITY OF TWENTE.

Student
Brian Schipper
S1854690
b.schipper@student.utwente.nl
+31 6 116 204 96

Education

Faculty	Faculty of Engineering Technology
Department	Design, Production and Management
Master programme	Industrial Design Engineering
Master track	Management of Product Development

Educational institute
University of Twente
Faculty of Engineering Technology
Drienerlolaan 5
7522 NB Enschede
The Netherlands

Company
TeaWall B.V.
Kopersteden 24-5
7547TK Enschede
The Netherlands

Examination date
15/06/2023

Assessment committee

Chair	Tom Vaneker
UT Supervisor	Peter Chemweno
External member:	Nina Jakubeit
Client Supervisor	Maarten van Vreeland

Master thesis Industrial Design Engineering,
Management of Product Development track at the University of Twente,
an assignment for TeaWall

Improvements in the development and design of the tea infuser production machine at TeaWall during continuous production.

DPM-2014
Brian Schipper
15th of June, 2023

UNIVERSITY OF TWENTE.

TEAWALL

Preface

I want to specifically thank Maarten van Vreeland and Daan Theoden for the oppertunities and the help I have received during my time at TeaWall. It has been a great learning experience where I could have a hands on approach to Industrial Design Engineering. In combination with the freedom that was provided during the redesign phases, and the opportunity to create a final design that is implemented within the machine directly, immediate feedback on the effectiveness of the changes I made was noticed.

- Brian Schipper, May 2023

Summary

Bad-quality end products and low production speed are examples of the numerous problems that can occur during mass production processes. However, while these problems can be easily recognised by checking the end product or by the experienced downtime of production, finding the root causes and the solutions to these problems proves to be more difficult due to the complexity of these systems. To be able to solve the problems experienced during production, methodologies, such as Lean Six Sigma, approach these problems in a structured manner to be able to find and solve the causes of the problems. This approach is also called continuous improvement, as these methods use iterative steps that can be applied to keep improving a machine or process over time.

The production machine for the tea infusers from TeaWall is such a production machine that experiences many different production process problems including low quality and low reliability. The main reason is the short lifetime of the machine, it has been developed and built within the last year. The machine, therefore, is moreso a conceptual machine than a completely finished mass-production machine. In this thesis, TeaWall's production machine will be used as a case to test a proposed framework, tailored to the needs of the project, functioning as a guidance structure for continuous improvement. A point of importance for the framework of the continuous improvement strategy is that the current production machine should be able to continue running production, as the company does need the product for their pilots and sales. This introduced the need for confidence in the redesign, which has to be tested outside of the current machine and has to be implemented quickly and correctly to lower the necessary amount of downtime.

The framework proposed in this thesis consists of two parts. The initial part focuses on determining the root causes of the overall problems that are experienced during the production process by using the Lean Six Sigma methodology, more specifically the DMAIC cycle. This cycle helps define the problems of the machine and find its root cause. The second part of the framework focuses on the improvement of the part, module, or process through means of the Design Thinking method. The framework uses the combination of the DMAIC and Design Thinking cycles to guide through the iterative process.

Multiple smaller case studies of the application of the framework on the tea infuser production is used to validate the different parts of the framework. These case studies are applied both during the initial part to show how problems can be defined and measured, as well as during the redesign process. During the validation of the framework, new insights could be made as well. During the redesign phase, the cases focused on the two possible different approaches to redesigning the modules during the redesign process. The first is an update to parts of the module which lowers the cost of development but has to be tested within the machine, while the second approach redesigns the complete module. The use of a complete redesign can be justified by the complexity of the updates that have to be done to the module. This option allows for out-of-machine testing and provides the redesign with more confidence in the correct operation of the complete machine when it is implemented, lowering downtime. However, this option leads to longer development time and financial investment. The two different methods are weighed against each other and it is seen that the complexity of the redesign should dictate the decision between the options.

The final result of the thesis is a significantly improved yield of higher quality tea infusers produced by the mass production machine when compared to the conceptual working machine as of the start of the thesis. This improvement is achieved through the structured approach to continuous improvement, as proposed by the framework, focusing on the most influential root causes of the machine and effectively improving them. Throughout the improvements, not only the failure modes have been addressed, but also the low production speed as of the start of the thesis and the lack of knowledge related to the machine.

The framework of the thesis is well fit for TeaWall and can be used as a guideline for other projects if the framework is adjusted to the specific needs of the other projects. A tool to have visual guidance through the steps of the framework with more in-depth steps for each of the cycles of the framework, as well as examples to further guide the user through the steps of the framework.

Table of contents

Table of Figures

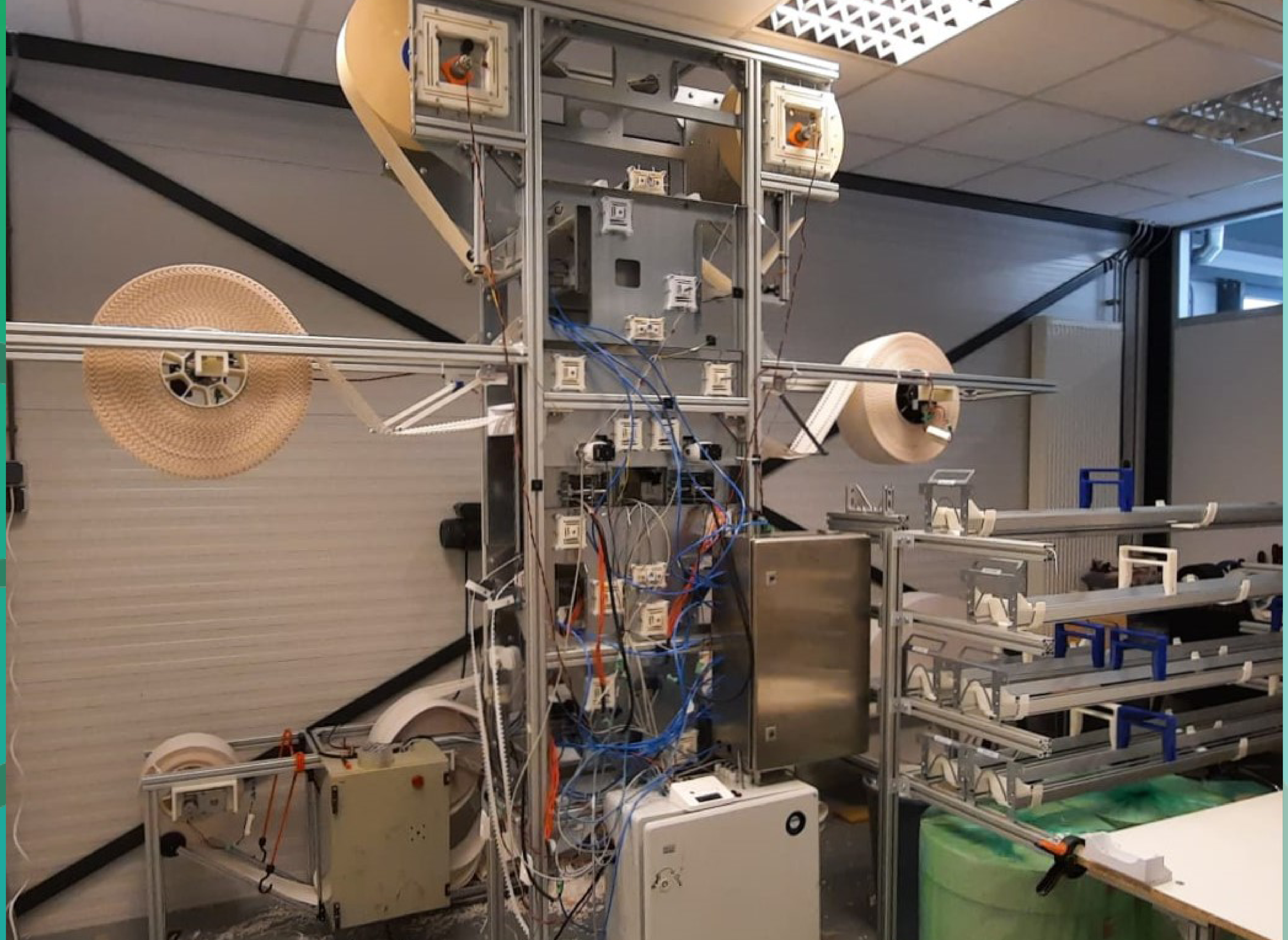
Table of Tables

Glossary

Word	Definition
Tea infuser	The complete tea infuser outside of the web is the final product created by TeaWall.
Filter paper	The material from which the tea infusers are made.
Web	The complete guided filter paper throughout the machine with the added parts to it. For example, the brackets or the filter hole.
Bracket	The cardboard part of the tea infuser, when referred to bracket a single one of these cardboard parts is meant.
Cardboard	The material from which the brackets are made.
Cartridge	A set of cardboard cartridges with additional cardboard teeth that keep the cartridge together and are used for guidance in the machine.
Filter hole	The cut-out is made in filter paper.
(Tea Infuser) Machine	The complete production machine used to manufacture the tea infusers.
Module [x]	Refers to a specific module within the machine, the explanation of each of the modules can be found in Chapter 1.
Setup	Machine settings that align the parts of the system in the x-, y-, and z-direction of the web as well as the parameters in the code.
Flexures	Hanging system for the modules, which can be used to change the setup of individual modules to create a better alignment of the individual steps.
Framework	The overall process as proposed in this thesis.

Abbreviations

Abbreviation	Definition
BOM	Bill of materials
DMAIC	Define, Measure, Analyse, Improve, Control
FMEA	Failure mode and effect analysis
LSS	Lean Six Sigma
RPN	Risk Priority Number



FRAMEWORK

1. Introduction

To get an initial understanding of the current state of TeaWall as a company and how continuous improvement within this company is needed for their production processes, an introduction will be given regarding the company, their products, and the current state of production processes. This will form the basic understanding on which the research questions will be based.

Figure 1: Original TeaWall

1.1. The TeaWall machines

TeaWall is a start-up company that has launched its integrated loose tea product-service system to the market after two years of development. Their product-service system was designed to fill the gap in the market where there are many solutions to get high-quality coffee at to-go locations, but there are little-to-no solutions for access to high-quality tea. Often the available tea is low-quality tea bags where the machines only provide hot water. These tea bags do not let the flavour of tea free completely and are often filled with lower-quality materials [1].

Their product-service system has undergone multiple iterations first of which was a fully integrated tea dispensing machine, the TeaWall, as seen in Figure 1. This machine accurately dispensed five interchangeable loose tea leaf types in their compostable tea infusers and filled the cup with water at the temperature most optimal for that specific tea. These tea infusers are part of the product-service system and are also produced by TeaWall themselves [2]. However, this concept was experienced by pilots to be too expensive. This has led to the redesign of TeaWall to TeaWall Basic, as seen in Figure 2. This new iteration of the machines misses out on the functionality to automatically add water and focuses solely on the accurate dispensing of the loose tea. TeaWall Basic provides the user with access to four flavours of tea. The machine is accompanied by a subscription model for the tea where the user can choose between eight different flavours of tea and is provided with TeaWall's patented tea infusers.

Figure 2: TeaWall Basic

1.2. The tea infuser

The TeaWall machines both have the need for a well-working tea infuser that allows for the seeping of the loose tea leaves. For this, the choice was made to use a newly designed tea infuser that fits the specific needs of TeaWall. The choice for a new design was made because many of the other infuser solutions for loose-leaf tea have disadvantages that do not align with the goals of TeaWall. For example, metal infusers, as seen in Figure 3, are hard to clean and are incompatible with the to-go model. While the infuser tea bags currently on the market, as seen in Figure 4, are either hard to fill or are made with plastics and therefore not compostable.

Figure 3: Metal tea infuser

Figure 4: Disposable tea infuser

The tea infuser of TeaWall, as seen in Figures 5 and 6, has been designed to overcome these disadvantages. The tea infuser is designed as a disposable product that is completely compostable and is able to fit nearly all cups with its one-size-fits-all design, the flyer used to market the tea infusers can be found in Appendix A. To achieve this the materials and production techniques are chosen to all be industrially compostable, as the tea itself does have compost value [3]. That a product is compostable means that the tea infuser completely decomposes into non-toxic materials which will not harm the environment. The specification that the product is industrially compostable refers to the need for a higher-temperature environment [4]. Thus, the tea infuser will not compost at home. The shape of the tea infuser is such that the cardboard brackets can be used as a spring which clamps the infuser within the cup. It is further stabilised with the two inlets at the sides of the cardboard brackets that can be placed around the rim of the cup. To make the opening of the tea infuser easier two flaps and inlets are added to the brackets. The use case scenario can be seen in Figure 7. To make sure the infuser opens easily, and the loose tea has room to float around, the shape of the infuser is made parabolic as well as the brackets which will lay nearly flat when the tea infuser is opened to ensure leaves do not spill out. This parabolic shape also makes that the tea infuser opens up the largest

Figure 5: TeaWall tea infuser

Figure 6: TeaWall tea infuser

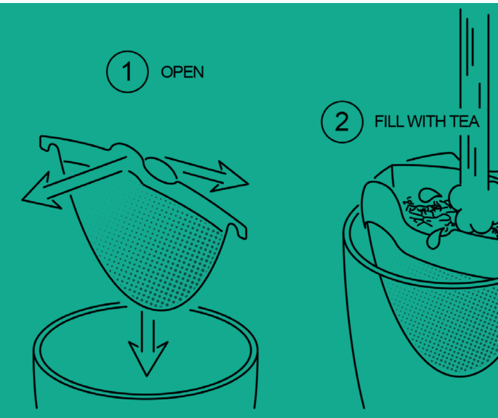


Figure 7: User instructions tea infuser

When used with the TeaWall or TeaWall Basic machines, the loose leave tea is dispensed in the tea infuser while it is placed on the cup, as seen in Figure 5. However, the end user could also fill the tea infuser manually if they are not combined with either of the machines. The tea infuser is also designed such that it can be folded around the edge of a cup to increase its use as a to-go solution. This is, in conjunction with the lower impact on the environment, one of the main reasons to use a disposable infuser has been that it is a unique selling point for to-go locations to serve fresh tea. This is because often there is little-to-no access to loose-leaf tea at these locations while freshly ground bean coffee is abundant.

Figure 8: Packaged tea infusers

While the TeaWall and TeaWall Basic machines have been ongoing projects over the last two years, the choice is also made to start selling the boxed tea infusers as a separate product. This is done in boxes containing either 40 or 100 tea infusers, as seen in Figure 8. This choice to start selling the tea infuser separately from the product-service system has increased the need for higher-yield mass production of these tea infusers.

1.3. Mass production problems

While the initial tea infusers have been made by hand, the need for mass production has arisen during the development of the TeaWall machines. Therefore, over the last year, TeaWall has designed and built the mass production machine, as seen in Figure 9, to start the mass production of their patented tea infusers. This machine has been designed from the ground up and has been working conceptually. However, this is only when it is under constant supervision of the operator. The machine currently can run for up to four hours at a time without critical failures that stop production completely as of the start of this graduation assignment. Many of the tea infusers do still have quality or usability problems. These problems occur due to the different failure modes within the different parts of the machine which range from misalignment issues to complete failures of a specific part or step of the production. The combination of different problems means that the yield fit for the consumer is at a low percentage of the total production. The machine also experiences high amounts of downtime due to critical failures of the machine which lowers the total production. The goal for the machine is to be able to produce tea infusers that are of high quality and produce little waste. Currently, as there can be many different failures of the machine, there is a need for continuous monitoring of the machine, while it is desired that the machine can run continuously with minimal need for the intervention and continuous monitoring of an operator.

Therefore, the machine has to be improved to be able to fulfil the aforementioned goals. To be able to achieve this, improvements must be made to the machine's parts, modules, electronics, and operational code to increase the overall yield of the machine. The main challenge of this improvement will be to create a strategy that will find the root causes of the most impactful failure modes that are observed within the machine. This is challenging, as the production machine is a complex system with many interacting parts. Most of the failure modes are the result of compounding tolerances or the compounding influences of different modules.

The secondary challenge is with the improvement implementations, where, after a solution is designed the new part or module will have to be implemented in a machine that is currently producing the tea infusers. This implementation of a solution within a continuously operating machine will most likely result in downtime of the machine. It is important to have a clear strategy for implementation such that the downtime of the machine is minimised. This also includes the ability that changes can be easily reverted when the designed solution does not impose the desired results.

1.4. Goals of the thesis

The goal of this graduation assignment is to research, based on the case study concerning the tea infuser mass production machine, how the reliability, quality, speed, and efficiency of a mass production machine can be increased while production is still able to run continuously. The research will focus on both the decision-making process and the implementation process. The former will focus on the choices that have to be made between different failure modes and decide which improvements of the machine have to be made. For this decision-making, finding the root cause is critical, as many failure modes will be occurring due to compounding factors. Therefore, the decisions on what changes should be made considering their effectiveness of solving the failure mode, ease of implementation in the machine, and overall costs. TeaWall is a start-up, and they will not be able to afford a high budget for the optimal solutions and should therefore also consider the most economical solutions for solving a failure mode. The latter part of the research will focus on how the implementation has to be structured as the machine is running continuous production. To be able to go through the decision-making process and implementation process, a framework will be applied that structures the approach. The research on the framework and thesis will be provided in Chapter 2, and the structure of the thesis based on the framework will be provided in Chapter 3.

The value for TeaWall from this thesis is that they can benefit from the continuous improvements that are being made to the machine during the case study, which increases the overall efficiency and reliability of the production process. Secondly, the researched framework will provide them with a structured approach with which they can continue the improvements done during the cases to further develop and optimise mass production.

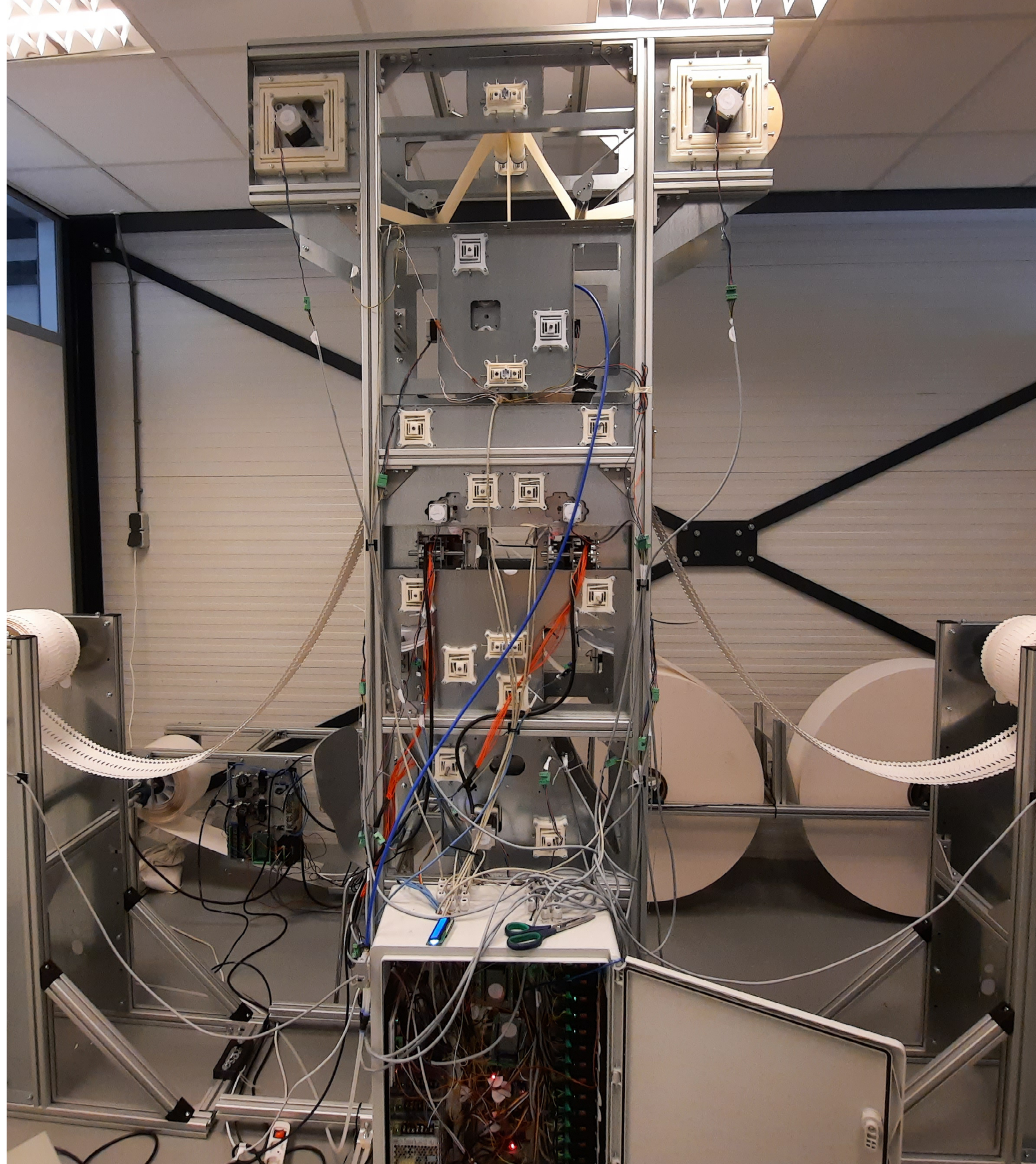


Figure 9: Production machine

2. Literature review

To be able to create the framework for TeaWall on how they can improve their tea infuser production machine, a structured academic approach has to be taken. In this chapter, the necessary literature review will be provided to substantiate the framework used for continuous improvement.

2.1. Continuous improvement

Within this thesis, the goal is to continuously improve the tea infuser production machine. The continuous improvement strategy allows for the production to continue, whilst simultaneously having the ability to grow the production machine in its reliability, efficiency, production speed, and quality of the end product [5]. The amalgamation of the improvements will result in a higher yield of end products with a lower failure rate [6]. All improvements will have to be implemented within a continuously running machine which results in the increased importance of the decisions made regarding which changes to apply, as well as the effectivity and the needed invested time of these changes to the system. Because the machine that produces the tea infusers is a complex machine, finding out what the problems exactly are and where these problems originate has to be done through the use of a clear and structured approach. This process is referred to as the implementation process.

Using continuous improvement, different directions and approaches can be taken. While there have been many different approaches, the majority has similar roots in the usage of an iterative structure throughout each of the phases of the continuous improvement cycle. One such example is the structured improvement strategy as seen in Figure 10 [7]. This strategy uses an iterative approach of firstly analysing the whole system, then a detailed analysis on the subsystem level, to finally be able to improve productivity.

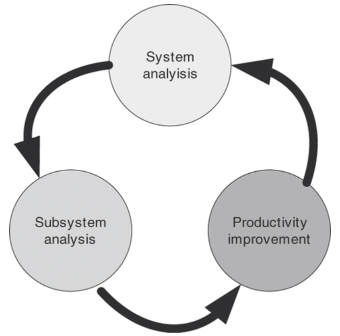


Figure 10: Structured improvement strategy [7]

Another strategy that can be applied to continuous improvement is the DMAIC cycle of the Lean Six Sigma (LSS) strategy [8]. The LSS methodology focuses on the continuous improvement of production through the combination of lean which focuses on reducing waste and six sigma which focuses on control over the process [10]. DMAIC stands for Define, Measure, Analyse, Improve, and Control [9]. DMAIC is the main structure that is used throughout LSS and provides the user with a clear step-by-step approach to determine the problems and create an improvement through each of the iterative cycles. The DMAIC approach is also often called the DMAIC cycle to put more emphasis on its iterative behaviour. However, LSS and DMAIC make use of more tools in their methodology as a means to support the tasks related to each of the different steps [11], some of these tools that are used and the structure of the DMAIC method can be seen in Figure 11 [12]. Examples of these tools are SIPOC (during the Define step), failure mode and effect analysis (during the Measure step) and the fishbone diagram (during the Analyse step) [6]. But other tools from the so-called LSS toolbox are also be applied to the improvement strategies [13].

DMAIC uses its steps to make sure that a structured approach will be taken for improvements. The tools then again used in the different phases of the DMAIC can be chosen by the user. An exploratory study on DMAIC [14] has revealed that the decision for these tools depends on the circumstances and can differ for each situation. This shows that DMAIC is often used as a baseline strategy but is substantiated with tools that fit the problem definition and approach used by the company. For example, while most cases in the research started with the same initial set of tools, they often ended up with a different finalised toolbox, suitable for their specific situation. Even though the difference was often found in just one method, it can be said that there is often not one true toolbox that should be applied at all times.

Another study, focussed on production [15], has set up a toolbox framework to be able to implement continuous improvement. The tools used in this specific toolbox were for example failure classifier, failure mode and effect analysis, and theory of constraints. Each is a vastly different method that has been used in the exploratory study. This shows that specified approaches are needed that fit the needs of the application, while each still can have the baseline structure from DMAIC. Based on the analysis of the effective implementation of DMAIC in different situations of production process improvement [15], the choice is made to use the DMAIC approach as the foundation of the framework for TeaWall. While DMAIC on its own structures the main thread of the framework, the application of other tools to substantiate it has shown to have a beneficial effect. The tools for the framework for TeaWall have to be chosen to fit with the goals that the project at TeaWall has.

The initial part of the DMAIC approach, including Define, Measure and Analyse, looks at discovering what the exact problems are and defines the root causes of these problems. The root causes are then used as the starting point for the improvement phase. How the improvements can be designed and applied is explained in the second part of the DMAIC approach, during the Improve step. After the improvements have been applied it is important to Control these changes. After which the complete cycle starts again. This shows that the overall approach can be divided into two distinct parts, *what* has to be changed and *how* these changes can be implemented and controlled. For this thesis and its framework, this distinct division will be used as the foundation of the structure.

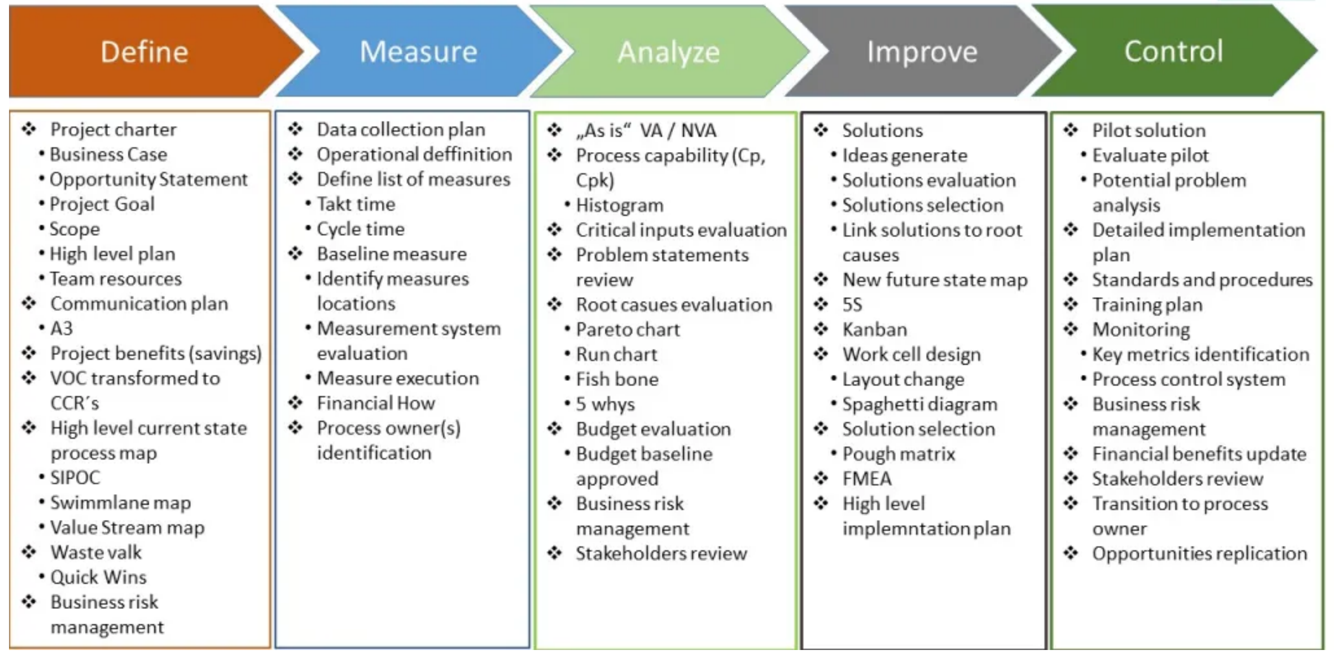


Figure 11: DMAIC tools

2.2. What (DMAIC cycle)

The coming sections will elaborate on the first three steps of the DMAIC framework and are summarised in this approach as the *what* step of the framework. This section focuses on collecting data and transforming this into knowledge of the existing problems of the production process. This baseline is needed to be able to start improving upon these problems. Therefore, the root cause of the problem must be found. It is undesirable that the effort being applied is only focused on solving symptoms, as this results in a solution that repairs the current problem instead of preventing the problem. To be able to access all this information, initial research on the production process will have to be done.

2.2.1. Define

The definition step in DMAIC is used to define the problem of the current production process. To be able to define the problems additional machine and process knowledge is needed. This is the definition of the machine, which can be established utilizing a functional description as well as determining the different failures that can occur during the production process. This information has to be structured in such a way that a problem can be defined and goals can be set for the improvement process.

2.2.1.1. Functional description

A functional description will explain and create a basic understanding of how each of the components of the machine work and interact with each other. This basic understanding helps the designer and the stakeholder understand what the failure modes and problems of the production process could be. Other factors important to the production process that can influence the failure modes such as material choices and software should be discussed as well for this similar reasoning.

2.2.1.2. Failure modes

In addition to describing the functions and descriptions of each of the used parts in the manufacturing process, the possible problems have to be defined as well. For this, another tool that can be effectively used is the failure mode and effect analysis (FMEA) [16]. This tool looks at comparing all current failure modes in terms of severity, occurrence, and detection. For this application of FMEA, initially, the failure modes will have to be defined. This is done during the Define step to gather knowledge on the possible failures and problems for which redesigns might have to be made. The further steps will be executed during the later Analyse step.

Defining the failure modes will also allow for the clear classification of each of the possible failures [16]. The application of the effect analysis of FMEA will be executed later in the process, during the Analysis phase of DMAIC, as there is currently too little information and measurements to be able to perform these steps. In this next part of the FMEA, the outcomes will be able to influence the decision-making process for the choice of failure mode for the redesign. For the initial analysis of the current state of the production process, only the failure modes are defined. The definition of the severity, occurrence, and detection will only be done later in the redesign process as this also needs to have more data on the failure modes as well, which will be measured later in the process. It is important to already determine the failure modes during this initial step of the improvement process as this helps substantiate the problem definition.

2.2.1.3. Gap analysis

When an overview is made of the current state and the possible failure modes, the goal of the re-design has to be formulated. For this, multiple methods can be applied such as the 5W2H method [17]. This method focussed on asking the right questions to break down a problem [18]. An example, of such an approach can be seen as having a discussion in which the counterpart continuously asks further questions. An advantage is that this helps with gathering more information, but is prone to be biased, based on the types of questions used to delve deeper. Another method could be applying the voice of the customer or business (VOC/VOB), this method focuses on gathering information from the stakeholders to formulate the goals of a project [19]. This places the data gathering more towards the stakeholders and can help with gaining a better understanding of their perspective towards the end product. While either of these methods provides tools that can help with goal definition, they lack the creation of an action plan based on their outcomes. This is for the application of continuous improvement more important, as the system is complex finding the actual goal that should be solved becomes more difficult. For the application of the improvement of the production process, however, implementing a method called the gap analysis could be a helpful tool. The gap analysis method is used to show what key steps must be made to a defined current state to be able to achieve the desired state [20]. These gaps can then be formulated into the multiple goals of the redesign process. The gaps also help with defining the actions that should be taken to get from the current to desired state.

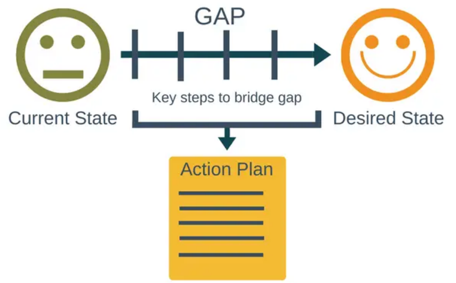


Figure 12: Gap analysis

Gap analysis is a broad term that considers different types of gaps. On of these gaps can be the market gap analysis, which focuses on the identification of possible products that can fill these gaps. Another example is the knowledge gap analysis, which can be used to determine what information and inisghts are lacking within a company or industry [21]. For the application in continuous improvement, gap analysis can be used to compare the current state of the production yield to the desired state of production [22]. The gaps can show the steps of the production process or the parts of the production machine that are good candidates for a redesign. In the context of gap analysis, the current state is the combination of the aforementioned analysis of the functionalities of the production machine as well as the possible failures. In comparison to the current state, the desired state defines what the production machine and the final product, the tea infusers, should work and operate like at the end of the redesign process. Visualisation of this structure can be seen in Figure 12. With clear definitions of the current state and desired state, the different types of gaps can be defined and substantiate the actions and design improvements that will have to be taken. The steps executed during a gap analysis according to Weller [23], are as follows:

- Identify the area to be analysed and identify the goals to be accomplished.
- Establish the ideal future state.
- Analyse the current state.
- Compare the current state with the ideal state.
- Describe the gap and quantify the difference.
- Summarize the recommendations and create a plan to bridge the gaps.

These steps make sure that the current state of the production process will be documented, what has not been done before at TeaWall. This lack of insight into the current state makes that the company does not know where the problems arise, and what possible improvements could be achieved. When this is compared to the defined ideal state, or desired states, problem areas of the production process will surface. Quantifying the difference between the current state and the gap gives insights into how pressing each of the problem areas is. With the gaps defined, an action plan can be made to bridge the gap. The actions that have to be taken to get from the current state to the desired state must be further substantiated by the decision-making process regarding the individual failure modes to be able to decide what improvements have the highest priority.

2.2.2. Measure

To be able to understand what the impact of the problems is, measurement data on the different failure modes is needed. This data can be either qualitative or quantitative data that gives a clear indication of the magnitude of the problem [24]. Currently, the company has little-to-no measurements of their products and production process, and therefore has low insights into their production process. To overcome this knowledge gap, data has to be gathered on aspects of production such as yield, failure rate, capability, and quality. This data can be gathered in different ways ranging from interviews with the end-users, to measuring the final product, timing the machine, or further process analysis. With the gathered data new insights cannot yet be made as they do not provide clear information on the subject. This is because gathering the data is not the same as gathering information on the current state, therefore, the analysis phase is needed which can help provide these insights [25].

2.2.3. Analyse

The next step, as determined by DMAIC, is the analysis phase. This is the step in continuous improvement where the gathered data has to be refined by finding relations between the data points. Similar to the definition phase, many different tools and techniques can be used. In LSS, one of these tools is the capability study.

2.2.3.1. Capability analysis

Capability analysis studies are a tool that will better define the current state of the production machine by giving insights into the precision of the production process and showing the places where improvements are necessary [11]. Mainly set-up changes can be defined with these measurement data as the centring within the acceptable tolerance window can be seen. This tool is often used in mass production applications [26] as it can distil information from longer production runs as well and can show where there is a need for improvements to increase the yield of mass production [26]. As the tea diffuser machine for Tea Wall is envisioned to become a mass production machine, the choice of conducting a capabilities study seems a suitable approach. While the capability analysis does provide insights into the measurement data, on its own it does not reflect the complete overview of the current state. For this aditional data that is not focussed on the dimensions is needed.

2.2.3.2. Failure mode and effect analysis

It is, after the initial findings have been made, important to start with the decision-making process for improvements. As each change that will be made takes time and effort, it is important to make the correct decisions on what failure modes have to be solved, made, and chosen by their order of effectiveness [27]. To be able to define the weight of each of the failure modes, it is important to substantiate the defined failure modes through the use of characterisation. As mentioned in Chapter 2.2.1.2, methods such as the FMEA provide numerical insights to help the decision-making process of the improvement strategy. Utilisation of the FMEA will result in a numeric ranking of the Risk Priority Number (RPN) for the different possible changes that can be made [27]. This ranking is normally based on occurrence, severity, and detection, as seen in Figure 13 However, for the application of continuous improvement on an operational machine, additional parameters in addition to severity, occurrence, and detection could be considered. These additional parameters will better define which of the changes will be most likely the most effective, both in the improvement of the machine and regarding financial and time effectiveness. [28] When the RPN has been determined for all of the failure modes the most influential failure modes can be chosen to be solved.

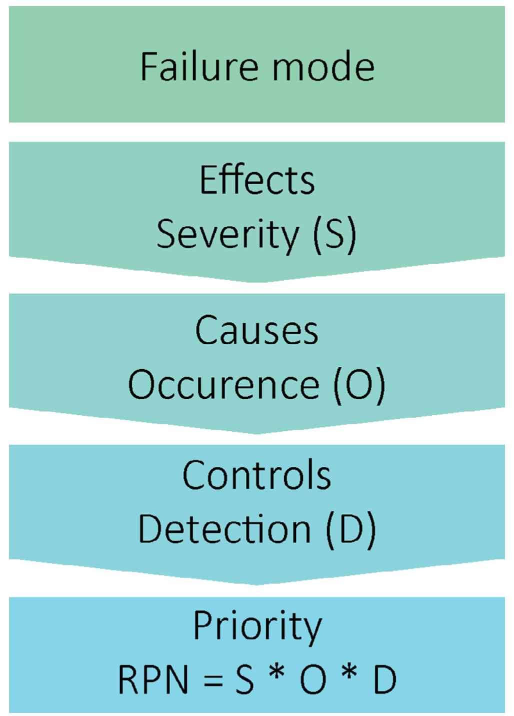


Figure 13: FMEA steps

2.2.3.3. Root cause analysis

In complex systems, however, the determination of the RPN leaves out the finding of the root cause of the failure mode. In a complex system, such as the tea infuser production machine this additional analysis will be needed.

Finding the root of the cause is critical to have an effective redeisgn or improvement stratagy. In these complex systems, different aspects can influence a certain problem or could even occur through the compounding of multiple root causes. These aspects can, for example, be the influence of the environment, human errors, or design mistakes. To be able to overcome these problems, finding the root cause is most important [29]. When the root cause is not determined, only symptoms of the actual problem will be solved. To be able to find the root cause, multiple methods can be applicable, such as the 5H2W, which has been discussed during Chapter 2.2.1.3, as this again helps wiyh guiding the research into the problem Another tool is the Ishikawa diagram, which finds the possible causes of the problem that needs to be solved by documenting all the different possible origins of the problem. The diagram used to document the possible causes can be seen in Figure 14 [30] [31]. Each of these methods uses additional analysis of the complete system, including people and more, to determine where the problem originates. In the framework, the root cause analysis will be executed by gathering additional data on the performance of each of the modules to determine the main influence of the compounded tolerances. From the Ishikawa diagram, it can also be determined that during the current state analysis, where possible origins of the failure modes are described, not only the equipment and process are important. Also, the people, materials, environment, and management can influence the origination of failures.

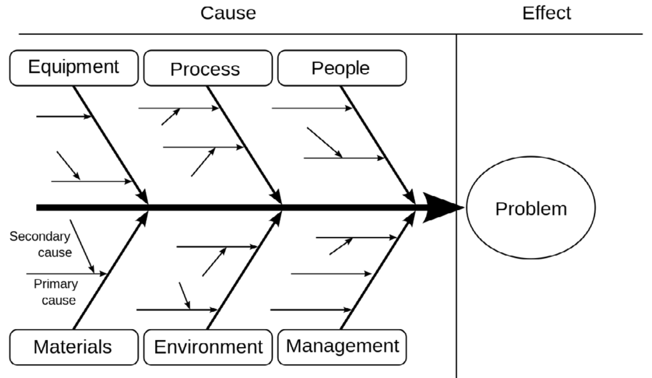


Figure 14: Ishikawa diagram

2.3. How (Design Thinking cycle)

With the root cause found for the failure modes during the initial *what* phase, the second part of the DMAIC is used. These are Improve and Control. The former uses a short term for a longer process as the failure mode has to be solved. For this, a design process will be applied. In this section, the different steps needed within the design process will be elaborated as well as the additional tools and steps which have to be applied in the case of TeaWall.

2.3.1. Improve

The production machine of TeaWall has parameters that can be adjusted to create a better production process. These adjustments allow for low-effort, and often high-impact improvements to the production process. These are also called quick win solutions from the action priority matrix, as seen in Figure 15 [33], and should be applied through the initial iterations of the DMAIC cycle. After all advantageous changes have been made to the machine through its already existing configuration options, further improvements should be made using redesign methods.

To answer the *how* question, one of the design methods such as design thinking method can be used. While each different design method has its advantages and disadvantages, the application of the more generic design thinking method as the base methodology for designing and implementing the changes to the production machine does provide an approach that correctly guides the desing process. The method focuses on gathering additional information during its steps to better define its problem statement to from there be able to create ideas. The method uses five steps, as seen in Figure 16, the steps are executed sequentially

Figure 15: The action priority matrix

but can go through multiple iterations [34]. The method helps with guiding the less structured design approach. However, as the method is generic it does not internally take the challenges of the to-be-designed changes for the production machine into account. Therefore, the specific challenges that arise will have to be elaborated. In the next part, the steps of design thinking will be elaborated in the context of the cases of the thesis:

1. Empathise
Initially, the challenges that occur within mass production will have to be defined. In this first phase of design thinking the production process and the current stage of the yield of the production machine will be elaborated.

2. Definition
In the second phase of design thinking, the challenges will be defined more clearly and substantiated with numerical values which reflect the current state in more depth.

3. Ideate
After the most important failure modes and challenges within the production process have been defined a choice can be made on what changes should be made. These changes will have to be designed with an ideation process where divergent possible solutions should be designed. These then will have to be substantiated with a proof of concept. As the full design and production of the redesigns are expensive and time extensive. Therefore, some of the prototyping and testing will already be at a lower level in the ideation phase.

4. Prototype
The concepts of the ideation phase will have had an initial proof of concept but will have to be tested more in-depth to ensure that their implementation in the production machine will have the desired effect on production.

5. Test
As a final step in design thinking the solution is tested. or the application in this framework the choice is made to initially test the final solution outside of the production machine. When working accordingly to the expectations, the solution will be tested inside of the production machine. This two-step approach will provide an initial level of confidence to implement the change in the machine. This is then the second step of testing, to test the solution inside of the production machine. This approach is taken as it is important to fully develop the solution separately from the actual machine to prevent the introduction of problems when implementing the designed solution directly into the tea diffuser machine. While it is impossible to completely negate the chance of implementation failure its occurrence can be lowered.

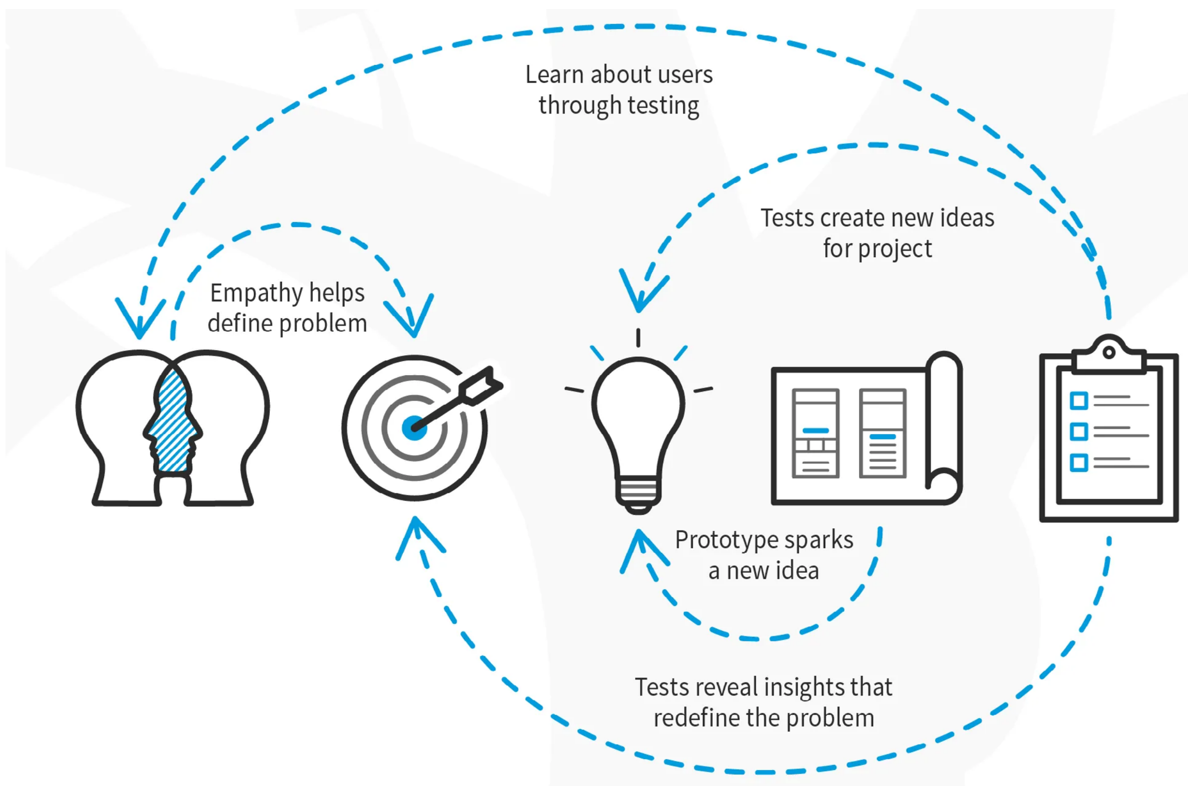


Figure 16: Design thinking approach

2.3.1.1. Design iterations

During the improvement strategy the cycles as decribed in the previous chapters, have to be taken iteratively (Figure 17). When a solution is implemented using the framework, the current state will have to be adjusted and will provide information on the next change that can be made to the machine, which in turn must be redesigned and go through the complete design phases to be implemented.

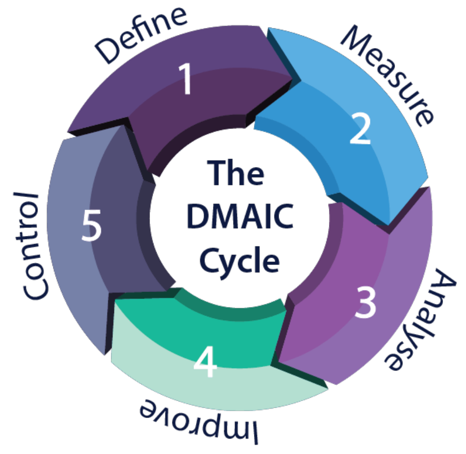


Figure 17: DMAIC cycle [36]

Design thinking is also an iterative design strategy (Figure 18)meaning the steps will not always be taken consecutively [36]. When problems occur in any of the steps the choice will have to be made to go back to a previous step to reiterate the choices or designs that have been made.

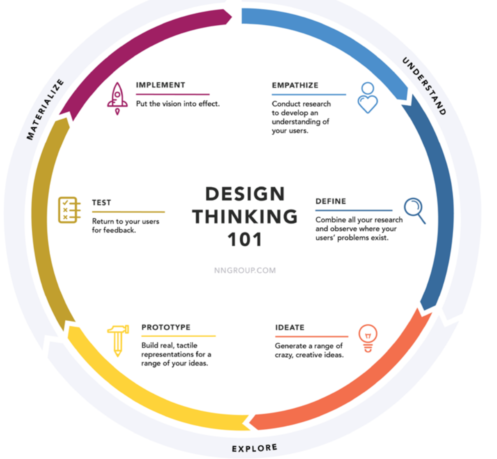


Figure 18: Design Thinking cycle [36]

2.3.1.2. Machine configuration

An important step in the improvement of the production machine is making use of all the adjustable settings that the machine has. The possibility of having different configurations of the machine has the chance to be a low effort, high impact improvement and therefore can be done initially before looking at possible redesigns. When changing configurations, the capability of each of the parts of the end product will have to be considered to be able to ensure that improvements can be made.

2.3.2. Control

First of all, after the update has been done to the machine it is important to control the improvements. This can be done in multiple ways. One of the methods of statistical process monitoring is by means of control charts, or statistical process control (SPC) [11]. These methods analyse the measurable parameters of the end product and the occurrence of each of the failure modes and can compare these to the original measurements that have been done. This gives the clearest distinction between the before and after states of an improvement.

Secondly, it will be important to control for new occurrences of failure modes. By changing the machine, there is the opportunity for new failure modes to arise. These have to be found over a longer period. When new failure modes have been found the current state will have to be compared to the before state to control if they are acceptable in comparison to the failure mode occurrences that were present before the update was done to the machine.

2.4. Continuous improvement framework

From the executed theoretic research, a suitable framework for the improvement of the tea diffuser machine is established (Figure 19). The framework can be summarised as the amalgamation of the DMAIC cycle and the design thinking cycle. The former represents what the necessary machine elements are to be changed and the latter represents how these should be changed. The switch between these cycles is made during the Improvement stage of the DMAIC cycle and returns after the testing step is completed in the design cycle.

The DMAIC cycle is chosen as it facilitates a well-thought-out approach to continuous improvement. Each of the steps of the DMAIC cycle will be substantiated with tools that contribute to the process. For the framework specifically for TeaWall, the choices are made to start with a functional description and gap analysis during the Define step. This fits with TeaWall as there currently is little-to-no documented information on the production process and these tools will help with determining the goals and actions needed for continuous improvement. After the Define step, gathering measurements on the process and applying a capability analysis will further substantiate the current state of the machine and will help with determining what types of improvements will be necessary. During this Measure step, the occurrence of the failure modes will be documented. During the next Analysis step, the failure modes will be analysed to determine improvement areas. During the Analysis, the other factors of FMEA, severity and detection, will also be defined in addition to the occurrence measured during the Measure step. To ensure the right problem will be improved upon there is a need for a root cause analysis of the failure modes. These will determine the specific parts of the machine or process that will have to be improved upon.

After the initial part, the what can be answered and the how question can be asked. During this Improve step, the choice can be made to apply machine improvements directly. These can be quick wins such as the changing of machine parameters. The other option is to enter the design thinking cycle to determine a fitting solution to more complex problems. During this cycle, the design has to be created or adapted while the machine is still operating daily, which means that the development has to be done in parallel. The choice for the complete design thinking cycle during the improvement step of the DMAIC cycle is that this will further help structure the design process as this can otherwise be a vague step. During the Emphasise and Define steps of the design thinking cycle, a more detailed approach to analysing the module and problems will be taken. As the machine is complex it is more useful to only get into the details during this phase to expedite the overall process. After the definition is made, the Ideation phase can be started. During this phase, the ideas will have to be tested, which shows the iterative nature of the Design Thinking cycle. The testing of the ideas is needed as the improvement that will be applied to the machine should have a high probability and confidence of working, as the improvements will introduce downtime to the process. This downtime can greatly increase when the improvements do not work as expected. Important during this Testing phase is to as closely as possible simulate the situation in the overall machine. Testing will thus be done, first, outside of the machine, and during implementation in the machine. When the improved design is completed and implemented in the overall machine, it becomes important to Control if the change has closed the gap defined during the gap analysis. This can be checked against the desired state. It is important to check if the process is improved as expected or that the answer to the what remains similar has to be improved upon differently.

During the initial cycle of the framework, most of the steps have to be completely and thoroughly executed. During this initial cycle, machine improvements can be mainly done through the use of machine adjustments. Such minor changes can ensure that the machine is aligned well, thereby eliminating the root causes of failure modes attributed to the machine's design, instead of retracing an incorrect setup. After the initial cycle has been completed, it can be used as the foundation of the subsequent cycles in which information often only has to be updated. While the framework shows an initial starting point, there is no clear endpoint to the framework as continuous improvement will be an ongoing process throughout the lifetime of the production machine.

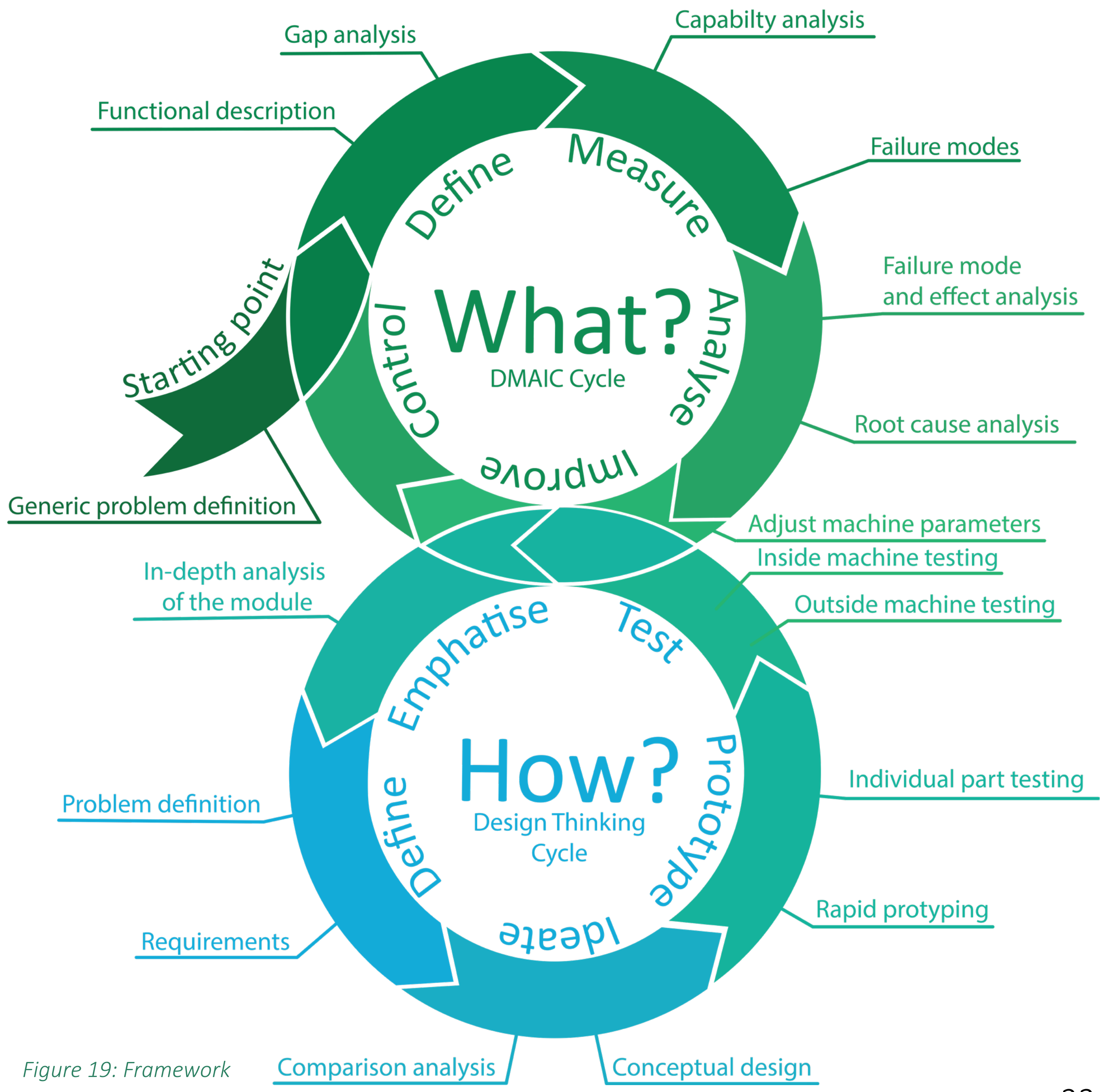


Figure 19: Framework

3. Thesis structure

The framework designed during the literature review will be the foundation of the thesis. In this chapter the structure of the thesis will provided. This structure has been divided into two parts, each corresponding to one of the two main parts of the framework: finding out what has to be changed and how these changes can be implemented.

3.1. Scope of the thesis

The scope of this thesis is the application and optimisation of the improvement framework for TeaWall's tea infuser production machine and process. This framework should facilitate the ability to improve consistency, quality, and production speed while lowering the failure rate. Each of these improvements will have to be made parallel to the continuous production of the tea infusers. During the thesis, a case study of the production machine of TeaWall will be used, in which different optimisation applications will be used to show the implementation of the framework in practice, and how the framework adjusts to different design challenges that occur during the process.

3.2. Research questions

To improve upon the current tea infuser machine, it is necessary to have a structured approach to the decision-making process of what to improve and how to implement these changes. Therefore, several research questions and sub-questions have been formulated to structure this research. As the framework will be based on two separate parts: the "What?" and the "How?". The research questions will be structured around these two parts.

What are the improvements that have to be made to the machine to improve the yield?

How can an operational production machine be evaluated to decide what parts or processes have to be improved?

- How does the production machine operate currently?
- What is the current state and yield of the tea infuser machine?
- What is the desired state and yield of the tea infuser machine?
- What is needed to move from the current to the desired output yield?
- What is the current capability of each of the parts of the produced tea infusers?
- What are the current failure modes and their occurrences within the system?

The goal of the first question is to define the current machine and find out what failure modes are present in the complete production process and the machine. The current stage of the mass production machine will provide with knowledge into the current processes and parts and can be used to determine the root causes of the failure modes. The current stage also in later stages will be used as a baseline to which improvements can be compared against. The definition of the current stage will then be compared to the desired state of production which will define the gaps that are currently present in the system and outlines the action plan that has to be taken to bridge these gaps.

How to choose the most effective improvements that should be executed to improve the mass production?

- What are the current changeable parameters of the system?
- How can the machine's parameters be changed to improve upon the production yield?
- Which failure modes have the most effect on the production process?
- What are the root causes of the failure modes?
- What is the probability of an improvement to be effective?
- How much downtime can be expected for the implementation of the solution?

This second question focuses on guidance in the decision-making process as many factors can influence the final produced tea infusers. Through the use of numerical values for different categories of influences these decisions can be numerically substantiated.

How are improvements designed, and implemented in the machine while it is running continuous production?

How to design improvements for a continuously operating production machine?

- What factors have to be considered in the redesign?
- Can multiple improvements be combined?
- How can a proof of concept be achieved outside of the production machine?

When the decision is made on what problems have to be redesigned for, the challenge becomes creating a solution that will work when integrated into the overall system. This means that there has to be proof of concept of the design solution before the implementation. As when the designed solution does not work in the integrated machine it can create a high amount of downtime in production.

How to implement changes to a continuously operating production machine?

- Can you make changes that do not interfere with the continuous operation of the tea infuser machine?
- How to verify the effectiveness of the improvements?
- What strategy is needed to lower the downtime of a change to the tea infuser machine?
- How to make sure that the system can be reverted if the designed solution does not work in the machine?

Finally, the designed solution must be implemented in the production machine. This provides the challenge that it will encounter unforeseen problems as well which will result in some amount of additional downtime for production. The downtime will have to be minimised through a well prepared implementation strategy which will have solutions to circumvent possible problems during the implementation.

3.3. Thesis structure

The thesis is structured following multiple iterations of the cycle as suggested in the framework, as seen in Figure 20. This will show the steps needed to be taken to achieve improvements in the tea infuser machine. This means that initially the current machine is analysed and a current state is defined. With the current state in mind, the desired state and the gap to this desired state are defined. Through the use of an FMEA, the decision-making process will be substantiated with the statistical analysis that will be executed. During the initial cycle of the process, the design thinking cycle will be skipped as improvements are able to be done by means of set-up adjustments. After these changes are made and controlled, the next iteration will be applied. During this second iteration, the focus of the thesis will be placed more on the root cause analysis and redesign process which utilize the design thinking methods.

With the failure modes defined and the actions chosen based on the FMEA, the design process will start for the cases that will be executed in this thesis. The design process also is an iterative process. A failure mode starting with the highest-ranking failure mode will be further analysed and a solution will be designed and tested, when this solution shows the possibility of increased yield it will be implemented in the machine. After which the next failure mode in the ranking will be chosen to be redesigned. For example, Chapters 11 and 12 will go through an additional iteration that focuses on a different redeisgn approach. In the end, an evaluation of all improvements will be executed, after which the final and updated overview of the framework will be given based on the findings from the case studies.

3.4. Final deliverables

The final deliverable for this thesis is the framework which allows for the optimal approach for improving the tea production machine from TeaWall. This strategy will focus on the problem and root cause analysis of the current system, how decisions are made on what changes to implement, and the strategy to implement these changes in the production machine whilst not creating long periods of downtime and loss of yield. Additionally, the improvements made to the tea infuser production machine will be provided and implemented in the production process, which will have the result of an improved production process.

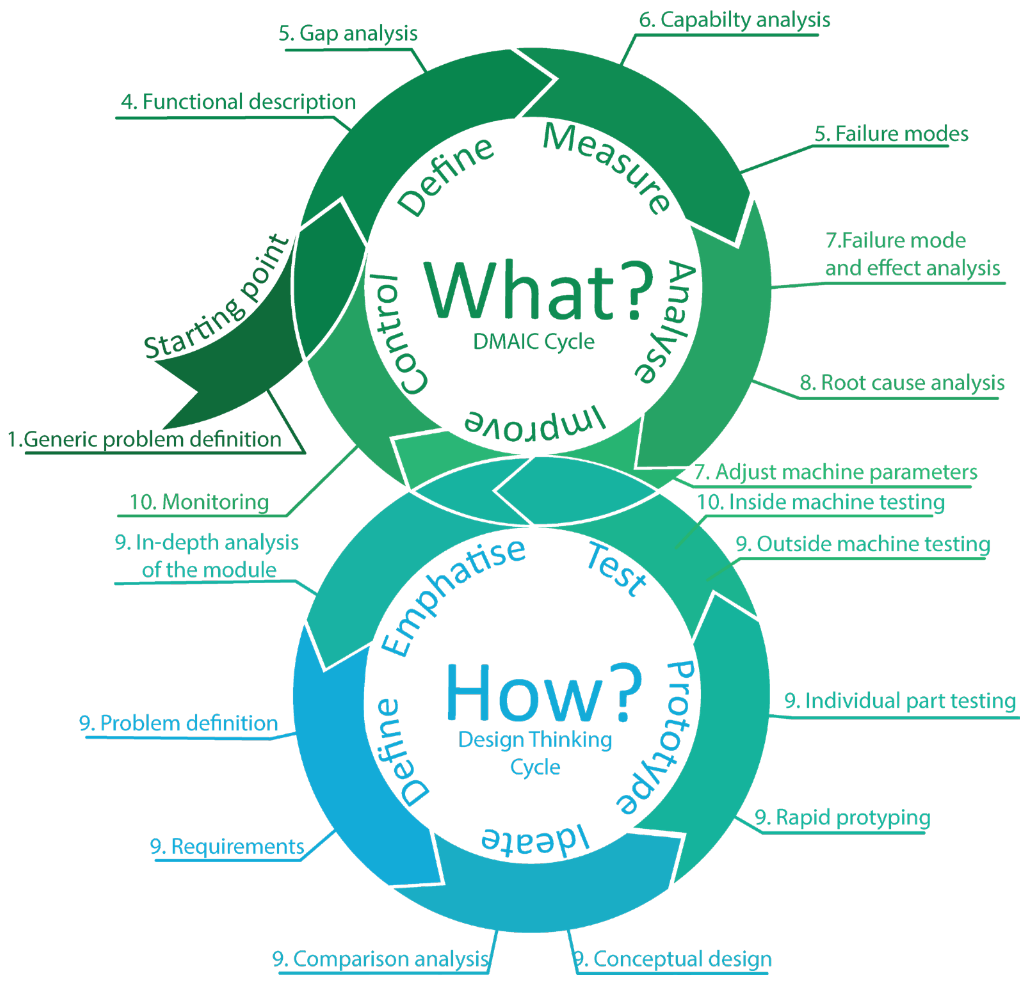
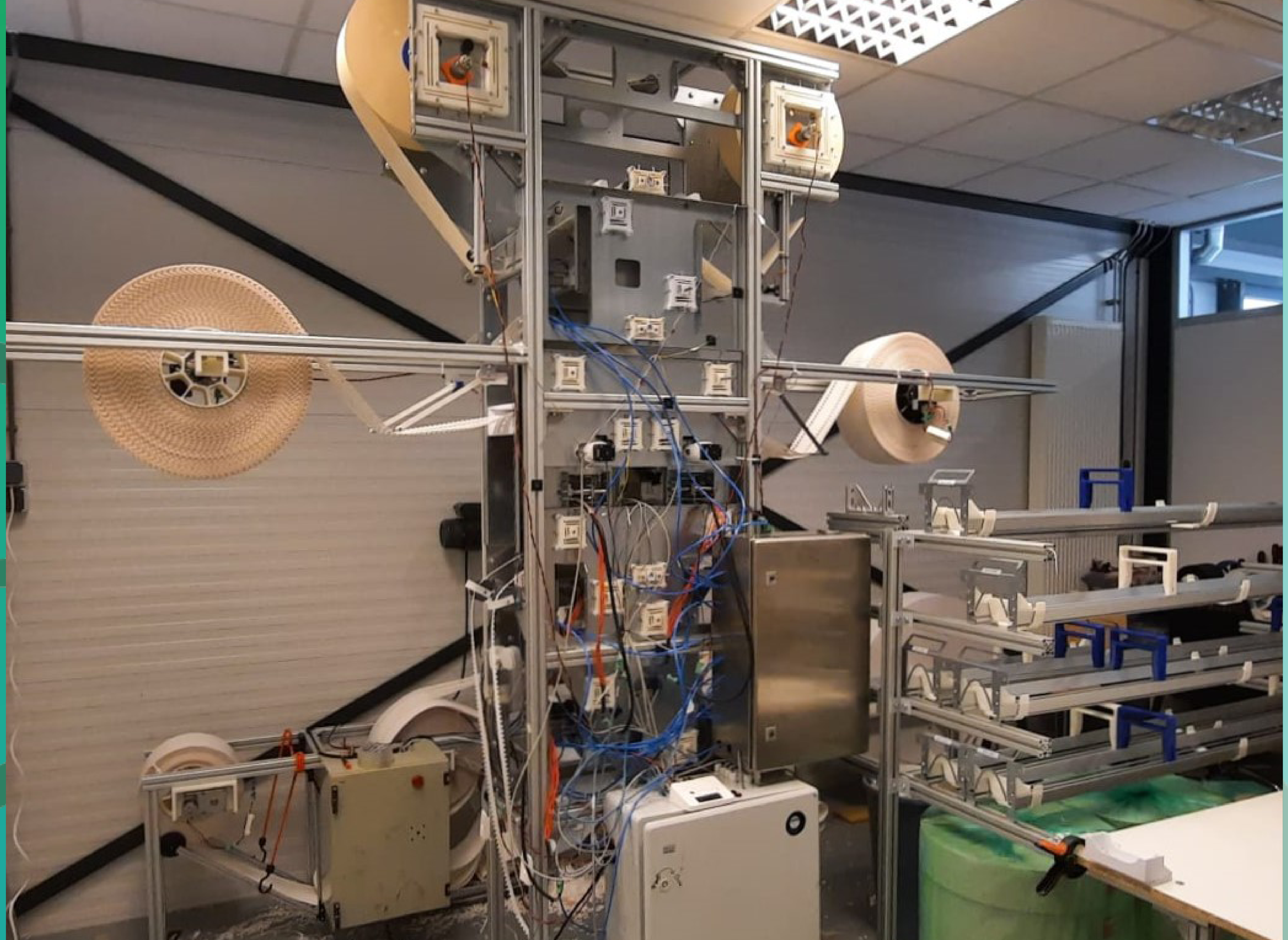


Figure 20: Thesis structure



PART 1 - WHAT?

4. Functional description of the tea infuser machine

In this chapter, the answer to the question "How does the tea infuser machine operate currently?" will be given. This is done through an explanation of the design of the production machine, as well as the production steps that are executed by the production machine to produce these tea infusers. This chapter consists of a description of the machine and production and is intended for the reader to understand how failure modes could occur and where they are located within the physical machine or the production steps. This complete understanding of the machine helps to know how each of the parts influences the produced tea infuser.

4.1. The tea infuser production machine

To be able to produce the tea infuser an automated manufacturing process had to be designed, the design of the original machine can be seen in Figure 21. This process, facilitated in the form of the production machine produces and combines all the parts of the tea infuser. The tea infuser consists of four distinct parts, two sides of the filter and two sides of the brackets. During the design and testing of the machine, these parts have been adjusted to be able to be produced by the machine.

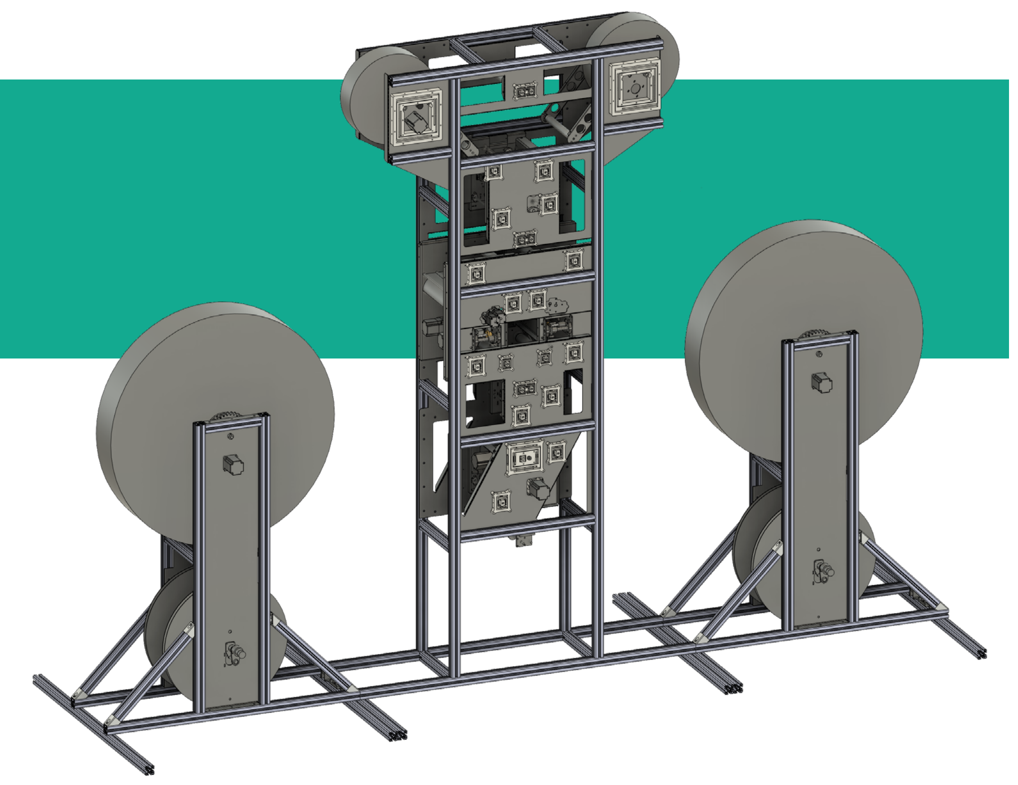


Figure 21: Production machine design

The original design of the tea infuser was a tea infuser with folded cardboard brackets, as can be seen in Figure 22, this design had advantages in user comfort but had a detrimental effect on the complexity of the machine. The folding of the cardboard showed to be a great challenge and the choice was made to use the elastic behaviour of the cardboard to let the tea infuser clamp itself within the cup instead of having a more complex tea infuser that had more points of contact with the cup for stability.

Figure 22: Old design of tea infuser

As the machine had to be designed from scratch and therefore had to go through many iterations of testing and redesigning working principles, the choice was made to work with a modular design. Using a modular design for the machine allows for easier changes of parts of the machine and improves the ability to have maintenance of the parts and modules. However, the modular design of the machine also has drawbacks, as each of the modules has to be aligned properly and the overall machine loses rigidity during operation as the are more compounding tolerances of the parts. The modular system is designed to work from a single master module, which controls and interacts with each of the other modules.

Each of the modules is connected to the outer frame with the use of axles which hang in flexures. These flexures allow for the adjustment of the module in all three axes, X- and Z-direction within the flexure and Y-direction by sliding on the axle. Through means of flexures, the machine can be set up correctly accounting for some of the tolerances within the system.

4.2. Production steps of the machine

To create a tea infuser using the production machine first the materials must be loaded into the machine, these are the two filter rolls and the two cartridge rolls. The latter of which must be produced first from the cardboard rolls in the separate module from the main machine, referred to as the cartridge machine. This additional separate machine was needed as the production of the cartridge rolls would have been of too low quality or would have been too expensive to be produced externally. After the materials have been loaded into the machine. The filter paper that is run through the machine is also called the web, it runs through each of the modules and connects from filter roll to the end product. During setup, the web has to be pulled through the machine as this cannot be done automatically. How the web is run throughout the machine and the locations of each step can be seen in Figure 23. When the web is under tension throughout the machine, the production of the tea infusers can be started. During production the tea infuser has to go through four distinct steps to be produced, these can be seen in Figure 24. Most of the steps is divided in a step Xa and step X, where the former relates to the movement within the machine and the latter the actual produciton step.

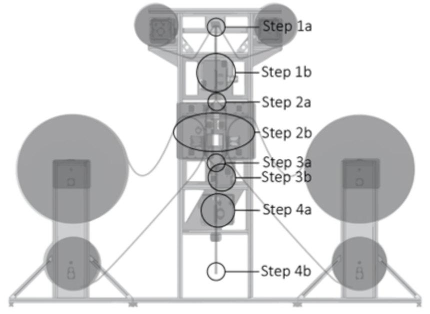


Figure 23: Production step locations

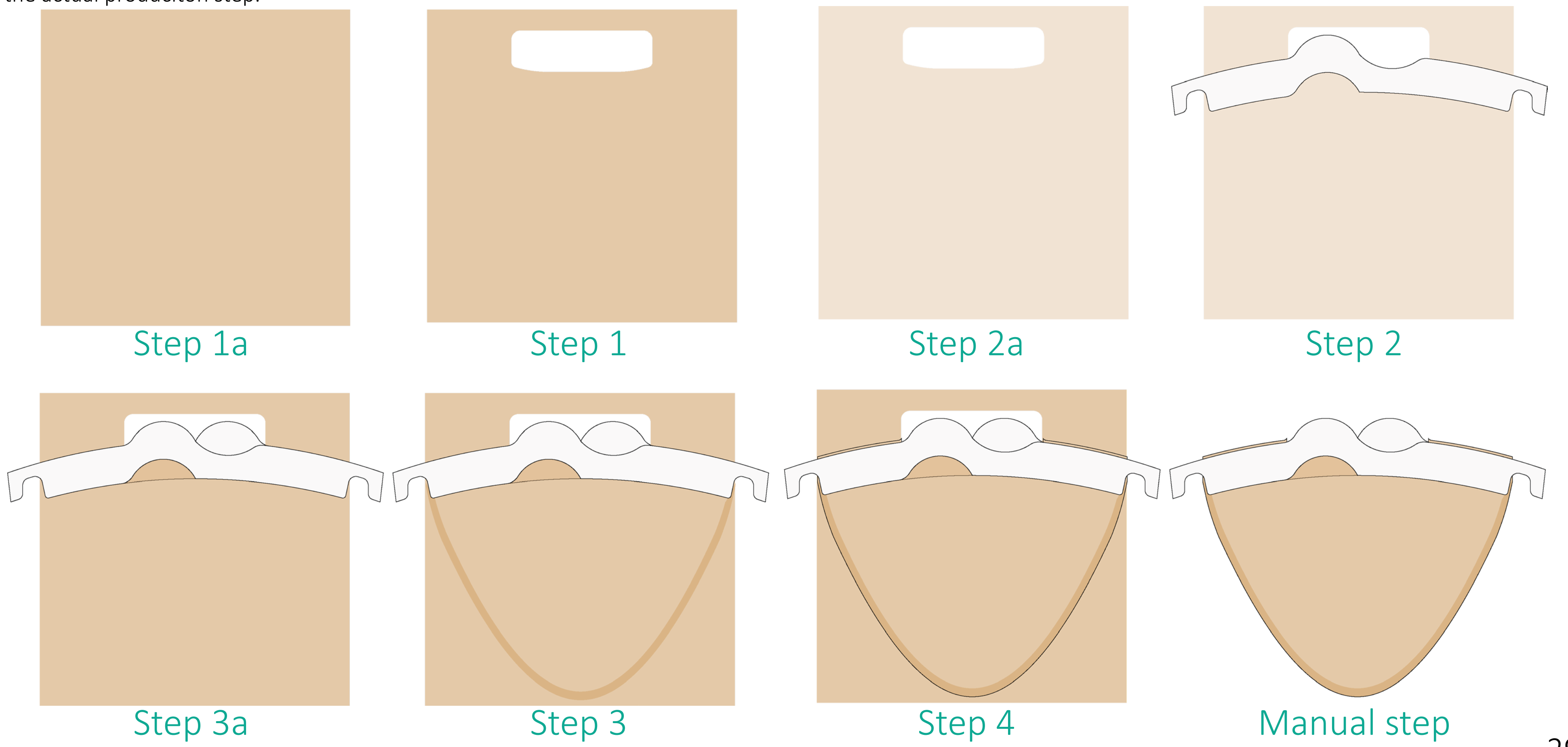


Figure 24: Production steps

The first step of producing the tea infuser is combining both sides of the web so the module can simultaneously cut a hole in both sides of the filter paper. This hole in the filter paper is needed because otherwise, it would be in the way of the user when they are opening the tea infuser. This step creates waste in the form of two pieces of filter paper that have to be disposed of this is done during the operation of the module.

Secondly, the web is pulled apart from each other to be able to perform the second step. This step needs a backside to which the filter paper will not stick to work. If the web would not be separated the tea infuser would be sealed shut at the top underneath the brackets as well. In step two, the brackets are fed to the machine in their cartridge and are aligned with the web. The brackets are heat-sealed to the web using a hot aluminium press, whilst in the same movement being cut from the cartridge by two knives. This module creates waste in the form of two strips of cardboard in both modules, this has to be taken out of the machine as well and again this is done by the module itself.

After this step, the web is combined again and the two filter papers and two brackets are heat-sealed together in step three. This step seals the two outer edges of the bracket and seals the two sides of the filter paper.

During the final step, the web is fulled through the pulling mechanism and is put under tension by slipping roller and the pulling mechanism. In this step the tea infusers have to be cut from the web by a knife, the knife is placed against the paper and a metal backplate over which a roller under high pressure will cut out the tea infuser.

As of the start of this thesis, the tea infusers are still connected to the web with thin pieces of filter paper as there hasn't been created a step in which the machine automatically separates the filter from the web. Therefore, the final product now has to be manually taken out of the web which results in an additional step. After the tea filters have been taken out of the web and checked for deformities and failure modes, they are manually filled in the cardboard boxes. The cardboard boxes are either filled per two sets of 50 tea infusers or a set of 40 tea infusers. These cardboard boxes with either 100 or 40 tea infusers are the final product which is sent to the end consumers.

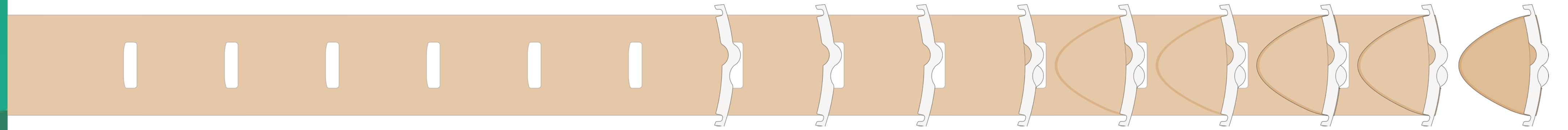


Figure 25: Expected production flow

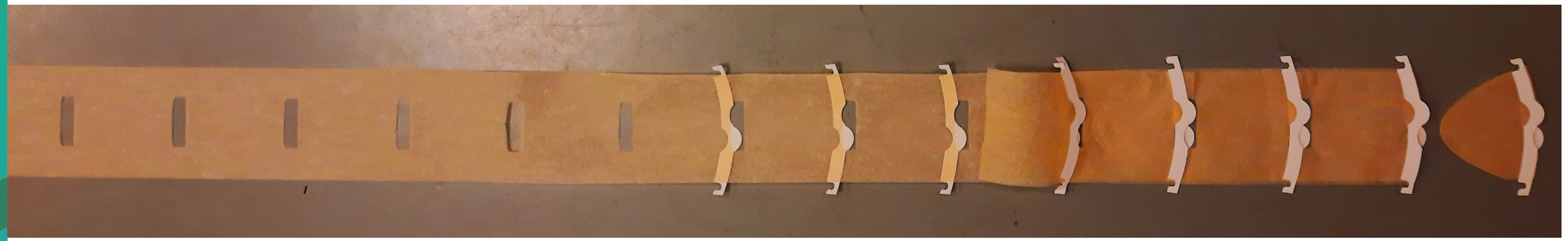


Figure 26: Actual production flow

4.3. Functional description of the modules of the machine

With the steps of production defined, a closer look will be taken at the design of each of the modules of the machine. Within the explanation, the working principles of each of the modules are explained at a basic level and the adjustable parameters of the module are given. This information is needed to understand why a failure mode can occur and helps define possible root causes. The parameters show already existing changes that can be made to improve machine capability. The placement of each of the modules within the machine can be seen in Figures 27 and 28. At the start of the thesis, the tea infuser production machine consists of the following modules:

- Module 00- Frame
- Module 10- Web handling filter paper
- Module 20- Initial cut on filter paper
- Module 30- Bracket sealing and cutting (Left)
- Module 35- Bracket sealing and cutting (Right)
- Module 40- Heat-sealing filter paper
- Module 50- Cutting filter paper
- Module 60- Puller (Master)
- Module 70- Final guidance
- Module 80- Cartridge inflow (Left)
- Module 85- Cartridge inflow (Right)

To be able to create the cartridge a separate machine is needed. This machine is referred to as module 90, the cartridge machine.

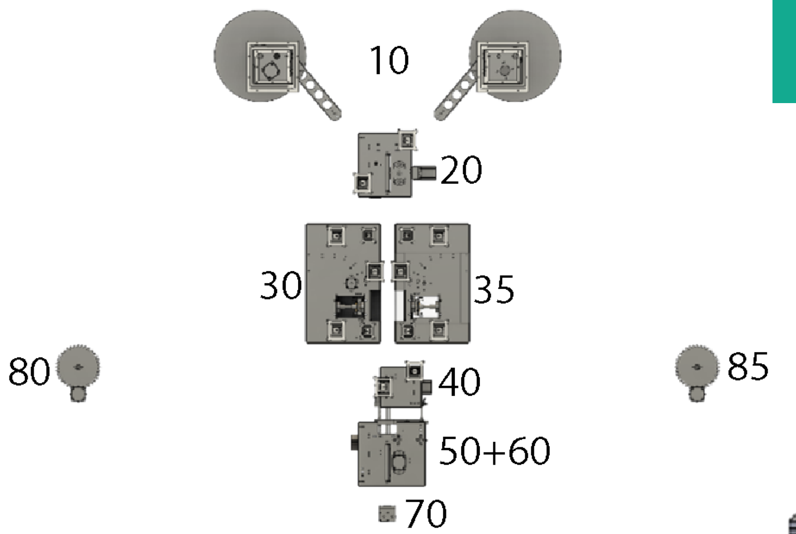


Figure 27: Module locations without frame

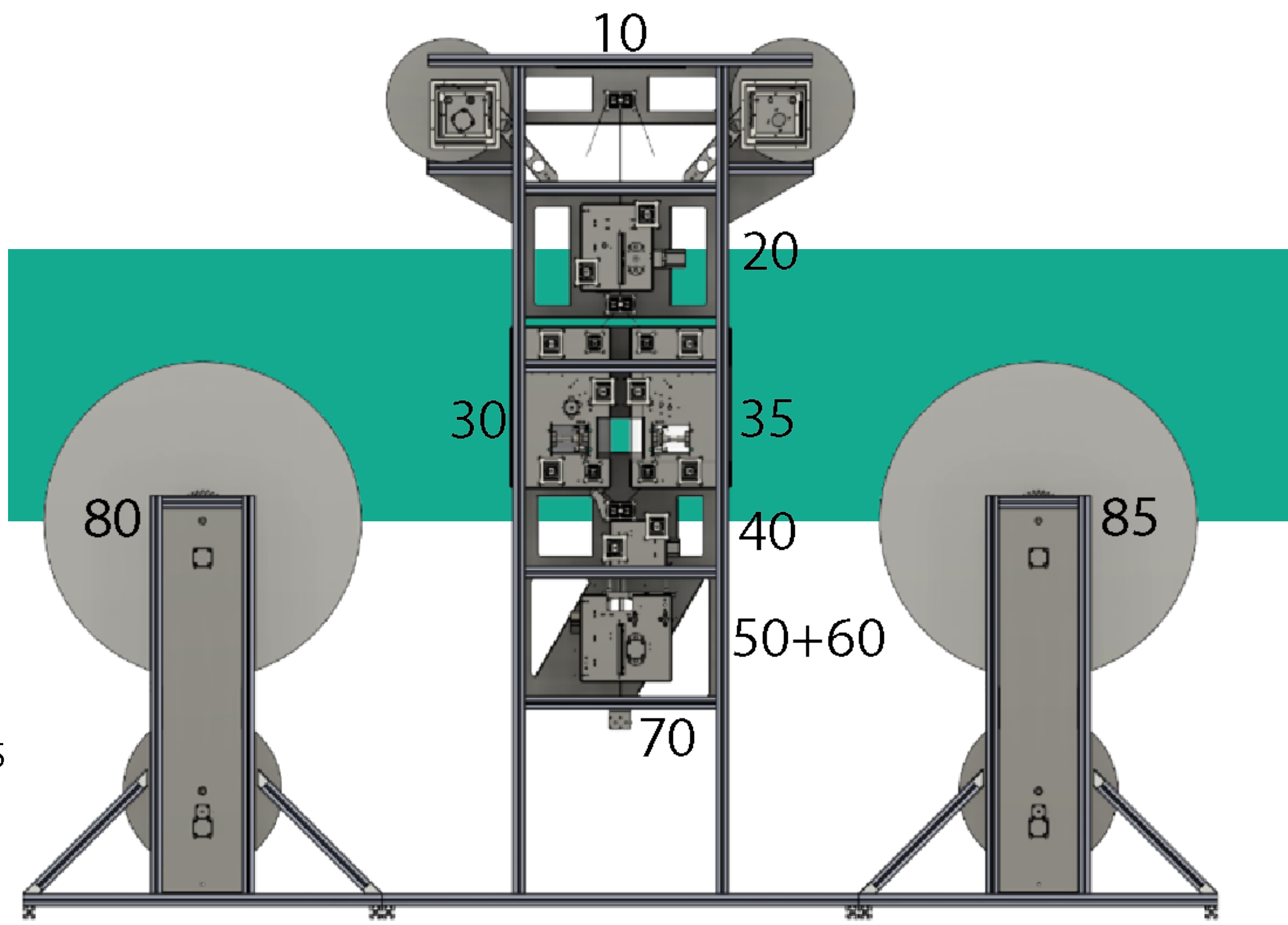


Figure 28: Module locations

4.3.1. Module 00 – Machine frame

While the frame is not an actual module, and therefore called module 00, it does play an important role in the overall machine. It is designed to have room for each of the modules by means of hanging them on axles which are connected with the aforementioned flexures. This gives the frame some flexibility in the placement of the modules in relation to each other as a completely rigid frame would need to completely redesign modules or more complex adjustments within the module when they misalign. The frame is made rigid through the use of side panels which have holes at locations where there might be a need for maintenance.

Adjustable parameters of the module are:

- The location of the flexures for each of the rollers.
- The location of the flexures for each of the modules.
- The left-right alignment of the module on the axles.

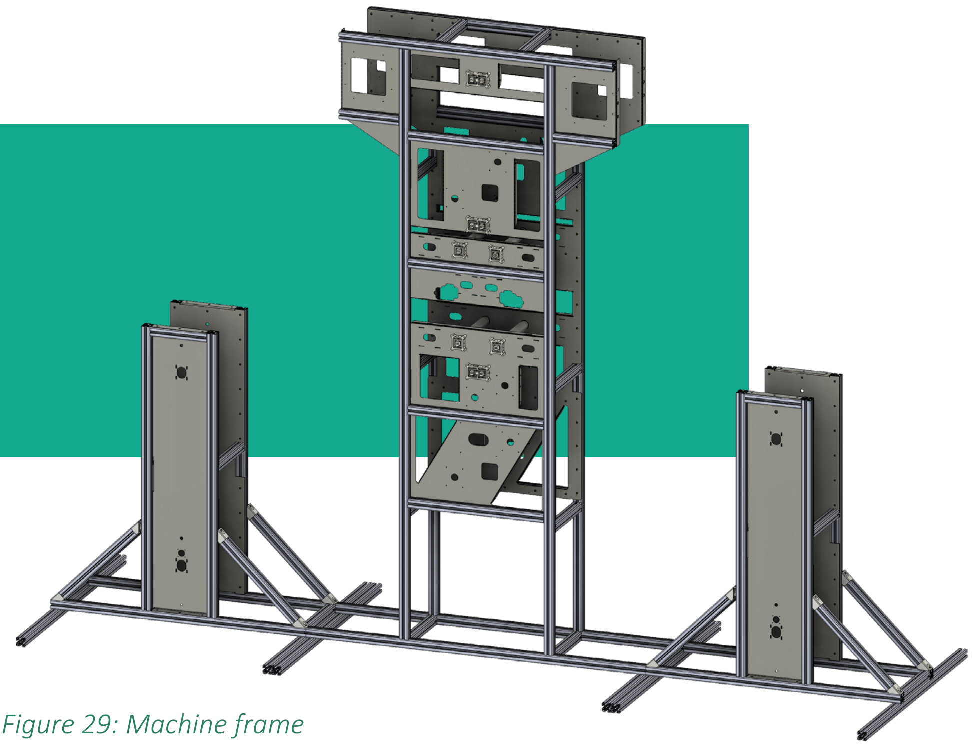


Figure 29: Machine frame

4.3.2. Module 10- Web handling filter paper

Module 10 consists of two mirrored parts which are used to hold the two filter rolls. Within these parts a bouncer is used, a bouncer is a part of web handling that adds a buffer to the web. This buffer is needed to keep the load on the web consistent and ensures that when the web is pulled through the system it pulls from the buffer which has a low load instead of pulling directly on the filter paper roll which creates a high load. The bouncer is kept at a consistent angle to ensure a large enough buffer by the stepper motor. This motor is used to unroll the filter paper and is kept powered to make sure the web stays under a consistent load. The stepper motor only moves when module 60 is finished.

The adjustable parameters of this module are:

- The speed of the stepper motors.
- How low the bouncer can move downward to stop the derolling of the motor.

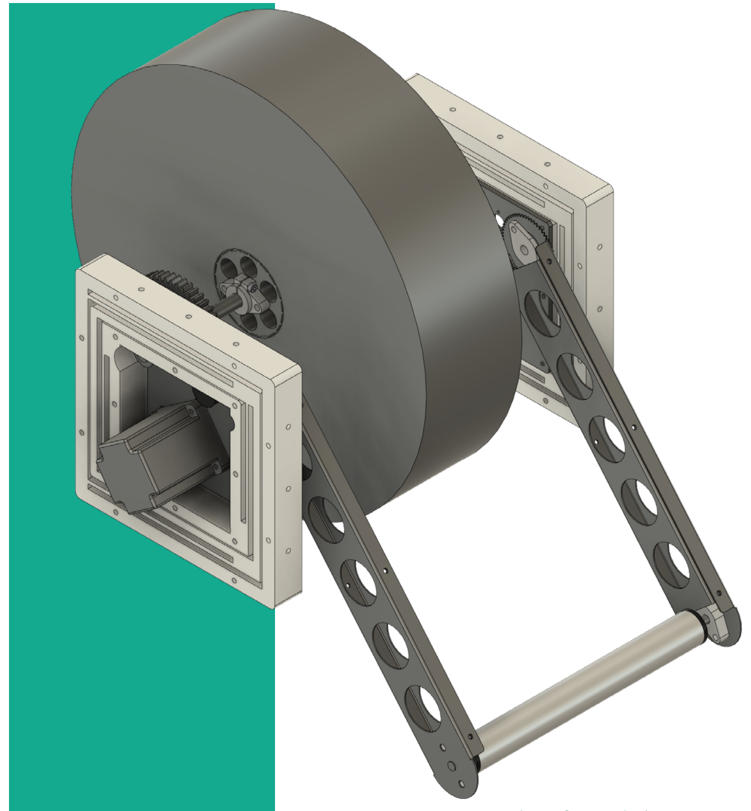


Figure 30:One side of module 10

4.3.2. Module 20 - Cutting the filter paper hole

Module 20 needs the two sides of filter paper to be combined, which is done by the web handling of the frame. It needs the combination of both sides of the filter paper to make the machine less complex. It becomes less complex because the cutting operation only has to be executed once, it also makes alignment of the holes later in the process easier as they are done by the same module and will therefore be inherently aligned. In the module, the two filter paper sides have a hole cut in them, this hole is needed to make the opening of the infusers possible. The module uses a special foil knife to cut the hole in the paper, the design of the knife can be seen in Figure 31 and the drawing can be found in Appendix B. When the filter hole is cut, air pressure is used to blow the waste out of the knife, and into the waste container.

- The adjustable parameters of the module are:
- The pressure of the air used to remove waste material.
- The speed of the stepper motors.
- Location of the knife in x and y direction.
- The depth of the knife into the countershape.

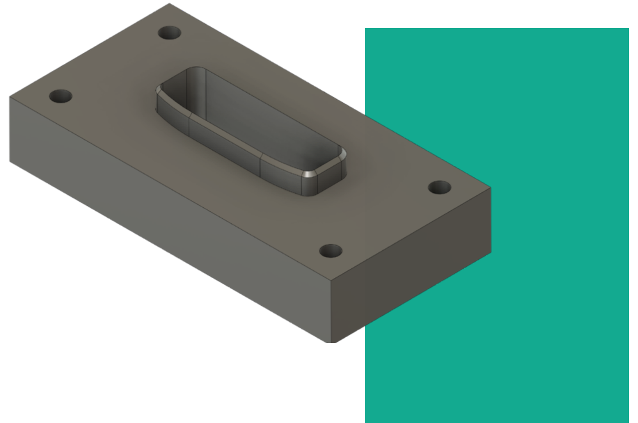


Figure 31: Knife design module 20

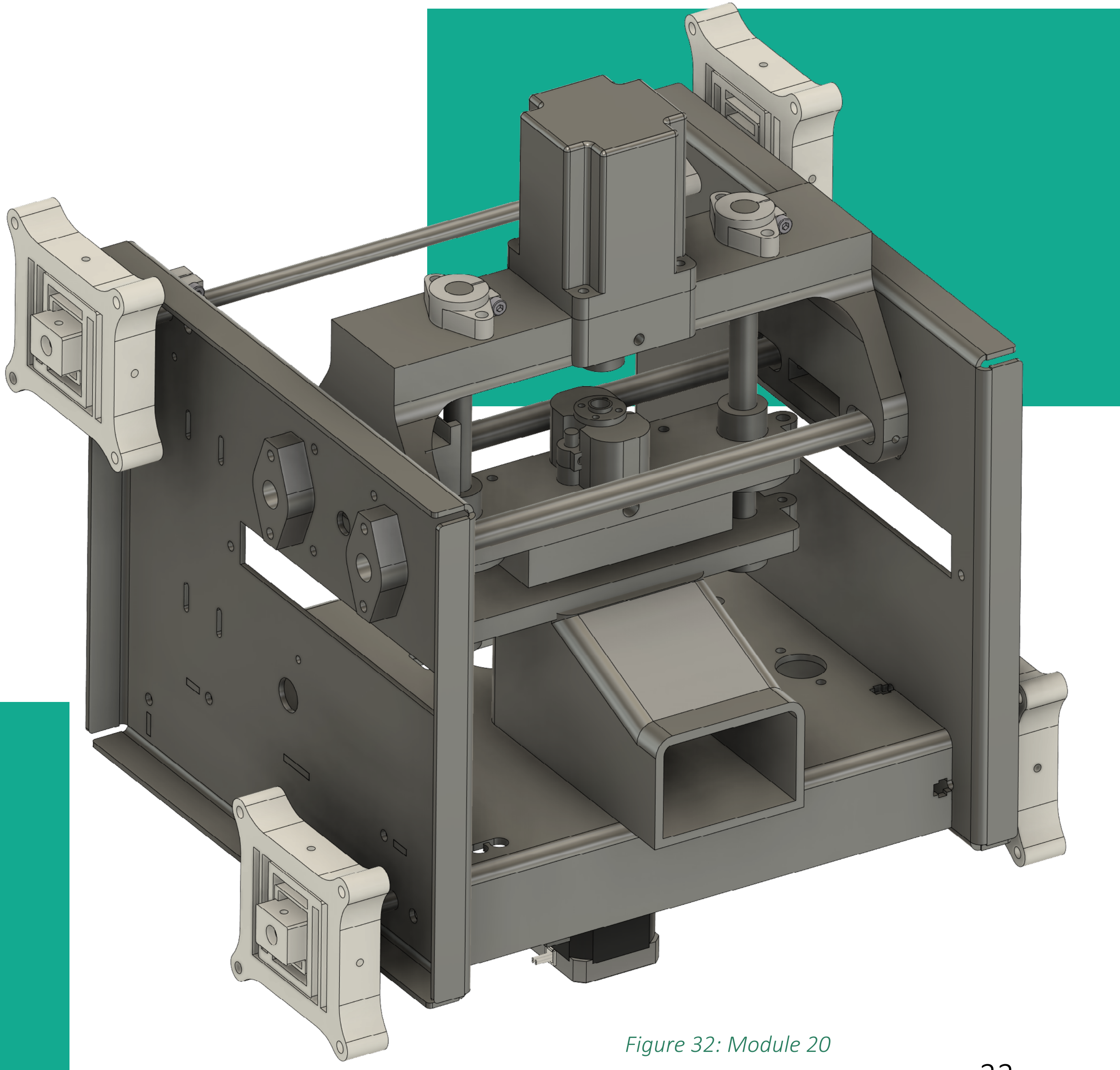


Figure 32: Module 20

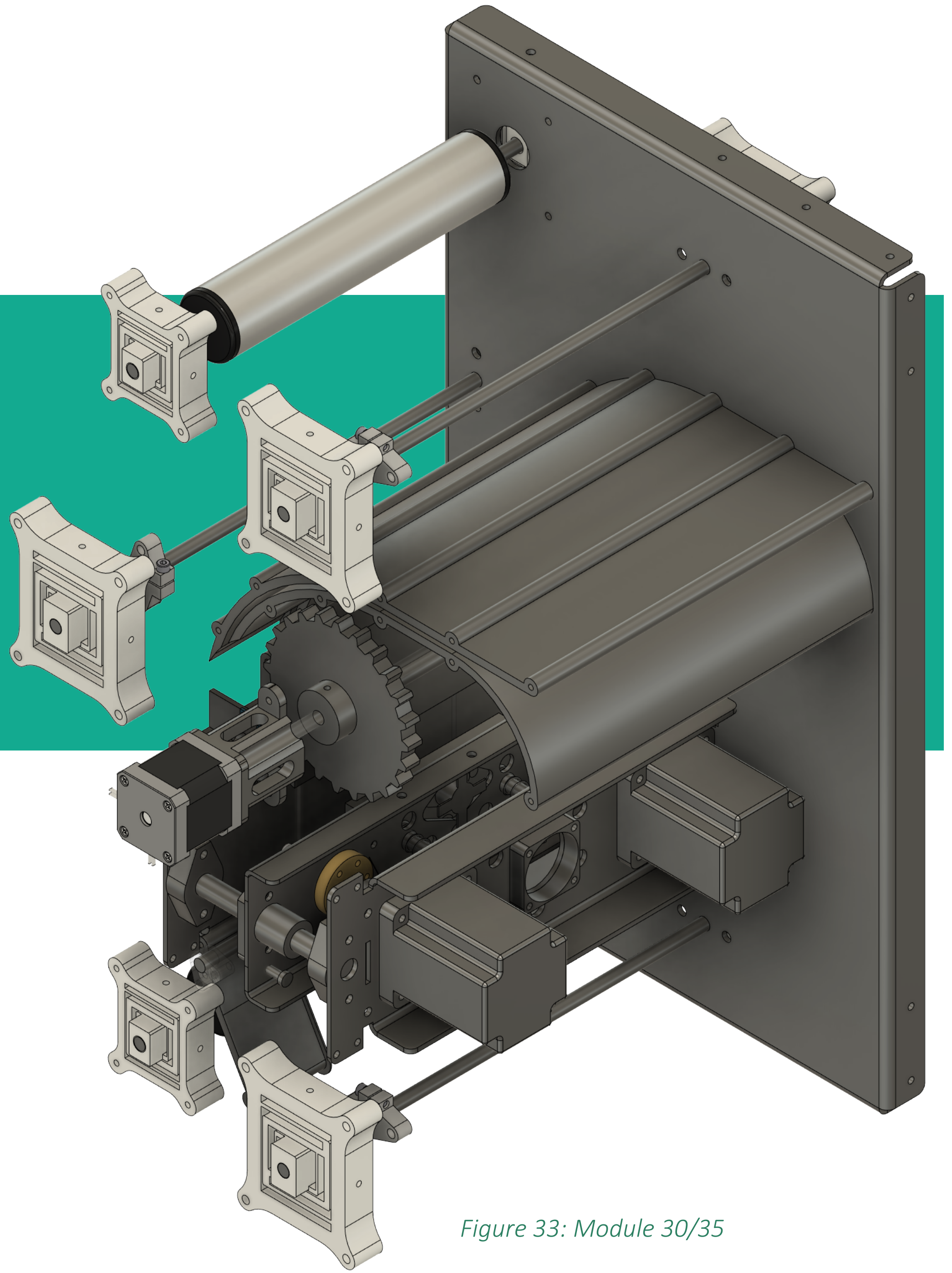


Figure 33: Module 30/35

4.3.4. Module 30/35 - Bracket sealing and cutting

Modules 30 and 35 are the same module as the same operation has to be executed on both sides. The modules are used to place and connect the brackets onto the filter paper. To be able to seal the bracket to the filter paper the two filter paper webs have to be separated again after module 20. This is done to prevent both sides of the filter paper are sealed together underneath the location of the bracket as they have the same PLA liner to seal them together. The alignment of the brackets with the filter paper is done by using gear teeth that have been integrated into the cartridge, these are seen by an optical endstop which allows it to align the bracket. These teeth have a secondary function n the movement of the cartridge which is pulled forwards by using a large gear. The bracket is heat-sealed to the paper and cut from the cartridge in the same movement. To do this the heating and cutting assembly, as seen in Figure 34, combines a the heat-seal with the knives. The heat-seal can be pressed down with the use of a spring allowing the knives to cut deeper into the cartridge. The excess material of the cartridge is disposed of in waste bins by guiding the strips of waste material out of the module through material guides.

The adjustable parameters of the module are:

- The speed of the stepper motors.
- The temperature of the heat-sealing aluminium block.
- The pressure of the heat seal on the bracket.
- The location where the bracket is placed compared to the heat-seal block and knives, this additional movement is referred to as furtherSteps.
- The left-right alignment of the cartridge.

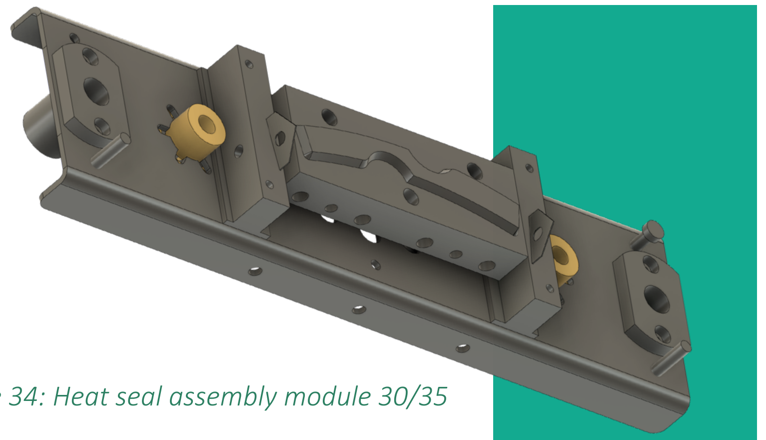


Figure 34: Heat seal assembly module 30/35

4.3.5. Module 40 - Heat-sealing filter paper

Module 40 again sees the combination of both sides of the filter paper which at this stage have the added brackets. In this module, the infuser shape is formed using heat-sealing. The heat seal block seals the two sides of the filter paper as well as the outer parts of the brackets., the shape can be seen in Figue 36 and the drawing can be referenced in Appendix B. The choice is made in this step to seal more than necessary to ensure a good seal after cutting out the tea infusers.

The adjustable parameters of the module are:

- The temperature of the heat-sealing aluminium block.
- The pressure of the heat seal.
- The speed of the stepper motor.

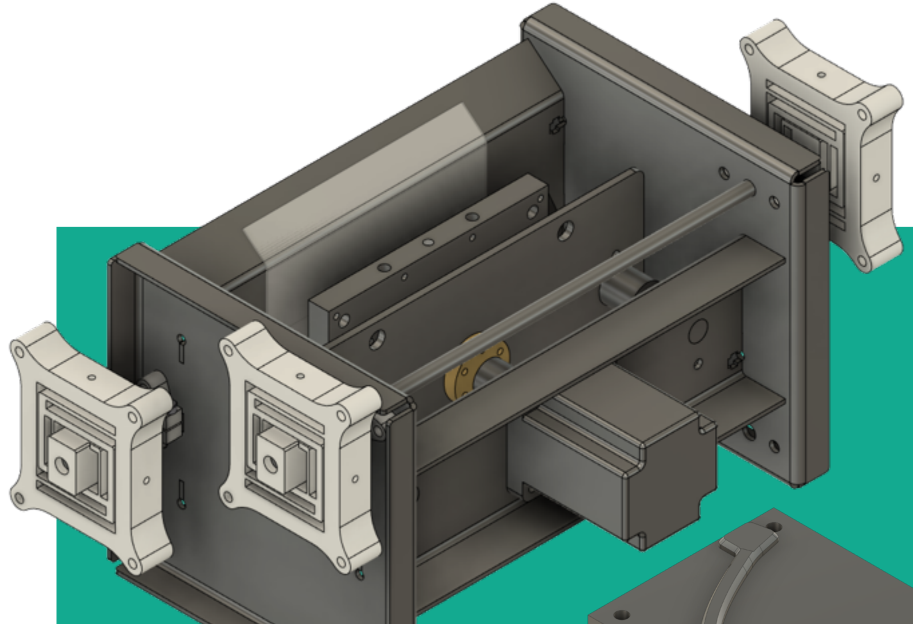


Figure 35: Module 40

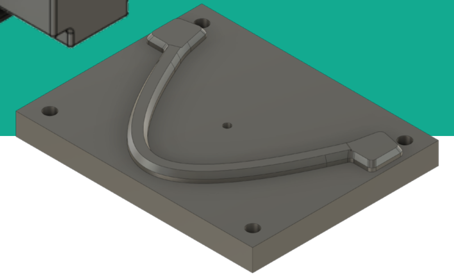


Figure 36: Heat seal block

4.3.6. Module 50 - Cutting filter paper

Module 50 has to cut the filter paper in the desired shape to take the infuser out of the web. The cutting is done by rolling an aluminium roller over a rigid knife. This choice is made as filter paper is extremely thin and therefore hard to cut, another option would have been a foil knife, however, when the alignment would be faulty the foil knife could break when it cuts the cardboard. To ensure the longevity of the machine the roller option was chosen. This knife is also designed to not fully cut the paper, this is needed so the web stays intact during the final pulling operation. This final operation is needed as there currently the machine is unable to take out the finshed product from the web.

The adjustable parameters of the module are:

- The pressure of the roller on the knife.
- How far the roller can move down on the knife.
- The distance of the knife in relation to the metal plate.
- The speed of the stepper motors.

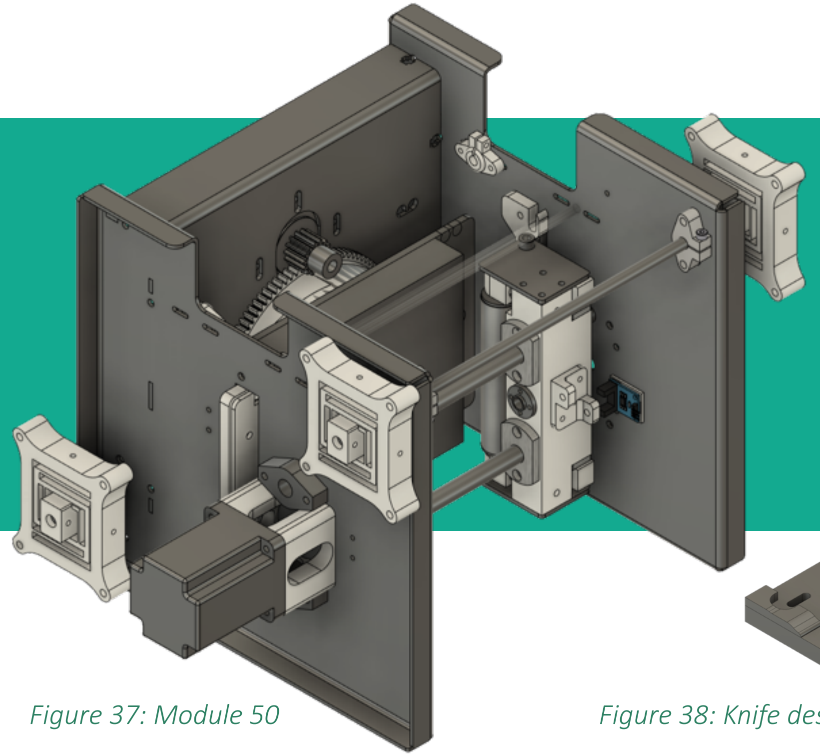


Figure 37: Module 50

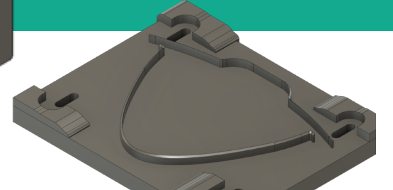


Figure 38: Knife design

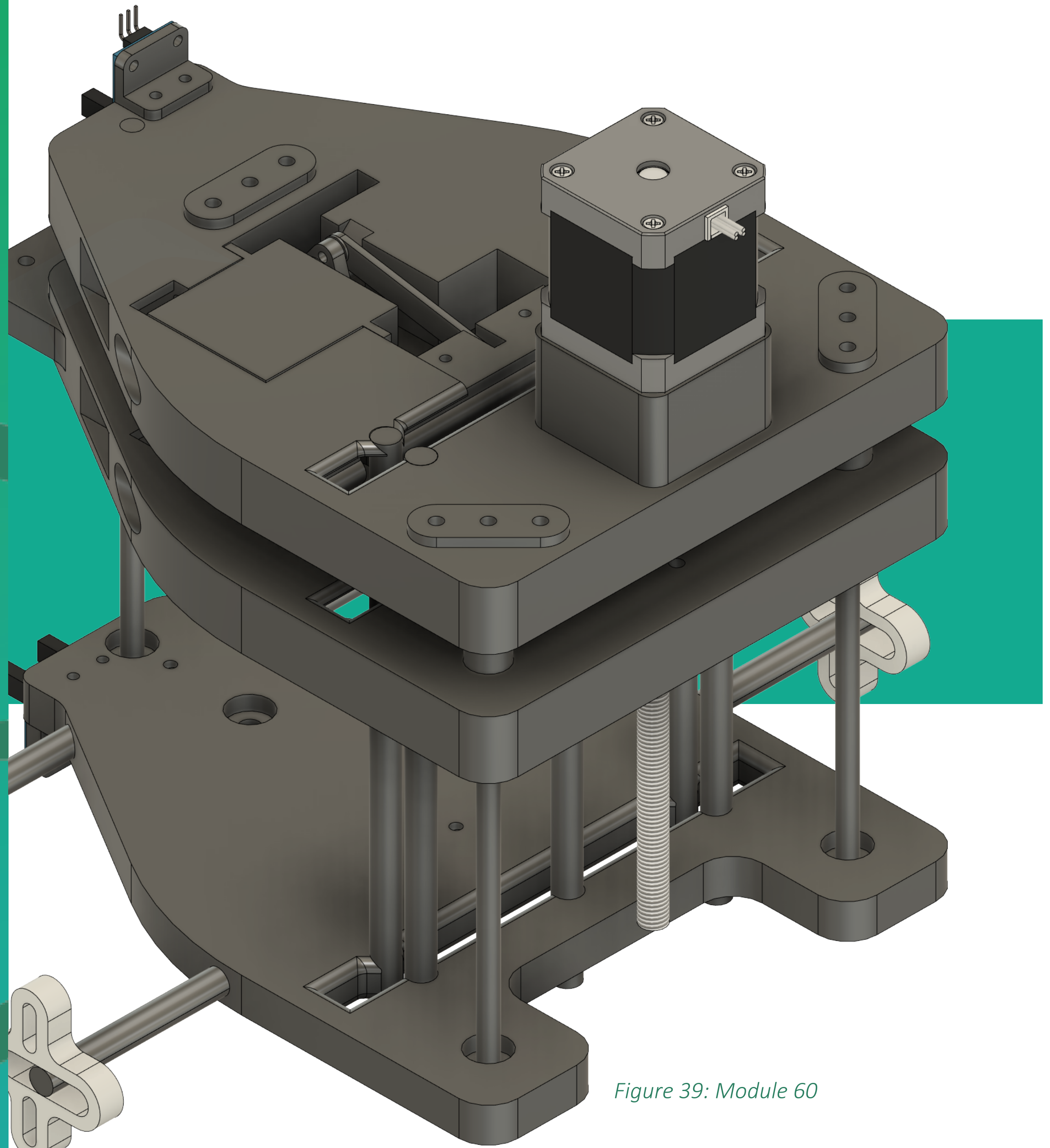


Figure 39: Module 60

4.3.7. Module 60 - Puller (Master)

Module 60 pulls the complete web throughout the machine. The module is connected directly to module 50 with smaller flexures to still be able to adjust module 60 separately from module 50. This is the case as during the initial design another type of pulling motion was imagined. This faulty design has led to the frame having too little space to add an entire module. This module uses servo motor-driven clamps and a stepper motor with mechanical end stops to be able to pull the web through the machine. The order of how the clamps open is important as the web is under a consistent load from the bouncers which will fall when both of the clamps would open. This consistent load on the web is needed for the machine and its modules to work. This module's settings are the main influence that assures correct alignment of the parts as the difference in the distance pulled through the machine is compounded heavily for the initial steps. This module is also used as the master module, as it operates separately from the other modules. This allows it to send and receive signals from the other modules. After all modules have finished their operations module 60 will go through its own operation.

The adjustable parameters of the module are:

- The clamping pressure the servos have on the web.
- The distance the web is pulled through per cycle.
- The speed of the stepper motors and servos.

4.3.8. Module 70 - Final guidance

Module 70 is the final puller that guides the web from the puller through module 50. This module is designed to have a slipping effect, such that it will ensure the necessary tension of the web, but will slip if there would be too high tension on the web. This is needed, for example, when the complete step is already pulled through and cannot be moved further as it would otherwise tear the web. This slipping is needed as the web is fragile during this phase as it is only connected with a few fibres to the web. The reasoning for the further running of the module is that the web has to be pulled through under tension and has to be loosened from the cutting plate of module 50, therefore the module starts up a little before the complete web is pulled through the machine and will continue to run a little longer to ensure all of the web has been guided through the roller.

The adjustable parameters of the module are:

- For how long the module pulls on the web.
- The speed at which the module pulls the web.
- Pressure between the two rollers.

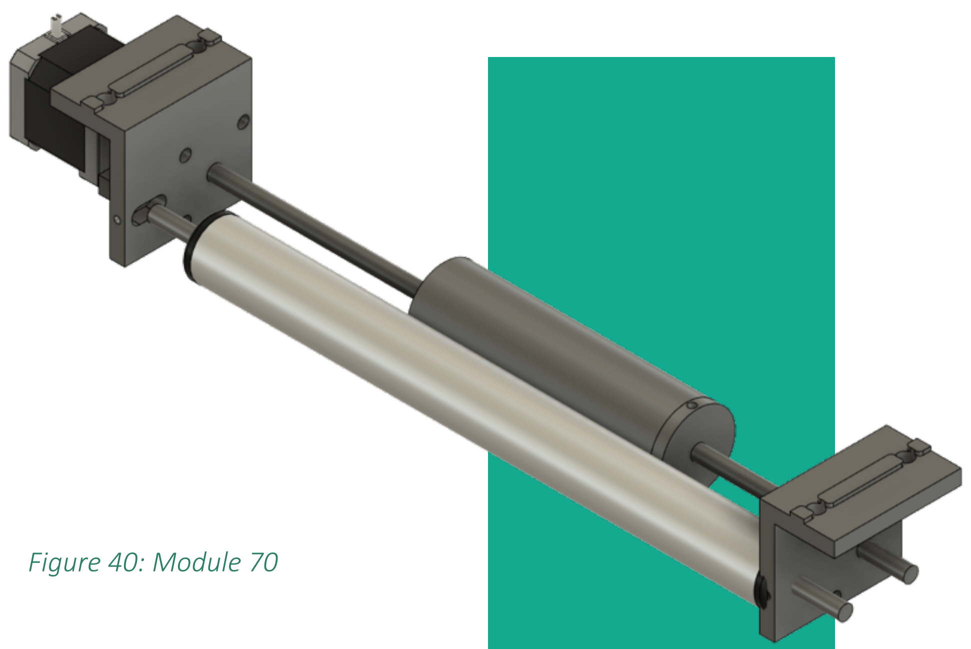


Figure 40: Module 70

4.3.9. Module 80/85 - Cartridge inflow

Modules 80 and 85 are two identical modules and are used to hold the two cartridge rolls. These modules work similarly to module 10 where they use a buffer to ensure a low load on the gears of modules 30/35. However, this module uses ultrasonic sensors to create the buffer as a bouncer would be too heavy and introduce too much tension itself to the cartridges.

The adjustable parameters of the module are:

- The speed of unrolling the cartridge rolls.
- How low the bouncer has to go to trigger the motor.

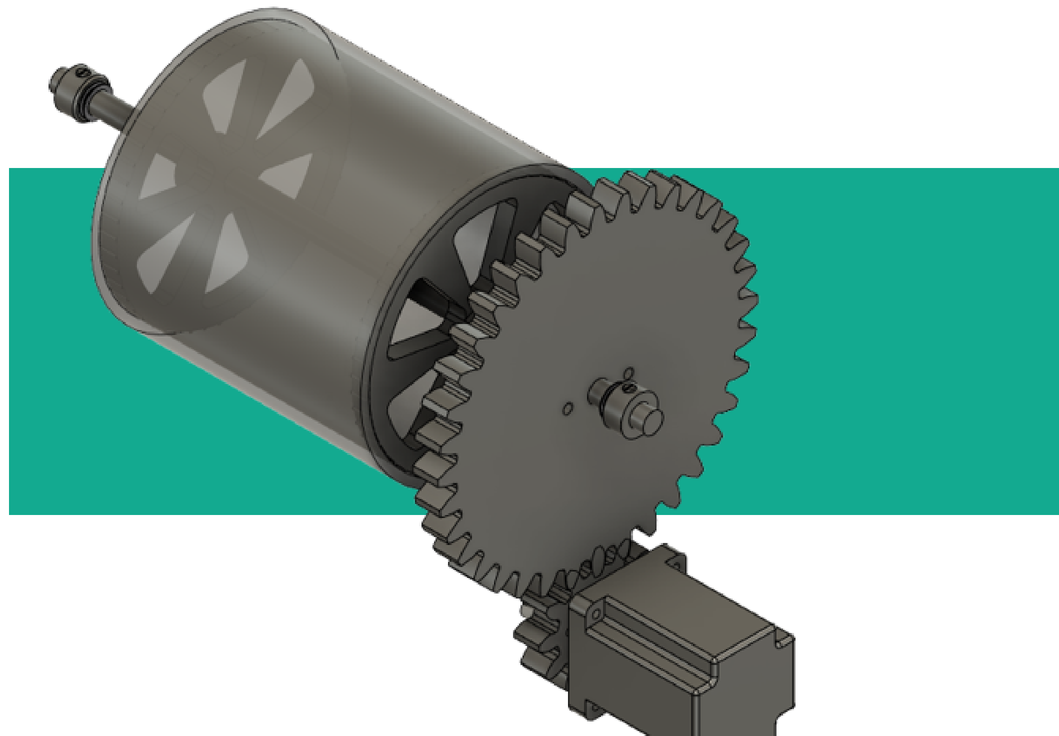
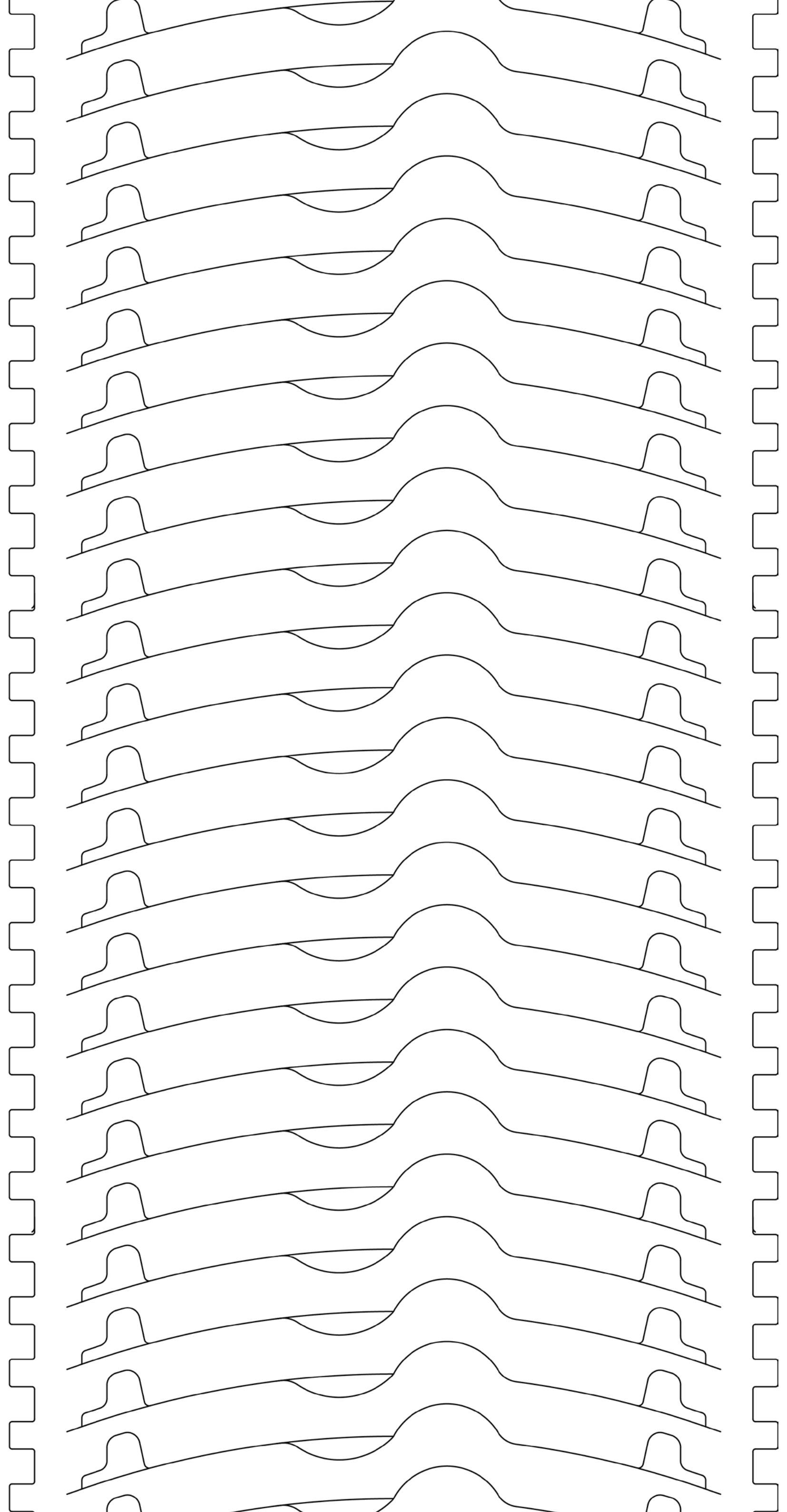


Figure 41: Module 80/85



4.3.10. Module 90- Cartridge machine

Finally, separate from the main machine, is module 90. This separate "module" is used to create the cartridge rolls. As it does not directly interact with the main machine it is often referred to as the cartridge machine instead of module 90. The cartridge machine is a punching machine that uses cardboard material to create cartridges of brackets, the continuous design of the cartridge is illustrated in Figure 43. The cardboard is first pressed with the knife and in the second part of the machine, the waste of the cartridge is punched out of the cartridge. To be able to get clean cuts an additional layer of cardboard is placed behind the cut layer. This material is then considered waste, to improve upon sustainability this material can be used for multiple cycles. The cartridge is then rolled onto the roll which is placed in modules 80/85.

The adjustable parameter of the module is:

- The distance between the brackets, and therfore the size of the brackets.

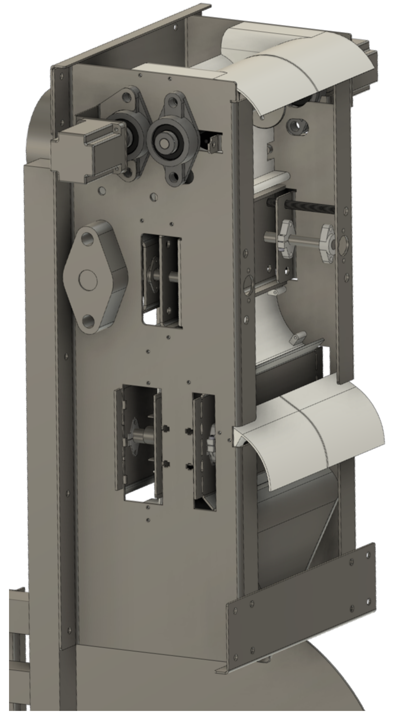


Figure 44: Module 90 closeup

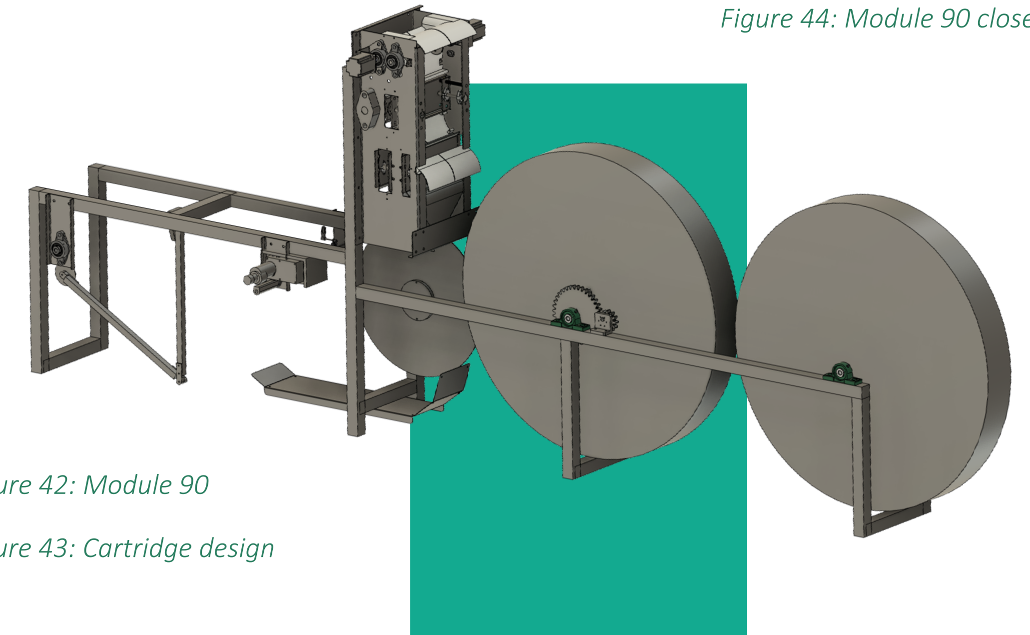


Figure 42: Module 90

Figure 43: Cartridge design

4.4. Functional description of the software system

Not only the hardware parts of the machine can have problems resulting in failure modes. The software of the machine could also be the root cause of the failure modes currently experienced. Therefore, a generic system overview of how information is communicated within the machine will be explained to gain a basic understanding of the applied software of the production machine.

The machine uses multiple microcontrollers that run on the Arduino software to be able to execute all the operations of the machine. These are all connected to a master module, which communicates with each of the other so-called slave modules. Communication between master and slave is mostly sending information to start the operation and receiving information on if the slave has finished its operational steps. modules 80 and 85 are the only modules not to communicate with the master module to be operated. The overview of interactions between modules can be seen in Figure 45.

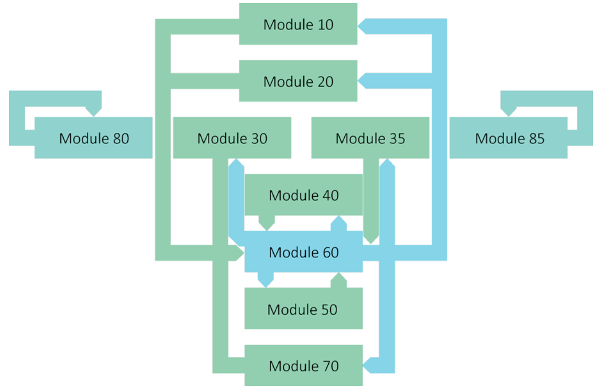


Figure 45: Software communication

The code uses two different parts of code, the first of which is the start-up sequence. This resets all components to their home positions and stays in their start-up mode. This mode allows for the heat seal blocks to heat up and the operator to guide the web through the system. After the machine is started by pressing the start button the operational code activates. For each of the slaves this means waiting in a receiving state on when they can start their operations, the operations they have to execute, and finally sending back information the module is finished. The master, module 60, will pull the web through the system one step, then send information that modules can start, after which it will stay in receiving mode until all modules are finished. When one of the modules does not complete its function the complete system will halt.

4.5. Adjustments that can be made to the placement of the modules in the machine

As mentioned in Chapter 4.3. many of the parameters of the modules can be changed. These changes are mostly facilitated through the use of either end stops, which are often accompanied by a bolt that can be adjusted to change the amount of movement, or through the use of hardcoded distances in the code. These changes in the code are mainly used for timed parts, such as the pneumatics. The other generic adjustment in the code is for the stepper motors which use the parameter FurtherSteps, which allows the precise adjustment of the placement of parts.

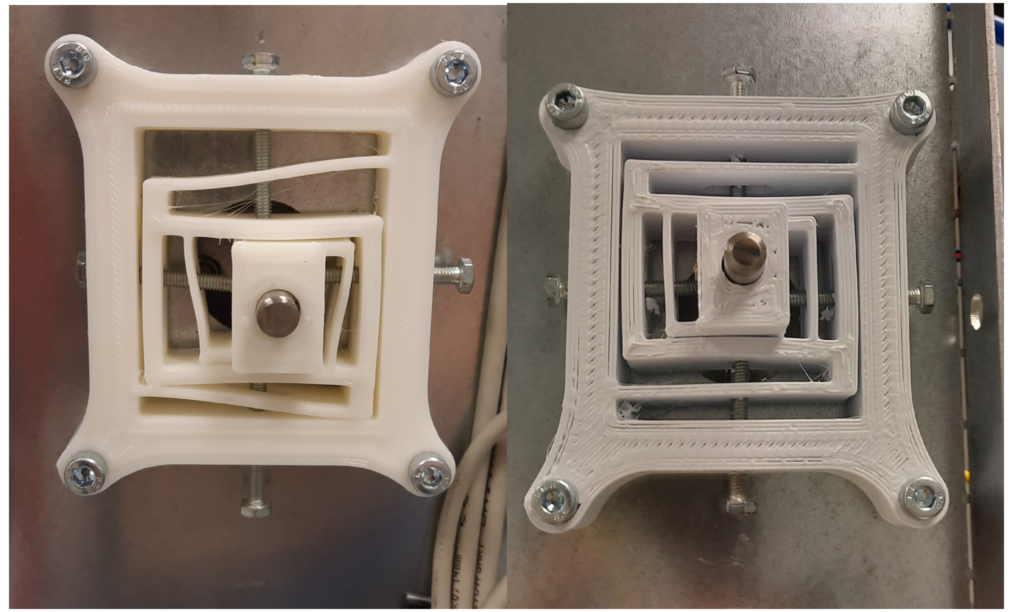


Figure 46: Flexure positions: Moved down (left) neutral (right)

Furthermore, all the modules are placed in the overall frame on axles which go through flexures that allows the modules to be moved in all directions within the machine. This is necessary to be able to adjust the placement of each of the parts in relation to other parts. The different positions of the flexures can be seen in Figure 46. The former is a flexure in its neutral position while the latter shows a flexure in its bottom position. This adjustment of the flexure changes the placement of that module to be 3mm lower than when the flexure would have been in its neutral position.

4.6. Materials and waste handling of the machine

The materials used to create the tea infusers also have a large influence on the operation of the machine, therefore, the material properties and flows have to be considered within the functional description as well. For the tea infuser, the material choices are made based on their compostability and ease of use for production. This also means that no additional materials such as glues are used within the production process to ensure that the tea infuser is fully compostable. The choices made for the materials of the tea infusers are a compostable non-GMO unbleached heatseal filter paper from Ahlstrom-Munskjö [38], as seen in Appendix C, and a compostable heatseal coated cardboard from JAZZ@HEAT [39], as seen in Appendix D. Both materials use a thin layer of PLA to be glued to the other parts of the tea infuser. This layer of PLA of each of the materials is only located on one side as the other side is not needed for the tea infuser design and this lowers the amount of plastic within the final product. As the company has sustainability as one of their priorities the amount of waste should be kept low. With optimal running the following waste percentage numbers can be derived: 33% of filter paper and 42% of the cardboard, as seen in Table 1.

Table 1: Material waste

Material	Used per tea infuser (mm2)	Effective material (mm2)	Waste (mm2)	Waste percentage
Cardboard	2000	1350	650	33%
Filter paper	10712	6145	4567	42%

Because no additional materials such as glues are used, the production machine only uses four inflows of material and has four outflows of waste material. The inflows of materials are the two sides of filter paper rolls and the two cartridge rolls, the waste flows are the cut part of the filter hole, waste of the cartridges and the completed web of filters. The different shapes of waste material can be seen in Figure 47. The material outflow methods can be seen in Figure 48. Currently the finshed web with tea infusers still contains waste material as well, which must be taken off manually.

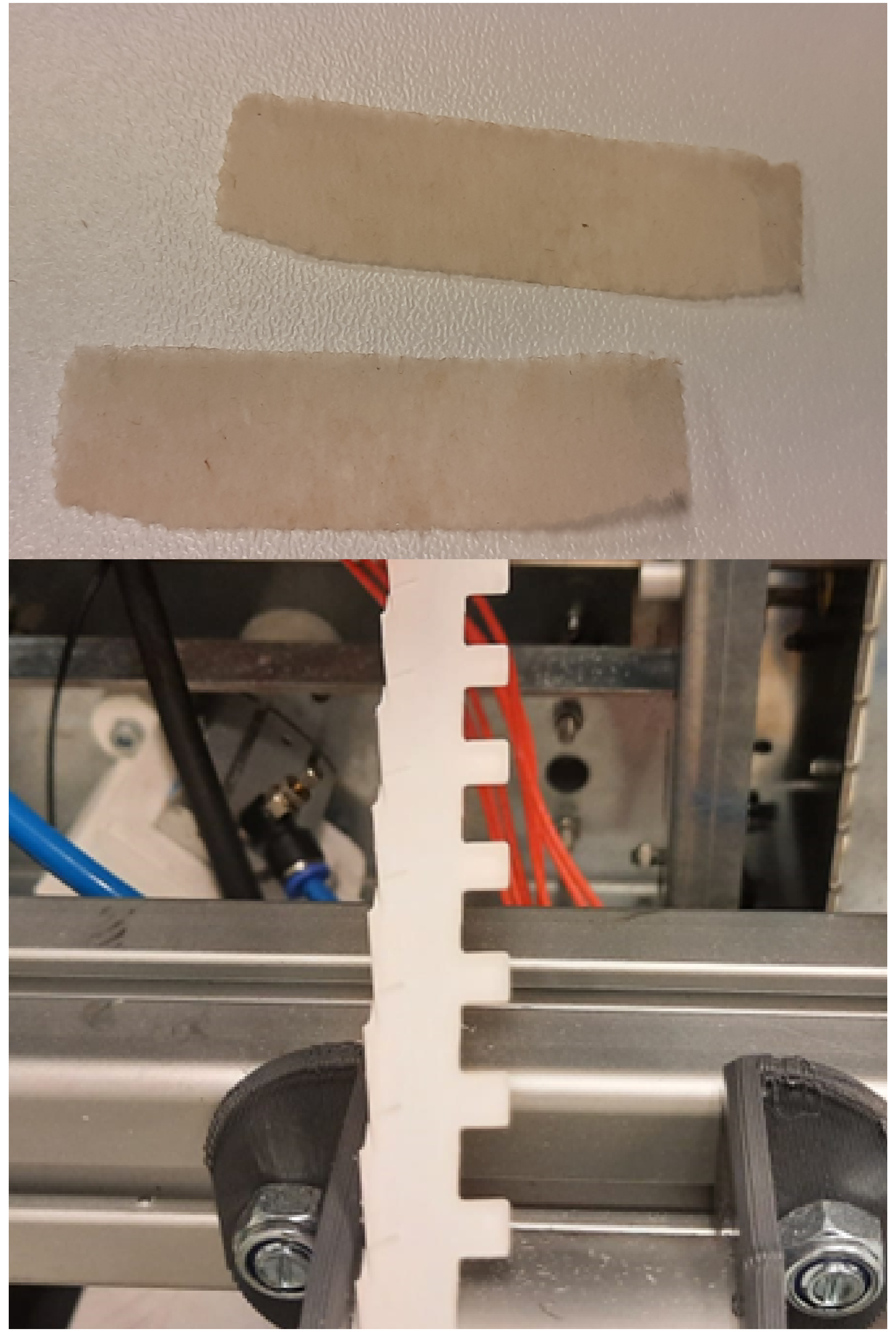


Figure 47: Waste material: filter paper (top), cartridge waste (bottom)

Figure 48: Outflow of waste material: filter paper (left), cartridge waste (right)

4.7. Start-up sequence

After the machine has encountered a critical error or when the materials have to be refilled, the machine has to go through its start-up procedure. This procedure differs from normal operation, as mentioned in during Chapter 4.4, as the web throughout the machine is missing the holes and brackets and therefore operates differently. The most important aspects are that the web is under a lower tension concentration due to the lack of holes in the filter paper, which makes the web being pulled a shorter distance. While this distance is relatively small it does create problems if normal operation would continue. Secondly, the web sticks more to the backplates of modules 30/35 and the metal plate of module 50. Finally, module 70 has less grip on the web and can struggle to guide the filter paper through itself or loosen the web from module 50.

These differences introduce the need for an operator to guide the process through its initial 13 cycles, after which the web is back to the continuous operation state. Additional effects that have to be accounted for during the start-up sequence are the correct placement of the filter paper, cartridge rolls, and the waste of the cartridges. The need for many manual interactions during the set-up creates a higher chance for human error to create failure modes.

4.8. Continuous operation of the machine

For the continuous operation of the machine, the web must be kept under a consistent load. This is the reasoning behind the use of bouncer modules that create a buffer combined with the puller which pulls consistently on the web. During continuous operation, a tea infuser is produced roughly every 30 seconds. Non-critical errors can occur during operation but will not break the web. Therefore, the system is allowed to continue its operations. When a critical error occurs, the web will most likely break and the operation has to be stopped. During continuous operation, there should be no need for interference from an operator. Except for emptying the waste bins and replacing the final storage for the completed tea infusers.

4.9. Conclusion

The machine is currently conceptually operational but does have many problems, including critical failures. Because these haven't been documented properly yet, it is nearly impossible to decide what changes should be made to the production machine or process. To be able to design solutions for the current problems the gaps in production and knowledge will have to be defined, this will be done in the next chapter through means of defining the current and desired state from which these gaps can be determined.

5. Improvement definition

In this chapter, the current state will be defined and compared to the desired state to allow a problem definition to be formed. To then be able to create the problem definition, answers to questions such as "What is the current output yield of the tea infuser machine?" and "What is the desired output yield of the tea infuser machine?" will have to be answered. Then these two answers will be compared with each other to find the gaps that have to be bridged. This will answer "What is needed to reach from the current to desired output yield?". To be able to better define the current state an answer is also needed for the initial part of the question: "What are the current failure modes and their occurrence within the system?" has to be answered to get an understanding of what has to be changed.

5.1. Current state

Currently, the machine can be operated for up to a maximum of four hours at once. This results in operation times between six to eight hours a day, however, these operating times are only achievable currently when there is constant monitoring of the production machine. This monitoring is needed as critical errors often occur during production. Critical errors in this context are failures within the production process, that cause the machine to be inoperable for an amount of time.

The yield of the machine is currently based on the sole specification that a tea infuser has to be usable by the end user. Usable in this context means that the bag is sturdy enough to be placed within the cup and the loose tea does not spill out of the bag. However, usable is still an unclear definition that only focuses on problems such as incomplete tea infusers, loose fibres of cardboard that can enter the cup, or large gaps within the tea infusers. These are considered to be non-critical errors. Non-critical errors are errors that do not stop the continuous operation of production of the tea infusers. But these non-critical errors cause out-of-specification, and therefore unusable, tea infusers which must be manually taken out of the production sets.

During operation a tea infuser is made every 30 seconds, this means that on average 120 tea infusers are produced every hour. However, due to the combination of non-critical errors which means that the tea infusers have to be discarded or critical errors which cause the production to come to a halt the actual yield of the machine is much closer to 90 tea infusers per hour.

The current state must be further analysed to get a concrete understanding of the shortcomings of the machine. To do this an initial overview of the failure modes that

Figure 49: Improvement definition

the machine experiences can be used. To be able to determine the actual yield the upper and lower specified dimensions of the tea infuser have to be defined, as well as a checklist of possible deformities the tea infuser can experience. From this, it can be seen that, next to the production gap, there also exists a knowledge gap within the company. This problem originates from the development approach that was applied to the machine over the last year, mainly the critical problems have been found and solved with a lean approach as the main goal was to get functional yield as soon as possible. This was needed as the tea infusers were currently made by hand which costs too much time and money for the company. With the machine currently producing enough for the initial pilots the focus can be placed on improving consistency and overall yield.

5.2. Tea infuser specification

The tea infuser is created using multiple parts that are added over multiple steps in the production process. These different processes all have tolerances that add up to the overall accuracy that can be reached by the machine. These compounding tolerances will result in tea infusers that have parts placed differently when compared to each other. Therefore, a standard consensus must be found to be able to decide what tea infusers are considered to be in specification. This consensus will consider the placement of each of the parts of the tea infuser but also will consider the possible deformities which make the tea infuser unusable or creates tea infusers that are not up to the aesthetic standards of TeaWall.

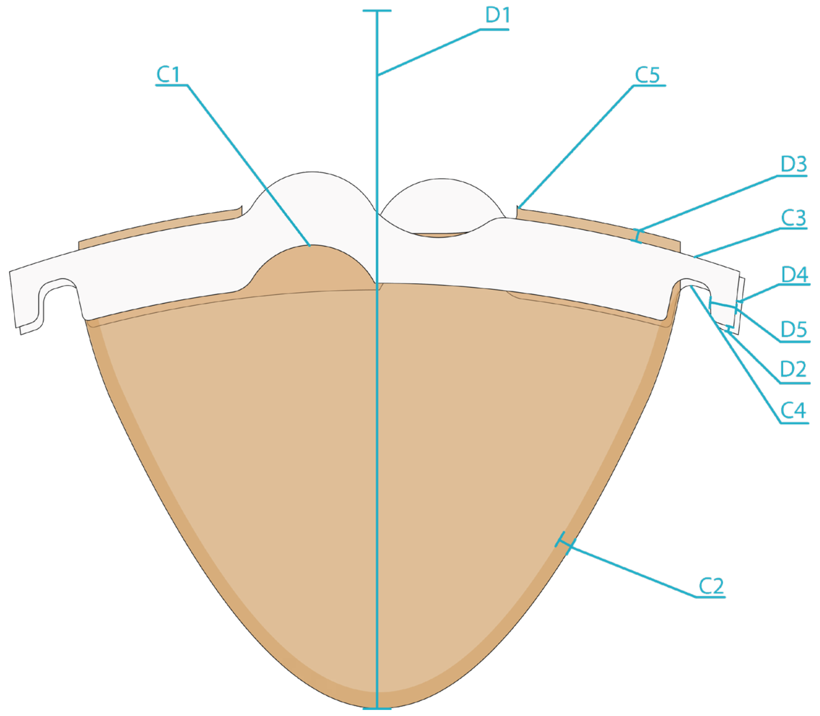


Figure 50: Tea infuser specification

First, the dimensions of each of the parts of the tea infuser are defined. The tea infuser consists of four parts. These parts are the two brackets and two sides of the tea filter. The most important dimensions of these parts for the quality of the tea infuser are defined as follows:

- D1: The distance between two tea infusers. (103-105 mm)
  - When this distance is higher additional waste is created when it is too low a cut can be made in the top of the next tea infuser.
  - While this is an important measurement and is related to the amount of waste that is produced per tea infuser, the main goal of this dimension is to gather insights.
  - Ensuring that the dimensions are within the defined tolerance window is therefore of a lesser priority.
- D2: Distance between the left and right bracket. (Up to 1.5 mm)
  - This is the distance between the brackets and will show inconsistency in the system, this is mainly an aesthetic problem as the quality of the infusers will be considered lower when alignment is incorrect
- D3: Part of the filter paper above the highest bracket. (Up to 2 mm)
  - This small part of filter paper above the brackets is inevitable as otherwise the brackets will be cut creating new problems. However, to keep the quality of the tea infusers high this dimension has to be as low as possible.
- D4: The left-right alignment of the brackets. (Up to 1 mm)
  - Similar to D2 this dimension focuses mainly on the quality of the product, however, this misalignment could make the inlet too small creating problems with placing the tea infuser on the glass.
- D5: The size of the smallest bracket arm. (Minimal 3.5 mm)
  - This makes the brackets sturdy enough to be able to hold the weight of the infuser and the tea.

When a dimension is out of specification as defined above, it is considered under the failure mode D1, D2, D3, D4, D5. This failure mode does not prevent the tea infuser from being used but does fall outside of quality control ass defined by TeaWall.

The dimensions D1-D5 mainly look at the aesthetic aspect regarding the production quality of the tea infusers, therefore, a list of possible failure modes has been made to check if a tea infuser is usable. The checks that must be made are as follows, and the visualisaiton of these failures can be seen in Figures 51 and 53:

- C1: The filter hole is below the bracket. (20)
  - Tea leaves can leave the infuser below the bracket.
- C2: The heat seal is not completely covering the bottom of the bag. (40)
  - Tea leaves can leave the tea infuser through its sides.
- C3: The knife of module 50 has cut into the top part of the brackets. (50)
  - This creates loose fibres of cardboard that can enter the glass.
- C4: The knife of module 50 has cut into the bottom part of the brackets. (50)
  - This creates loose fibres of cardboard that can enter the glass.
- C5: A step is skipped during production. (20/30/35/40/50)
  - The tea infuser will not be complete.
- C6: There is a piece of waste in the tea infuser. (20/80/85)
  - This creates aesthetic problems and can even create problems where the tea infuser does not hold the tea leaves within the infuser.
- C7: Creasing of the tea infuser.
  - This is an aesthetic problem and can induce problems with opening the tea infuser.
- C8: The cutting line of the knives is not straight. (30/35)
  - This is an aesthetic problem which could also lower the rigidity of the brackets on the cup and could occur, for example, by the broken knife of the module (Figure 52).

Figure 51: Zoomed in failure modes C1,C2, C3, C4 (Ordered from the top)

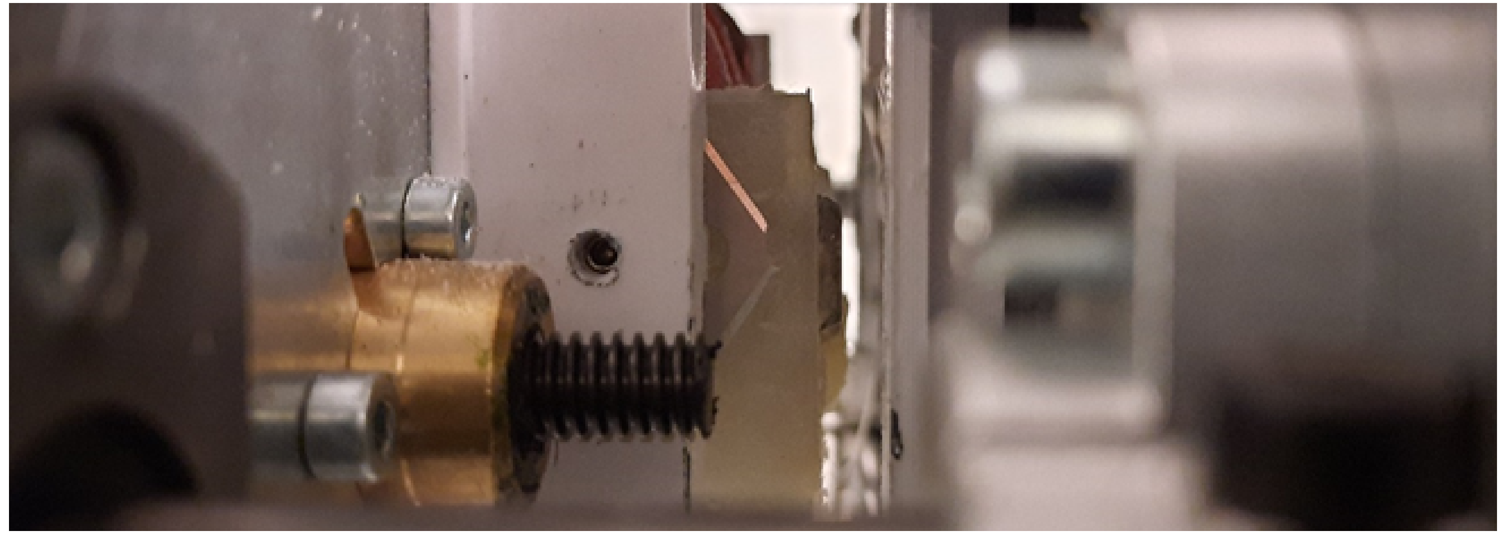


Figure 52: Broken knife resulting in C8

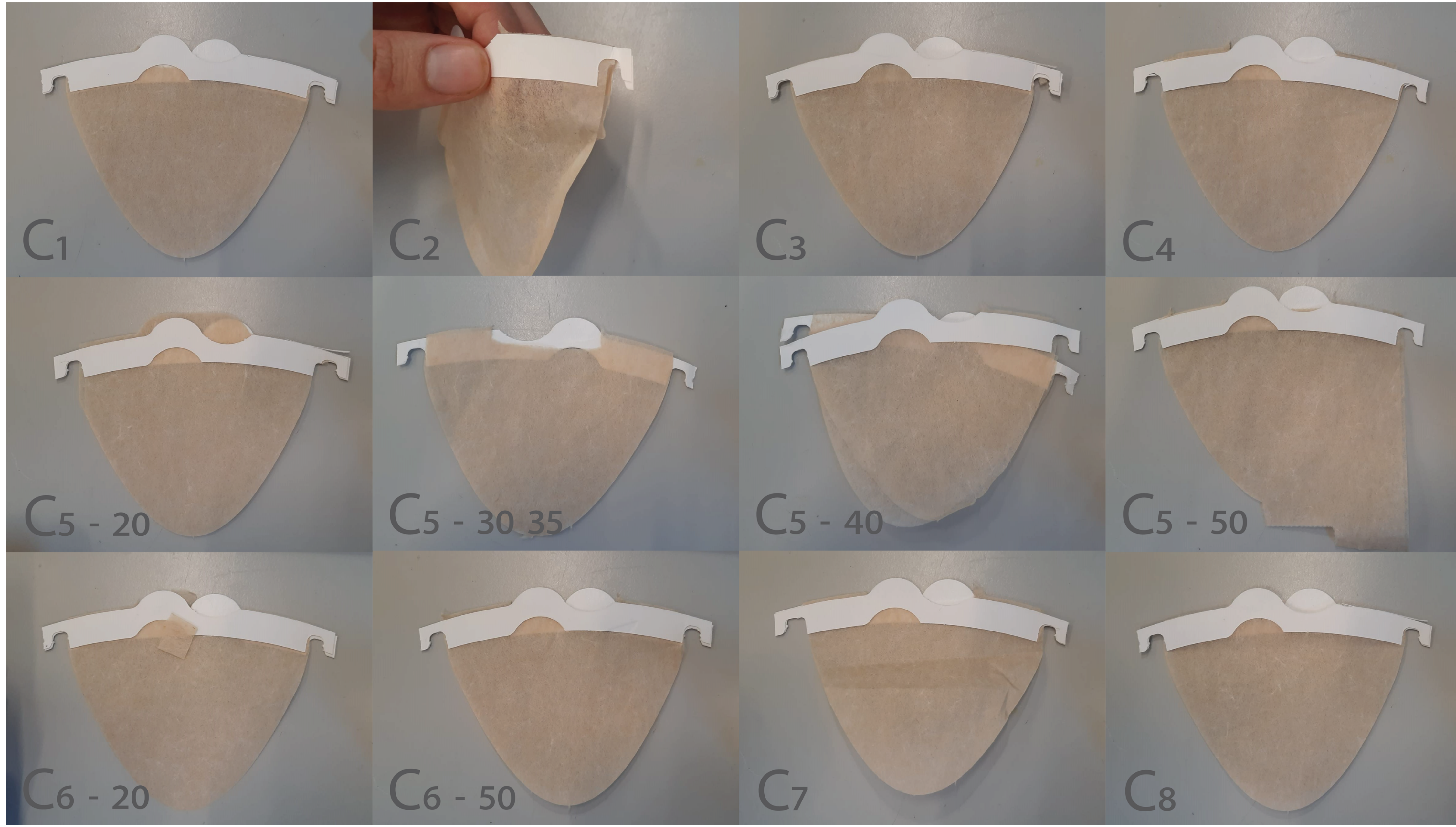


Figure 53: Failure modes visualised

vWhile the previous failures can be seen from the final product, and often are non-critical errors, different problems can occur during production that most likely will create a critical failure for the production process by tearing the web or getting in an unrepairable state such that production has to be restarted. The most prevalent and recognised problems that can occur during the production process are:

- P1: The web is weakened.
  - Often when a small failure occurs or when the web is damaged by external fators.
- P2: There is a software error.
  - When a mistake is made in the software it can go unnoticed for a long time.
- P3: One of the stepper driver fails.
  - When a stepper driver fails the motor behaves differently from its intended behaviour.
- P4: One of the motors gets stuck due to too high a load.
  - In modules 30 and 35, two motors are used when these misalign from each other they can become stuck under high tension.
- P5: One of the relays experiences sticky behaviour.
  - Sometimes a relays can get "stuck" and not execute the program properly.
- P6: The heat seal block gets too hot.
  - When one of the thermocouples or relays fails the heat seal can get too hot and burn the cardboard.
- P7: The material or web gets stuck to the final roller.
  - The material should fall own under its weight but can get stuck to the roller due to static build-up
- P8: A piece of waste gets stuck in the machine.
  - Because pieces of waste from module 20 or the cartridge can get into the machine they can create many problems such as triggering endstops or getting stuck between moving parts.
- P9: One of the materials of the web gets stuck to a module.
  - When the web is pulled while one of the modules is still in its operation.
  - This can also happen as the PLA gets sealed to the module itself.
  - The web sticks to the small burrs on the metal plates used in the cutting modules.
- P10: The web slips from the clamps of module 60.
  - When one of the servos enacts too little force or the final puller pulls too

Finally, during the set-up or changing of the materials, human errors can be made. These occur due to limited documentation on how the machine should be operated, due to haste, or due to forgetting important operations that have to be done by the operator. These often create faulty tea infusers, and more often create critical failures. These possible human errors are:

- H1: The operator misaligns the filter paper after replacement.
  - When the paper is not aligned this can create problems with getting a complete seal on the bottom.
- H2: The operator misaligns the cartridge roll within the module.
  - The cardboard has two sides when he paper is placed in the wrong direction the bracket is sealed to the heat seal block instead of the filter paper.
- H3: The operator starts the machine when the heat seals are still cold.
  - If the cartridge is placed wrong in the machine it can trigger the endstop to early or the cartridge can be placed sideways by misaligning the teeth.
- H4: The operator forgets to connect a piece of electronics.
  - The brackets will not stick to the filter paper.
  - The filter falls apart after it is cut.
- H5: The operator is too late with replacing the material.
  - Because there is no communication with most electronics a step can be missed this way.
  - This can also create to much tension on the web
- H6: Fasteners are too added to loose.
  - When the material runs out it tears due to too much tension
  - When a fastener is not properly attached with Loctite or is placed too loose, during operation it can come out of the machine which will break parts of the module.
- H7: The operator has not cleaned or checked the web properly.
  - When the web is not properly replaced or checked before restarting the system after a failure or when the materials have to be changed, it can more easily tear as it was not designed with that specific web.

It is important to note here that the problems the system can experience are not limited to all the different failure modes that have been mentioned here, other problems that have not yet been recognised could occur as well. Because the system is complex, when a critical failure occurs, finding the root cause can often be a hard task. For this, cameras already have been stationed around the machine that can help get insights into the root cause of the problems.

5.3. Desired state

With the specification defined for the tea infusers, the desired state can be defined. Considering the aesthetic and usability of the infusers they will have to have none of the specified failure modes whilst also having more optimal versions of the dimensions. The desired state of quality of the tea infuser can be seen in Figure 54. The optimal dimensions of the tea infuser can be defined as follows:

- D1: The distance between two tea infusers. 104 mm
- D2: Distance between the left and right bracket. 0 mm
- D3: Part of the filter paper above the highest bracket. 0 mm
- D4: The left-right alignment of the brackets. 0 mm
- D5: The size of the smallest bracket arm. 4 mm

However, for these measurements, it must be considered that when D3 is at 0mm there is a high probability of C3, cutting of the bracket, occurring. Therefore, it will be ideal to have the occurrences be centred within their acceptable tolerance ranges. This desired state will be a narrower definition than the current specification and will therefore initially lower the yield as the quality of the tea infusers that are in the specification will be higher.

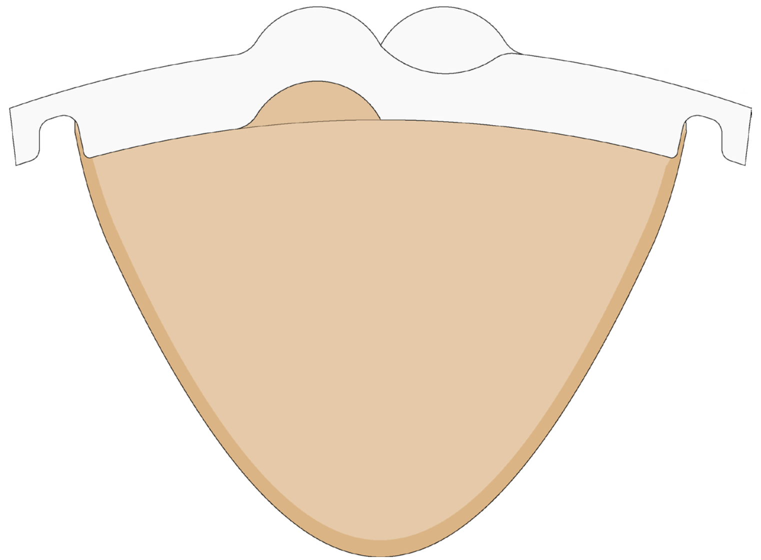


Figure 54: Desired state of tea infuser

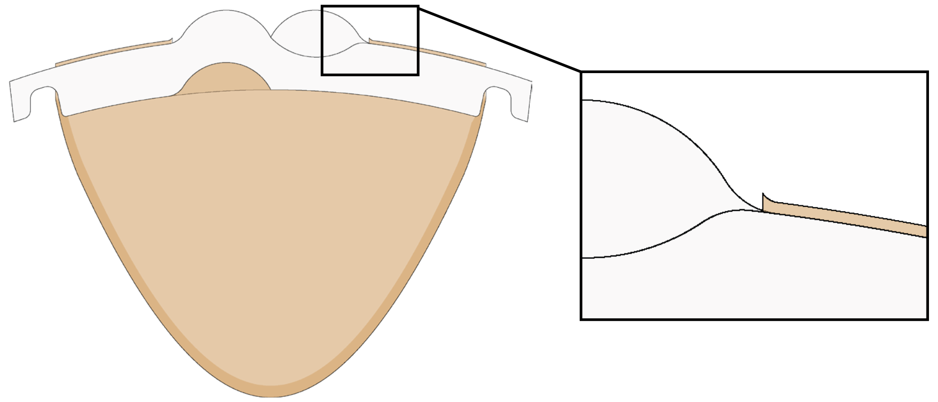


Figure 55: Achievable desired state of tea infuser

To then determine the achievable desired state a closer look is taken at the knife designs and bracket designs, when these are overlayed to create the ideal production scenario the tea infuser of Figure 55 is generated. From this image it can be noted that there are little additional pieces of filter paper. This is because the knife design of module 20 that was made was to small in comparison to the other knife in module 50. This gathering of insights shows why additional information gathering on the current state and desired state can help understand the problems that can be seen within the final tea infuser.

The desired state does, however, look at more than just the final tea infuser. Other aspects must be considered as well, these are the lowering of critical errors to improve the continuous operation and the poduction capacity of the machine per hour. First, the continuous operation, where the desired state is to ensure that the machine can be operated continuously apart from changing material inputs. To achieve this second perspective, it is needed for the machine to eliminate all its critical errors. Secondly, the final production yield is considered. While the addition of continuous operation does add additional yield for a full day, the machine must be optimised for hourly yield as well. Currently, the production yield per hour is roughly 90 tea infusers. The desired state for a single machine is up to 300 tea infusers an hour as a production time of 12 seconds is deemed reachable. As a final consideration, it should be noted that when there is a need for a yield upwards of 7200 tea infusers a day there will be a need for additional production machines as the machine will most likely not get over 300 tea infusers a day.

Figure 56: Occurrence of failure mode C6-85

5.4. Gaps

Now that the current state and future state have been defined the gaps between the two become apparent. The important categories that have been chosen are at first the yield, which consists of the amalgamation of production speed, out-of-specification tea infusers, and the operational time of the machine. These all influence the yield of the machine and help gain an understanding of what part of production is mainly lacking to achieve the desired state of production. While, on the other, the knowledge gap as well as the human errors that still occur can show reasoning for the problems that occur from which the root cause cannot be determined. An overview of the gaps can be seen in Table 2.

Most of the gaps that are currently present result from the fact that the production machine is not set up yet for continuous production as many of the parts are still to be changed and tested. This means that the overall production suffers from the many failure modes that can occur due to changes or wrong set ups. To transfer the machine from its current state to the desired state it is needed to implement changes that mitigate the failure modes it currently experiences. However, to be able to decide what changes have to be implemented it is first needed to analyse the failure modes to find out what their root causes are. This is especially a necessity in a complex system such as the tea infuser machine, where the operation of each module influences the operations of other modules as well. The gaps currently in the machine's yield, consistency, reliability, and quality are also heavily dependent on the calibration of the code, flexures, and physical end stops. As changes in these parameters heavily influence the placement of different parts of the tea infuser. This means that adjustments to the parameters might be a low-effort but high-impact solution to some of the existing failure modes.

5.5. Conclusion

From the analysis of the current state, it can be seen that there the main problems in production are the low production speed, low quality of the end product as well as low reliability of the overall machine. These are the main problems that will have to be improved upon during the redesign phases. But other problems such as lack of knowledge of the overall system and the influence of human errors have surfaced as well. Even additional insight into the production process, such as the problems with the knife design have come to light due to the more in-depth definition of the production process.

To be able to bridge the gaps that have been defined in this chapter, the machine has to first be analysed in-depth by means of measurements such as a statistical analysis and capability analysis. This analysis will provide the information on which problems are the most pressing, and if the problems that currently occur during production are mainly due to lack of precision of the modules or by misalignment of the modules. The gathering of this information on the production process starts bridging the knowledge gap as well.

Table 2: Gap analysis

Categories	Previous	Desired	Gap
Production speed	120 per hour	300 per hour	Increase production speed from 30 seconds to 12 seconds per tea infuser.
Quality of tea infusers	Low-quality	High-quality	Most tea infusers are considered in the specification as of the start of the thesis, with the only determining factor if they ware useable. However, the quality therefore, is low. For the further development of the machine it is necessary to increase quality as well ass the product will be sold instead of tested. This does mean that most currently in specification tea infusers will become out of specification.
Out of specification tea infusers (D)	1 in 4	1 in 161	Currently, over 25% is eliminated from the production batches, this equates roughly to 2σ status of production. As production scaleds most tea infusers should be in specification which has to be increased to 3σ lowering the failure rate less than 1%, specifically 1 in 161.
Failure modes of tea infuser (C)	1 in 10	1 in 200	With the machine running there can occur non-critical failures in the machine induce out-of-specification tea infusers. To be able to reach over 3σ the number of failures has to be lowered drastically. These failure modes create tea infusers that are unusable and therefore create larger problems than problems that can occur due to tolerances which mainly influence quality.
Critical errors (P)	1 in 240	1 in 7200	To be able to have the production run for 24 hours, the number of critical errors has to be lowered to 1 in 7200. This number is chosen as this is the point where production runs of on average 24 hours can be had.
Human error (H)	1 in 5	1 in 100	While the machine should run automatic production there still is the needed interaction from an operator during set-up and during the final manual step. Currently the machine does not recognise mistakes made by the operator such as the misplacement of one of the materials or forgetting to reconnect one of the steppers. The system should be made more intuitive to use and should where possible recognise these mistakes.
Operational time	6-8 hours	24 hours	The current system has critical failures which create downtime for the machine and prevent it from being operated during the night
Yield	567 per day	7153 per day	With the many problems the machine has an the significant lower production per hour and operational time the difference between the current yield and desired yield is over a factor of 10. While this is a large gap to bridge, it can dor example be achieved due to increasing speed by a factor of 2.5 and operational time by a factor 3.
Knowledge	Little-to-none	High-level knowledge	While the main gap analysis is done on the gap in production, there also is a great knowledge gap that should be bridged. Currently almost no insights are made in the accuracy and failure occurrence of the machine which make decision-making more difficult as well as the possibility to improve the production process.

6. Statistical analysis of the machine

To overcome the knowledge gap there Is the need to get insights into the production machine by means of measurements and failure mode data. This knowledge is needed to start looking at improvements that can be made to reach the desired state of the production machine. For this, the second part of the question "What are the current failure modes and their occurrence within the system?" must be answered as well as "What is the current capability of each of the parts of the produced tea infusers?". As these questions will provide insights into the possible changes that have to be made.

6.1. Statistical analysis of tea infusers

Initially, many of the failures of the new stricter definition of what is considered an in-specification tea infuser can be attributed to the incorrect set-up of the flexures of the modules. This can be seen from the measurements done on the initial batch of 50 tea infusers, as seen in Figure 57 and Table 3. Here most of the deviations from the

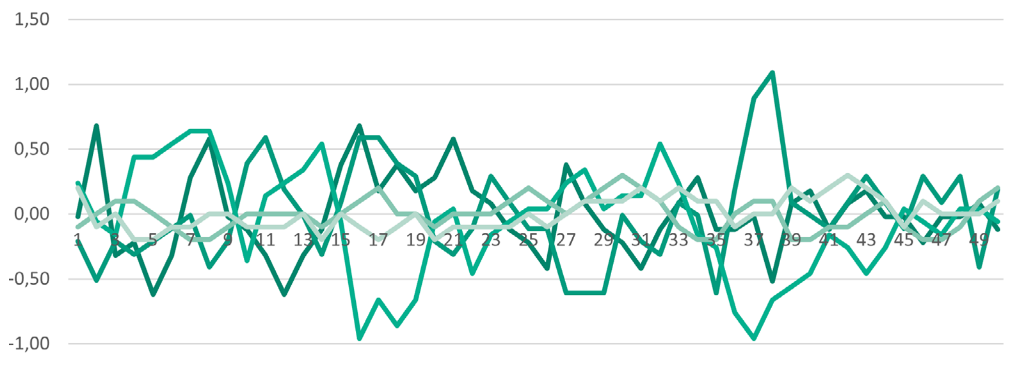


Figure 57: Deviation from the mean of the dimensions

mean can be seen to be within 0.5mm, which implies that when the machine is set up correctly most of the tolerances of the parts can fall within specification. As most specifications have an acceptable tolerance window of 2mm.

It is observed that the tolerances within the different dimensions of the tea infusers follow a pattern similar to a wave function. This is because, for example, when the puller moves half of a millimetre further for one cycle, the next 13 tea infusers will have this shift forward. When multiple different modules experience different shifts this wave characteristic can be seen. The reason this wave function does look quite sporadic is that many of the dimensions are influenced by multiple modules, which can strengthen each other by compounding their individual tolerance shifts (Figure 58). When only looking at D2 in Figure 59 these more extreme peaks can be seen. This compounding of multiple tolerances results in the possibility of tea infusers becoming out of specification. Therefore, a root cause analysis is needed to determine the most influential modules of the specific out-of-specification dimensions or failure modes.

Table 3: Basic statistics of the tea infusers

Variable	N	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	Maximum
D1: The distance between two tea infusers	50	104,12	0,0433	0,306	103,5	103,9	104,1	104,3	104,8
D2: Distance between the left and right bracket	50	1,014	0,0524	0,3703	0,4	0,8	1,0	1,225	2,1
D3: Part of the filter paper above the highest bracket	50	1,792	0,0583	0,4125	0,9	1,575	1,8	2,1	2,5
D4: The left-right alignment of the brackets	50	0,396	0,0183	0,1293	0,2	0,3	0,4	0,5	0,7
D5: The size of the smallest bracket	50	4,1	0,0178	0,1262	3,9	4,0	4,1	4,2	4,4

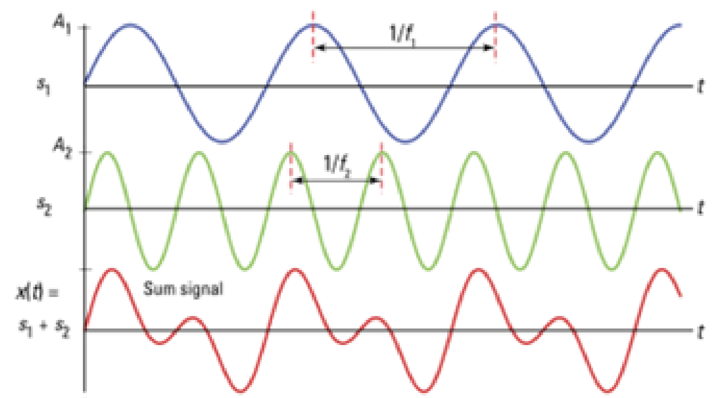


Figure 58: Compounding wave functions

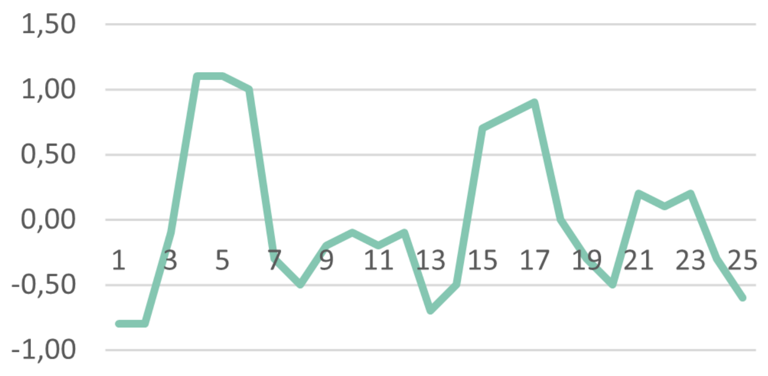


Figure 59: D2 wave function of dimensions

6.2. Capability study

To better define what the standard deviation means for the tea infuser machine a capability study is executed to gain insights into the possible capability of the machine, as well as how centred the process is currently. The latter of these insights can be used as the basis for the changes to be made to the setup. As the use of the flexures is to recentre the parts in relation to the complete tea infuser.

The statistic used for this is Cp and Cpk, where Cp is the overall possible capability of the system and Cpk is the current capability which considers the centring. Pp and Ppk respectively are used for systems that are statistically in control, this is hard to say about the tea infuser machine and look at multiple batches over a longer time. As this is not the case for the initial measurements of the first 50 tea infusers, these statistics will not be considered for the capability study. Using the capability studies as seen in Appendix F.1 it was noticed that most parts seemed partially in control, however, when the dimension could not be lower than one. As this would again bring a positive value for D2 for example. Another problem with this method was that D3 when it is 0 or less than 0, it creates failure modes. Therefore, a second capability, as seen in Appendix F.1 was executed to take these problems into account. From this, the statistics in Table 4 have been derived.

Table 4: Capability of the tea infuser production machine

Dimensions	Cp	Cpk	PPM	Centred
D1: The distance between two tea infusers	1.34	1.34	55	Yes
D2: Distance between the left and right bracket	0.96	0.62	31110	No
D3: Part of the filter paper above the highest bracket	1.57	0.33	162898	No
D4: The left-right alignment of the brackets	2.14	1.70	0	Yes
D5: The size of the smallest bracket	-	4.5	-	-

From this table it can be seen that D1, D3, D4, and D5 are all above 1.33 Cp, meaning that if they are centred, they could achieve a Cpk of 1,33 which is the guideline for capability, and implies the dimension has a sigma level of four. Sigma levels explain how well a production process work, a sigma level of four for each of the dimensions except D2 already show a yield percentage of 99.6% or less than 1 failure every 161 tea infusers which aligns with the desired state as presented in Chapter 4. This is already close to the desired state of the tea infuser. However, from the Cpk, it can be derived that D2 and D3 are not centred. Resulting in an effective sigma level for this batch of one to two. Through means of the flexures the individual steps as seen in Chapter 2.3. the mean of the location of the parts can be shifted. However, as most steps do affect each other, changing a part of the setup will influence other parameters as well. This overview of changes to modules in relation to changes in parameters can be seen in Table 4.

To overcome the current misalignment issues of the production process, the modules have to be better aligned. The lowest Cp that was encountered was Cpk=0.96 which implies roughly a sigma level of three. This means that by means of adjustments to alignment, the highest possible yield achievable is 99% yield. However, as the measurements do not take into account when a bracket is cut and thus D3 would be less than 0, lowering the mean and capability of the machine.

6.3. Influence of changes on dimensions

While most changes to the parameters of the system, such as the location of the flexures, only change one step of the process. For example, moving the flexures of module 20 one millimetre upwards will only shift the location of the hole one millimetre upwards. This is the same for moving the module on the axles and most of the additional step options throughout the machine. However, this adjustment is not the case for module 60, which has a great influence on each of the dimensions and locations of the steps as the filter paper is moved further in each of the steps. This means that when module 60 can move an extra 0,1 mm, because module 20 experiences this shift 13 times, the additional movement for this module is 1,3mm. All of the shift distances can be seen in Figure 60. This module is a strong option to quickly change many of the locations of the steps, especially when the movement is outside the reach of the flexure. However, this should be done cautiously as this will shift each of the modules which can create larger problems, as seen in Figure 61.

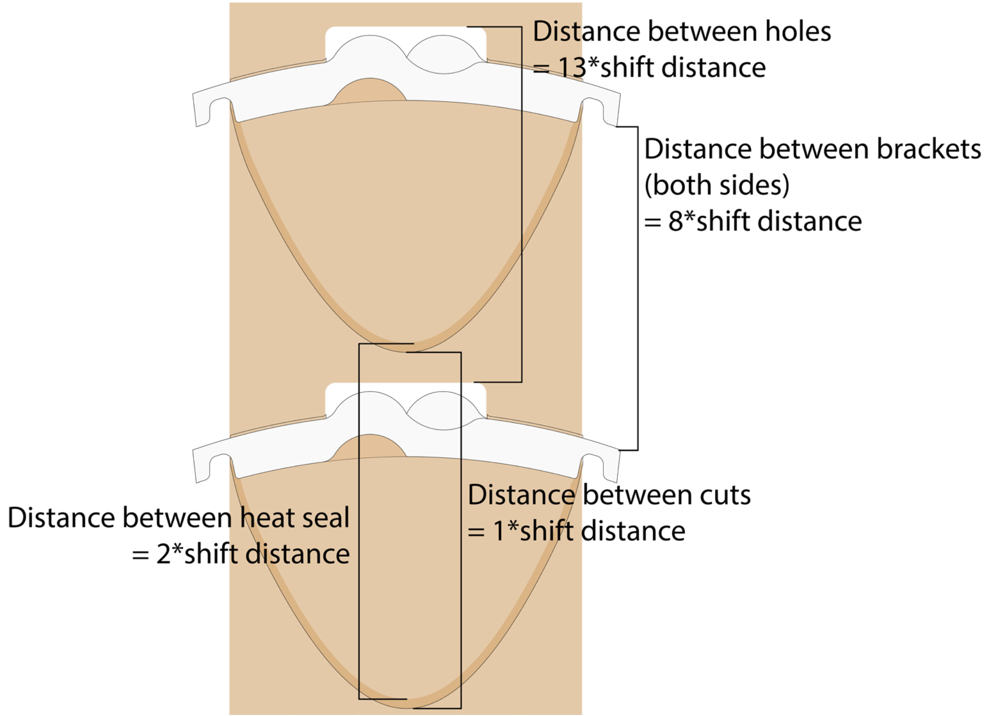


Figure 60: Influence of module 60 changes to the overall tea infuser specification

6.4. Conclusion

It can be seen that most of the dimensions of the system are within the tolerance window, however, they are shifted, to overcome this misalignment the flexures of the system have to be used to create a better set-up for the machine. Therefore, to improve the yield of the machine initially the set-up must be changed. These are low-effort, high-reward changes that immediately increase the yield of the machine which is made necessary through the need to sell the tea infusers as of this point in time. Additionally having the system set up in such a way that the failure modes that occur originate from the design of the modules instead of the set-up ensures that the problems that are solved are with the design and not to counteract the misalignment through redesign. The steps and strategies taken for these improvements can be found in the next chapter. For further iterations, more emphasis is needed on finding the root cause of the failure modes, however, as can be retrieved from Table 5, most changes can be easily applied to each of the locations of the parts of the tea infusers.

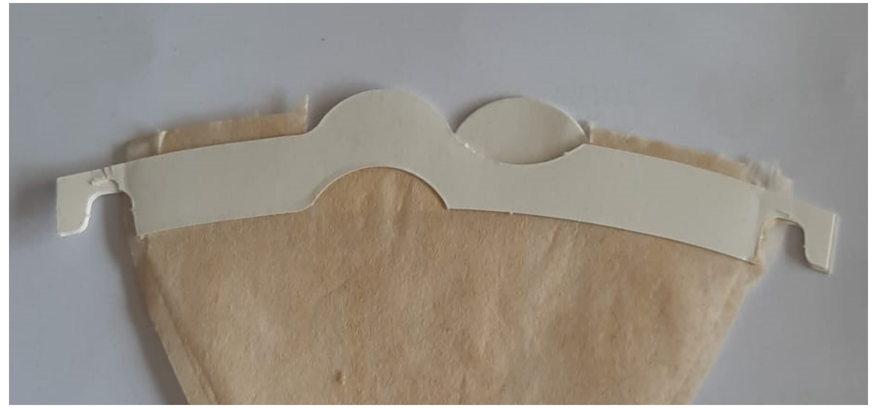


Figure 61: Too large of a shift in module 60 resulting in problems with placement of bracket

Table 5: Influence of the modules on failure modes

Module	10	20	30	35	40	50	60	70	80	85	90	Human	
D1: The distance between two bags.							x						1
D2: Distance between the left and right bracket.			x	x			x				x		4
D3: Part of the filter paper above the highest bracket.			x	x		x	x				x		5
D4: The left right alignment of the brackets.			x	x							x		3
D5: The size of the smallest bracket arm.			x	x							x		3
C1: Filter hole is below the bracket.		x					x						2
C2: The heat seal is not completely	x				x	x	x						4
C3: Cut into the top part of the brackets.			x	x		x	x				x		5
C4: Cut into the bottom part of the brackets.			x	x		x	x				x		5
C5: A step is skipped during production. (20)		x											1
C5: A step is skipped during production. (30)			x										1
C5: A step is skipped during production. (35)				x									1
C5: A step is skipped during production. (40)					x								1
C5: A step is skipped during production. (50)						x							1
C6: There is a piece of waste in the tea infuser. (20)		x											1
C6: There is a piece of waste in the tea infuser. (80)									x		x		2
C6: There is a piece of waste in the tea infuser. (85)										x	x		2
C7: Creasing of the tea infuser.	x						x	x					3
C8: Cutting line of knifes is not straight. (30)			x								x		2
H1: Misalignment ofthe filter paper.												x	1
H2: Misalignment of the cartridge roll.												x	1
H3: Heat seals are still cold.												x	1
H4: Disconnected piece of electronics.												x	1
H5: Too late with replacement of the material.												x	1
H6: Fasteners are too added to loose.												x	1
H7: Web not cleaned or checked properly.												x	1
P1: Web is weakened	x	x	x	x	x	x	x	x	x	x	x		11
P2: Error in software.	x	x	x	x	x	x	x	x	x	x	x		11
P3: Stepper driver fails.	x	x	x	x	x	x	x		x	x			9
P4: Motor gets stuck.	x	x	x	x	x	x	x	x	x	x	x		11
P5: Sticky behaviour of relays.	x	x			x			x					4
P6: Heat seal gets too hot.			x	x	x								3
P7: Material gets stuck to final roller.								x					1
P8: Piece of waste gets stuck in machine.		x	x	x		x							4
P9: Material gets stuck to module. (30)			x										1
P9: Material gets stuck to module. (35)				x									1
P9: Material gets stuck to module. (50)						x							1
P9: Material gets stuck to module. (70)								x					1
P10: Web slips from module 60.							x						1
	7	9	15	14	8	11	13	7	5	5	13	7	

7. Application of machine improvements through set up

In this chapter, examples of the quick win improvments are applied to the machine using the measurements done in the previous chapter. In this chapter, the answer will be given to the question “How can the machine set-up be changed to improve upon the production yield?” through the use of failure mode occurrences. This chapter focusses on the how part of the improvement cycle, but does not go through the complete Design Thinking cycle.

To get a better idea of the adjustments to be made failure modes will be defined and the dimensions that can be changed to circumvent these failure modes will be initially changed with the use of the flexure system. The reason why these adjustments were not done earlier while they are low-effort, high-impact changes is that it was unknown that this improved yield could be achieved through machine adjustments. It was expected that the machine would be able to perform better, however, where to begin with these changes shows difficulties when there is no insight into the current abilities of the machine.

7.1. Machine setup improvements

The capability study mainly looked at the measurable dimensions D1-D5, but to better decide on what changes have to be made to the system other failure modes have to be considered as well. To get information on these failure modes batches are tested in between each adjustment to the machine.

As can be seen in Table 6 and the pie chart in Figure 62 the tea infuser machine creates many out-of-specification tea infusers, the most present problem is C1, the misalignment of the filter hole. To update the location of the filter hole it can be seen in Table 6 that module 20 and module 60 influence this location. To make sure that changing the setting does not interfere with many other parameters of the system the choice is made to change the flexures of module 20 as this only influences three other parameters that do not get interfered with by changing the y-distance of the flexures, while module 60 does influence other parameters by either changing the distance between the top and bottom position of the puller or by changing the y-distance of the flexures.

Table 6: Failure mode occurrence V1

Type	Count
Total	220
Yield	45
C1	125
C3	1
C4	35
C5: 50	11
C6: 20	2
C7	1

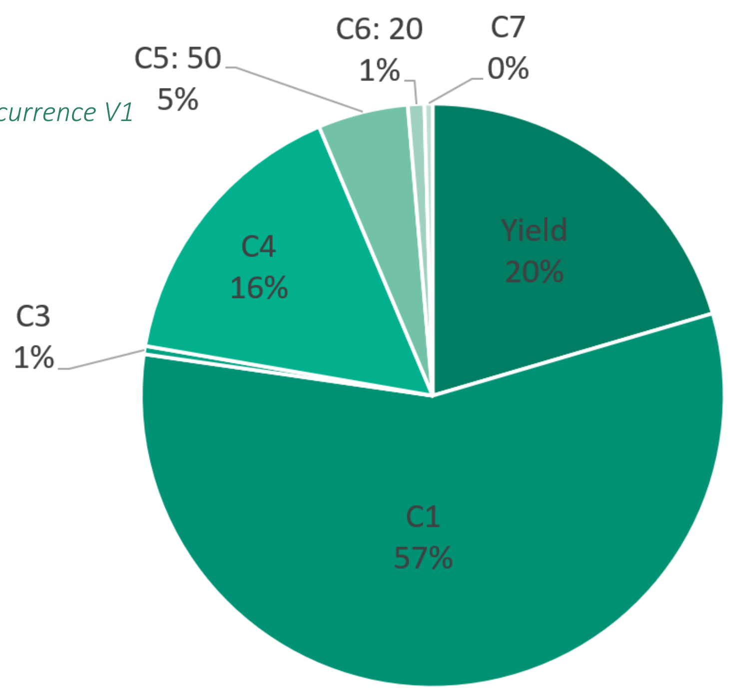


Figure 62: Pie chart of failure mode occurrence V1

Table 7: Failure mode occurrence V2

Type	Count
Total	323
Yield	224
C4	83
C6: 20	5
C7	6
C8: 35	5

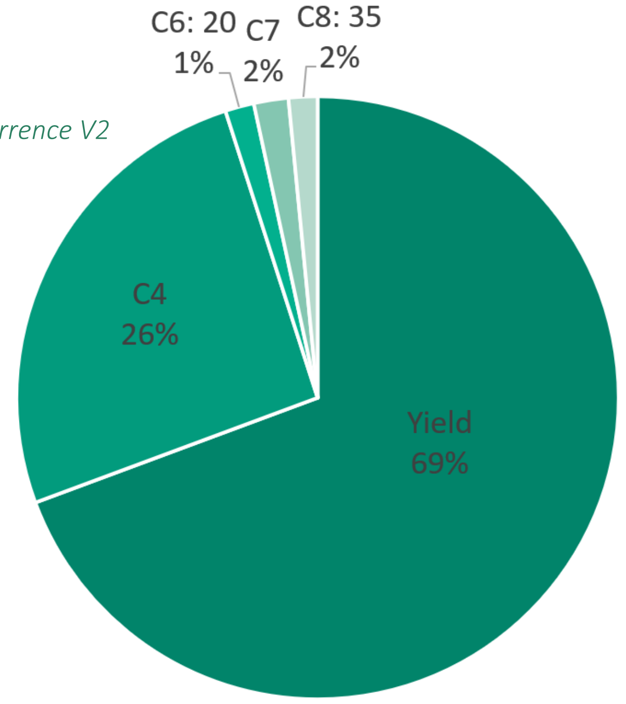


Figure 63: Pie chart of failure mode occurrence V2

With the update to module 20, the number of failures decreased from 80% to 31%, which still is an unacceptable level of failures, therefore, the second iteration of failure mode analysis is executed. Here it can be seen that the most present failure mode is C3, the cutting of the bottom of the bracket. In the table, it can be seen that this failure mode is influenced by modules 30, 35, 50 and 60. The choice here is made to move both modules 30 and 35 up and move 50 and 60 down. As each of these modules highly influences other parameters. And in this manner, the influence is spread over multiple parameters. This will most likely prevent too large of a shift in one of the other parameters.

Table 8: Failure mode occurrence V3

Type	Count
Total	234
Yield	172
C1	1
C3	50
C4	2
C6: 20	6
C6: 80/85	3

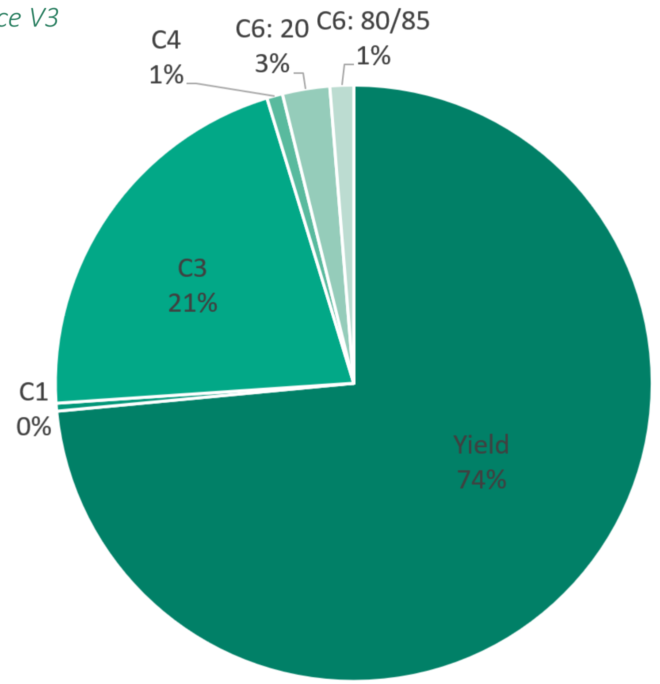


Figure 64: Pie chart of failure mode occurrence V3

While this update did improve the failure rate slightly from 31% to 26% it can be seen that now the most present problem has become C4, cutting the top of the bracket. Other failure modes did not increase in occurrence. Therefore, it can be concluded that the adjustments to modules 30, 35, 50, and 60 have been too great and will have to be re-adjusted closer to their previous settings.

Table 9: Failure mode occurrence V4

Type	Count
Total	291
Yield	272
C3	12
C4	4
C6: 20	3

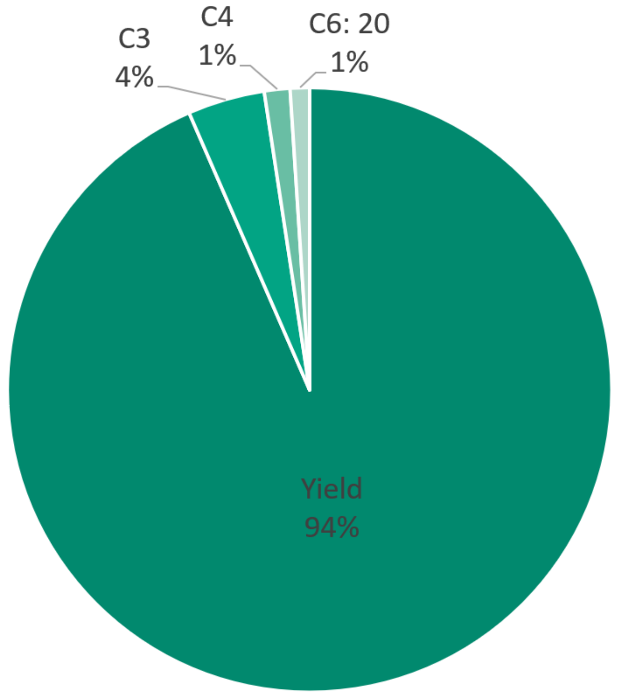


Figure 65: Pie chart of failure mode occurrence V4

This final adjustment has decreased the failure rate from 26% to 7%, the now most present failure modes can be concluded not to be able to be mitigated through adjustment of the machine settings. These failure modes will have to be mitigated through redesign of the modules. The failure rate of 7% is deemed to be an acceptable failure rate for the initial production, as per the capability analysis the maximum achievable yield is 96%. With the machine running, further improvements can be designed parallel to the continuous operation. This is necessary as the tea infuser has to be used in the pilots of TeaWall and as of the end of this phase will have to be sold separately as a product as well.

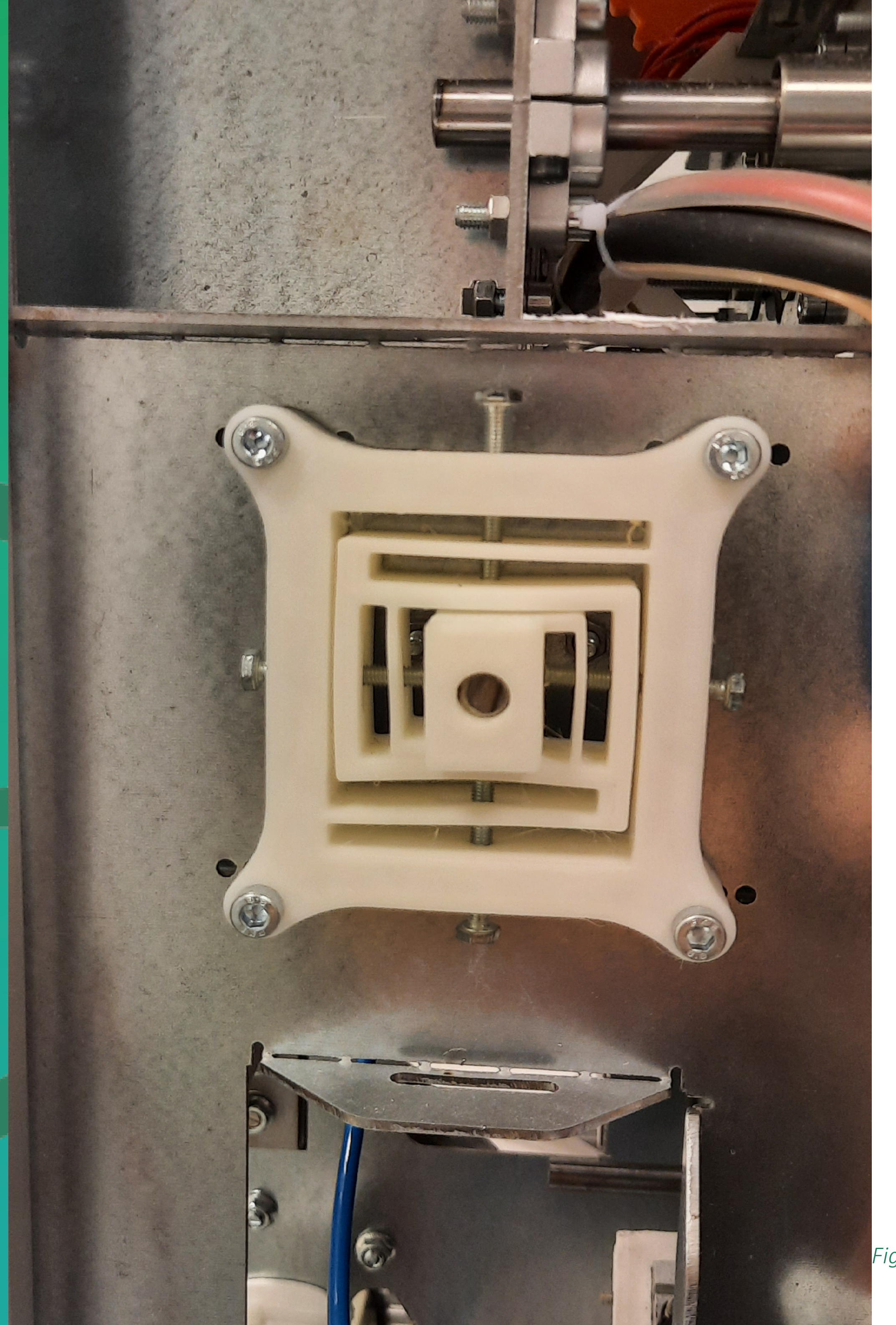


Figure 66: Flexures at the end of the alignment

7.2. Evaluation of updates

Due to the high impact low effort changes made to the machine parameters, specifically the changes made to the locations of the flexures (Figure 66). Many of these changes have been small, however as the tolerances are in the order of magnitude of less than a mm these changes to flexures can often be small but impactful. Some of the gaps have already shrunk significantly. While this lowers some of the gaps, the main application of these parameter changes is that it allows for a more accurate determination of the problems that the machine still faces.

7.3. Conclusion

It can be concluded that the adjustments that can be done to the flexures of the system result in a significantly higher yield of high-quality end products. This was expected due to the analysis done on the tolerances and capability of the tea infusers. This shows that gathering quality measurements can provide a strong basis for initial changes made to the production machine. Without the measurements that were done in Chapter 6, it would have been unclear what precision was reachable with the current tolerances of the machine.

However, the changes made to the flexures of the system are still limited to shifting the parts in relation to the end product. This does not improve the precision of modules or prevent failure modes such as C6:20, the waste of Module 20 entering one of the tea infusers. For this redesigns of parts, or complete modules are needed. These, however, are more intrusive changes for the production process and will cost more resources for the company. This means that the small, substantiated trial-and-error method used in this chapter will not be structured enough. Also, the problems could be complex resulting in wrong decision-making when deciding which changes have to be made. For this, a structured decision-making process is needed during a second iteration of the what (DMAIC) cycle. With the latest FMEA of this chapter, the start of the decision-making process will be elaborated in the next Chapter.

Table 10: Gap analysis V2

Categories	Previous	Current	Desired	Gap
Production speed	120 per hour	120 per hour	300 per hour	Production speed does not change due to parameter changes, except motor speeds, which have not been considered during this stage.
Quality of tea infusers	Low-quality	Medium-quality	High-quality	The quality of the tea infusers is increased by centring the modules within their tolerance windows creating more desirable tea infusers.
Out of specification tea infusers (D)	1 in 4	1 in 10	1 in 161	Similar to quality the amount of out-of-specification tea infusers has been lowered by centring the modules.
Failure modes of tea infuser (C)	1 in 10	1 in 17	1 in 200	Secondly to the improved in specification tea infusers, the amount of failure modes has sighnificantly decreased due to the improvements in alignment.
Critical errors (P)	1 in 240	6-8hr	1 in 7200	Operational time has not increased as mainly the non-critcal failures have been addressed as well sas quality. Tthe root causes of the critical failures have not been solved.
Human error (H)	1 in 5	1 in 240	1 in 100	Similar to the critical errors, human intyeraction with the production process has not beenaddressed by changing parameters.
Operational time	6-8 hours	6-8 hours	24 hours	When critical failure have not been addressed, operational time will also not change.
Yield	567 per day	718 per day	7153 per day	Yield is improved as the out-of-specification tea infusers are lowered.
Knowledge	Little-to-none	Basic knowledge	High-level knowledge	Knowledge has been gained during the measurement and this step, which can form the baseline for the choices of areas of improvement.

8. Decision-making for the improvement of a complex system

As most failure modes within a complex system such as the tea infuser machine can have multiple or even compounding causes, there is a need for a root cause analysis. This analysis is used to ensure that changes that are made to the system change the behaviour in direct relation to the failure mode instead of focussing on a symptom of another problem. After the root cause has been found the probability o a solution solving the problem and the ease of implementation will also influence the decision-making behaviour.

8.1. Failure mode and effect analysis

For this, the failure mode and effect analysis methodology will be applied. For the decision-making process, the failure modes will be weighed against each other based on occurrence, severity, and detection to provide the Risk Priority Number which can be used to decide what failure modes are most important to improve upon. Occurrence is the category that focuses on the number of failures that are observed relating to the specific failure mode. Severity takes the influence of the failure mode into account, for this, the influence on aesthetic problems, failure of the tea infuser, influence on critical failure of the machine and possible harm to the end user will be considered. The final category is detection which considers how easily a failure can be spotted. As how harder the failure is to spot the more easily this failure can be overseen. For the infusers, the failures of the tea infuser should be spotted in the packing process of the boxes. If one of the failures is hard to spot or requires specific actions to be spotted, they have a high risk of getting in the final product that is sent to the end user.

While FMEA will show what the main problems are through the RPN and could be used to determine what failure modes will have to be chosen for the redesign process it does not show what module the root cause of the failure mode is. The root cause analysis and initial ideation on problem-solving of the root causes are also needed to be able to fully determine what modules or parts are most critical and can be improved upon most effectively. For the root cause analysis, an Ishikawa diagram can be used in combination with individual measurements of the sub-parts to determine what is most likely the root of the problem. After the possible root causes are determined, conceptual designs and tests can be done to add a proof of concept to the possible solutions. These are necessary to determine a probability of a redesign being effective at solving the root cause. Comparing the solutions to existing products, solutions to similar problems and literature research can be used to determine the probability of successful implementation as well.

As mentioned during the literature research, often additional factors are added to the FMEA to better fit with the project it is applied to. For this application, the choice is made to add three factors to the FMEA to further guide the decision-making process. The first factor will be named probability which provides added weighing to a failure mode which is more likely of being the root cause of the failure mode. Secondly, the factor of implementation will add weighing to problems that have easier to solve problems. The third is the probability of the solution solving the problem. The value created by the complete set of factors will show what failure modes will have to be designed for initially. This value will differ from the risk factor and will help decide if a redesign is still useful to execute. A caveat to applying these additional values is that failure modes that have scored low on the final value could still be a pressing problem when they have scored high on the initial FMEA. These should be considered as possible points of improvement even if the possible solutions are hard to implement or have less probability of solving the problem. As this system could otherwise overlook important failure modes.

Table 11: Initial FMEA

Failure mode	Occurrence	Severity	Risk	Detection	RPN
C1	2	5	10	9	90
C2	1	8	8	3	24
C3	7	3	21	4	84
C4	6	5	30	8	240
C5 - 20	1	6	6	1	6
C5 - 30/35	2	8	16	1	16
C5 - 40	1	8	8	3	24
C5 - 50	1	10	10	2	20
C6 - 20	6	6	36	4	144
C6 - 80/85	3	6	18	6	108
C7	2	4	8	2	16
C8	2	2	4	3	12

8.2. Structured approach to factors

To be able to get useful information from the FMEA the scoring for the occurrence, severity, and detection should be executed with a structured substantiated approach. As these numerical values are prone to biases the values should be built up using a formula. This will be shown by first writing an FMEA based on experience with the machine, taking into account the observed statistics, and can be seen in Appendix I.

Secondly, an FMEA will be written using numerical values based on a formula. This will show how a structured approach differs. The added advantage here is that the results are reproducible. In the explanation of each of the factors, an example of calculation will be given with C4.

8.2.1. Occurrence

For the occurrence, the number of observed failures per 1000 infusers has been taken as the base measurement for determining the occurrence factor of the failure modes. The occurence value for these failure modes will be based on a logarithmic scale which sets the value of ten if there is 1000 failures per 1000 produced tea infusers. With steps of factor ten per decrease or increase of the value of occurence by two. The choice for the logarithmic scale is made to ensure that both ends of the extreme have similiar influence on the occurance factor as well as preventing that a failure mode that occurs once per ten tea infusers has a factor of near infinite over a failure mode which is much more critical but only occurs once every 1000 infusers. This is to prevent that occurence is the most influential factor. Secondly if it were to be split up er 100 occurences the differentaion with smaller amounts of failures would not be present. The formula used is: [Occurence]=2*LOG([Failures per 1000])+4.

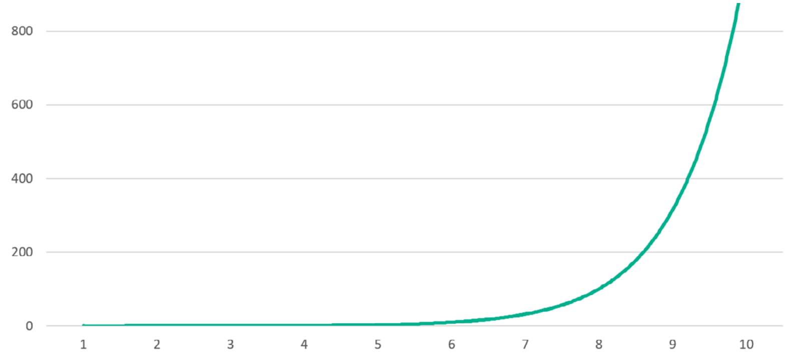


Figure 67: Occurrence factor

As an example, failure mode C4 occurred on average 44 times per 1000 tea infuser and therefore has a value of 7 if it is filled into the equation. The complete occurence values for the failure modes can be found in Appendix I.

8.2.2. Severity

To be able to determine the severity of the failure modes multiple questions are used to add to the value. Each failure mode starts at value 1 and can go up to 10 if all questions are answered.

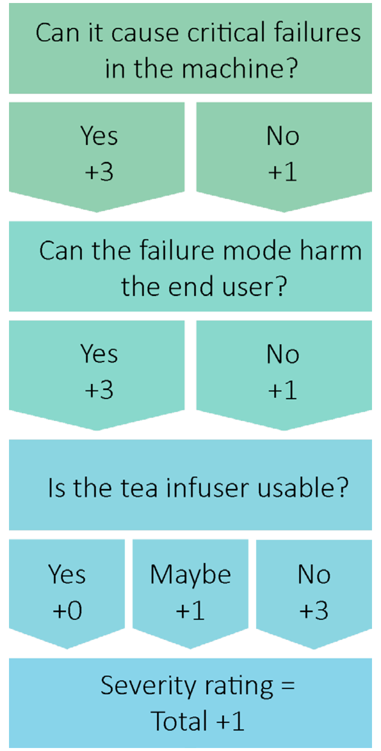


Figure 68: Severity factor flowchart

As an example, C4 has the chance to create a critical failure as when it occurs the bag can be sealed to the paper as well. Thus "Maybe +1". It can harm the user as a part of the cardboard can get in the cup. Thus "Yes +3". The tea infuser is still useable, but if the cut is too far is can cause problems. Thus "Maybe not +1". This results in an overall value of 6. The complete Severity values for the failure modes can be found in Appendix I.

8.2.3. Detection

Finally, for the detection value, a similar system to severity will be used. Where different aspects will increase the value for detection.

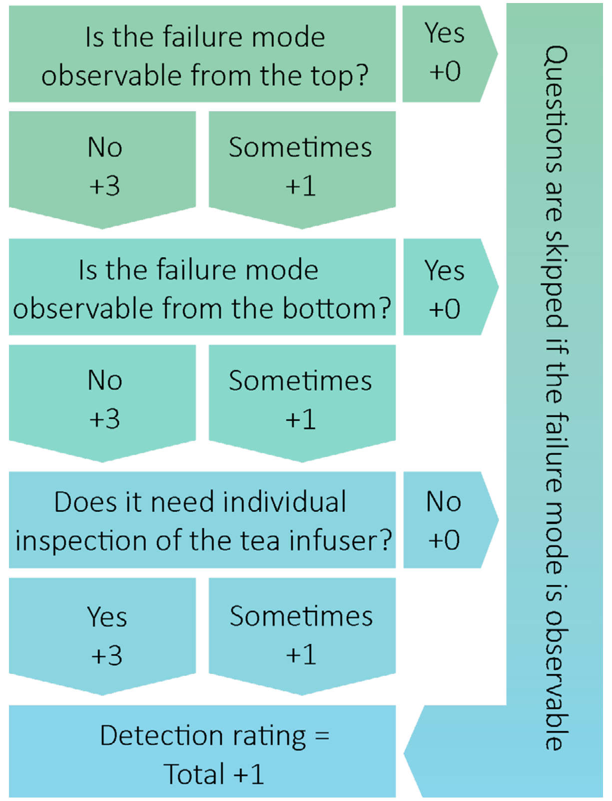


Figure 69: Detection factor flowchart

For example, C4 cuts the bracket at the bottom, this lowers the strength of the teabag and can introduce loose pieces in the cup. This problem is unobservable from the top of the tea infuser and should be checked from the bottom, where it can be observed, But this can be hard in stacks. This implies that sometimes the tea infusers have to be inspected individually. This gives back values, 3,1,2, and therefore provides a total of 7 including the standard given value of 1 for the detection value.

8.2.4. Updated Failure mode and effect analysis

The resulting FMEA shows similar results to the initial FMEA but has small differences in the rankings. The highest risk priority is again C4, which is as expected as it occurs often and is harder to detect than C3, which is the other often occurring failure mode.

Table 12: Updated FMEA with repeatable factors

Failure mode	Occurrence	Severity	Risk	Detection	RPN
C1	4	6	24	9	216
C2	3	6	18	3	54
C3	7	8	56	4	224
C4	6	8	48	8	384
C5 - 20	1	5	5	1	5
C5 - 30/35	5	7	35	1	35
C5 - 40	1	5	5	3	15
C5 - 50	4	7	28	2	56
C6 - 20	6	6	36	4	144
C6 - 80/85	5	6	30	6	180
C7	6	1	6	2	12
C8	5	1	5	3	15

Table 13: FMEA comparison

Failure mode	FMEA 1	FMEA 2	Normalised 1	Normalised 2
C1	90	216	3,75	5,625
C2	24	54	1	1,40625
C3	84	224	3,5	5,833333
C4	240	384	10	10
C5 - 20	6	5	0,25	0,130208
C5 - 30/35	16	35	0,666667	0,911458
C5 - 40	24	15	1	0,390625
C5 - 50	20	56	0,833333	1,458333
C6 - 20	144	144	6	3,75
C6 - 80/85	108	180	4,5	4,6875
C7	16	12	0,666667	0,3125
C8	12	15	0,5	0,390625

To get a better comparison between the two different FMEAs that have been executed it can be seen that with pre-knowledge similar results can be found. However, the specific failure modes that score higher differ between the two methods. Additionally, when this method has been defined updated FMEA and new failure modes can more easily be categorised as well. With the application of a structured approach to the FMEA, biases will be lessened and the chance to oversee a pressing problem is lowered. Both FMEAs show that C4 has the highest risk priority with C1, C3, and C6-20 having higher scores as well.

8.3. Root cause analysis

Now the risk priority assessment is done, the root cause of each of the failure modes should be investigated as these should be the basis of the redesign. For this, an additional look will be taken at the statistical analysis which was done on the dimensions of the tea infusers. For C1 dimension D1 is influential on the occurrence of the failure mode. For C3 and C4 the dimensions D1, D2, and D3 are influential. For C6-20 and C6-80/85, there are no influential dimensions. To better understand the possible root causes Table 5 is used again to see which modules influence the failure modes and their corresponding dimensions. C1 is influenced by modules 20 and 60. C3 and C4 are both influenced by Modules 30/35, 60, and 90. And C6-20 is solely influenced by Module 20.

When considering the measured tolerances of the tea infusers and the allowed tolerance windows of the final design it can be noted that each of these values should be able to fall between this window. However, it can be seen that still some of the failure modes can occur.

As mentioned before in Chapter 5, many of the problems occur due to compounding tolerances. For C3 and C4 the problems occur due to the compounding tolerances of modules 30/35, 60, and 90. To find out what it is the root cause of the failure mode the tolerances of each of the specific modules should be determined. The module which has the highest influence then is most effective to be redesigned.

8.3.1. Individual parts testing

To get a better understanding of the root causes of failure modes, each of the influential individual modules is tested. These tests should be made as isolated as possible whilst maintaining normal operating conditions. This will give the most accurate insights on what problems originate where, as isolating a module greatly can influence its behaviour. This method of testing does have the disadvantage that it becomes harder to get accurate measurements and therefore has a lower accuracy when it comes to working out what the root cause is based on these measurements. The tests that can be done to determine individual tolerances are:

- Module 30/35, the distance the cartridge is moved forward by the gears and the rotation of the bracket induced by this pushing.
- Module 60, the distance the web is pulled by module 60
- Module 90, the precision of the length of brackets on the cartridge
-

As the operations in modules 30/35 and 60 do have the compounding tolerances problem, it is chosen to do the testing in order of application. For this test that implies that first the tolerances of Module 90 are observed as this influence the testing of Modules 30/35 which is tested second in relation to the static part of Modules 30/35. This is to prevent the influence of Module 60 on the measurement data. Finally, Modules 30/35 and Module 90 are compared against Module 60 which will use the measurement data of the completed tea infuser as there all tolerances are compounded. This stepped approach will show the increase in the total deviation of each of the added operations of the modules.

8.3.1.1. The precision of the length of brackets on the cartridge

The Initial influence on the location of the brackets is the production of the cartridges. If these inflows already have a high tolerance this is seen again in the placement of the brackets. These cartridges are measured by hand in four batches of 25 brackets.

Table 14: Influence of module 90 on bracket placement

Variable	N	Mean	SE_Mean	StDev	Minimum	Q1	Median	Q3	Maximum
Module 90	100	12,478	0,00719	0,0719	12,3	12,4	12,5	12,538	12,6

8.3.1.2. The distance the cartridge is moved forward by the gears

This individual test focuses on the specific motion modules 30/35 where the bracket is placed on the web. During this test, the tolerance of the gears is checked. To ensure that the measurements are made correctly an additional measurement will be done of a rigid part of the system as there will be some vibrations in the overall machine.

Table 15: Influence of module 30/35 on bracket placement

Variable	N	Mean	SE_Mean	StDev	Minimum	Q1	Median	Q3	Maximum
Module 30/35	100	12,502	0,0172	0,172	12,3	12,35	12,5	12,45	12,8

8.3.1.3. Influence of Module 60

Finally, the overall tolerance is taken into account as having the additional influence of Module 60. These are based on the measurements done in Chapter 4.

Table 16: Influence of module 60 on bracket placement

Variable	N	Mean	SE_Mean	StDev	Minimum	Q1	Median	Q3	Maximum
Module 60	50	1,014	0,0524	0,3703	0,4	0,8	1	1,225	2,1

8.3.2. Conclusion of individual testing

From these individual tests, it can be seen that module 60 has the highest influence on the precision of the bracket and therefore will be considered the most useful module to be updated. Looking at the standard deviation it can be determined that Module 90 adds 0.07, Module 30/35 adds 0.10 and Module 60 adds 0.2. This implies that changing the design of Module 60 will have the highest benefit regarding the improvements of the tea infuser regarding failure modes C3 and C4. For this, it is again necessary to change machine parameters to be centred within the tolerance window.

8.4. Design implementation

With the conclusion on which module has the greatest influence over the most important to solve failure mode, other aspects will have to be considered during the decision-making process as well. These are the ease of implementation, the probability of design changes to improve upon the failure mode, and the influence a design change may have on the other modules. For the latter, we consider that changes to modules 30/35 will also improve dimensions D3 and with lower certainty D4 and D5. These are all related to the improvement of the quality of the tea infuser. Changes to module 60 will improve the dimension of all parts in the vertical direction as this is improved in consistency. This means dimensions D1, D3 and failure modes C1, and C2 are all also improved. This improves the yield significantly and improves more than C3 and C4 as C1 has a high-risk priority as well. Changes to module 90 improve the dimensions of the bracket, improving upon D3 as well.

Secondly, the ease of changes and their probability of improving on the current state should be considered. For Modules 30/35 one of the solutions is lowering the backlash in the stepper motor or improving upon its micro-stepping, with as final option to do a complete redesign of the module. Each is hard to justify having actual improvements as the current specifications are considered to be higher end with <1% backlash.

Module 60 has the highest chance of yielding large improvements but is considered a complete redesign of working principles as only changing parts have been tried during an earlier redesign and yielded too few improvements. The complete redesign does mean that the improvement to module 60 is the hardest to implement. A harder-to-implement redesign also implies that there will be more downtime of the machine during implementation. Module 90 has little room for improvement without a complete redesign, due to the already good tolerance of the bracket cartridges is it expected that a redesign will have little improvement upon the current design.
To be able to quantify each of the additional factors used for the decision-making process, and to be able to repeatably apply the quantifications it is again necessary to

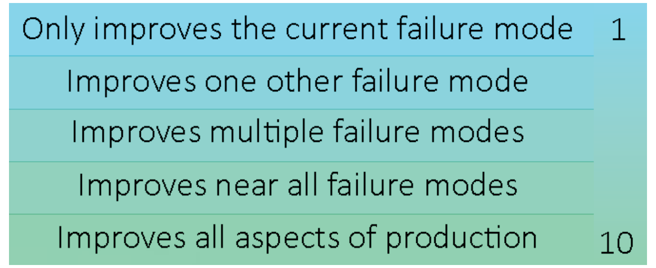


Figure 70: Additional improvements factor determination

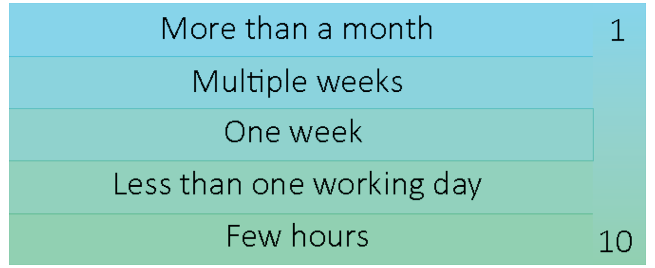


Figure 71: Ease of implementation factor determination

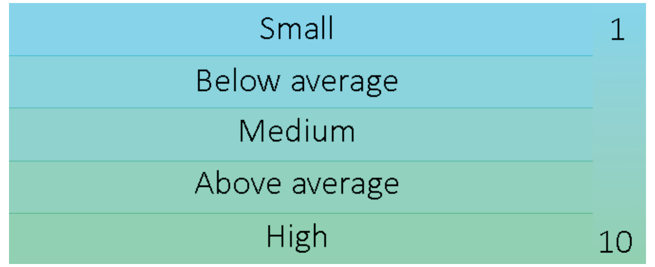


Figure 72: Probability of improvement factor determination

base the factors on a standardised approach. As there is less possibility to use a flow chart for the quantification of the factors scales, represented in Figures 70-72, are used. As an example, the complete redesign will improve multiple other factors as the placement of the bracket is critical in many failure modes and will gain an additional improvement factor of 5. A complete redesign can be tested outside of the machine and will with that lower the implementation time, however, a complete redesign also bring implementation risks and overall time investment to the redesign. gaining factor 2 for implementation. The probability of improvements done is medium-high as it did have the second highest influence and the overall redesign allows for multiple improvements to be made to the production process. Thus will have an above-average probability of improvements being made gaining factor 7.

8.5. Decision making

Based on the extended partial FMEA, as seen in Table 17, which results from the values of the design implementation it can be seen that overhauling Module 60 and improving the components of Module 30/35 are considered the best practice improvements to be made to solve the failure modes C3 and C4. Changes to Module 90 are considered to have a too-low return on investment. A complete overview using all failure modes as well as all implementation factors allows for a comlete overview of the possible changes that could be made. However, making a complete overview asks from the company to find out all possible root causes and measure all influences, as this takes a lot of time, the two-step approach taken in the example of this chapter can be used. Where first, the most influential failure mode is chosen and only this failure mode is extended upon.

Table 17: Implementaion factors of the possible changes to the poduction machine

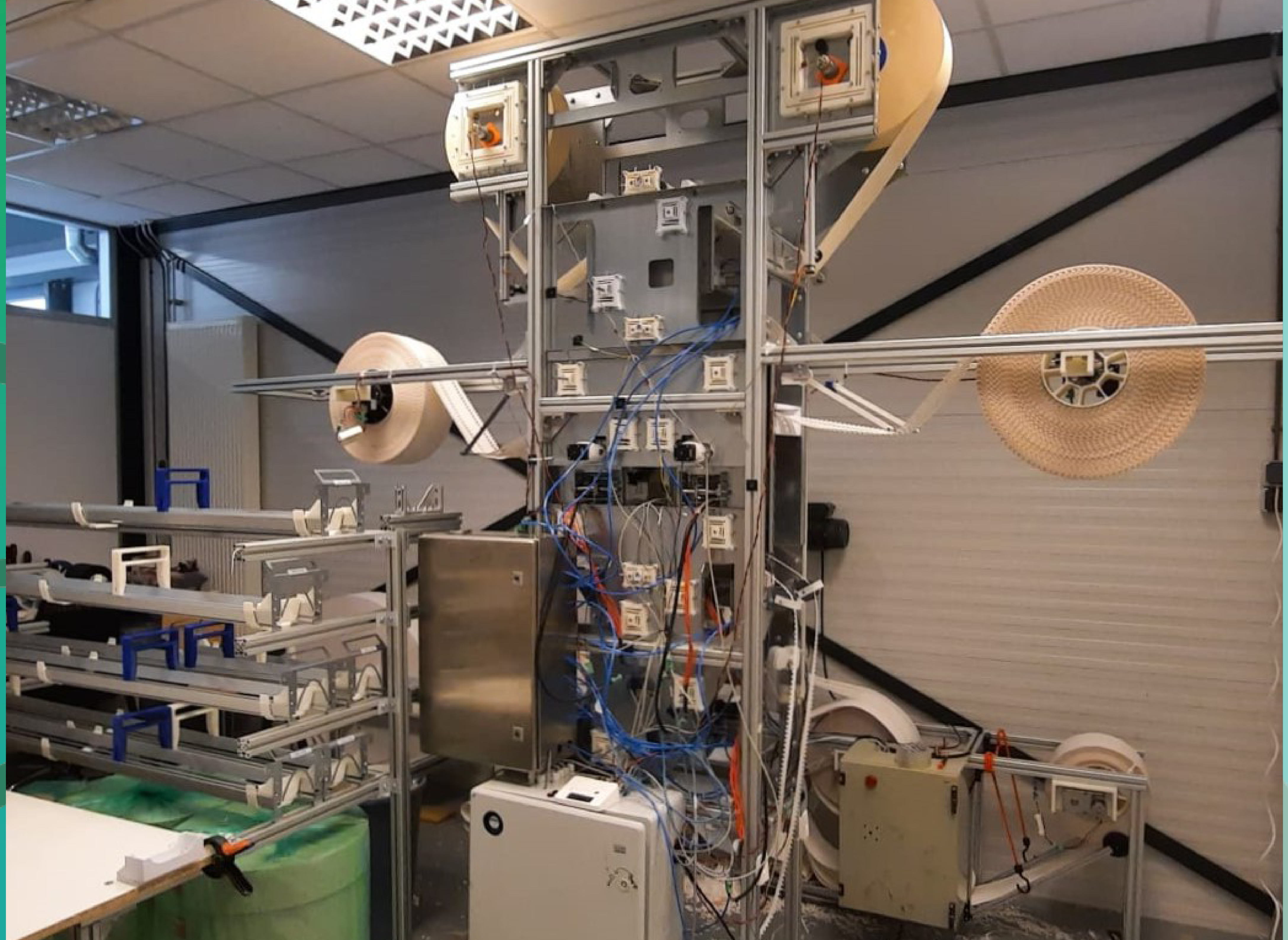
Module	Risk priority	Design Solution	Additional improvements	Ease of implementation	Probability	Implementation Factor
30/35	384	Redesign	4	1	7	10752
30/35	384	Change parts	4	2	5	15360
30/35	384	Change gear ratio	4	5	1	7680
60	384	Redesign	10	1	10	38400
60	384	Improved parts	7	2	3	16128
90	384	Redesign	2	4	3	9216

8.5.1. Further decision-making iterations

This process is reiterated throughout the cycles of continuous improvement. And other failure modes which had a high-risk priority will be considered for further iterations. For the following iterations of the decision-making processes of this thesis, the addtional failure modes were C1 and C6-20. For C1 the root cause was considered to be Module 60 as this introduces the only tolerance to the cutting of the filter hole, Module 20 can only be changed rigidly through the use of the flexures. Module 60 was already going to be redesigned, and this redesign will have to improve upon C1 as well. For C6-20 the root cause was considered to be Module 20 as it solely influences the failure mode of the waste handling of the filter hole. For this, the whole waste handling will have to be redesigned.

8.6. Conclusion

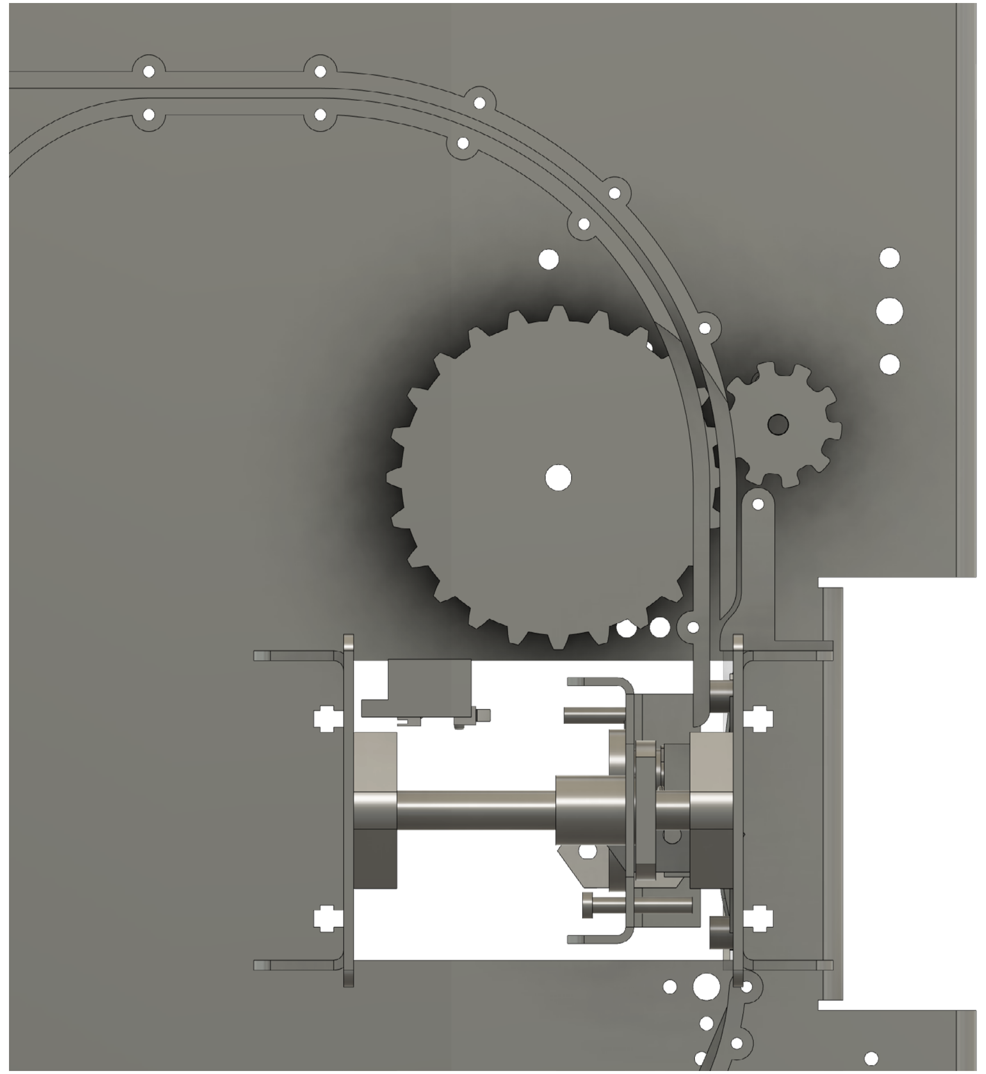
The decision is made to initially have a complete redesign of Module 60. Through further iterations, the decision is made to improve module 20 as failure mode C6-20 continued to be present. Also, part changes will have to be made to modules 30/35 to further lower the failure modes related to bracket placement after the implementation of the redesign of module 60. The redesign of Module 60 will be executed outside of the scope of the thesis. The redesign of Modules 20 and 30/35 will be covered in Chapters 8 through 11, these are chosen to show the difference between partial and complete redesign of modules. All other changes made during the time of the thesis will be discussed briefly in Chapter 12.



PART 2 - HOW?

9. Redesign of Modules 30 and 35

This chapter will initially answer the question: "How to design improvements for a continuous working machine?" During this redesign, it is important to also consider other changes that could improve the overall use of the machine as well instead of only the main focus of the redesign. This will prevent the need for multiple versions of the same module to be designed, which increases the overall cost and downtime for implementation. To ensure that the redesign is compatible and improving over the original design the sub-question: "How can a proof of concept be achieved outside of the production machine?" needs to be answered.



While a redesign will mainly focus on the improvement of the different root causes of failure modes that have been found, each of the redesigns will also have to take on other problems as well. This is because the production will be put on hold during the implementation of the redesign. To make sure that the total amount of downtime of the machine is kept low these redesigns of other problems have to be considered during the redesign as well. Also, when parts of the redesigned part have encountered fatigue problems, need replacement, or maintenance has to be done this is also taken into account during the implementation of the redesign. To be able to determine the additional problems within the module, further analysis of the module will have to be done which goes into more detail than the initial functional description.

9.1. Analysis

As mentioned in Chapter 4.1.4., modules 30/35 are used to add the brackets to the filter paper. The brackets are added to the module utilizing the cartridges. These cartridges are guided into the module through the plastic guides that align the cartridge to the middle of the filter paper. The cartridges are pulled through the guide with the use of a geared wheel that aligns with the teeth on the cartridge (Figure 73). The gears are placed on an axle which is connected to a NEMA23 stepper motor which has 400 steps per revolution or 0.9 degrees or rotation per step, added to the stepper motor is a gear reduction box to improve the precision of alignment. This gear reduction box is chosen based on its low, less than 1%, backlash. The teeth of the gears are used both for the pulling of the brackets as well as the alignment of the bracket. At the end of the guide, the brackets are measured by an optical end stop which gives information on the alignment of the brackets. As the current placement of the end stop is within a rigid bracket the adjustments are done by the use of code. For this, the parameter furtherSteps is used. The guide used for the cartridge also guides the filter paper to the sealing station.

Figure 73: Detailed inner view of module 30/35

When the bracket and cartridge are aligned with the filter paper the heat seal assembly is used to seal the bracket to the filter paper while simultaneously cutting the bracket from the cartridge. For the heat sealing of the bracket, an aluminium block that is milled in the shape of the heat-sealable area is used. In this aluminium block, four 24V 40W heater cartridges are used to heat the block to the heat sealing temperature of 160 degrees Celsius. To be able to control the heat, a K-type thermocouple is used to measure the temperature of the heat seal block. To prevent excessive heat in the system due to the failure of software or hardware the heater cartridges are also connected to a clixon thermostat that breaks the circuit when the block exceeds 200 degrees Celsius. Failures in the hardware that have been noted over the lifetime of the machine are the sticky behaviour of a relay which allows the heaters to continuously heat the block as well as the faulty measurements of a thermocouple which had an offset of more than 40 degrees Celsius.

During the heat-sealing operation, the whole assembly as seen in Figure 74, is pressed further than the heat-seal block. This is possible as the heat seal block is placed on guided springs and can be pressed down a further 5mm. This extra travel is used to simultaneously cut the bracket from the filter paper during sealing. The springs also create extra pressure on the heat-sealing allowing for a stronger bond between filter paper and bracket. The cutting is done by two triangle-shaped knives that cut the bracket which lays on a raised part with a counter shape for the knives.

The entire heat seal assembly is moved by two NEMA40 stepper motors that use lead screws to move the assembly. The movement is based on the number of steps from the home position. Which is determined by a mechanical end stop.

After the complete module is finished the filter paper with the added brackets is pulled further. The waste of the cartridges is guided out of the module with the use of 'slides' that push the cartridge waste into the waste bins located next to the machine.

9.1.1. Problem definition

The current problem with the module is that there is still unreliability in the placement of the brackets related to the filter paper. In this module, this is the result of the tolerances of the geared wheel which moves the cartridge, the backlash and accuracy of the stepper motor and its driver, as well as the accuracy of the optical endstop. The goal is to overcome a part of these compounding tolerances by making the placement of the bracket smoother and more reliable.

9.1.2. Additional problems

To improve further upon the module additional changes will be considered as well. For this, these additional current problems will have to be defined. One of these problems arises from the use of two stepper motors. When either of the motors has a small error in their driver or during operation, the heat seal assembly can be pushed sideways which creates high stresses and seizes the complete module. Also, the motors create a high amount of noise, need lubrication to be able to work properly, as well as having a high power consumption. These should be exchanged for a single part which solves these problems.

Secondly, the clixon on one of the modules has encountered a failure and will have to be replaced. For this further investigation on the reliability of the clixon has to be done as well as it is a safety measure that has failed. The clixon might not be reusable while the datasheet did say the part was reusable.

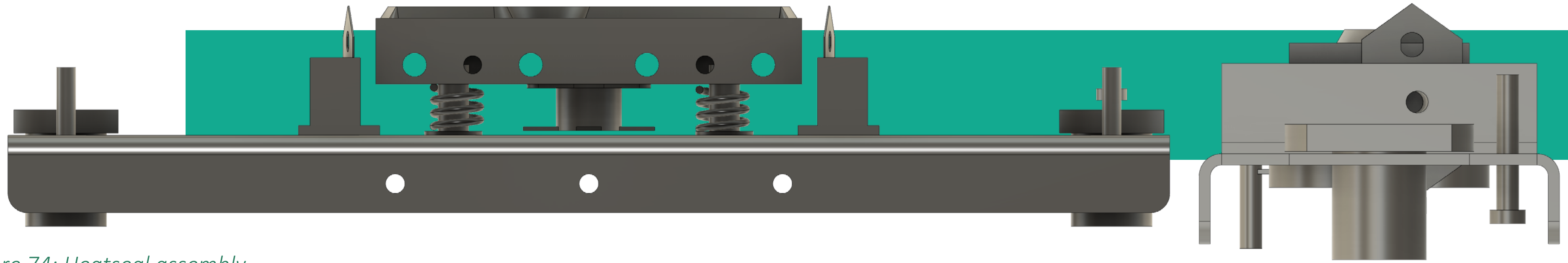


Figure 74: Heatseal assembly

As a third problem, it is noticed over continuous use that the current thermocouples can encounter drift in their measurements. In one case that was observed this was more than 40 degrees difference. This temperature difference can result in burnt paper or incompletely sealed tea infusers.

As a final remark, the cables run between moving parts and can get stuck or cut by the sharp edges of the sheet metal. Each can cause different problems such as the failing of the cables or not cutting the bracket as the knife cannot move down enough.

9.1.3. Requirements

Main problem: Bracket for the optical endstop

- Able to adjust the full length of a bracket on the cartridge. (12.5 mm)
- Should be rigid when adjusted. (Less than 0.1 mm)
- Should have little to no drift over time. (Less than 0.1 mm)
- Can be placed in the current module without the need to change other parts.
- Easy to adjust when placed in the machine. (Less than 1min)

Additional problem 1: Change the stepper motors.

- Heat-seal assembly should deliver enough pressure so that none of the tea infusers breaks during normal use. (Less than 1 failure per 10.000)
- The heat-seal assembly should not be able to get stuck during normal operations.
- The complete module should have a faster cycle time. (Less than 12 seconds)
- The change should have no additional wear on the knives. (Able to run 10.000 cycles)
- The new system should have little to no maintenance.

Additional problem 2: Replace the clixon.

- Clixon should break at 200 degrees Celsius
- Clixon has to turn back on when under 200 degrees Celsius. (160-190 degrees Celsius)

Additional problem 3: Improve temperature measurements.

- There should be no drift in temperature. (Less than 5 degrees Celsius per year)
- Have more consistent temperature measurements between modules. (Less than five degree Celsius of drift)

Additional problem 4: Ensure that cabling does not interfere with normal use.

- Cabling cannot come in contact with the sharp edges of the module.
- The heat seal assembly should not lose movement due to the cabling.

9.2. Ideation and testing

Each of the individual problems will have to be solved by redesigning that specific part, the final concept will combine all of the different solutions into one update to be done to the machine. The ideation is done using multiple iterations where each of the iterations will be tested outside of the machine. These tests will have to show that the changes will indeed have the desired effect. Only after this can be stated with some confidence the changes should be implemented in the operational machine. During this implementation, testing, and adjusting of the changes the machine will have downtime. Testing everything that can be tested outside of the machine will expedite this process. This testing will also indicate the chance of success when the part is implemented in the machine. While this iterative process is done for each of the parts the complete design process will only the main problem of the improvement of accuracy for the placement of the brackets will be explained here in detail. This explanation will help the reader understand the steps taken in the design process. The different iterations of the other parts can be found in the appendix.

9.2.1. Improving the accuracy of the alignment of the bracket

To improve upon the accuracy of the alignment of the brackets to the filter paper it was devised that change the adjustability of the optical endstop from furtherSteps to a mechanical adjustment system so that the motor can immediately stop when the bracket is located correctly. The idea is that the change to this mechanical adjustment will take out some unreliability of the stepper motor and lower the influence of backlash to the alignment.

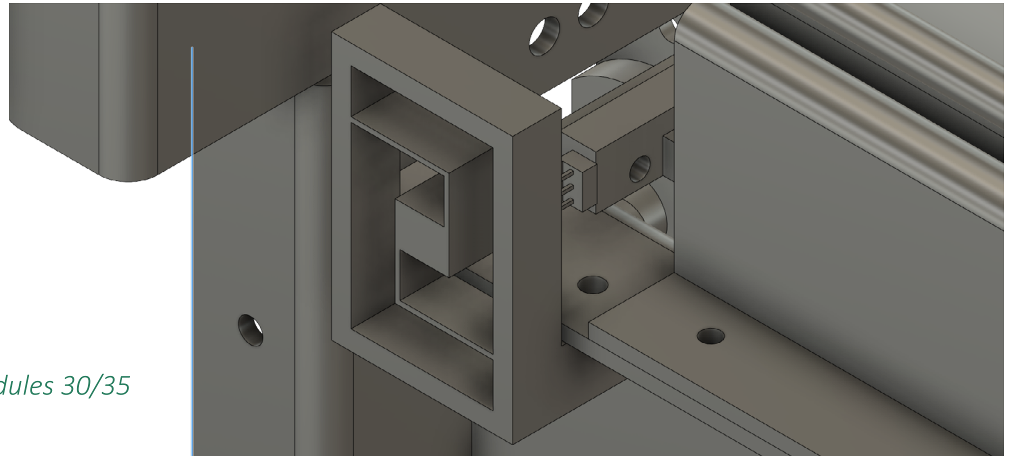


Figure 75: Redesigned flexure for modules 30/35

As an initial design, a simple flexure design was devised that holds the optical endstop. As the endstop only needs vertical movement the flexure can be made more basic as seen in Figure 75. This initial idea was roughly made in the CAD program and printed to be the model as seen in Figure 76. This initial design had the problem that it was unable to reach the desired vertical movement of 12.5 mm, it also was small and therefore not strong enough to withstand accidental high forces. Also, it can be seen that the holder can be under an angle, due to the length of the arm this displacement will quickly be above 0.1 mm. Therefore, the choice is made to use two set screws to make it impossible for the arm to be under an angle.

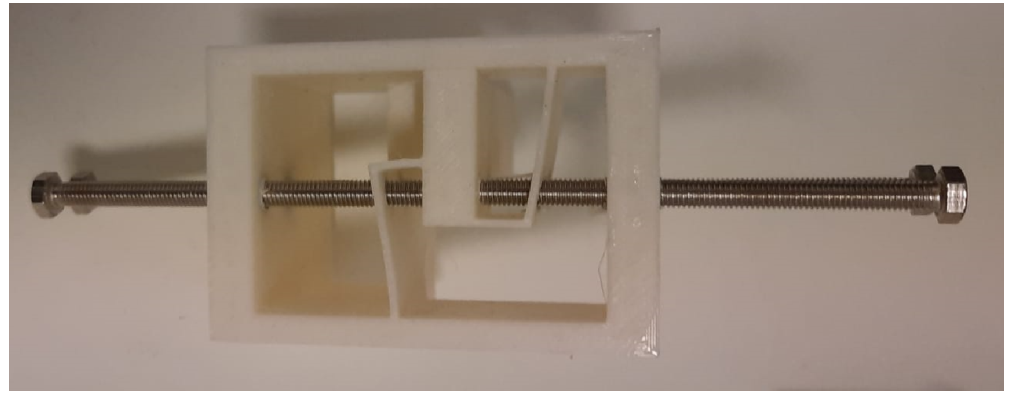


Figure 76: Failure of initial flexure for modules 30/35

To overcome the initial problems seen in the first design the overall design was scaled up allowing for more movement of the endstop. This is possible as the complete holder will be placed in the large unused area at the back of the module. Adjusting the holder to the outer limits makes that the holder will break at the sharp corners of the flexure. This shows there is a need for a redesign of the sharp corners of the flexure. Therefore, it was chosen to make this shape continuous, as seen in Figure 77. This would allow the holder to access the outer limits of its adjustability. During the testing of the outer limits it was also seen that the holder comes to be under an angle, while this is solved on one side where it leans against the side of the holder, the other side cannot have this due to the placement of the cabling of the endstop. As a solution, another adjusters-crew is used to keep the holder at the correct angle.

To check what most likely was the situation a look was taken at the code. This set the cartridges at a furtherSteps = 80. This meant that the endstop most likely had to be placed more to the bottom. Looking at the design it was noticed that placing the holder on the other side of the module allowed for more downward movement. This is because the endstop has a top and bottom which differ in thickness. With this final change, the design is finished. It is then printed and test fitted in the machine, when everything seems correct the part is placed to the side to be implemented with all the other improvements at once.

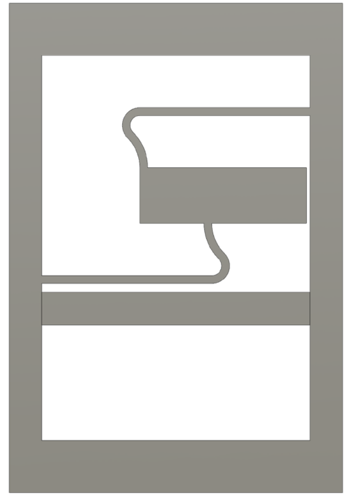


Figure 77: Final design flexure

9.2.2. Pneumatic movement instead of stepper motors

For the improvement of the movement of the complete heat seal assembly, the idea is to use pneumatics instead of the two stepper motors. Air has the advantage that only a single cylinder will have to be used. It also has the advantage that it is quicker and consumes less power. And as pneumatics have been used in updates in other parts of the overall machine as well it lowers the number of spare parts that have to be stored for maintenance as well.

The pneumatic cylinder that was chosen for the application in modules 30/35 is the FESTO 25mm. This choice is made as this module only requires a small movement. To be able to place the pneumatic cylinder and connect it to the heat seal assembly a bracket is needed for both. This bracket is designed to have optimal strength while being able to reach all of the necessary parts in the module. The choice is also made to add a clamp to the bracket which can neatly hold the cables.

9.2.3. Replacement of the clixon

Due to an encountered failure of the clixon, which did not reset after the temperature had exceeded its 200 degrees Celsius threshold the clixon was taken out of the assembly which reintroduces a failure mode. Therefore, higher-quality clixons have been chosen to replace the current clixons in the heat seal assemblies. For the placement of this clixon, no additional changes will have to be made to the design.

9.2.4. Improved temperature sensing

As the heat seal block has to be at the right temperature correct temperature sensing is important, the current thermocouples used in the system have shown problems in sending out the incorrect temperatures resulting in too high temperatures burning the paper. The current thermocouple is a type-K thermocouple connected to a MAX6675 decoder and has a range of 0 - 600°C. While the choice does correctly fit the application the product is of too low quality to be able to be used for industrial purposes. To overcome this lack in quality a new look has been taken at different thermocouples and thermistors of higher quality.

In the end, the choice was made for an NTC thermistor as this was available at a high enough quality for its price and could be easily adapted to fit the overall electronics. The thermistor is chosen to be able to operate in temperatures of up to 250°C. To be able to replace the thermocouple with the thermistor, the heat seal block will have to be given additional holes that fit the thermistor cartridge. Secondly, the code will have to be changed to allow for the calculations that have to be done to determine the temperature.

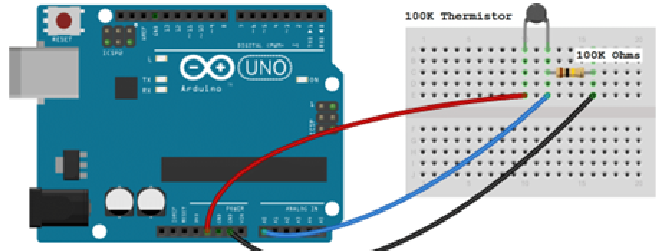


Figure 78: Basic overview of updated electronics

9.2.5. Changes to the software

Due to the changes in electronic components, there also is a need to update the software. The goal of this update is to also lower the complexity of the complete software in such a way that multiple modules can be run on a single microcontroller again. This should be easy to achieve as pneumatics specifically are quite easy to implement by not needing to know where they are in space. As they move from one physical endstop to the other. The thermistor also introduced less complex software as it does not need a library to function. It solely needs some simple mathematics. Both of the updated lines of code for the modules can be seen in Appendix K.

9.3. Combining the different designs to form the redesign concept

With all the separate solutions designed and initial tests completed, the concept of the redesign can be formulated. This concept will include the combination of the design changes made in the previous chapter. The changed module can be seen in Figure 79. This design has all the parts that have to be changed and taken out, this can be found in the bill of materials (BOM) as seen in Appendix J.

9.4. Conclusion

The different solutions for the problems currently faced within modules 30 and 35 have been tested and show promising improvements for the overall system. However, to be able to seamlessly implement the different solutions in the overall system it is important to create a correct implementation strategy to prevent unnecessary downtime of the overall machine.

Figure 79: Redesigned parts for module 30/35

10. Implementation of changes to Modules 30 and 35

Now that the designs have been prototyped and tested the final versions of the parts can be produced. Each of the designs is made from printed PLA, this allows for quick implementation and has high enough strength and rigidity for the application they are used for. These parts must consider the lifetime of the system and therefore must be printed at a higher infill percentage to increase the strength and durability of the part. Furthermore, the additional parts from the BOM are ordered. The implementation will only start when all of the necessary parts are in stock to ensure that the implementation can be done at once, which will lower the total amount of downtime of the machine.

10.1. Implementation of the updates to modules 30/35

For the implementation of the changes into the machine, the machine will encounter some downtime, to lower the necessary downtime for the implementation a structured approach to disassembling and reassembling has to be taken. For these, references will be made to the parts that can be found in the BOM in Appendix. The parts needed for the implementation of the machine can be seen in Figure 80, the parts are assembled as far as possible outside of the machine.

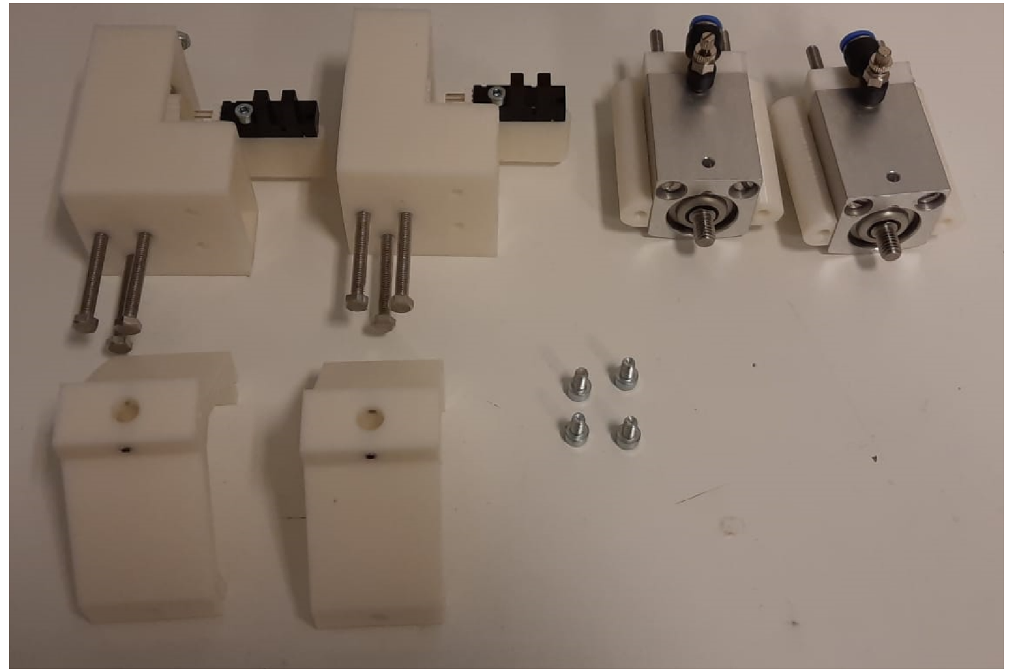


Figure 80: Parts that have to be changed in the module

When the machine is turned off the old parts have to be taken out of the module. This can be done with the module still in the frame due to the accessibility of the parts that have to be changed, by not taking out the module from the machine, the re-alignment of the module will not be necessary. Therefore, the choice is made to apply the changes within the machine. The heat seal assembly will be taken out completely and the cable management will be undone to have better access to the assembly.
While the complete implementation was modelled in the CAD program, and was checked for fitting, problems were still encountered during the implementation of the machine. The main problem that was encountered was that there was little room for the adjustable end stop mounts due to guides for the cartridge which were added to the machine during its development but were not added correctly to the CAD model. These, therefore, had to be taken out of the machine and were adjusted to be able to fit both the guides and the adjustable mounts to the module. This problem was encountered both in module 30 as well as module 35.

The final implementation of the parts can be seen in Figure 81 on the next pages. The first image shows the placement of the updated mount for the end stop. In the second image, the change to pneumatics can be seen where a pneumatic cylinder is added which is held in place with the newly designed mount. And finally, in the third image, the connector piece for the heat seal assembly can be seen. The implementation of the new thermistor, clixon, and coding do not have distinct visual changes and therefore are not shown in these figures.

10.2. Testing and adjusting the updates to modules 30/35

Now that the updates have been implemented in the machine, they should be tested to work as expected. While the expectation is that the testing that has been done during the conceptual design stage is representative of the application in the machine other factors can have an influence as well. This can be seen in the encountered problems that were had during the testing which are as follows:

- The thermistors showed an incorrect temperature.
- The coding changes for the stepper motor were incorrect.
- The heat seal of the bracket to the filter paper was not strong enough.

The first test was to test the thermistors and to control if they are connected to the correct heat seal blocks. This first test showed that each of the thermistors was coupled correctly but did show a lower ambient temperature, to check this the machine was turned on completely to start the heat-up procedure of the machine. Here the temperature stagnated at a temperature of roughly 80 degrees Celsius which does not align with previous tests. By use of an external thermometer, it could be measured that the given temperature from the thermistor was too low. To find the root cause of this problem the electronics were checked as well as the thermistors. Both showed correct measurements, thus further investigation was needed. The test set-up and actual set-up were compared, here it was noted that in the machine the Vin-pin was used instead of 5V-pin. To check if this was the problem the voltage of Vin ad 5V were measured. The Vin pin had a voltage of 4,45v while the 5v pin had 5,02v. Because 5v is the calibrated voltage of the thermistor this could be the root cause of the problem. The pins were exchanged, and the machine was operating normally after that.

After the heating was corrected, modules 30 and 35 were tested. In the first running test, it was noticed that the stepper motors were not operating correctly. This was due to a change in its code, where it does not use the method of furtherSteps anymore. This now meant that the motors were not running, through redesign of the code this problem was alleviated. This new code made use of a different manner of furtherSteps which allows for the endstop to ensure it does not check for location on the edge of the cartridge. This could create failure modes where the motor does not turn at all. This final version of the code can be seen in Appendix I.
Because the endstop mount was changed and the adjustability was taken out of the code, the module will have to be set up again for these changes. This meant that the mount would have to be used to adjust the placement of the bracket on the filter paper. By iterative changes, the machine was able to be set up correctly again for both modules.

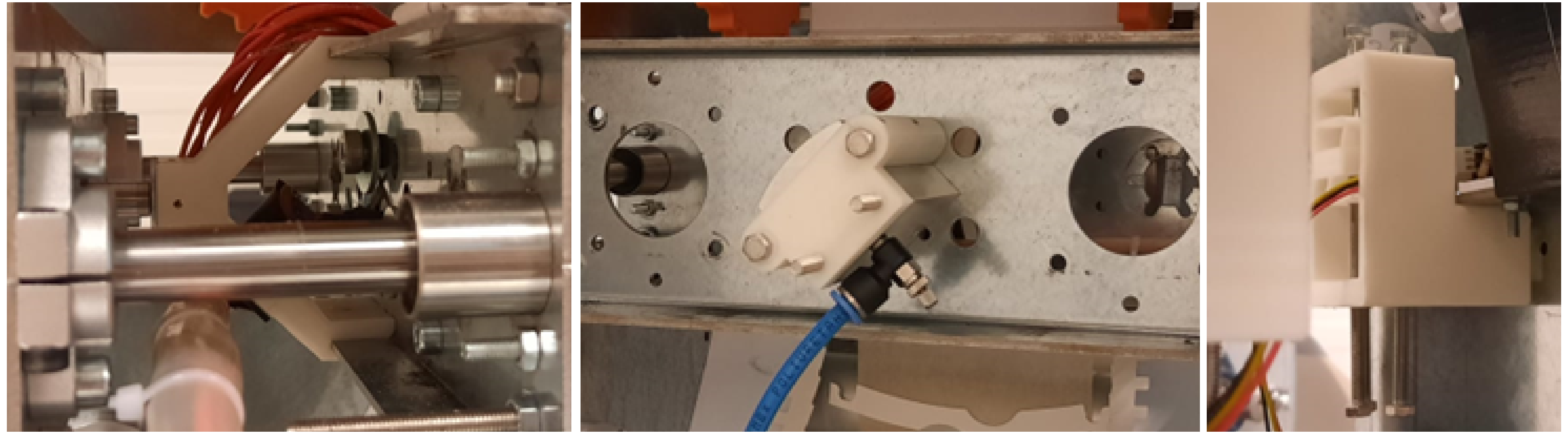


Figure 81: Redesigned parts for module 30/35 implemented

With the module now working as expected, the tea infusers have been tested. During the test of the tea infusers, it was noticed that the sealing was below standard. The brackets were able to be easily removed from the filter paper. This can result in the tea infuser disintegrating in the cup and spilling out the loose tea leaves. This could be the case due to the change from the stepper motors to the air cylinder. To counteract this lower-quality sealing the pressure of the cylinders was increased, but this still did not have the desired outcome. Therefore, the sealing time was also elongated from 5 seconds to 7 seconds. This created a representable seal and in-specification tea infusers. This also meant that the machine was considered to be correctly adjusted.
Overall, the machine had a downtime of ten hours which is at this stage in time roughly 3000 tea infusers and a cost of 200euros, which is similar to 100 boxes or 10000 tea infusers. This means that over time this module should at least have an increased yield of 13000 tea infusers. This means that a break-even point will be after 214 hours of running. With the expectation of 10 running hours a day for 5 days a week this means break-even will be after little over four weeks. After which an increased yield of 20% can be expected.

10.2.1. Monitor changes

After this, the machine has been running for a full day. While the machine now operates as normal again the changes will still have to be monitored continuously. This monitoring includes the quality of the tea infusers, power consumption, and possible new problems originating from the change to different parts. This can for example be that the pressure of the heat seal is applied inconsistently due to the use of one pressure cylinder instead of two stepper motors. While these types of failure modes are explicitly expected monitoring them is still important.

10.3. Conclusion

During the redesign, many of the possible tests had been done to improve the probability of a seamless implementation of the updates to the module. Although these tests are a good indicator of the success of the updates, new problems due to the complex interactions within the module will arise. This is even more so present within the complex environment of the complete machine. This shows that testing part individually still is not completely indicative of its function within the machine. Therefore, the choice could also be made to test the parts in a complete module outside of the machine. This does, however, greatly increase the costs of testing as a complete module has to be built to be able to do this testing. With the additional downtime that was experienced with testing the module inside the machine, the added costs of a complete redesign can lower the additional cost of the downtime. The problems encountered with the code on the other hand could be easily tested as the complete set of electronics was present. This would have alleviated the additional downtime that was encountered there and should therefore be considered an important part of testing during further redesigns.

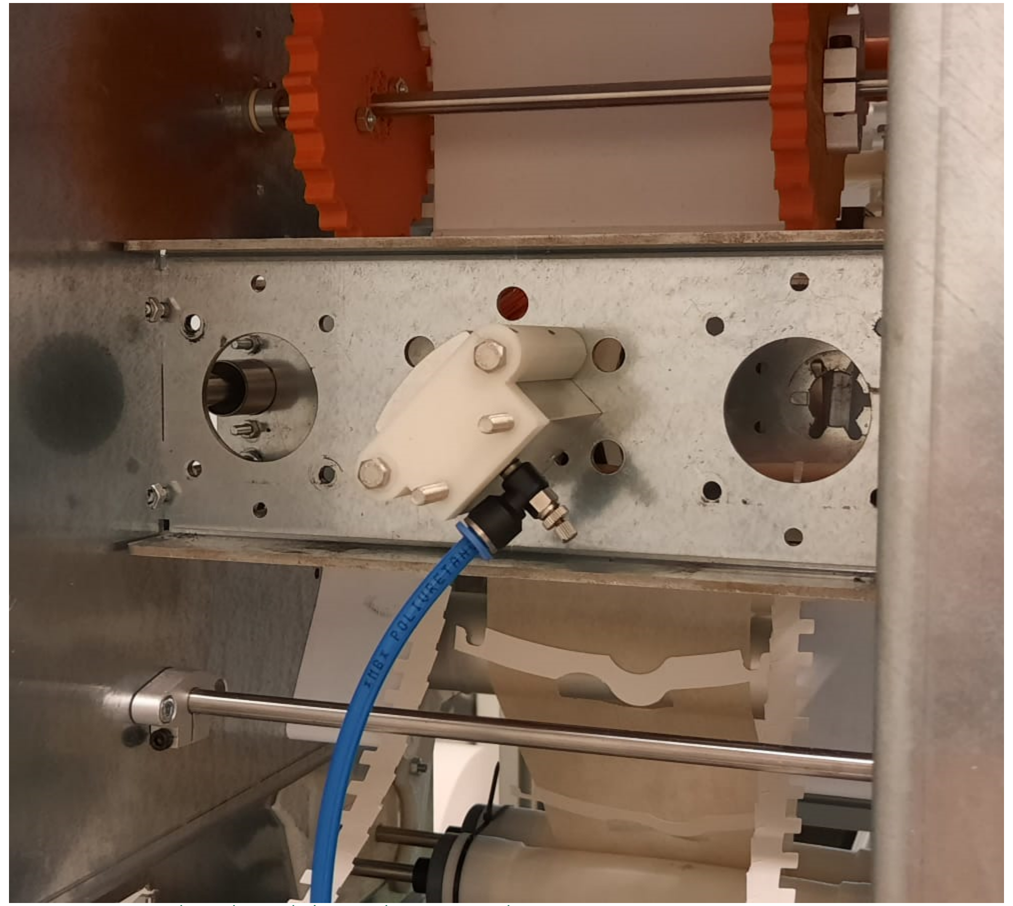


Figure 82: Updated module 20 during production

11. Redesign of module 20

Since many of the tea infusers still experience problem C6:20 (There is a piece of waste in the tea infuser.) the choice was made to redesign the module. This redesign has to improve the waste handling of module 20 to prevent the loose pieces of filter paper to enter the tea infuser. For the improvement of module 20, a closer look will be taken at its current design, but also the previous design used for this module to see what changes already have been made.

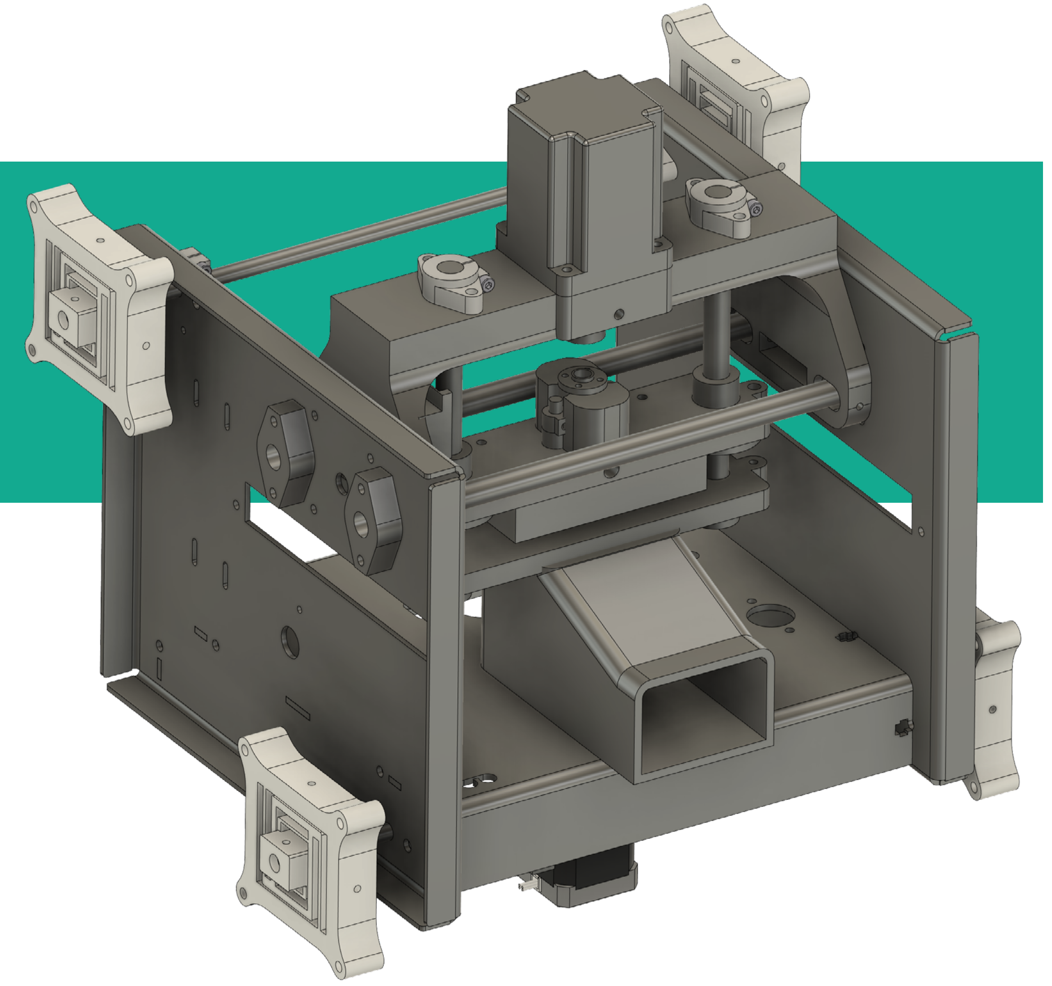


Figure 83: Module 20 as of the start of the thesis

11.1. Analysis

Module 20 is used to cut the filter hole in the filter paper. This hole is needed to open the tea infusers properly. To do this a foil knife is used, this knife starts cutting the filter paper at multiple points at once and has a sharp pointed blade to cut through the filter paper. To make sure that the filter paper does not fold or buckle during the cutting operation it is held in place by two opposing silicone parts, as seen in Figure 83. Similar to modules 30/35, the inner part of the silicone holder is placed on guided springs this allows a single movement to hold, cut, and push the waste out of the filter paper. This movement is executed by a stepper motor with a threaded axle and nut. On the other side, an inner and outer layer of silicone is used. The inner piece is pushed forward and pulled backwards by a stepper motor. This movement is necessary for the spring to extend and make sure the waste becomes loose. This waste is then blown out of the pusher with a burst of air whilst simultaneously being sucked in by a vacuum.

11.1.1. Previous design

The previous design was intended to work similarly to module 50, where a roller would move over a flat knife that would cut the filter paper. However, creating a clean cut with this method was deemed inconsistent. While this was not a problem for module 50 as the waste material had to be taken out with manual labour, the waste of module 20 had to be taken out with the machine. In this design, this was done with a burst of air. Multiple iterations of nozzles and pressures were used, none of which consistently would remove the waste material. This was the reason to apply a foil knife that is supported on both sides with silicone holders for the filter paper, as well as using suction in combination with the air burst to remove the waste material more consistently.

From this previous design the frame, as seen in Figure 84, was re-used. However, it does not have the optimally designed shape for the functionality of module 20. This frame should be re-designed when completely re-designing the module to allow for optimal design freedom. A new frame also allows for the complete redesign to be tested outside of the machine without the need for stripping the current design for parts.

11.1.2. Problem definition

In this module multiple problems still are present, the most pressing is C6:20. This failure mode refers to the presence of a piece of waste of this module in the tea infuser. This can be the case as sometimes the waste does not get loose from the pusher, or the air burst blows it back through the cutting hole.

11.1.3. Additional problems

However, this is not the only problem. The hole that is currently made has jagged edges. These are the result of the knife manufacturer's error in the knife, where the smooth side is placed inwards. Therefore, the knife has to be replaced.

Another improvement that will have to be made during this complete redesign is the change from stepper motors to pneumatic cylinders. This change is similar to modules 30/35 where this improves speed and consistency as well as reduces complexity and power consumption. The waste is currently collected by a vacuum which has a high power consumption and noise level and should therefore be replaced with a system that is easy to change whilst not using power or noise.

11.1.4. Requirements

With the main and additional problems defined, requirements can be set for the partial redesigns.

Main problem: Filter paper waste can get back into the overall machine.
- Should make sure no waste can back into the machine. (one-way operation)
- Should not use high power consumption.

Additional problem 1: Change the knife.
- Filter holes should not have jagged edges.
- Should still cut the filter paper without problems.
- The strength of the web should not be lowered.

Additional problem 2: Change the stepper motors.
- The assembly should not be able to get stuck during normal operations.
- The complete module should have a faster cycle time. (Less than 10 seconds)
- The change should have no additional wear on the knives. (Able to run 10.000 cycles)
- The new system should have little to no maintenance.

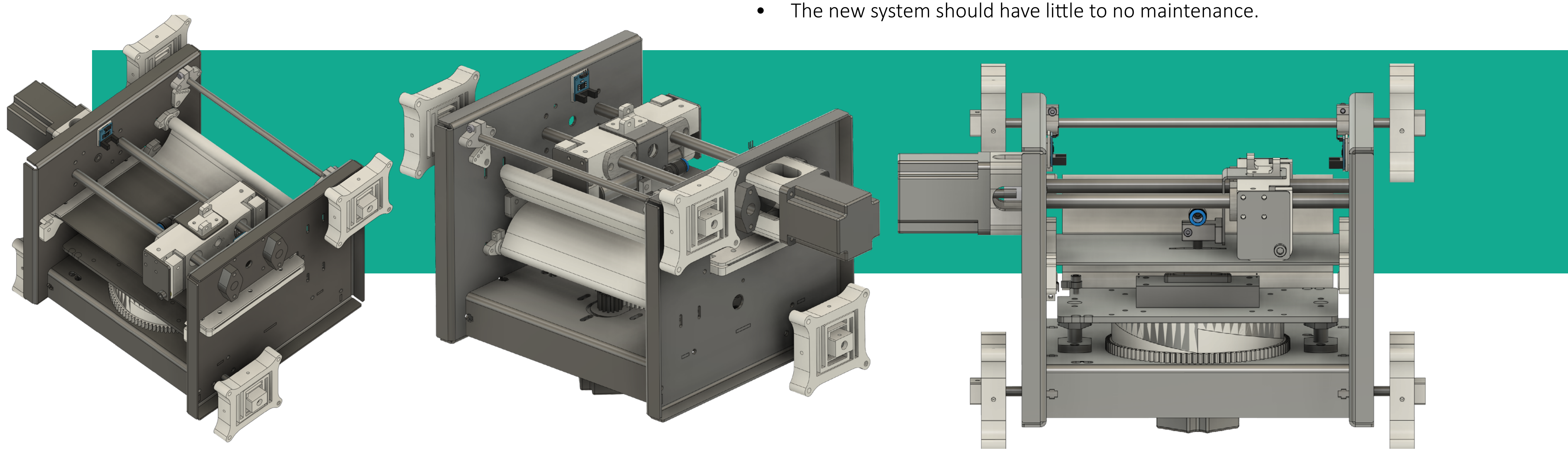


Figure 84: Initial design of module 20 (before thesis)

Additional problem 3: Improve waste handling.

- Waste should have to be able to be changed in under a minute.
- There should be little-to-no power consumption.
- There should be little-to-no noise.

11.2. Ideation and concept testing

Similar to the steps taken in Chapter 8, the subparts of all the problems will be individually ideated for and tested. This testing will give an initial level of confidence in the design choices that are made. Contrary to the design changes of modules 30/35, this module will be fully built outside of the machine. This allows for complete testing of the module before the module is added to the machine. This should lower the downtime significantly. However, when placed in the machine, adjustments to alignment will always have to be made.

11.2.1. Change the knife

The current knife in the system uses knives with the incorrect orientation which creates jagged edges, to solve this problem the knives have to be inverted. The knife this resulted in still has some unexpected changes made by the knife manufacturer. These are first of all the knife has more angled edges instead of the more pronounced fillets as well as having welding marks on the inside of the knife making the knife need a bigger opening to be able to glide through it. Secondly, this has to be taken into account when designing the other parts based on the expected knife design. To

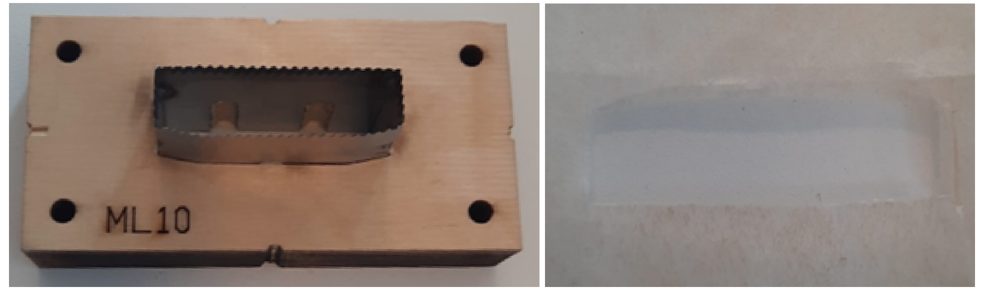


Figure 85: Knife design and manual cutting test

get a better understanding of the improvements of the new knife, it knife is tested by pressing the knife through the filter paper which is pulled tight with stiff foam as the counter shape. This initial test does not show great improvements which were also expected as the foam does not work as an ideal counter shape. Further testing of the knife will be done with the improved counter shape from Chapter 11.2.2.

11.2.2. Filter paper waste can get back into the overall machine

Currently, the waste of the filter is blown away from the pusher and then sucked in by a vacuum. This is a rather inefficient method and was only applied as a quick fix for the larger problem. To solve this problem the idea was to push the waste material through a chute with a type of one-way gate. Allowing for easy movement in the machine that does not need a lot of compressed air to be executed.

The counter shape was designed to have supports on both sides of the knife, this does mean that the chute through which the filter paper has to be pressed is smaller. Therefore, this idea had to be tested. For this, multiple iterations of the initial counter shape have been made. Each changing the offset of the knife. This will show which offset creates the best result for cutting the filter paper. During this test, multiple findings were made. First, if which was that the knife differs quite a lot from the drawing sent to the manufacturer as seen in Appendix B. This meant that the shapes with the lower offsets from the knife were unable to work as the counter shape for this knife. Secondly, the filter hole still is not of high enough quality, the edges are still jagged. And finally, the filter paper tends to pull away in one direction as it is not held in place at the inside of the knife. These are all problems that have to be overcome during a possible redesign.

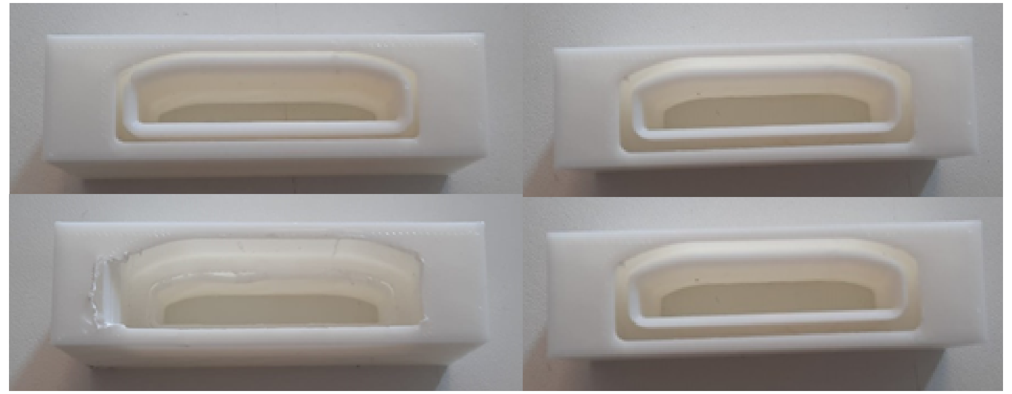


Figure 86: Countershape iterations

To ensure that the waste only moves in one direction in the chute, barbs were added in the counter shape that could catch the waste material. To make sure that these barbs work the waste must be pushed beyond the barbs, whilst the pusher itself should not catch on the barbs. This will be something to keep in mind when the pusher is designed.

The idea for the pusher has come in the form of using a plastic pusher with silicone flaps that catch the filter paper waste against the walls of the counter shape. This ideation can be seen in Figure 87. To ensure that the filter paper is pulled through the chute the silicone is oversized in relation to the chute. To make sure that the waste gets loose from the pusher the counter shape should have an empty area to let the flaps turn over. The comoplete design of the inside of the countershape can be seen in Figure 87.

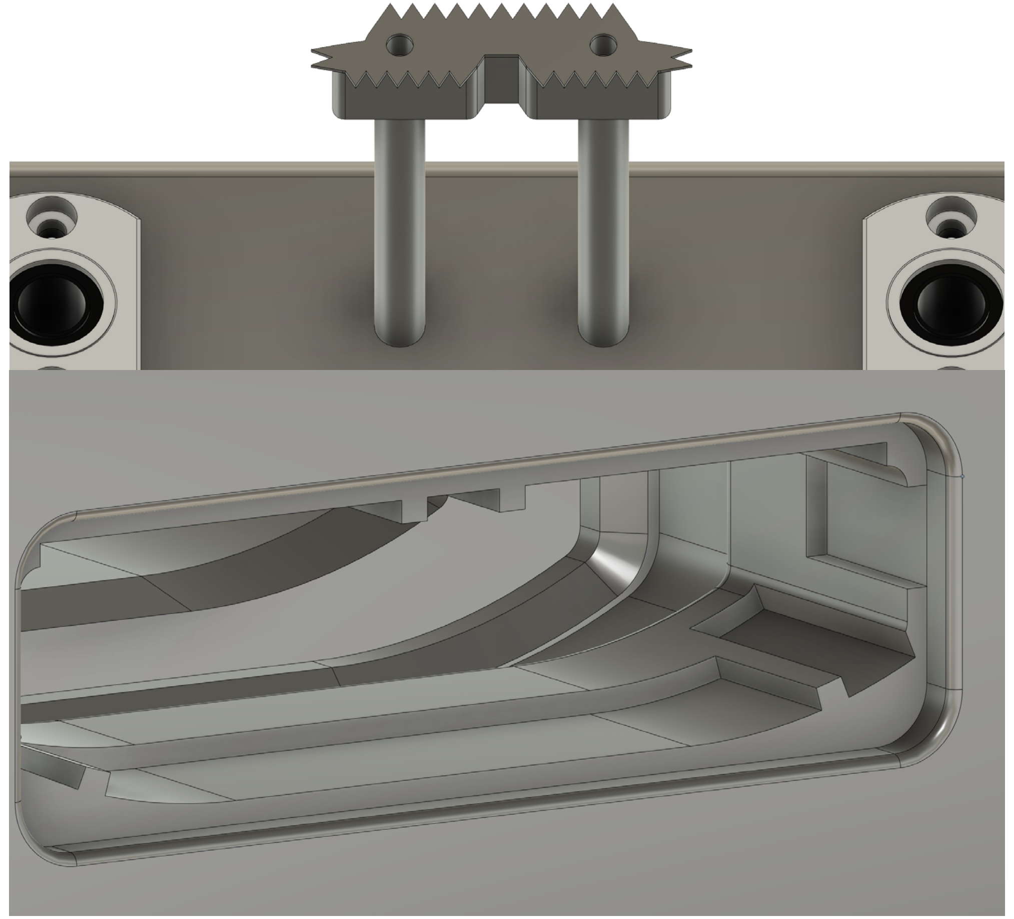


Figure 87: Combination of countershape and pusher designs

During testing with the counter shape and the knife, it was noticed that the knife 'grabbed' the filter paper after cutting, as seen in Figure 88. This behaviour would imply that there is less need for the complex pusher shape and additional metal pieces in the counter shape. To test the reliability of this behaviour the test was executed up to a hundred times to see if this is an consistent behaviour. From this testing, this behaviour was deemed consistent and the final design of the counter shape was simplified. The behaviour of the waste being pushed out of the centre shape still has to be controlled during the testing of the machine as there have been made changes to its behaviour.

Figure 88: Sticky behaviour of the knife

11.2.3. Change the stepper motors

Similar to modules 30/35 the choice here is made to change the overall design from steppers for linear movement to air cylinders. Contrary to modules 30/35, the choice here was made to use cylinders that use pressure for the backwards movement as well instead of springs to ensure this movement succeeds. This is needed as the knife and the pusher could get stuck on the counter shape more easily. This is less so the case for modules 30/35. The cylinders are also chosen to have a larger maximum movement as the knife has to cut deeper and the pusher will have to push through the complete knife as well. The functionality of the linear pneumatic cylinders is known and therefore there is no need for testing these individually and will only be tested in the complete module.

11.2.4. Improve waste handling

Due to the improved pushing of the waste through the knife, the waste handling is already improved greatly, this subchapter will mainly focus on the further handling of the waste. Because the changing of the container that collects waste has to be improved as well for ease of use. The idea used for this is to push the filter paper waste completely through the chute and the backside of the metal bracket as well. After the waste is pushed through the bracket it will be received by the waste tube as seen in Figure 89. This tube is made to allow for up to a week of continuous production before it has to be replaced. The replacement of the tube can be done by lifting it from the two bolts which do not have to be unscrewed as the waste tube leans on them.

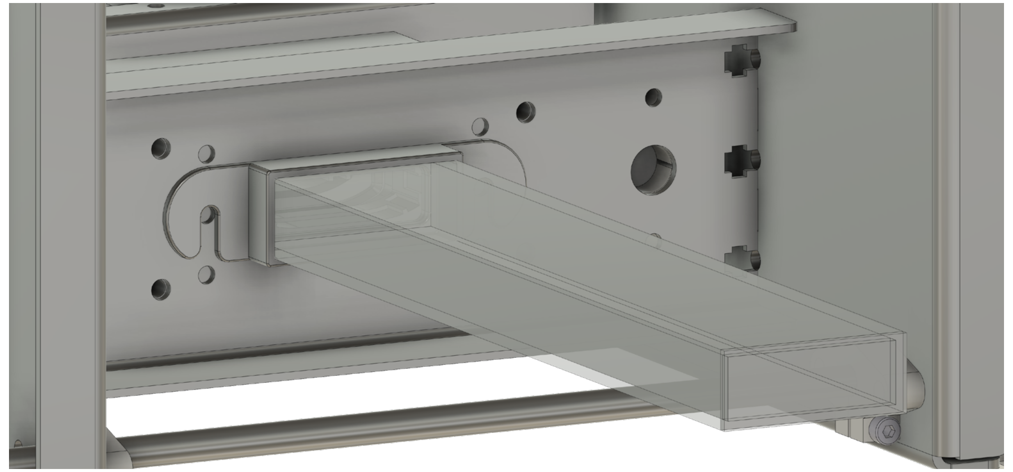


Figure 89: Design of the waste container

To make the tube as easy as possible to exchange the bolt that holds it should not have to be taken out while maintaining a strong connection to the module, the initial design has the problem that it makes it hard to get the complete chute out. This is changed in the final design to have a rectangular shape that is more flat to allow easier access to change the container. As a second benefit the waste has less freedom to move around in the container which might prevent blockage in the container. The chute is made from a standardised aluminium profile.

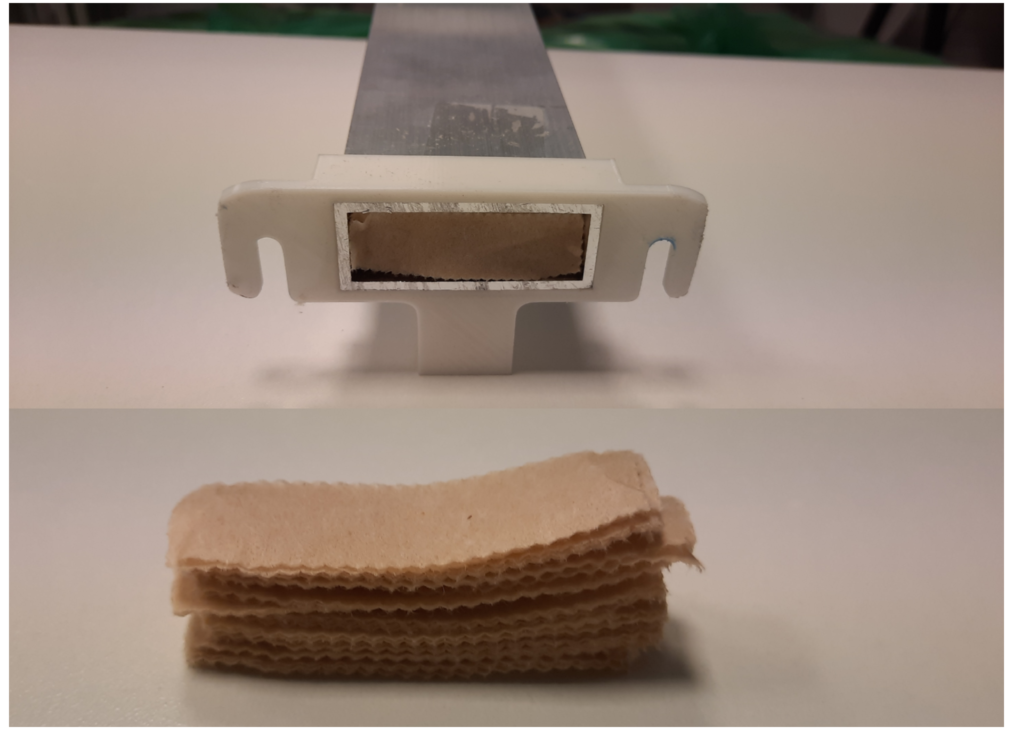


Figure 90: waste container

11.2.5. Changes to the code

Similar to the changes made to modules 30/35 The code was simplified greatly due to these additions only four switches of the relays are needevd to completely execute the steps of the module. The complete code needed for module 20 can be seen in Appendix M.

11.3. Final design

Now that all concepts are initially designed and tested the module can be built up in the CAD program to form the final design. This design can then be sent to the manufacturers and 3D printers to be made. When all parts are delivered, the final concept can be built and tested. The complete list of parts can be found in the BOM in Appendix L.

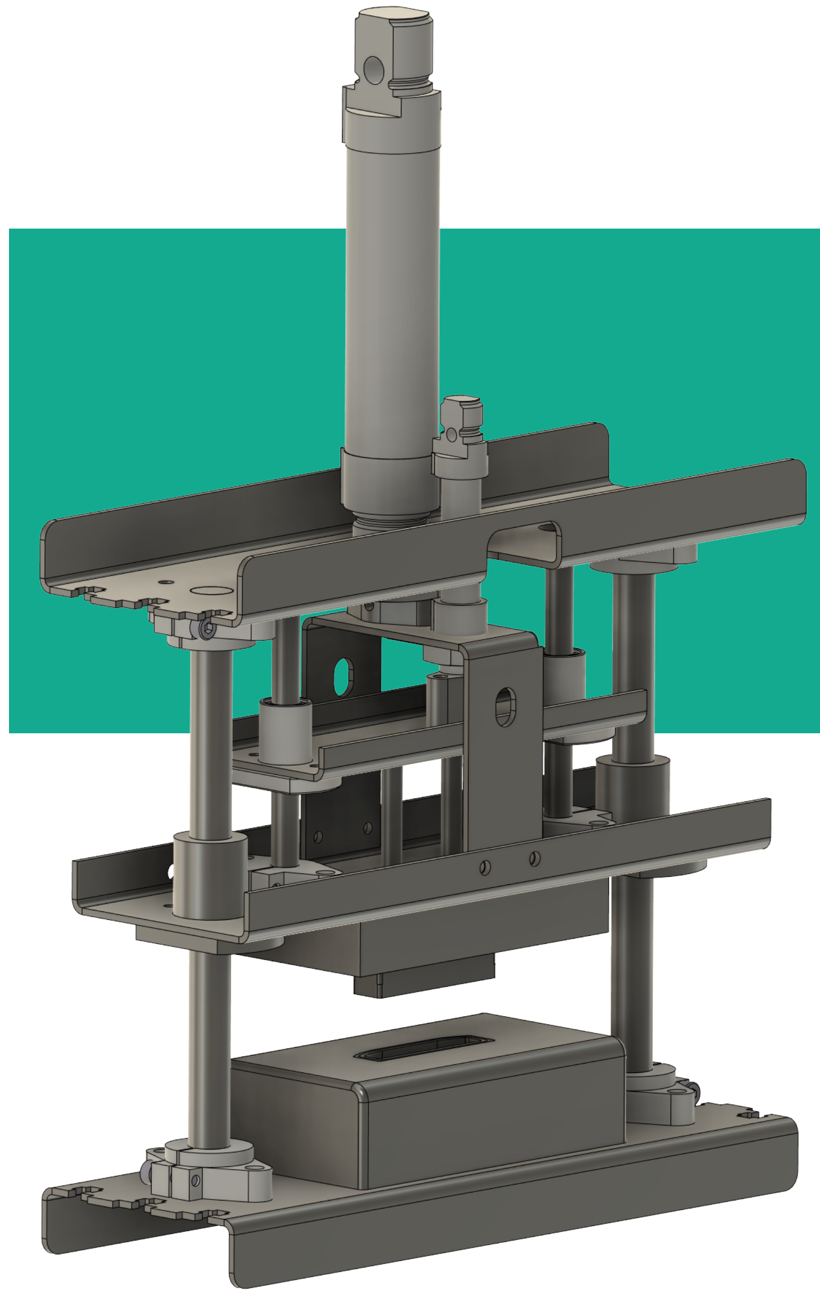


Figure 91: Final design of the working parts of module 20

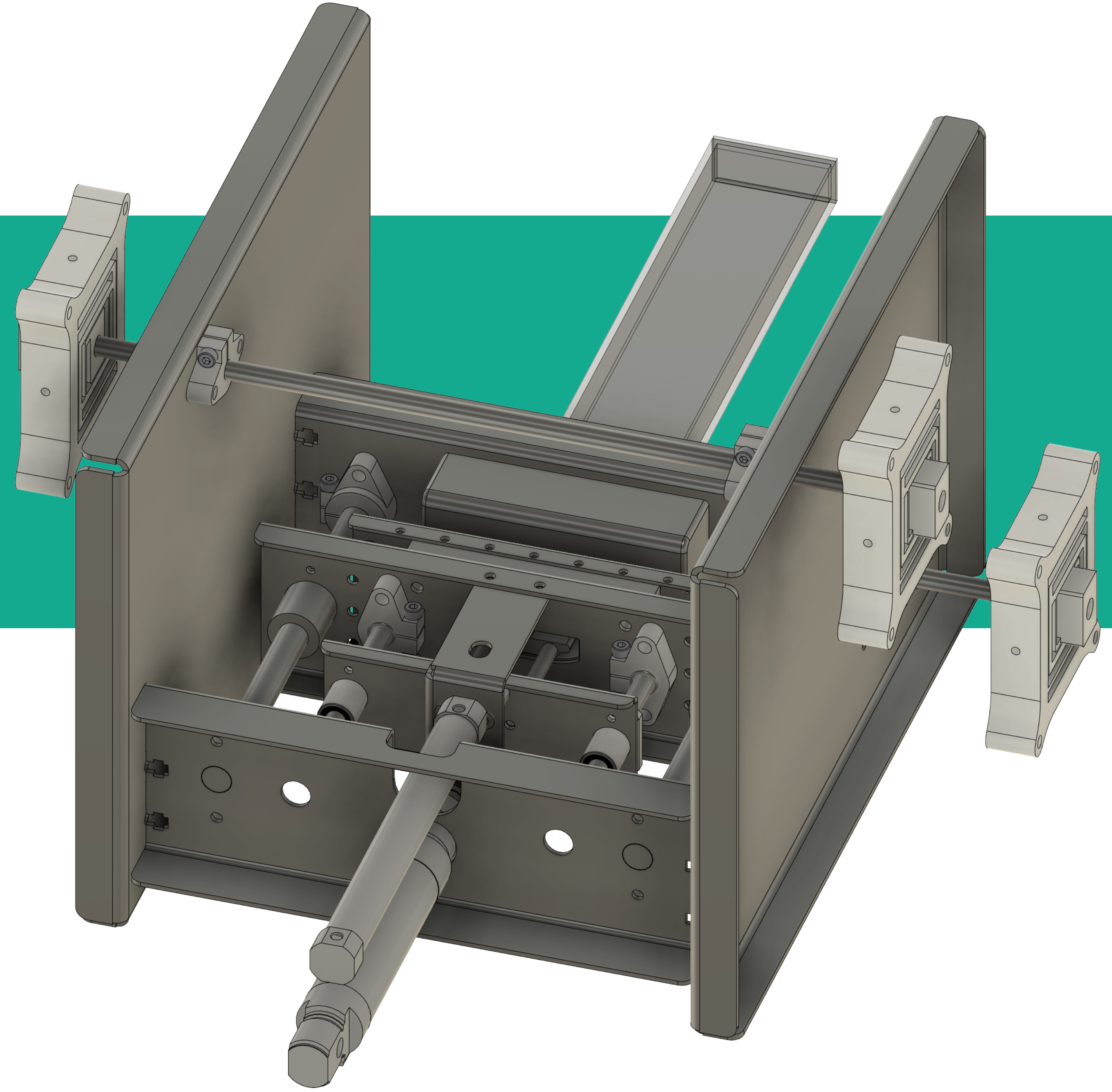


Figure 92: Final design of complete module 20

11.4. Testing of the module outside of the machine

When all parts were delivered and made the module could be built up outside of the machine, during this building an initial problem was immediately encountered. Where one of the sheet metal pieces was incorrect. The hole as seen in , was not cut from the sheet, therefore this part had to be reordered. However, as the system can be tested outside of the machine the part could manually be adjusted to have the missing hole cut from the sheet. This would result in a sub-optimal part and should therefore not be placed in the complete machine but does allow for further testing in the time window where the part had to be delivered.

With the module completely built an initial test can be done without the use of the pneumatics by manually cutting and pushing the parts of the system, this allows for more controlled testing without the chance to greatly damage any of the parts. When manual testing is finished testing with the pneumatics is needed as well as this does introduce new behaviours to the module.

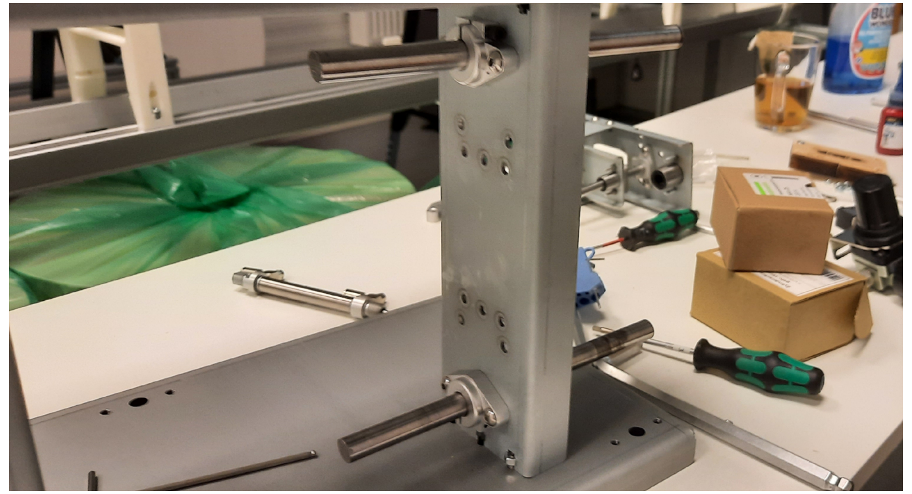


Figure 94: Incorrect backplate

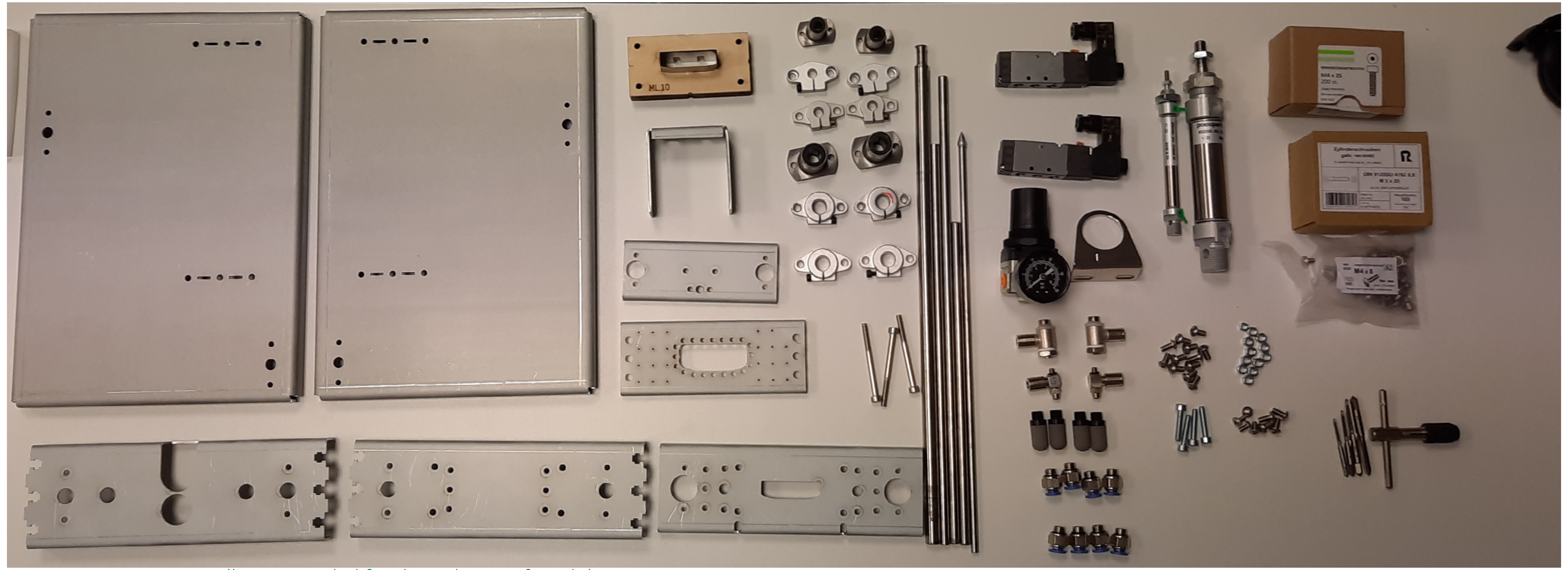


Figure 93: All parts needed for the redesign of module 20

During the manual testing, the added benefit of the additional plate with silicone that would clamp the filter paper during cutting was not experienced. To check if the plate had no influence, it was taken out of the module. During this further testing, no clear difference was encountered between the execution of the module. As additional parts that do not have a positive influence on the operation of the module can only create additional failure modes the choice is made to take out the additional plate. This is an example where testing outside of the machine can lead to additional insights on the module. When the module would have been tested only inside of the machine with its pneumatics working from the get-go, the fact that the plate did not offer any benefits

During testing, it was noticed that the knife was able to hit the counter shape, which could result in damaged knife points. As a countermeasure a physical end stop was added to ensure that the knife is unable to be damaged by the countershape. This physical endstop is added in the form of a bolt that can be adjusted in the maximum cutting depth of the knife. The additional threaded holes that were added to the back plate of the module were also added to the re-ordered plate.

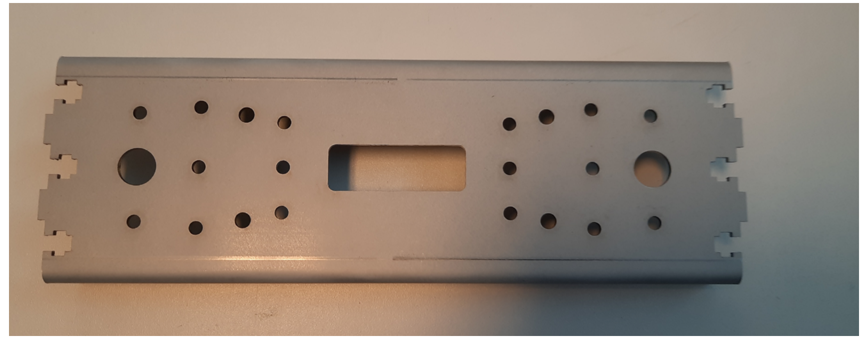


Figure 95: Updated backplate

With the manual testing done a set-up is made where the module is tested with its electronics and pneumatics outside of the main machine. The code for the module is greatly simplified as it only needs to switch two different relays two times. During this test a problem was encountered with the speed regulators, these most likely were one-way gates instead of the needed two-way gates for this specific set-up of the pneumatic cylinders. These parts also had to be reordered resulting in a bit of delay again. However, the advantage is again seen for testing outside of the machine as this does not create downtime for the overall machine which would have been the case for testing inside of the machine.

11.5. Conclusion

Because the module has been completely built and tested outside of the operating machine it has not had any downtime yet, while the module has been completely tested. This allows for the module to be placed in the machine with higher confidence in its success.

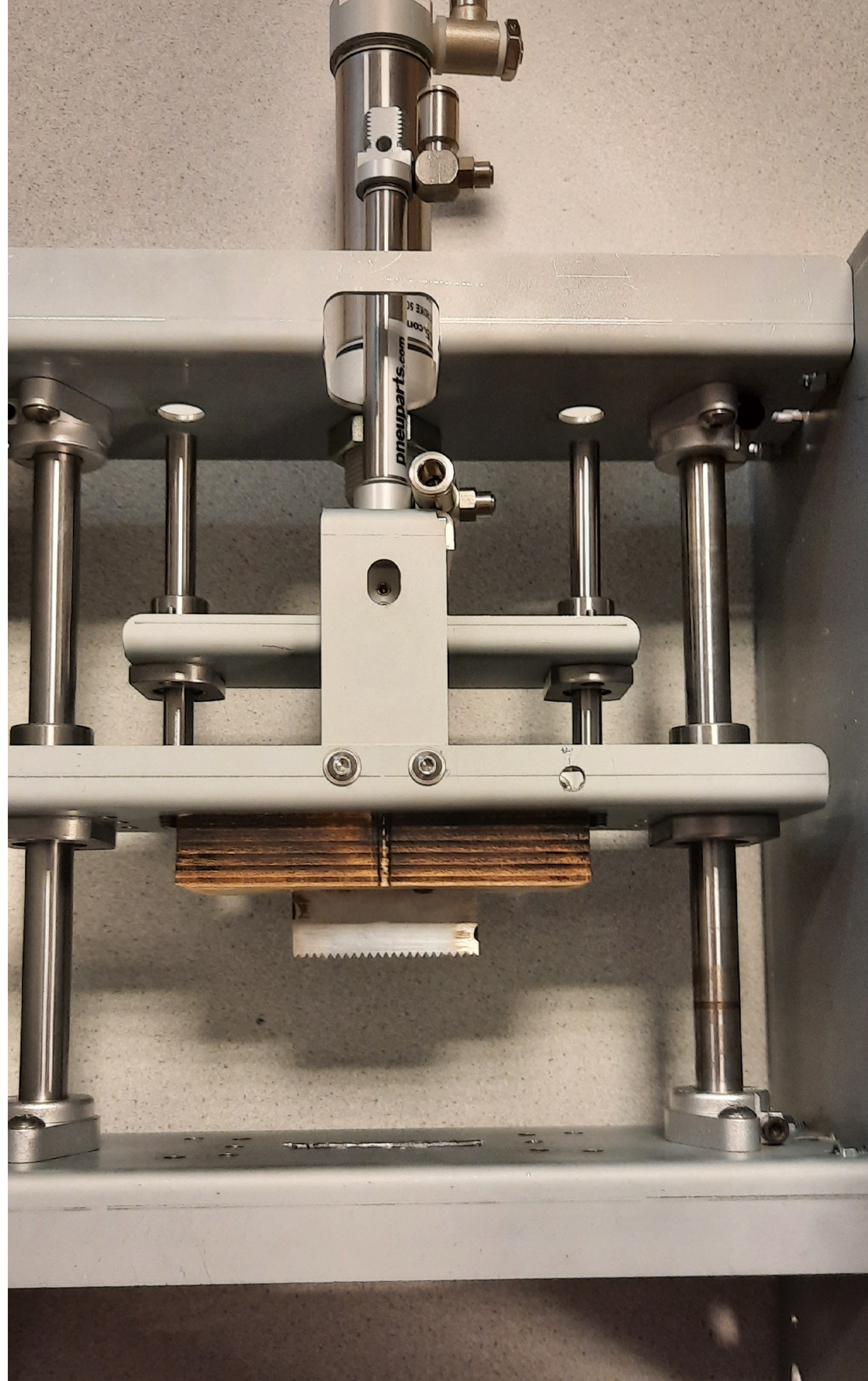


Figure 96: Manual test setup of module 20

12. Implementation of changes to Module 20

With the module tested outside of the machine, the next step is its implementation. This implementation will have to go more smoothly as most parts have been completely tested in a similar setting as the final implementation. And because the changes have been designed to make use of the alignment of the module this should be as close as possible as well. However, while this in theory is how the implementation goes the practice often differs.

12.1. Implementing the change in the machine

For the implementation of the module, the complete old version of module 20 has to be taken out first. This is immediately where a problem occurs. Because there were changes made to module 10 and the web of the overall machine in another update, as seen in Chapter 13, the module is unable to be taken out. Therefore one of the item-profiles of the frame has to be taken out of the machine to allow access to the module. After this item-profile is taken out the old version of the module is taken out. The new module is placed without making changes to the flexures and is centred on the axles of the machine. This is done to try to achieve an as close as possible alignment from the implementation of the module.

The item profile that was taken out could not be placed back in the overall machine due to the large waste chute the new module has. This chute interferes with the placement of the item-profile. This problem has occurred due to the 3D model showing a different location of the combination of module and item profile because the alignment with the flexures is not updated in the 3D model. This is not a pressing problem as the frame is overengineered and can easily miss one of these item profiles.

Figure 97: Placement of the waste container that would have interfered with the item-profile

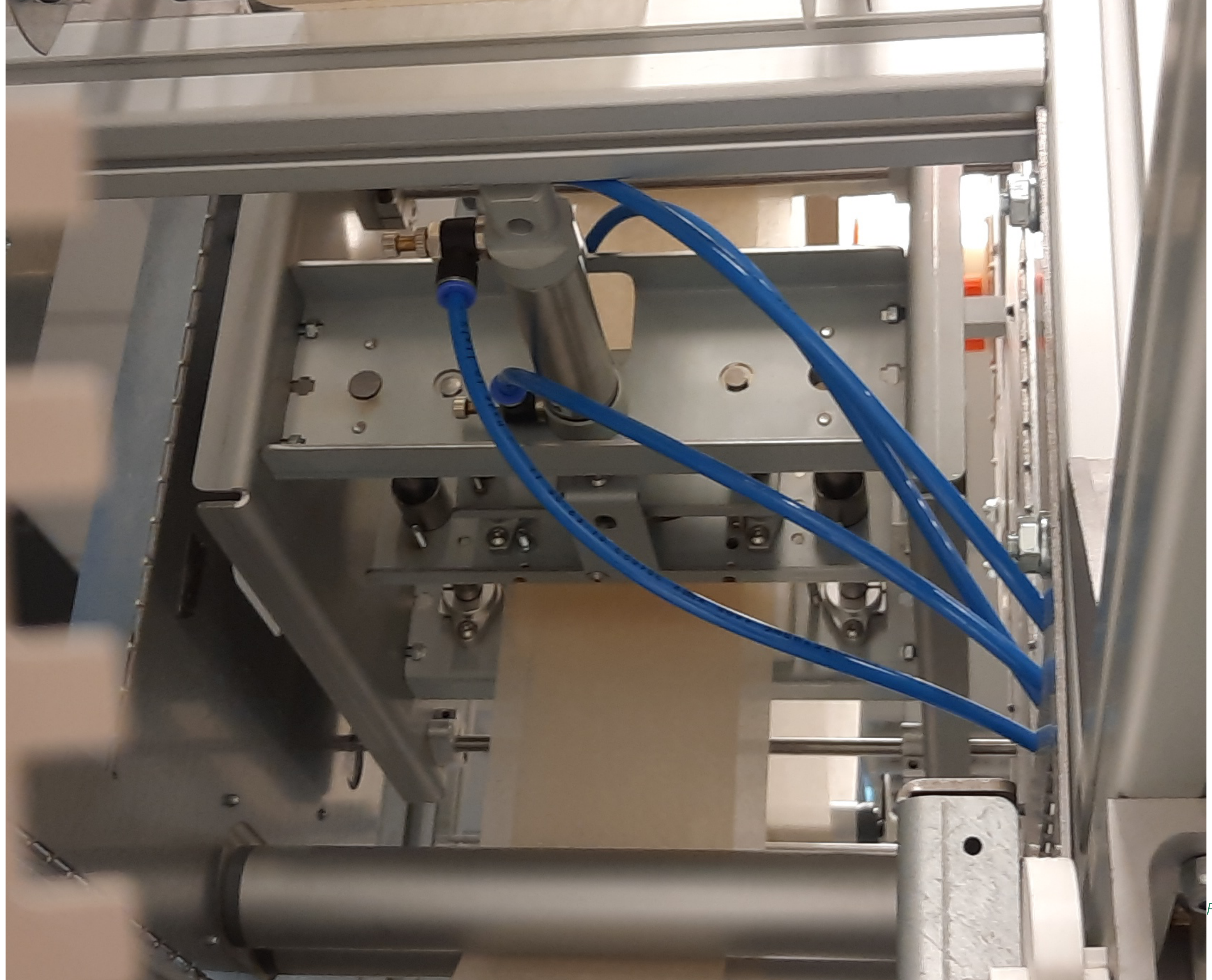


Figure 98: Final implementation of module 20

With the module placed in the machine testing of the complete machine can be done. During this test, it is important to monitor the alignment which should be correct but still can have small deviations. As well as testing of the tension on the web is similar to the tension that was placed on the web by hand during testing outside of the machine. This tension has an influence on the cutting of the module as well as on the possible tearing of the overall web in the machine.

As a final step of the implementation, the code of module 20 will have to be compounded to the complete code on the master module. This is possible as the microcontroller is now able to execute all the less complex modules at the same time.

12.2. Monitor Changes

With the module now implemented in the machine, the changes again should still be continuously monitored as most critical failures only occur once in more than a thousand tea infusers. If there are significant increases in failure modes that could originate from module 20 the module should be controlled more closely. Also, long-term testing could show problems with waste handling and should therefore be monitored during normal operation.

During the monitoring of the module, additional problems were not encountered. It was deemed important to keep track of the waste handling. Because when the chute is filled the pressure of the waste increases quickly which could lead to problems in the module.

12.3. Conclusion

The implementation of module 20 has gone relatively quickly when compared to the implementation of the changes in modules 30 and 35 as almost all testing could be done outside of the machine. This allowed for a shorter downtime of the machine.

13. Other changes to modules that were made during the thesis

Throughout the thesis, more failure modes have been experienced, as well as possible problematic design choices. These have been changed during the time of the thesis as well, but their complete redesigns and decision-making processes fall outside of the scope of this thesis. In this chapter, the changes and decisions that have been made will be summarised to be able to understand the overall influence of the changes made both inside and outside the scope of the thesis.

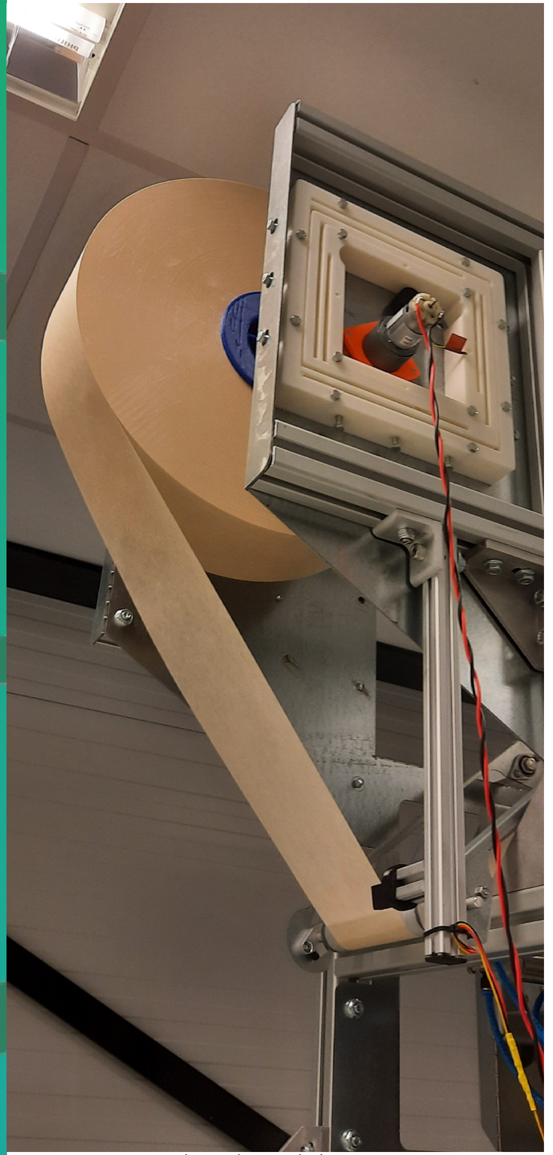


Figure 99: Updated Module 10

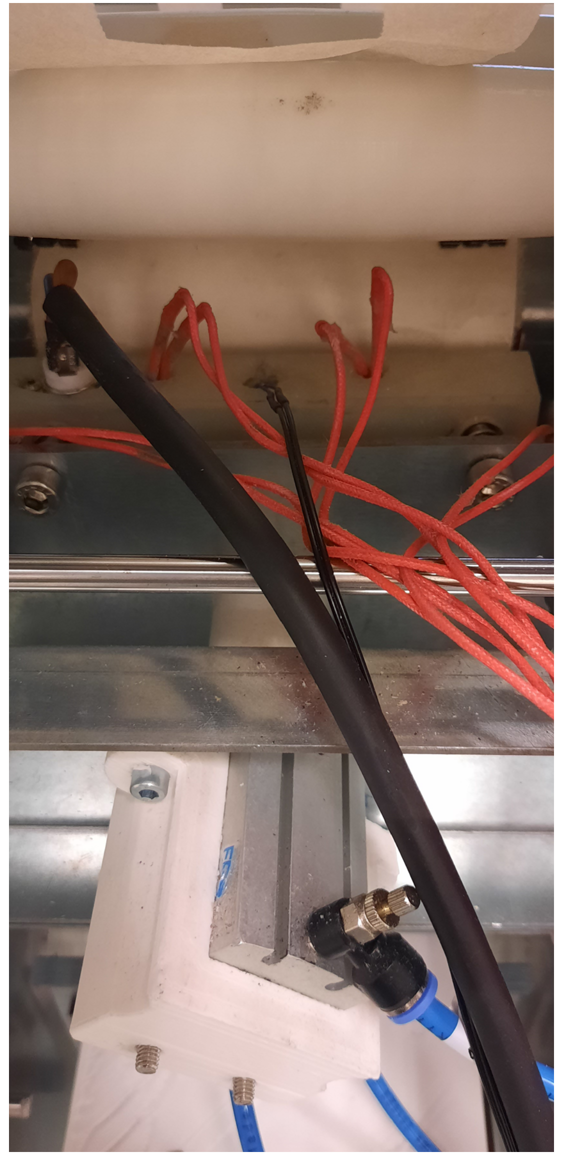


Figure 100: Updated module 40

13.1. Module 10

First, the heat-sensing capabilities of module 10 have been changed during the redesign of modules 30/35 and will therefore not be further elaborated here. Secondly, the change made in this module is how the filter rolls are hung in the system. This was initially done by placing the roll on an axle that hangs in a flexure in the frame. However, during the replacement of the roll the alignment had to be redone and the replacement of the rolls took a long time. Therefore a quick release system was applied as seen in Figure 99. This meant that the rolls could be more easily replaced as well as having a set alignment lowering the set-up time after roll replacements. During this change, the change was also made from stepper motors to DC motors as they use less power.

13.2. Module 40

As mentioned before, module 40 was one of the earlier modules that changed from stepper motors to pneumatic cylinders. The choice was made here as this module experienced frequent driver failures and noise on the endstops, resulting in faulty execution of the module. Changing from stepper motors to pneumatic cylinders has greatly reduced failures, power consumption, and complexity of the module.

13.3. Modules 50, 60, and 70

Modules 50, 60, and 70 have been problem modules throughout the development of the tea infuser machine and have had the most iterations. During this thesis, this continued as well. For module 50 the knife had created more and more issues and a look had to be taken at using a foil knife in this module as well. For module 60, the servos experienced problems such as jitter and were quite slow. While module 60 ran on its own outside of the time of the other modules this added time from module 60 added a lot of overall time to a production cycle. And module 70 often was pulling too hard or too soft on the filter paper inducing tears and therefore critical failures. All of this combined resulted in the need for a redesign of the complete set of modules. During this redesign, all three modules had been combined into a single frame and most of the systems had been changed from stepper motors and servos to pneumatics and DC motors. The knife has been changed to a knife that resembles a foil knife. While these changes were mainly used to counteract the possible failure modes of the system, they also should increase the consistency and speed of the machine greatly. Finally, the redesign also looked at removing the need for the manual labour step as this step costs a lot of time and money for each filter, as well as leaving scars on the final product. This change was achieved by cutting the complete tea infuser and then pressing the complete tea infuser through the counter shape of the knife into the cartridge. This process is similar in its function to the process of module 20 and can be read there. Since there was no need for the manual step anymore the tea infusers had to be collected in a cartridge that is added to the side of the machine and can easily be replaced when full with a new cartridge during continuous operation.

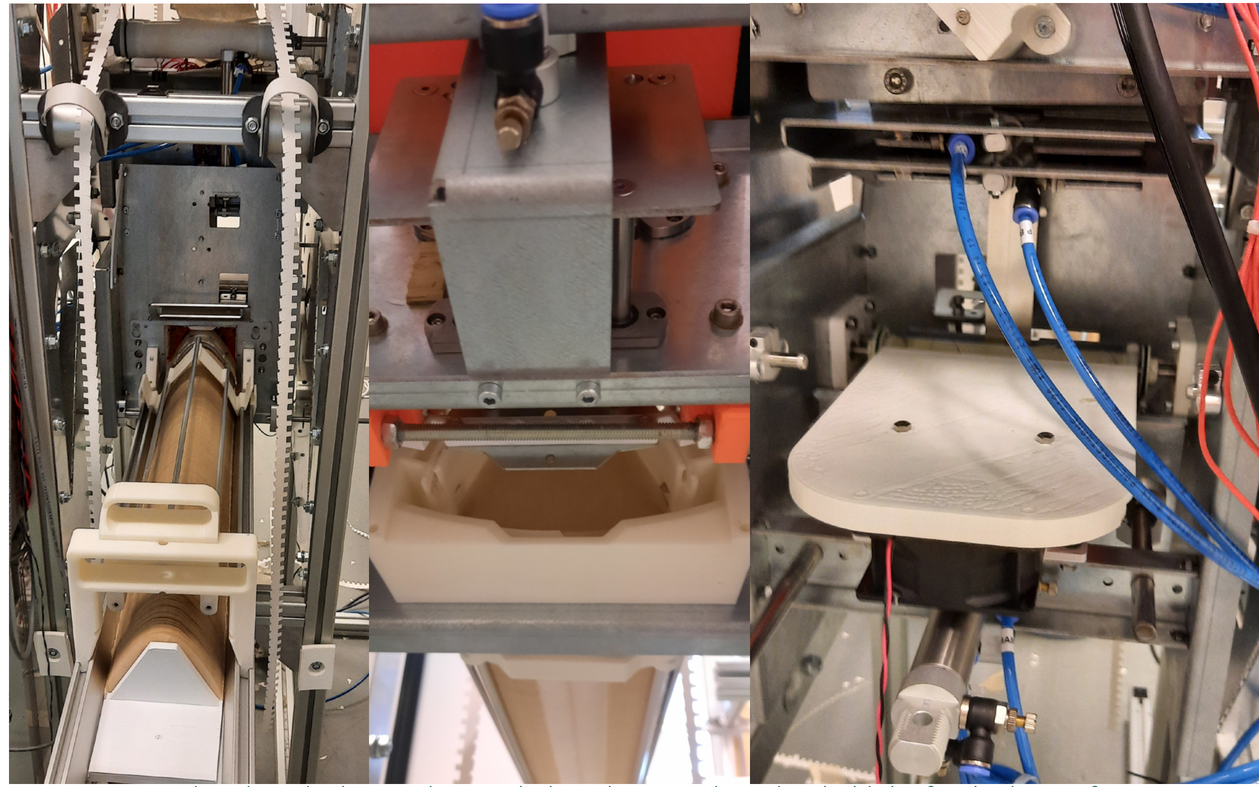


Figure 101: Updated moduel 50 and 60, including the cartridges that hold the finished tea infusers

13.4. Modules 80/85

Initially, modules 80/85 had been designed for both rolls of the cartridge while simultaneously collecting the waste of the cartridges. This, however, created more failure modes and was therefore changed to a simpler waste-collecting system. This meant that the frame was overengineered for its current application. The rolls of cartridges also are produced in-house instead of the expected external production which meant smaller rolls had to be made. The choice was made to incorporate the modules within the main frame as seen in Figure 102. During this change in design, a similar approach the replacing the rolls as in module 10 was made. Using a quick-release system the turnover time for the replacements of the rolls was greatly lowered and made more accessible to do by a single operator. The stepper motors in these modules have also been replaced by DC motors following the same reasoning as in other modules.

13.5. Compiling of the software

Because most of the modules have been greatly simplified the need for multiple microprocessors to be able to execute the multiple complex software systems of the machine is not needed anymore. Therefore most of the slave modules have been compiled on a single Arduino, lowering the possibility of communication errors between the different microprocessors.

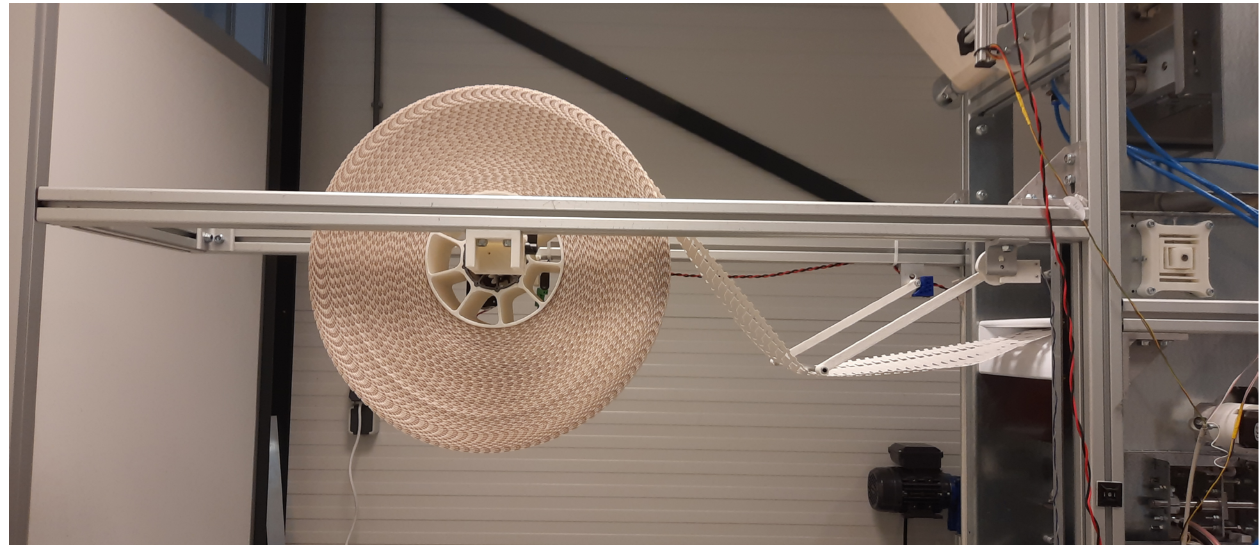
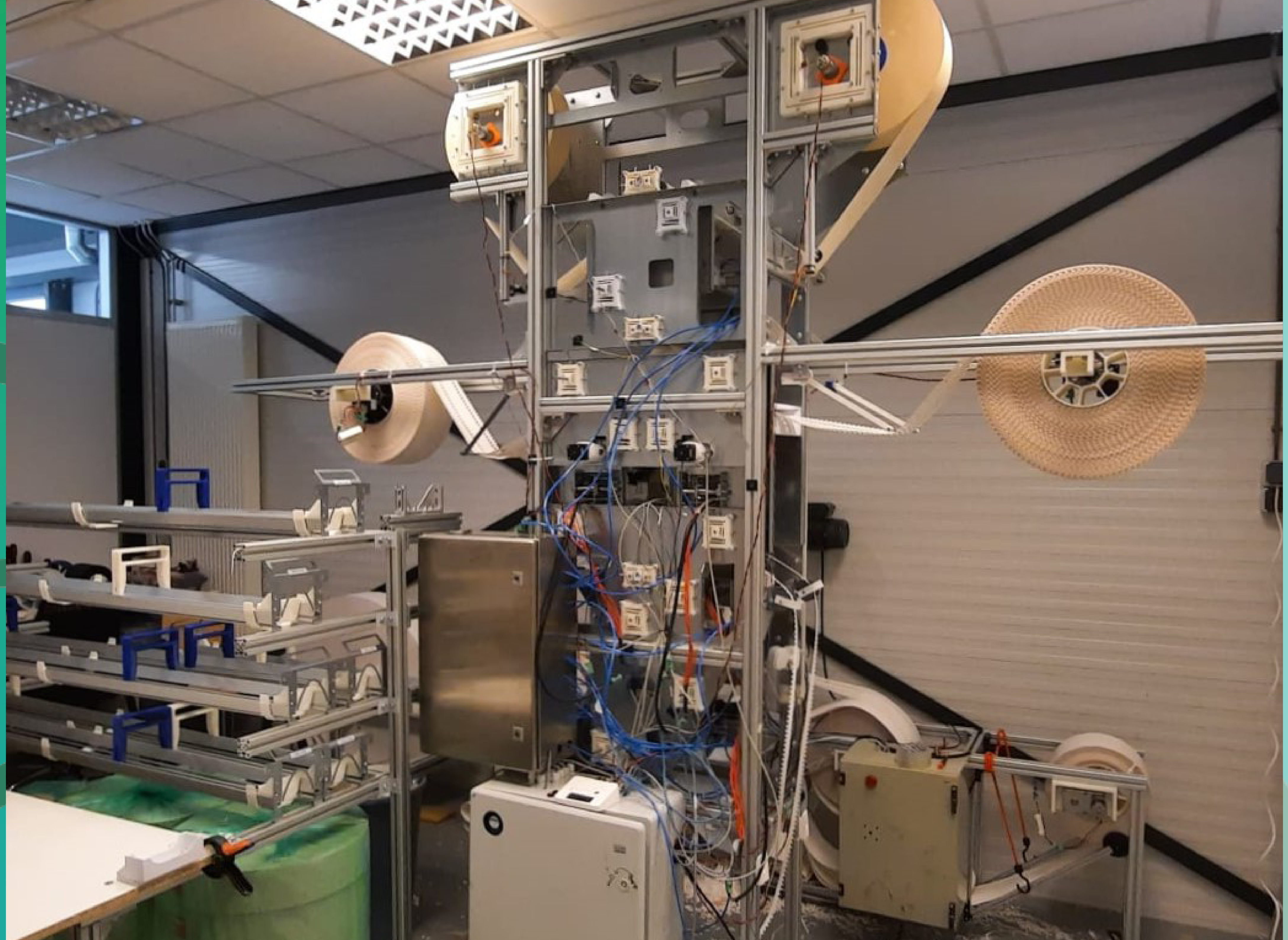


Figure 102: Updated module 80



CONTROL & EVALUATION

14. Evaluation of the improvements

With all the changes made to the production machine, a final evaluation and control can be done. This evaluation will show the progress made to bridge the gaps. To compare the current state with the state of the machine at the start of the thesis, measurements of the finalised production process and failure modes are needed. The tools used for this are the statistical analysis done during Chapter 5. Important to note is, that due to the change to automatically taking the tea infuser from the web, D1 is not measurable anymore and will be taken out of consideration for the statistical analysis.

14.1. Measurements

Two random sets of 25 tea infuser production runs are used as the basis of the statistical analysis. The complete measurements can be found in Appendix N. The basic statistics resulted from these measurements can be seen in Table 18.

Table 18: Basic statistics of evaluation

Variable	N	Mean	SE_Mean	StDev	Minimum	Q1	Median	Q3	Maximum
D2	50	0,4420	0,0212	0,1500	0,1	0,4000	0,50	0,50	0,8
D3	50	0,6320	0,0209	0,1477	0,3	0,5000	0,60	0,70	1,0
D4	50	0,3560	0,0188	0,1327	0,1	0,2000	0,35	0,43	0,6
D5	50	4,3700	0,0181	0,1282	4,2	4,2750	4,40	4,50	4,6

The basic statistics of the tea infusers show that the standard deviation of D2 and D3 have been significantly lowered, while D4 and D5 are roughly similar to the deviation at the start of the thesis. This can be explained as there have been no direct changes that relate to these dimensions and they should therefore not have changed throughout the improvements. The improvements done to D2 and D3 have significantly lowered the maximum and minimum deviation from the mean, which means that fewer products will fall outside of the specification range and the probability of failure modes occurring will be lowered as well.

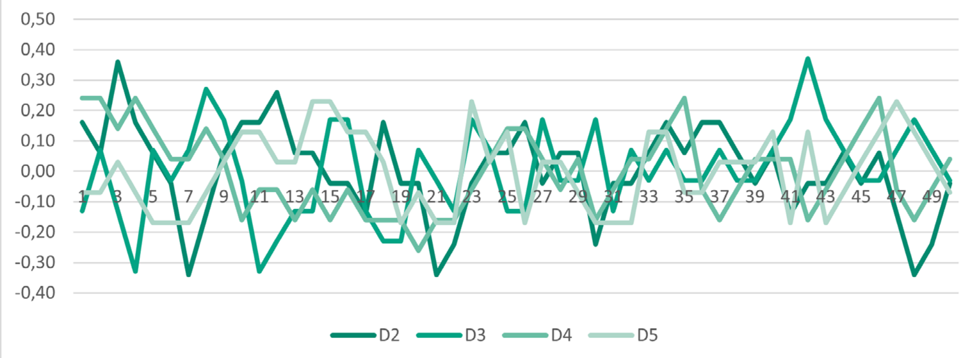


Figure 103: Deviation of the mean during the evaluation

Secondly from the table, the shift of the mean towards zero can be seen for D2 and D3, this shift shows the improved quality that can be achieved due to the lowered maximum deviation, the old version of the machine would have had increased occurrence of failure modes when the mean would have been shifted by means of setup adjustments.

14.2. Capability study

With the measurements of the dimensions, the capability of D2 and D3 can be analysed as well, as they are the dimensions to which changes have been made. From the capability analysis results, as seen in Appendix O and Table 19, it can be seen that the capability is greatly increased in comparison to the initial analysis. The dimensions are not centred between the lower specific limit (LSL) and upper specific limit (USL) as shifting towards the LSL increases the quality of the tea infuser. To get a better idea of the actual improvements, the failure modes will therefore be more influential. Because the disadvantage of the shift towards quality for D3 is that, when the shift is under 0, one of the failure modes C4 can occur, this is also why not only the basic statistics have to be accounted for during evaluation but also the failure mode and effect analysis.

Table 19: Capability study results

Dimensions	Cp	Cpk	PPM	Centred
D2: Distance between the left and right bracket	2.23	2.67	1600	Yes
D3: Part of the filter paper above the highest bracket	12.67	1.69	10	Yes

14.3. Failure modes

As mentioned, not only measurements D2 and D3 are important for the evaluation of the improvements. Since failure modes have been lowered significantly in comparison to the start of the thesis, a longer production run of over 1000 tea infusers had to be checked for failure modes to be able to measure their occurrence. The less prevalent, but still occurring, failure modes are recorded over a longer period and will be estimated based on their noticed occurrence during total production runs.

As can be seen from Table 20, many of the failure modes have been significantly lowered due to the improvements made to the machine with yield currently at 99,2%. However, there are still failure modes that occur that cause critical failures of the machine. These are the P and H failures. These still cause major problems during production thus there is still a need for further improvement to be able to run production for longer amounts of time in succession.

Table 20: Failure mode occurence during evaluation

Failure mode	C1	C2	C3	C4	C5-20	C5-30	C5-35	C5-40	C5-50	C5-60	C6-20	C6-80/85	C7	C8	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	H1	H2	H3	H4	H5	H6	H7
Occurrence	0	0	4	0	0	0	0	0	0	0	0	2	2	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	4

14.4. Quality improvements

As mentioned bore, the shift of the mean towards zero has improved the quality related to the start of the thesis. However, more changes have improved the quality of the tea infusers, for example, the change in the knife in module 20 has greatly increased the outline of the filter hole. The change in the knife in module 50 has increased the quality of the cut and prevents the additional fibres needed to keep the web intact. The change top module 50 also takes out the handling of the web after the final module lowering the creasing of the tea infusers as well. The combination of these changes is reflected in Figure 104, where the improvements in quality can be seen.

Figure 104: Difference in quality of the tea infusers

14.5. Gap analysis

At the beginning of the thesis the desired state was defined, to evaluate how much improvement has been made the new state of the production process can be compared to the desired state. This will show if the gaps have been completely bridged or if further development is needed. The overview of the changes can be seen in Table 21. It shows that most categories have been improved upon, however, the desired state has not been reached in each of the categories. The main reasoning is that critical errors still occur too often, this lowers operational time as the machine cannot be run overnight. And because the machine cannot be run overnight the overall yield is significantly lowered as well.

14.6. Conclusion

Throughout this thesis, the tea infuser machine has had multiple improvements in almost all of its modules. These changes have been decided upon through the use of the decision-making methods explained in the framework of this thesis, and therefore are grounded with a high probability of improvement. The high probability shows to have been accurate as all aspects of production have been improved. The yield has increased from 567 to 4289 tea infusers per day, which are of a higher quality as well. The framework has also increased the knowledge of the production process and machine which can be used for further development, which is still needed to achieve the desired state.

Table 21: Final state in comparison to goals set by gap analysis

Categories	Previous	Current	Desired	Gap
Production speed	120 per hour	360 per hour	300 per hour	The speed is now below 10 seconds per tea infuser which easily reaches this goal
Quality of tea infusers	Low-quality	High- quality	High-quality	The new method of cutting and improvements throughout the machine has made it so that the new tea infusers are almost all within specification
Out of specification tea infusers (D)	1 in 4	1 in 120	1 in 161	While failure mods still occur, failures due to too little aestatical value have generally eliminated. The failure rate regarding aesthetic values is only once every 3000 tea infusers which reaches this goal. However, due to the failure modes that still occur there still are 8 out-of-specifcation tea infusers per 1000 produced infusers.
Failure modes of tea infuser (C)	1 in 10	1 in 125	1 in 200	These occur much less frequently as the system has been made more reliable, has less waste material that can get stuck in the machine, and is greatly simplified. Each of these factors lowers the non-critical errors. However, they have not been completely taken out, as module 50 sometimes still has problems with waste handling.
Critical errors (P)	1 in 240	1 in 2000	1 in 7200	To be able to have the production run for 24 hours, the number of critical errors has to be lowered even further to ensure that it will not have a failure during the night.
Human error (H)	1 in 5	1 in 20	1 in 100	Because the machine is made more simple the chances of the operator making mistakes have been lowered significantly. However, since there is still the need for an operator during set-up, mistakes can still be made that result in errors.
Operational time	6-8 hours	12 hours	24 hours	Due to the critical failures the system still has it is unable to run for more than 12 hours, which means turning it on in the morning and turning it off at the end of the day remotely. It is not consistent enough to be able to run through the night as a critical failure could have too large of a negative effect.
Yield	567 per day	4289/day	7153 per day	While there has been an increase in knowledge on the production process as well as the machine, there still are unknown origins of specific problems. To be able to overcome these problems further research into these topics has to be done.
Knowledge	Little-to-none	Above average Knowledge	High-level knowledge	Due to the framework, many insight have been gathered. However, currently there still is a partial knowledge gap relating to the root causes of the critical failures.

15. Evaluation of continuous improvement framework

Now that is clear from the evaluation that the framework has helped throughout the improvement process at TeaWall, the framework can be updated to take the findings that were made throughout the thesis into account. These include findings such as the need for accurate measurements, additional preparation time for unforeseen problems, and additional considerations to be made during the decision-making process regarding the level of improvement.

15.1. Accurate measurements

As seen during the measurement stage, as well as during the root cause analysis, the accuracy of the measurement has a great influence on the reliability of the testing. This is needed to substantiate choices accurately as with inaccurate measurements misinformed choices can be made based on biases. One example of such a wrong expectation was that module 90, the cartridge machine, was the main problem for the misalignment of the brackets. With the use of accurate measurements, it was determined that the cartridge machine had the lowest influence on this misalignment in comparison to modules 30/35 and 60. While measurements done to the final product can be easily done with high accuracy, measurements within the machine such as the placement of the brackets in modules 30/35 are harder to be done accuratwly. Here additional thought and time should be put into creating an as accurate as possible system to measure. Additionally, the measurements done in this stage should take into account for determining the probability of the root cause, the higher chance for incorrect measurements being taken.

15.2. Unforeseen problems

While a lot of problems can be foreseen and planned for, such as including more adjustable parameters, testing all of the functionalities of the improvement, or comparing the newly designed solutions with existing solutions to similar problems. There still can occur unforeseen problems, during cases these were problems such as the module being unable to be taken out of the machine due to misalignment between the physical machine and the digital version or ordered products being faulty. While these often can be prevented due to even more rigorous checking of the orders or constantly updating the digital twin, most likely another problem could occur even then. This shows the additional need in the planning for the implementation of an update to account for probable delays during the ordering, the testing, and the implementation of the module. For this, a stepped planning such as in Figure 105 can be used. This inherently allows for the additional needed time for implementation. Most important here is the additional time needed on the day of implementation as this not only takes time for the employees but also induces the downtime of the machine, spreading the implementation over multiple days greatly increases the necessary downtime.

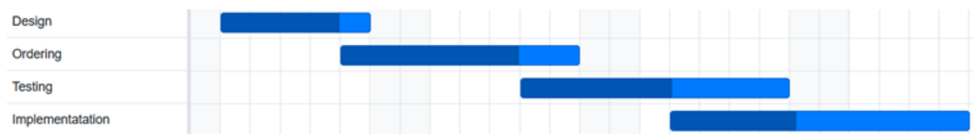


Figure 105: Unforeseen problem accounted for in planning

15.3. Decision-making process

From the two different case studies, it was seen that the choice of partial or complete redesign has to be taken into account. The first case study focussed on only updating a module partially which lowers the development time and production cost of the improvements but does increase the downtime of the machine. The second case focussed on a complete redesign of a module, which increases design and production costs but the redesign can be tested completely outside of the production machine. Testing outside the machine lowers the downtime significantly in comparison to the first case. Even though the changes to the operation of the entire module was more greatly changed. From this, the additional need for consideration for what type of improvement is implemented came to light.

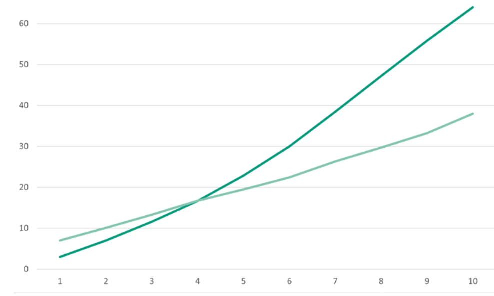


Figure 106: Cost of development

The decision-making on what type of improvement will have to be used has to have a consideration between the improved cost of development and production or the additional downtime. To be able to make this consideration initial design ideas have to be made that by estimation of the designer are given weight to their development cost and downtime. (Figure 106) While due to the additional testing outside of the machine, the downtime is lowered, unforeseen problems will most likely still occur.

15.4. Control

For the initial framework, the control is taken up by the DMAIC Cycle, as part of the what of the framework. However, while this is fitting as it decides if the changes have improved the current state significantly, it could also be considered as a final step of the framework for each cycle. Because when it is considered to not have significant improvement the redesign has to be iterated upon. While on the other hand, a new cycle will be started when improvements were made.

15.5. Finalised framework

The framework has not changed much throughout the thesis. This is mainly because the framework defined during the literature review illustrates the foundation of the continuous improvement process and should, by design, be changed to fit the specific needs of the decision-making and redesign processes. Therefore the framework is similar to the initial framework as described in Figure 19. It still uses the combination of the DMAIC and Design Thinking cycles as the foundation of the complete continuous improvement cycle. In this chapter, however, some additional caveats are added to further guide the process of continuous improvement for TeaWall. To better illustrate the steps needed in the framework the framework illustration, as seen in Figure 107, will be transformed into a baseline tool which explains each of the steps concisely and guides the user through each part of the process. Milestones and decision trees can be used to further enhance the useability of the framework for those who have not directly worked with the framework or have less knowledge of the used tools. The tool uses the illustration as the guide through the process, each of the parts of the continuous improvement will be substantiated with concise steps and decision trees that the end user can apply to their process. To illustrate each of the steps, and possibilities examples from the case study of this thesis are given. These are examples using the tools specific to the application of the framework for TeaWall, and could be changed to better fit with other companies. The tool will not provide in-depth explanation of each of the steps, as it is meant to use as a guideline for continuous improvement. The tool can be interacted with using the following link: https://tinyurl.com/ContinuousImprovementTool.

Before the framework is used a generic problem definition should be made that substantiates the reason the framework has to be used. For the example of TeaWall, it was generally noticed that the current production process has too little production yield for their needs, originating from critical failures of the production process and low-quality end products.

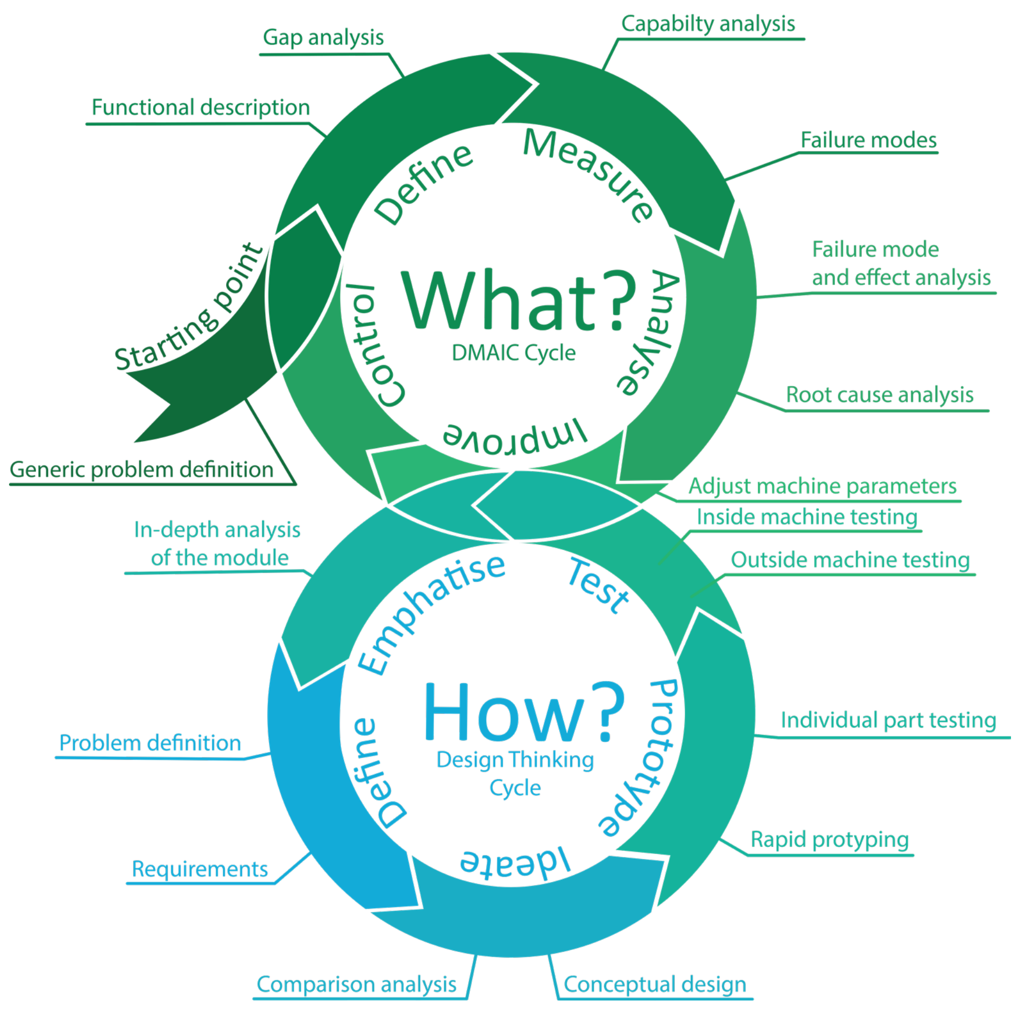
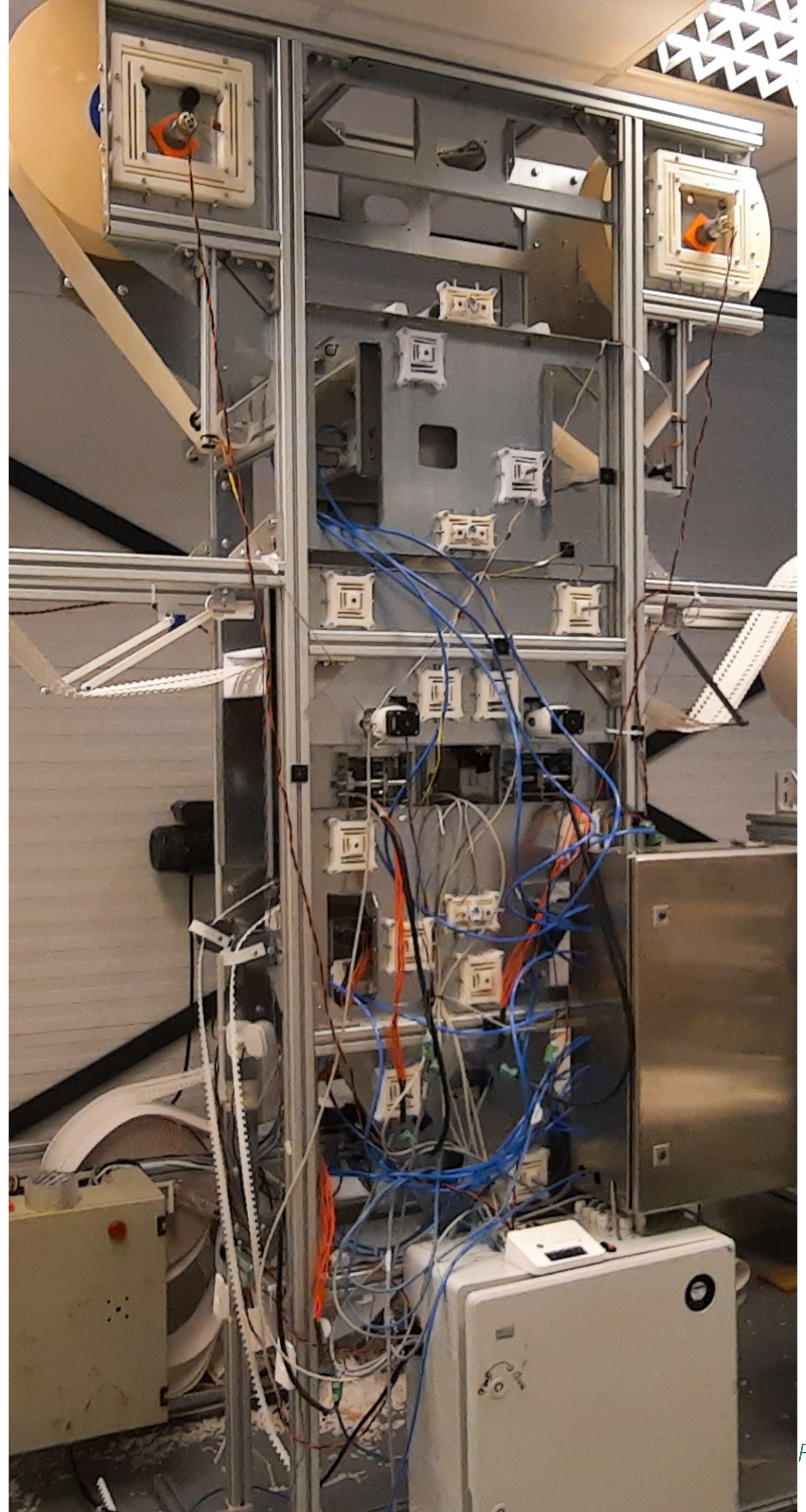


Figure 107: Finalised framework



16. Discussion

The framework in this thesis is a more generic approach to the design problem of continuous improvement and makes use of specific tools fitted to the application to be able to make the improvements. For each application of continuous improvement, it will be important to adjust the tools to fit the specific design problem. Therefore, additional tools could be added to the research and framework to be used as options with their advantages and disadvantages provided. This could, however, create the problem that the framework provides too many options, and loses out on the effectiveness as wrong tools could be applied to processes.

Because measurements are leading in most of the decision-making processes, the quality of the measurements increases. First of all, for this thesis, most measurements are done by hand with digital callipers. However, they are only done by one person and are therefore more prone to human error. To overcome this problem an additional person could check the same tea infusers and the measurements should be set next to each other to ensure correct measurements have been taken. Secondly, due to time constraints and the time intense method of measuring smaller sample sizes have been used. For more accurate decision making utilising larger batch sizes for the measurements could be beneficial.

Due to the complexity of the machine, it was noticed during the thesis that accurate testing of improvements showed additional challenges due to failures of other modules. When, for example, there is a problem with module 60, it influences all other modules making it harder to determine if there have been improvements made to the module that is being tested. This has to be taken into account when determining if an improvement has been successful or if it, perhaps, could be the reason another module experiences new problems. This is a complex problem with continuous improvement and should be focussed on more during the control step of the framework.

Often it was noticed that problems occurred due to external factors, such as problems with electronics or faults by human error. These problems are not directly influenced by machine design, and can therefore not directly be redesigned for. However, it is possible to simplify the electronics and the need for human intervention during the production process. These steps were considered during the redesign processes but can be made more explicit by deciding what type of redesign is needed. A redesign of working principles or changes to parts, or by gathering more knowledge on the operation of the machine.

During the gap analysis, the desired state has been to have the machine running for 24 hours at a time. However, due to the complexity of the critical failures, the root causes have not been determined and eliminated yet to such an extent that the machine is able to run continuous production. For the gap analysis, the goals that were set have been too generous in relation to the available time. However, the desired state can still be used for further development outside of the scope of this thesis.

Figure 108: Production machine as of the end of the thesis

17. Conclusion

The goal of the framework is to guide the user into answering the following questions: “What are the improvements that have to be made to the machine to improve the yield?” and “How are improvements designed, and implemented in the machine while it is running continuous production?”. The former of these questions was answered through the use of the DMAIC cycle and additional tools. This approach initially helped gain insights into the current state of mass production. The insight is used by the stakeholders to define the problems of the overall machine and production process and which of the failure modes or inaccuracies of the modules were most important The gap analysis was used to create an action plan on what changes have to be made to get from the current state to the desired state of production. By further analysing the machine and production process, utilizing FMEA and root cause analysis, it becomes able to define the root causes of the failure modes and problems of production. The root cause can, for example, be problems with the alignment of the machine, the need for a redesign of parts or modules, or problems with human errors. The root causes in combination with their possibility of successful implementation and improvement are weighed against each other to be able to decide which possible improvement has the most likely highest influence on the production process.

The second question was answered by either changing the machine setup or through the use of a redesign which uses the Design Thinking cycle of the framework The improvement due to the change of setup of the machine is possible as the production machine has changeable parameters, the main of which are the flexure designs used to hold the modules. Through the capability analysis, the optimal alignment of the modules can be determined. The optimal alignment is such that there are little-to-no failures due to failure modes C1-C8 while improving the quality by lowering the additional filter paper above the bracket (D2) or misalignment between brackets (D3).

When a root cause of a failure mode cannot be solved by changes to the setup and therefore requires a redesign of parts or even a complete redesign of the module, the Design Thinking process guides the redesign and improvement steps. The process is executed external to the current machine, this allows for ideas to be executed and tested without interference with the day-to-day operation of the machine. After the designs have been made and thoroughly tested outside of the machine, an implementation strategy can be made. The strategy focuses on mitigating the possible problems that can occur during implementation.

At the end of the case study of the thesis, a clear improvement in yield, reliability, and speed of the production machine and process can be noted as well as an improvement in quality end product in the tea infuser. The main increase in quality and yield is due to the increased precision of modules 30/35 and 60 which has lowered the main failure modes significantly. The other large influence in increased production yield is the change to pneumatics and DC motors in all modules. This change has greatly increased production speed, simplified the software and hardware, and lowered energy consumption. The change to waste handling of module 20 has nearly eliminated the possibility of waste entering the production machine, which either created out-of-specification tea infusers or was able to cause critical failure when the waste got stuck somewhere in the machine. While the improvements have been significant boasting an increased yield from 567 to 4289 tea infusers per day of a higher quality, not all goals set by the gap analysis have been reached. The main reason is the occurrence of critical failures, as the machine is complex many of the root causes of problems are difficult to find. As the root causes have not been determined for each of the problems the machine still experiences, it has not been possible to improve upon these problems.

Overall the application of the framework can be seen as beneficial to the continuous improvement approach. It has well guided the development during the time of this thesis. Each of the improvements made has been seen to have a significant influence on the production process. However, the added benefit of the framework is only seen in its effect as there has not been a control variable in a secondary project which has not applied the framework. The difference, however, can be compared to improvement strategies that were applied before the application of the framework of this thesis. During those improvements, similar tools were applied to some extent but often were not substantiated with measurement. One such example is the initial improvement of the module from using the flat knife on a metal plate with a roller to the foil knife and counters shape design. This was an update that focused on one of the problems where the material was not correctly cut, and therefore, not handled correctly by the waste collecting. However, the improvement was not complete, as during the thesis another iteration had to completely redesign the module because the problem with waste handling was still not helped. The module could have been further improved during the initial redesign if further analysing the problems and testing the possible solutions had been applied.

18. Recommendations

The framework and tool should be tested by TeaWall by a user that has not gone through each of the steps before, to ensure that the framework can be used on its own. The tool for the end user should be clear in its explanation of the steps, with little additional research needed to be done by the user to be able to execute the framework. During the use of the tool, the user could refer to the previous examples of decision-making processes and improvement executions to help with understanding the steps The framework has been defined for the application within TeaWall when it will be continued to use for the application in other companies, it is important to adjust the tools used to best fit with the current process. The framework can be used as a guideline.

While the machine has been improved significantly, it still has some major problems in the form of critical failures (Figure 109). These are the main reason why production cannot run for over 12 hours and will have to be improved upon with more priority. The difficulty of these problems is that finding the root cause is difficult, they do not occur often and when they have occurred it can be hard to determine the root cause. For this the addition of live feed cameras that record critical points of the production process have been added already, however, these will not catch each of the root causes. The design changes that will have to be made to overcome the problems will most likely be complex. As an example, the expected reasoning for the failure mode is that the web tears around module 30/35 can occur due to problems in module 30/35, but could also originate from too high tension in the web, or the weakened web due to problems with cutting in module 20. Only if the root cause is found, these problems can be solved.

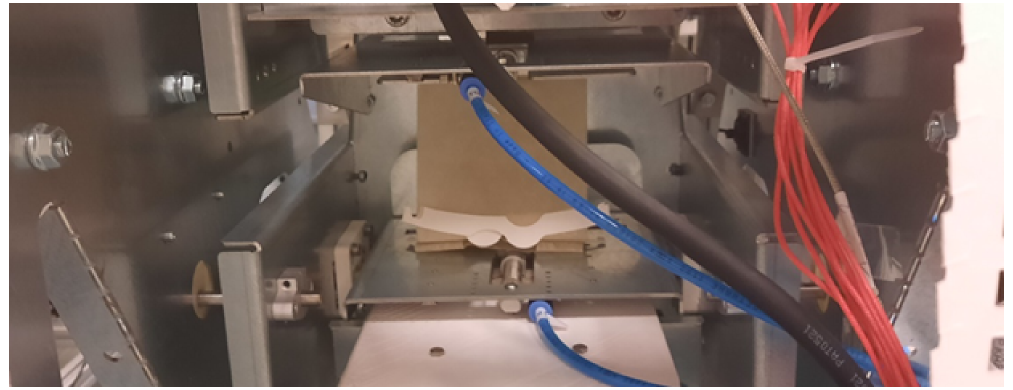


Figure 109: Still occurring critcial failures

The recommendation then is to continue with monitoring the current production to determine the root causes, and during this time also design and test conceptual solutions outside of the machine. With the additional iterations of the framework, the goal becomes to reach the desired state, specifically improving running time and yield by eliminating critical failures (Figure 110). As these complex problems will most likely require a more complex redesign process orientating on possible improvements is a necessary step to determine if the probability of the improvements is high enough for the choice of implementation to be made.

Figure 110: Further steps needed to get to the ideal state

It is recommended to start exploring possible further development of additional, or version twos, of the machine to further increase production. Because the current machine will at some point hit the metaphorical ceiling of the production yield. During the current stage, there is still improvement possible in production time, however, the increase possible in the quality, production speed, and production yield percentage will decrease in effectivity each improvement cycle. The maximum yield is expected to be roughly 7200 tea infusers per day of production when the company will move more product than this metaphorical production ceiling a second production machine is needed.

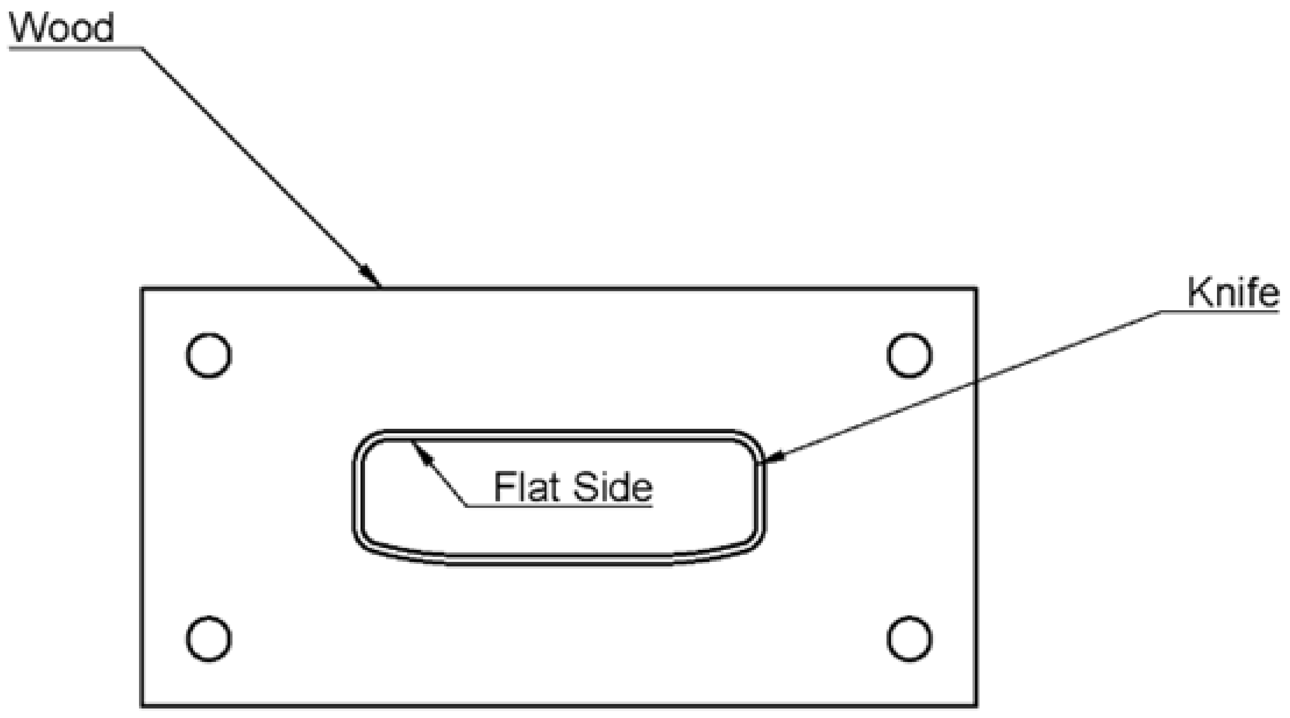
References

[1] TeaWall Homepage, https://www.teawall.co
[2] Proef thee zoals het hoort. Hush.nl- Voor De Lekkerste Vers Belegde Broodjes. https://www.hush.nl/teawall-proef-thee-zoals-het-hoort/
[3] Grant, A., & Grant, A. (2023, February 13). Composting Tea Bags: Can I Put Tea Bags In The Garden? Gardening Know How. https://www.gardeningknowhow.com/composting/ingredients/composting-tea-bags.htm
[4] https://www.ecoenclose.com/blog/8-things-to-know-about-compost-facilities-and-6-tips-to-be-a-responsible-composter/
[5] Singh, J., & Singh, H. (2015). Continuous improvement philosophy – literature review and directions. Benchmarking: An International Journal, 22(1), 75–119. https://doi.org/10.1108/bij-06-2012-0038
[6] Narottam, Mathiyazhagan, K., & Sharma, V. (2020). Defect Reduction in Manufacturing Industry Using Lean Six Sigma Approach. In Lecture notes in mechanical engineering (pp. 19–30). Springer Nature. https://doi.org/10.1007/978-981-15-1071-7_3
[7] Mauri, F., Garetti, M., & Gandelli, A. (2010). A structured approach to process improvement in manufacturing systems. Production Planning & Control, 21(7), 695–717. https://doi.org/10.1080/09537280903563485
[8] Feng, T., Zhang, Y., Wang, X., & Li, Y. (2018). Application of lean six sigma in energy saving lamp assembly process. Journal of Physics, 1053, 012129. https://doi.org/10.1088/1742-6596/1053/1/012129
[9] Lean Six Sigma Groep. (2023, April 19). DMAIC- Lean Six Sigma Groep. https://leansixsigmagroep.nl/lean-agile-en-six-sigma/dmaic/
[10] Theisens, H. (2021). Lean Six Sigma: Green Belt : Mindset, Skill Set & Tool Set.
[11] Montgomery, D. C. (2008b). Introduction to Statistical Quality Control. Wiley.
[12] Erikuscernota. (2021, April 21). DMAIC Process, DMAIC Model – How to successfully use it – Six Sigma Mania. https://sixsigmamania.com/?p=55&utm_source=rss&utm_medium=rss&utm_campaign=dmaic-process-dmaic-model-why-how-to-use-it
[13] Gijo, E., Palod, R., & Antony, J. (2018). Lean Six Sigma approach in an Indian auto ancillary conglomerate: a case study. Production Planning & Control, 29(9), 761–772. https://doi.org/10.1080/09537287.2018.1469801
[14]Subagyo, I. E., Saraswati, D., Trilaksono, T., & Kusmulyono, M. S. (2020). BENEFITS AND CHALLENGES OF DMAIC METHODOLOGY IMPLEMENTATION IN SERVICE COMPANIES: AN EXPLORATORY STUDY. Jurnal Aplikasi Manajemen, 18(4), 814–824. https://doi.org/10.21776/ub.jam.2020.018.04.19
[15] Jevgeni, S., Eduard, S., & Roman, Z. (2015). Framework for Continuous Improvement of Production Processes and Product Throughput. Procedia Engineering, 100, 511–519. https://doi.org/10.1016/j.proeng.2015.01.398
[16] Rausand, M., & Hoyland, A. (2003). System Reliability Theory: Models, Statistical Methods, and Applications. John Wiley & Sons.
[17] Neves, P. L., Silva, F., De Souza Ferreira, L. C., Pereira, T., Gouveia, A., & Pimentel, C. (2018). Implementing Lean Tools in the Manufacturing Process of Trimmings Products. Procedia Manufacturing, 17, 696–704. https://doi.org/10.1016/j.promfg.2018.10.119
[18] Vorkapić, M., Bogetić, S., Tanović, D., Hasan, M. K., & Kovačević, A. (2019). 5S elements as steps to bridge the GAP in transmitter manufacturing process. Journal of Engineering Mangement and Competitiveness, 9(2), 148–158. https://doi.org/10.5937/jemc1902148v
[19] Srinivasan, K., Muthu, S., Prasad, N. E., & Satheesh, G. (2014). Reduction of Paint line Defects in Shock Absorber Through Six Sigma DMAIC Phases. Procedia Engineering, 97, 1755–1764. https://doi.org/10.1016/j.proeng.2014.12.327
[20] Balm, G. J. (1996). Benchmarking and gap analysis: what is the next milestone? Benchmarking for Quality Management & Technology, 3(4), 28–33. https://doi.org/10.1108/14635779610153345
[21] Li, G., Yuan, C., Kamarthi, S., Moghaddam, M. E., & Jin, X. (2021). Data science skills and domain knowledge requirements in the manufacturing industry: A gap analysis. Journal of Manufacturing Systems, 60, 692–706. https://doi.org/10.1016/j.jmsy.2021.07.007
[22] dataPARC. (2022). How to Perform a Manufacturing Gap Analysis. dataPARC. https://www.dataparc.com/blog/how-to-perform-manufacturing-gap-analysis/
[23] Weller, J. (n.d.). The Complete Guide to Gap Analysis. Smartsheet. https://www.smartsheet.com/gap-analysis-method-examples
[24] Martin, E. C., Morris, A. P., & Kiparissides, C. (1999). Manufacturing performance enhancement through multivariate statistical process control. Annual Reviews in Control, 23, 35–44. https://doi.org/10.1016/s1367-5788(99)90055-x[24] https://www.wikinoticia.com/uploads/7/4/8/7/7487334/dikwchain.pdf
[26] Statisti, U. P. O. R. A. B. O., & Tehnike, N. (2009). Improving the process capability of a turning operation by the application of statistical techniques. Materiali in tehnologije, 43(1), 55-59.
[27] Stamatis, D. H. (2003). Failure Mode and Effect Analysis: FMEA from Theory to Execution. Quality Press.
[28] Ouyang, L., Zheng, W., Zhu, Y., & Zhou, X. (2020). An interval probability-based FMEA model for risk assessment: A real-world case. Quality and Reliability Engineering International, 36(1), 125–143. https://doi.org/10.1002/qre.2563
[29] Yanti, M., Lubis, F. S., Nazaruddin, N., Rizki, M., Silvia, S., & Sarbaini, S. (2022). Production Line Improvement Analysis With Lean Manufacturing Approach To Reduce Waste At CV. TMJ uses Value Stream Mapping (VSM) and Root Cause Analysis (RCA) methods.
[30] Ishikawa K, Loftus JH, (Eds): Introduction to quality control Tokyo, Japan: 3A Corporation, 1990
[31] Ito, A. S., Hagström, M., Bokrantz, J., Skoogh, A., Nawcki, M., Gandhi, K., Bergsjö, D. H., & Bärring, M. (2022). Improved root cause analysis supporting resilient production systems. Journal of Manufacturing Systems, 64, 468–478. https://doi.org/10.1016/j.jmsy.2022.07.015
[32] Nagyova, A., Pačaiová, H., Gobanova, A., & Turisová, R. (2019). An Empirical Study of Root-Cause Analysis in Automotive Supplier Organisation. Quality, Innovation, Prosperity, 23(2), 34. https://doi.org/10.12776/qip.v23i2.1243
[33]Wibawa, A., Budiardjo, E. K., & Mahatma, K. (2021). Improving the Quality of Requirements Engineering Process in Software Development with Agile Methods: a Case Study Telemedicine Startup XYZ. https://doi.org/10.1109/icadeis52521.2021.9701962
[34] Cross, N., Dorst, K., & Roozenburg, N. (1992). Research in Design Thinking. Amsterdam, Nederland: Amsterdam University Press.
[35] Dam, R. F. (2022, May). The 5 Stages in the Design Thinking Process. The Interaction Design Foundation. https://www.interaction-design.org/literature/article/5-stages-in-the-design-thinking-process
[36] Design Thinking. (2022, December 12). Let's Talk Science. https://letstalkscience.ca/educational-resources/backgrounders/design-thinking
[37] Six Sigma DMAIC Cyle. (n.d.). https://www.professionaldevelopment.ie/lean-six-sigma-dmaic-cycle
[38] Compostable oil based plastic free teabag solutions. (n.d.). Ahlstrom. https://www.ahlstrom.com/products/beverage-filter-media-and-packaging-solutions/tea-packaging-solutions/compostable-plastic-free-teabag-solutions/
[39] Speksi: ECO-BARRIER-HEAT. (n.d.). https://ipp.nl/wp-content/uploads/2016/06/ECO-BARRIER-JAZZ-@-HEAT_TrayformaNatura.pdf

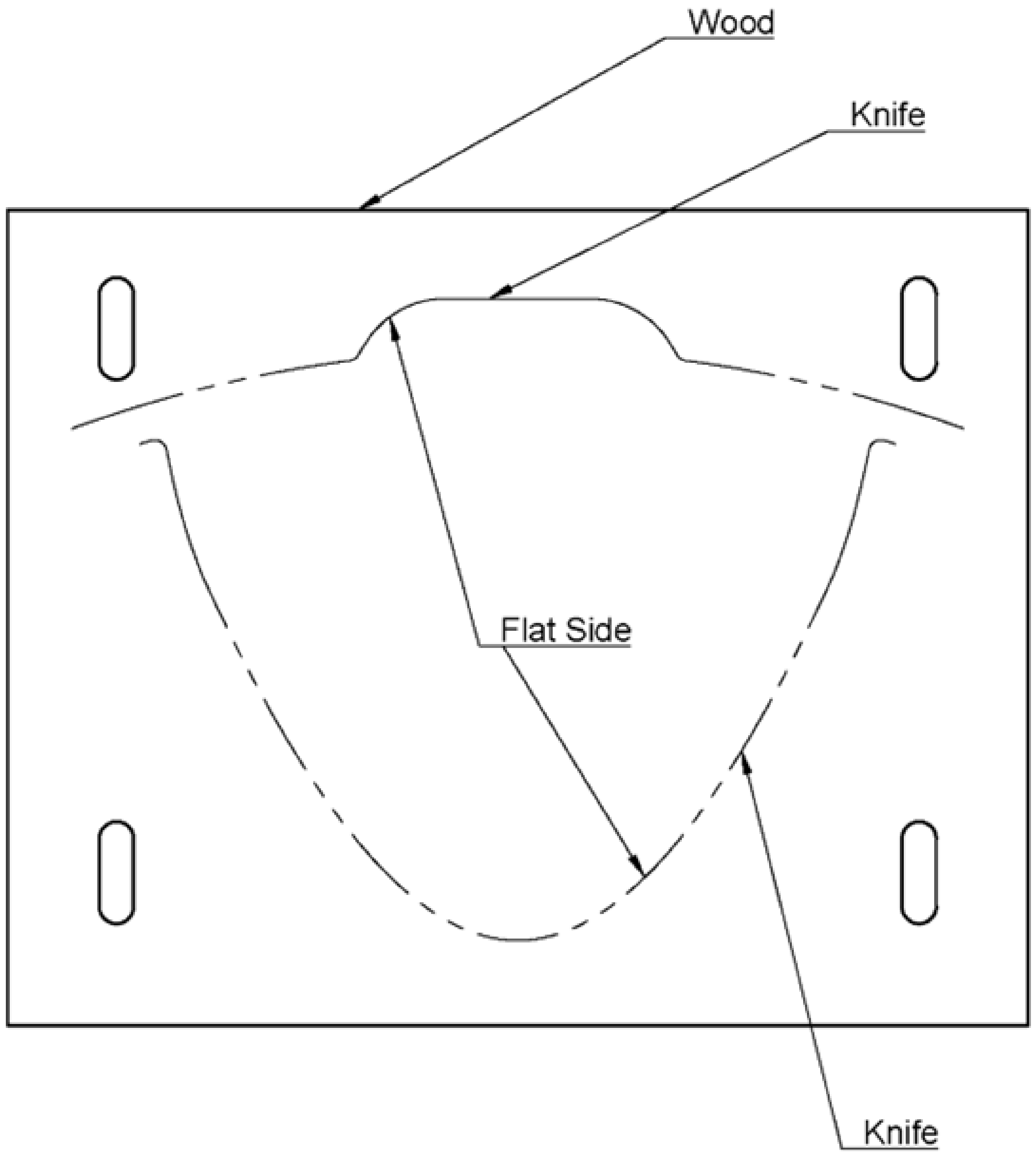
APPENDICES

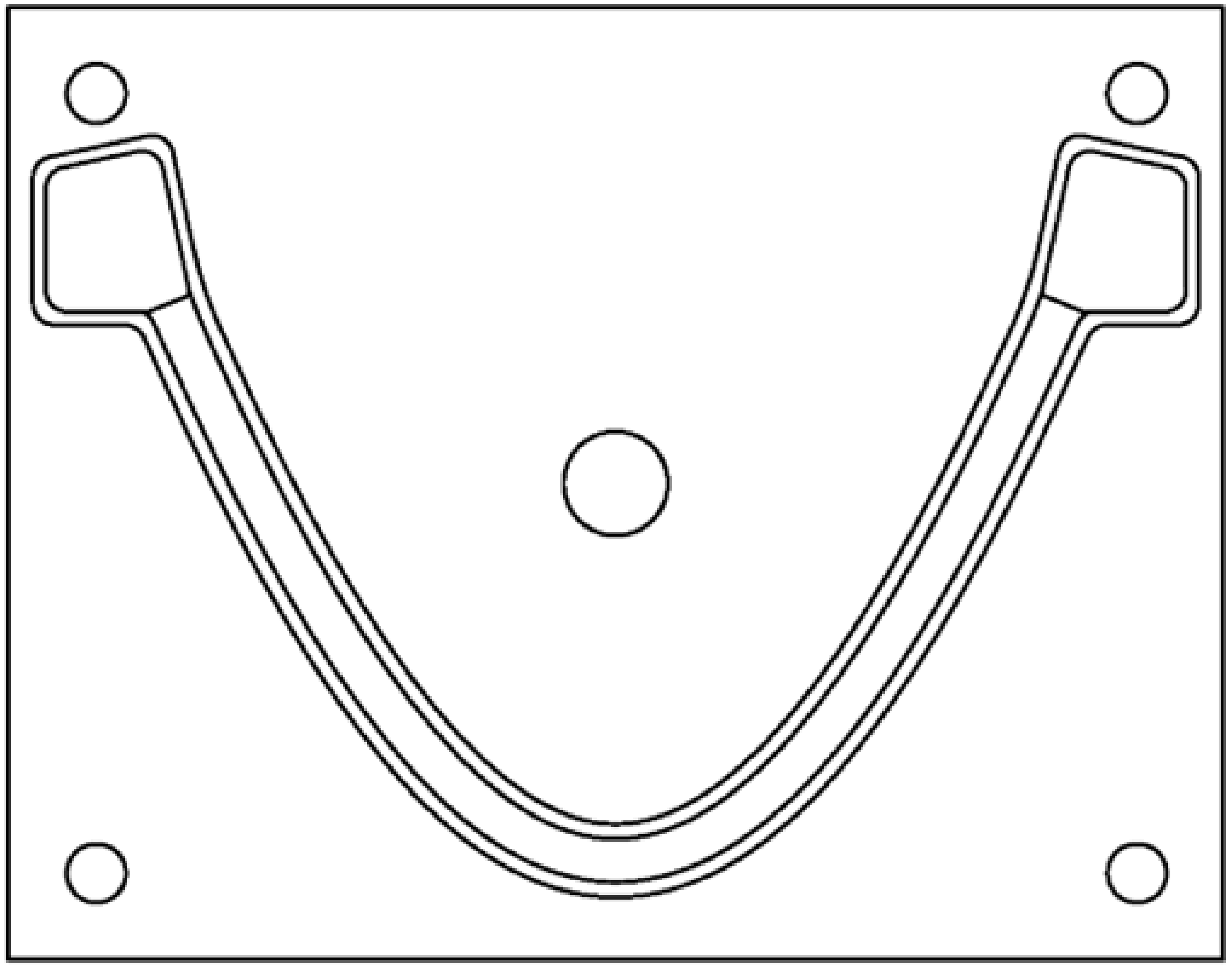
Appendix A. TeaWall Flyer

Appendix B.1 Knife design module 20



Appendix B.2 Knife design module 60





AHLSTROM

Composed of heatsealable fibres (PLA), abaca and selected cellulosic fibres. Recommended sealing temperature is 180-200°C. This material is compliant with the European norm EN 13432 requirement for composting. The difference between material 4 and this material, is that this one is unbleached.

Weight	16.5 g/m^2
Dry tensile strength (machine direction)	700 N/m
Dry tensile strength (cross-machine direction)	220 N/m
Dry elongation (machine direction)	60 N/m
Delamination seal strength (machine direction)	175 g/25mm
Air permeability	1200 l/ min/100cm^2
Colour	Brown (unbleached)

Appendix D Cardboard datasheet

PRODUCT SPECIFICATION

PRODUCT: ECO BARRIER JAZZ @ HEAT

ECO BARRIER JAZZ @ HEAT:
Gives barrier to below mentioned applications

TYPICAL APPLICATIONS:
Ovenable trays, bakery products, non-food packaging.

SPECIAL FEATURES:
Dual ovenable, moderate WVTR, good water resistance, excellent oil and grease resistance, compostable, repulpable, recyclable, glueable, heat sealable (coating against coating).

CONSTRUCTION:
Dispersion coated product where 190 - 390 g/m^2 SBS board has been coated with heat resistant barrier coating material.

PRODUCT SAFETY:
This product fulfills the requirements of Regulation (EC) N:o 1935/2004 and Commission Regulation (EU) No 10/2011 on materials and articles intended to come into contact with food.This product is suitable to use in conventional oven (220 °C, 30 minutes). The product does not contain substances that have been classified as dangerous for health.

FIRE HAZARD:
The product burns, but it is not classified as an inflammable substance. To extinguish you can use water mist, extinguishing powder, foam or carbon dioxide.

WASTE HANDLING:
Raw materials used in manufacturing are compostable. The product is recyclable and clean product can be re-used for example in re-pulping. Un-clean product can be transported to a dumping area or it can be disposed of by burning, depending on the local regulations. Gases occurring in proper incineration do not require special cleaning equipment.

DIMENSIONS:
Coated board
- Basis weight ordered ± 5 %
- Width ordered ± 3 mm
- Moisture ordered ± 5 %

Reel diameter ordered ± 20 mm

TECHNICAL DATA:

Property	Unit	Typical values	Test method
Weight	g/m²	200-400	ISO 536
Thickness	µm	255-550	ISO 534
Moisture	%	8 - 10	ISO 287
WVTR	g/m²/24h	<50	ISO 2528
Cobb 1800s	g/m²	<10	ISO 535

Appendix E Measurement tables

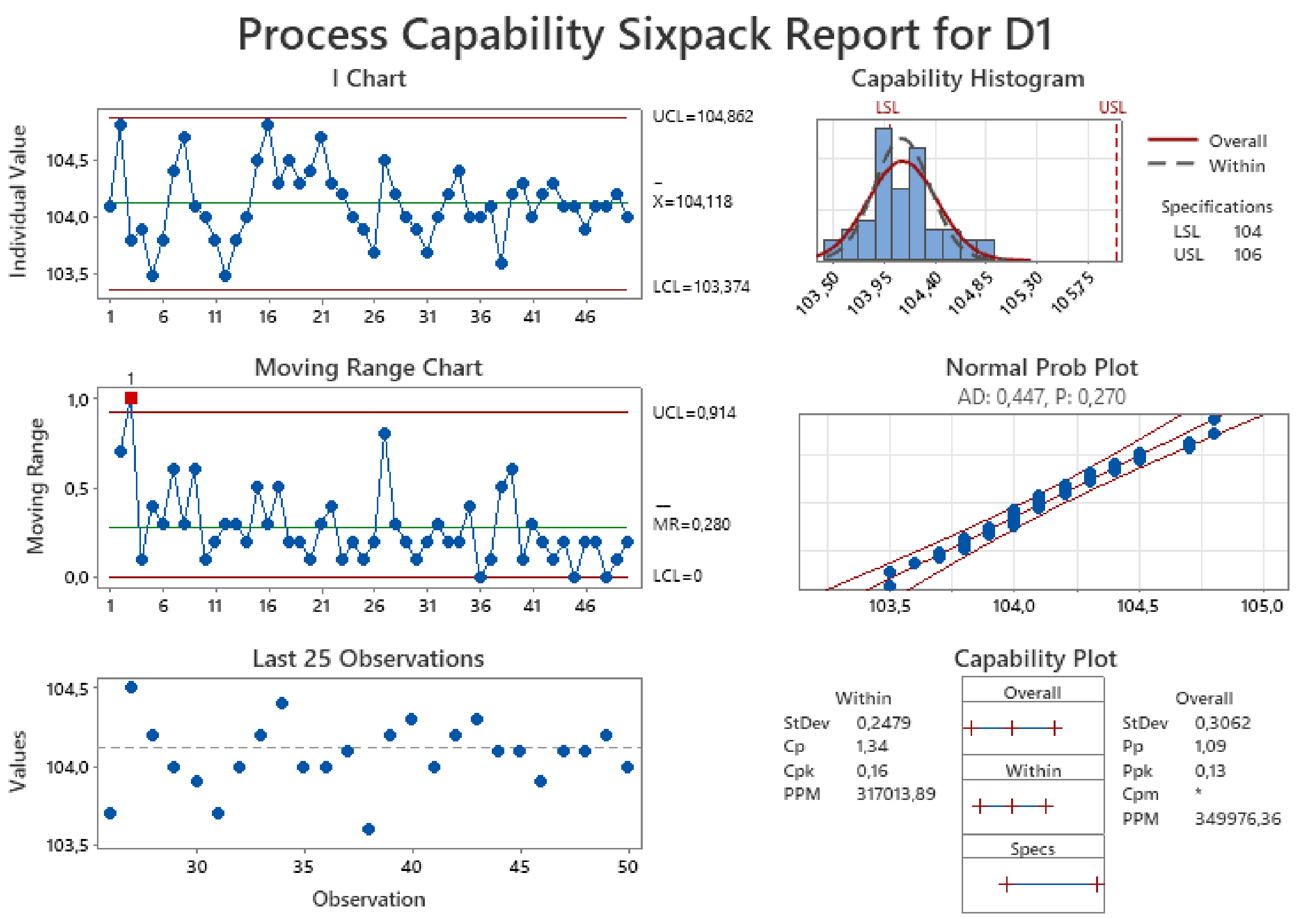
Table 22: Batch #1

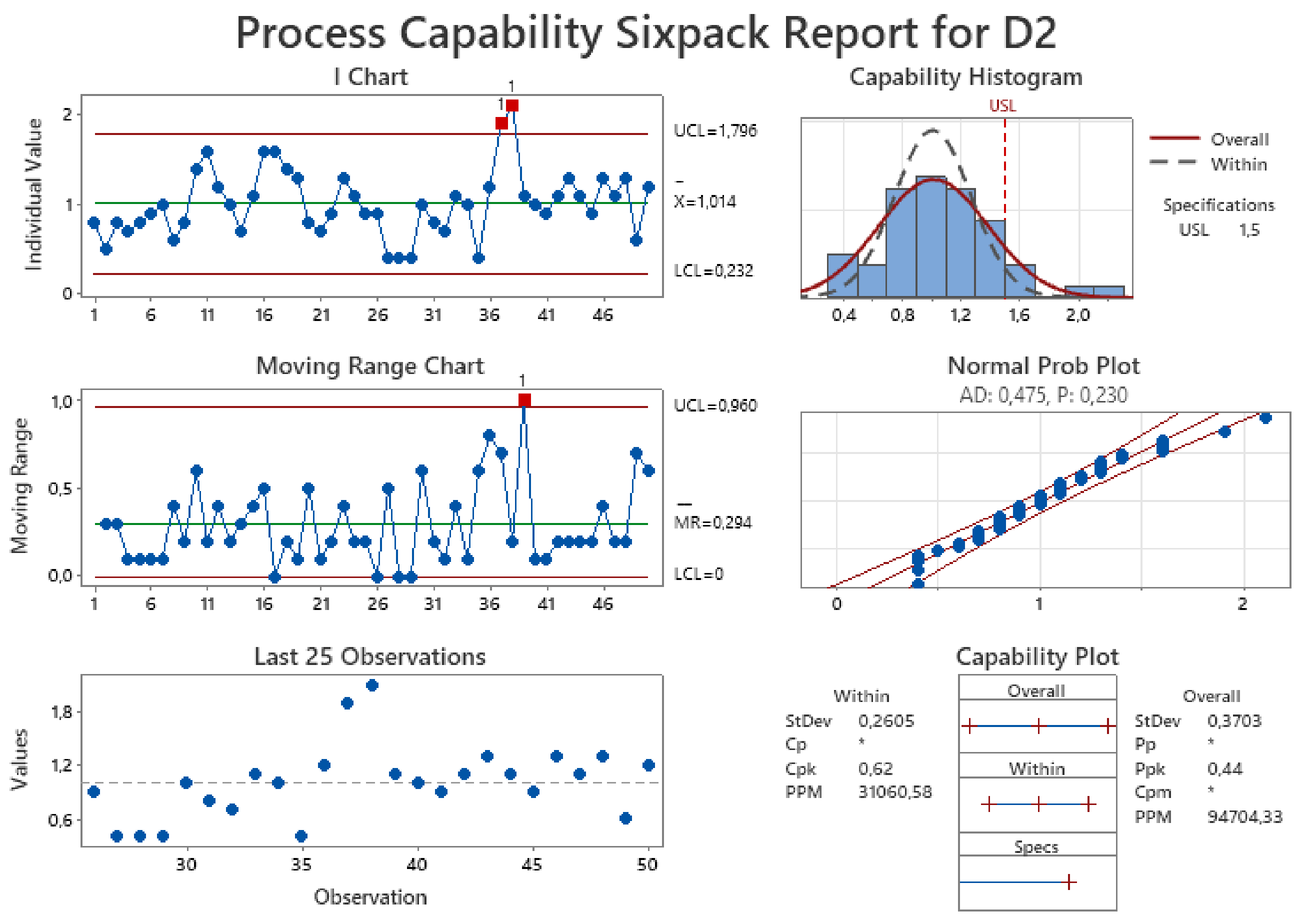
Nr	Waste	D1	D2	D3	D4	D5	C1-8
1	x	104,1	0,8	2,1	0,3	4,3	
2		104,8	0,5	1,8	0,4	4,0	
3		103,8	0,8	1,7	0,5	4,1	
4	x	103,9	0,7	2,3	0,5	3,9	x
5	x	103,5	0,8	2,3	0,4	3,9	x
6	x	103,8	0,9	2,4	0,3	4,0	x
7	x	104,4	1,0	2,5	0,2	4,0	x
8	x	104,7	0,6	2,5	0,2	4,1	x
9	x	104,1	0,8	2,1	0,3	4,1	
10		104,0	1,4	1,5	0,4	4,0	
11	x	103,8	1,6	2,0	0,4	4,0	
12	x	103,5	1,2	2,1	0,4	4,0	x
13	x	103,8	1,0	2,2	0,4	4,1	x
14	x	104,0	0,7	2,4	0,3	3,9	x
15		104,5	1,1	1,8	0,4	4,1	
16	x	104,8	1,6	0,9	0,5	4,0	
17	x	104,3	1,6	1,2	0,6	3,9	
18		104,5	1,4	1,0	0,4	4,0	
19		104,3	1,3	1,2	0,4	4,1	
20		104,4	0,8	1,8	0,3	3,9	
21		104,7	0,7	1,9	0,4	4,0	
22		104,3	0,9	1,4	0,4	4,0	
23		104,2	1,3	1,7	0,4	4,0	
24		104,0	1,1	1,8	0,5	4,0	
25	x	103,9	0,9	1,9	0,6	4,1	x
26		103,7	0,9	1,9	0,5	4,0	
27		104,5	0,4	2,1	0,4	4,1	
28		104,2	0,4	2,2	0,5	4,2	
29		104,0	0,4	1,9	0,6	4,2	
30		103,9	1,0	2,0	0,7	4,2	
31	x	103,7	0,8	2,0	0,6	4,3	x
32	x	104,0	0,7	2,4	0,5	4,2	x
33	x	104,2	1,1	2,1	0,3	4,3	x
34		104,4	1,0	1,7	0,2	4,2	
35		104,0	0,4	1,6	0,2	4,2	
36		104,0	1,2	1,1	0,4	4,0	
37		104,1	1,9	0,9	0,5	4,1	
38		103,6	2,1	1,2	0,5	4,1	
39		104,2	1,1	1,3	0,2	4,3	
40	x	104,3	1,0	1,4	0,2	4,2	x
41	x	104,0	0,9	1,7	0,3	4,3	x
42		104,2	1,1	1,6	0,3	4,4	
43	x	104,3	1,3	1,4	0,4	4,3	x
44	x	104,1	1,1	1,6	0,5	4,2	x
45	x	104,1	0,9	1,9	0,3	4,0	x
46	x	103,9	1,3	1,8	0,2	4,2	x
47	x	104,1	1,1	1,7	0,2	4,1	x
48	x	104,1	1,3	1,9	0,3	4,1	x
49	x	104,2	0,6	1,9	0,5	4,1	x
50	x	104,0	1,2	1,8	0,6	4,2	x

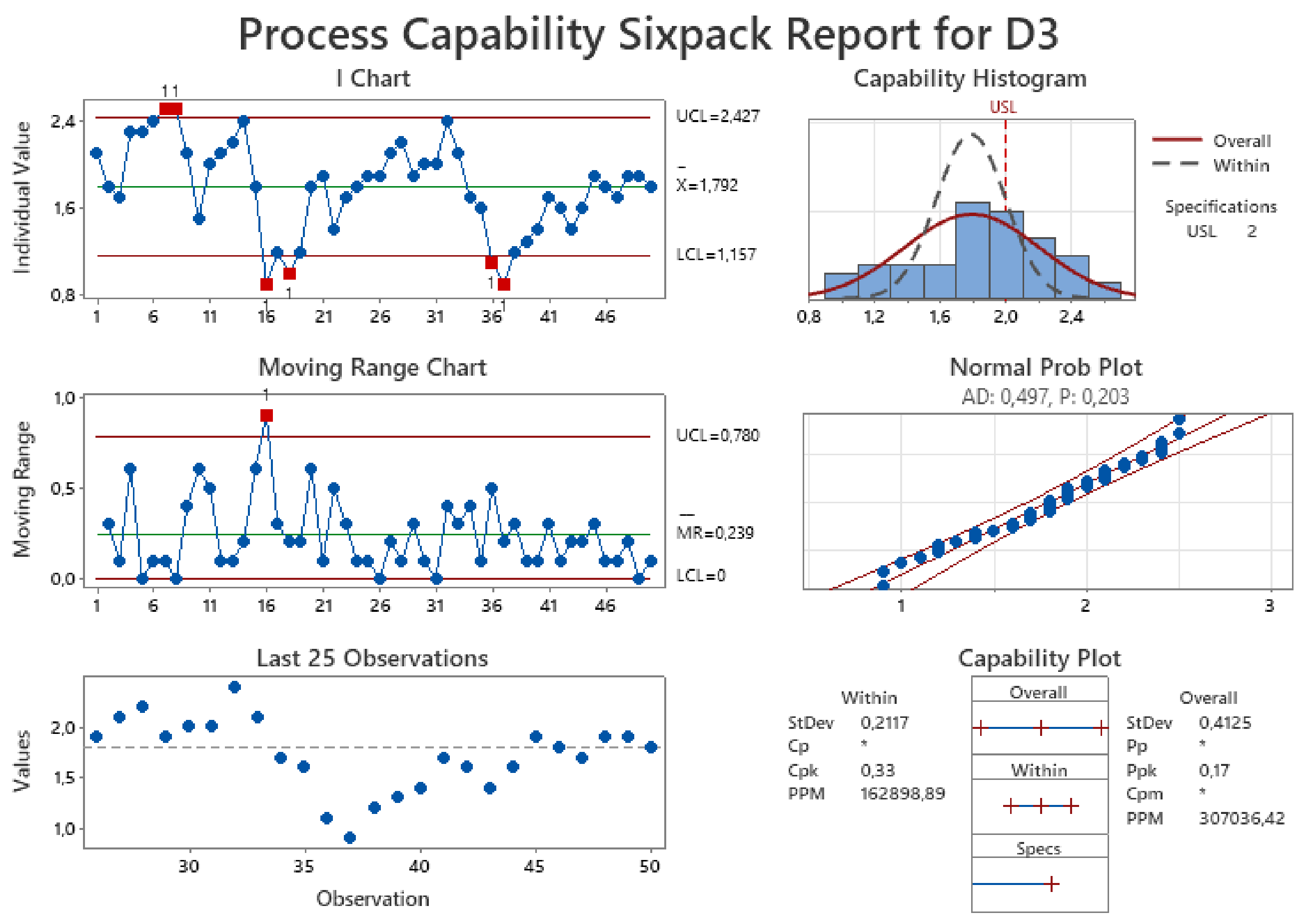
Table 23: Batch #2

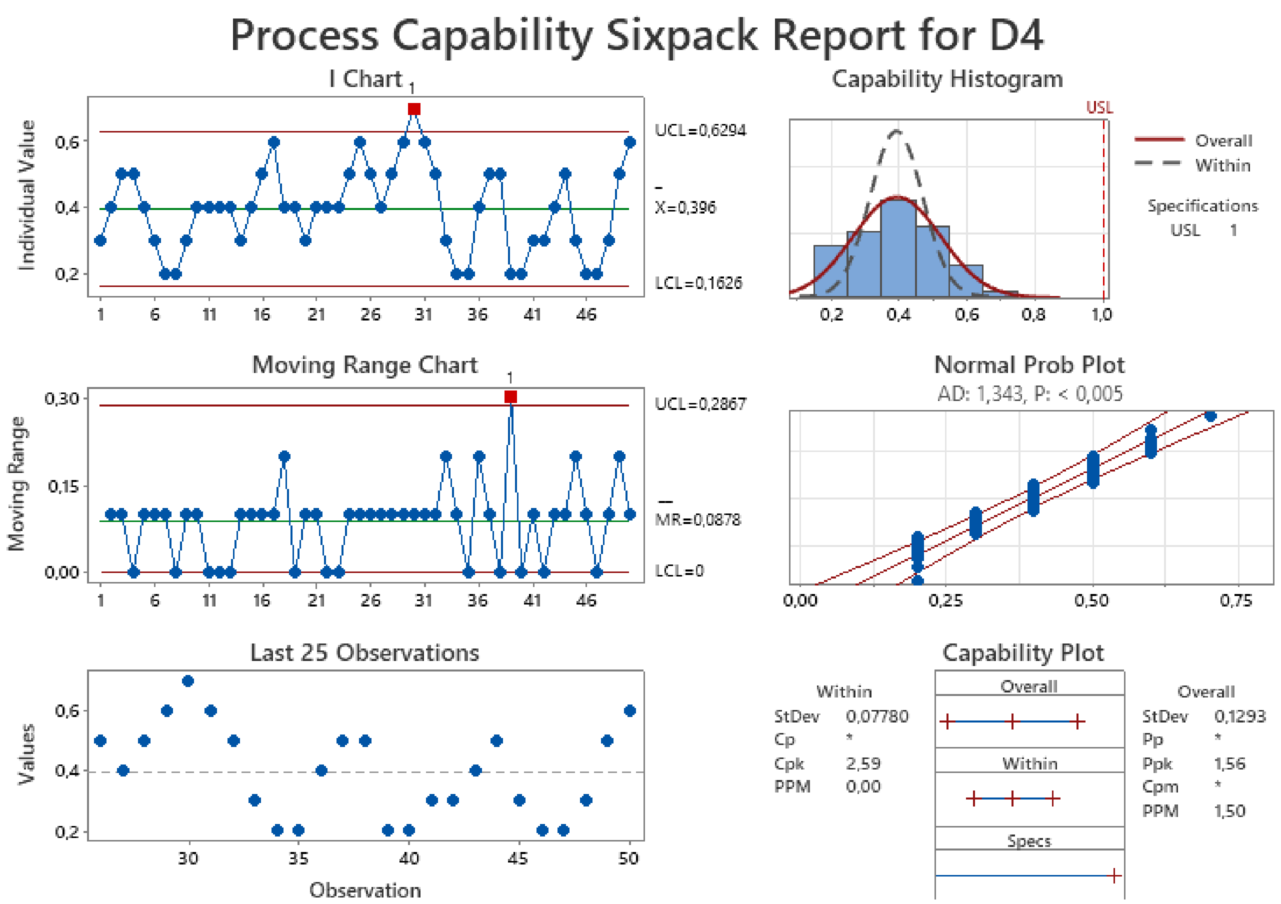
Nr	Waste	D1	D2	D3	D4	D5	C1-8
1		104,3	0,2	0,3	0,3	4,0	
2		104,3	0,2	0,3	0,2	4,0	
3		104,8	0,9	0,2	0,2	4,1	
4	x	104,0	2,1	0,0	0,4	4,2	x
5	x	104,5	2,1	0,0	0,4	4,1	x
6	x	104,1	2,0	0,0	0,3	4,3	x
7	x	104,1	0,7	0,0	0,2	4,0	x
8		104,2	0,5	0,4	0,4	4,2	
9		104,0	0,8	0,1	0,5	4,0	
10		104,2	0,9	0,1	0,2	4,1	
11		104,4	0,8	0,2	0,6	4,0	
12		104,3	0,9	0,3	0,4	4,1	
13		104,2	0,3	0,1	0,4	4,1	
14		104,3	0,5	0,2	0,3	4,1	
15	x	104,3	1,7	0,0	0,2	4,2	x
16	x	104,2	1,8	0,0	0,4	4,3	x
17	x	104,2	1,9	0,0	0,4	4,2	x
18	x	104,5	1,0	0,0	0,5	3,9	x
19		104,4	0,7	0,3	0,3	3,9	
20		104,2	0,5	0,2	0,4	3,9	
21	x	104,0	1,2	0,0	0,6	4,2	x
22	x	103,9	1,1	0,0	0,7	4,1	x
23	x	104,1	1,2	0,0	0,5	4,2	x
24	x	104,3	0,7	0,0	0,6	4,0	x
25	x	104,2	0,4	0,0	0,5	4,1	x

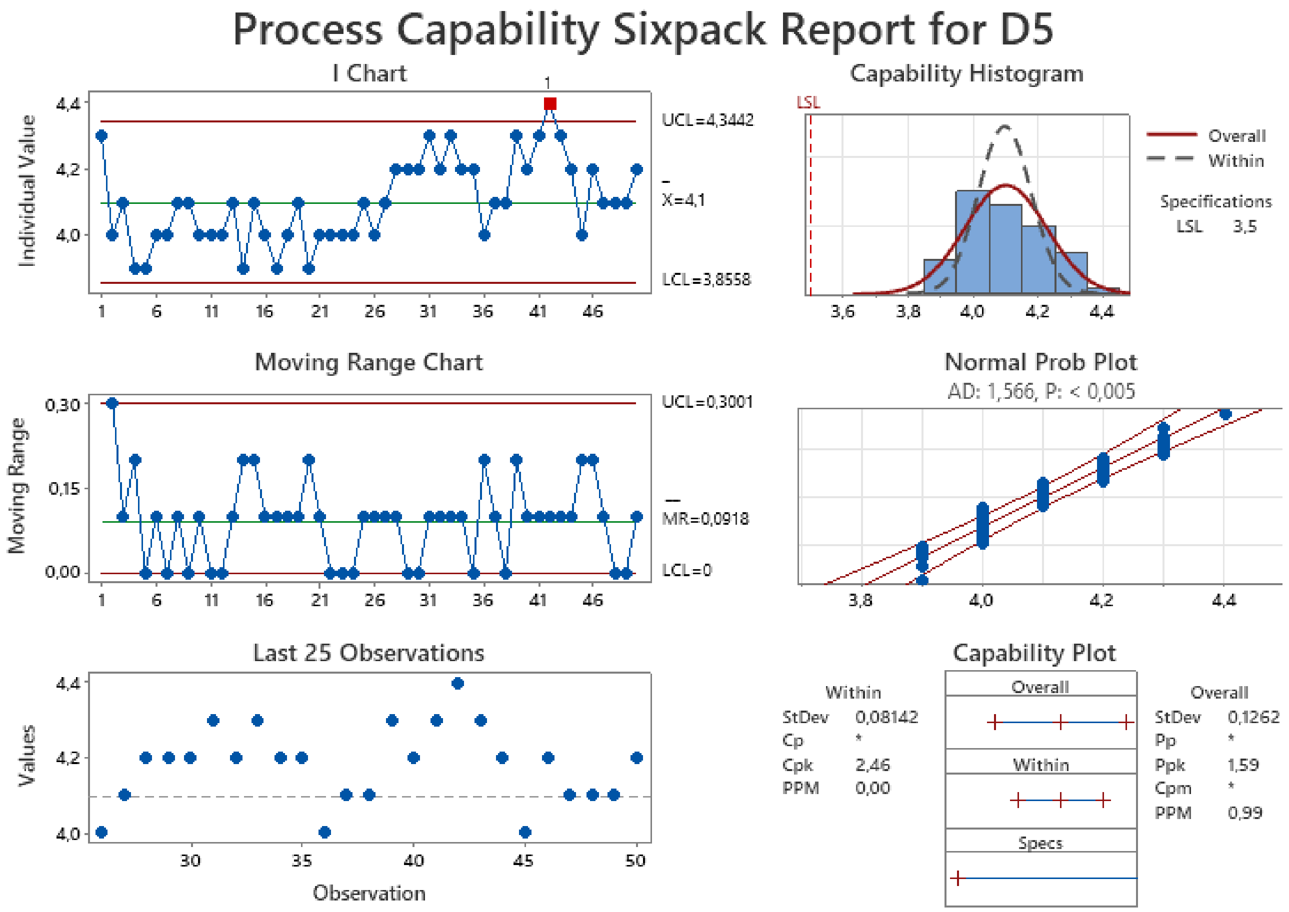
Appendix F.1 Capability analysis



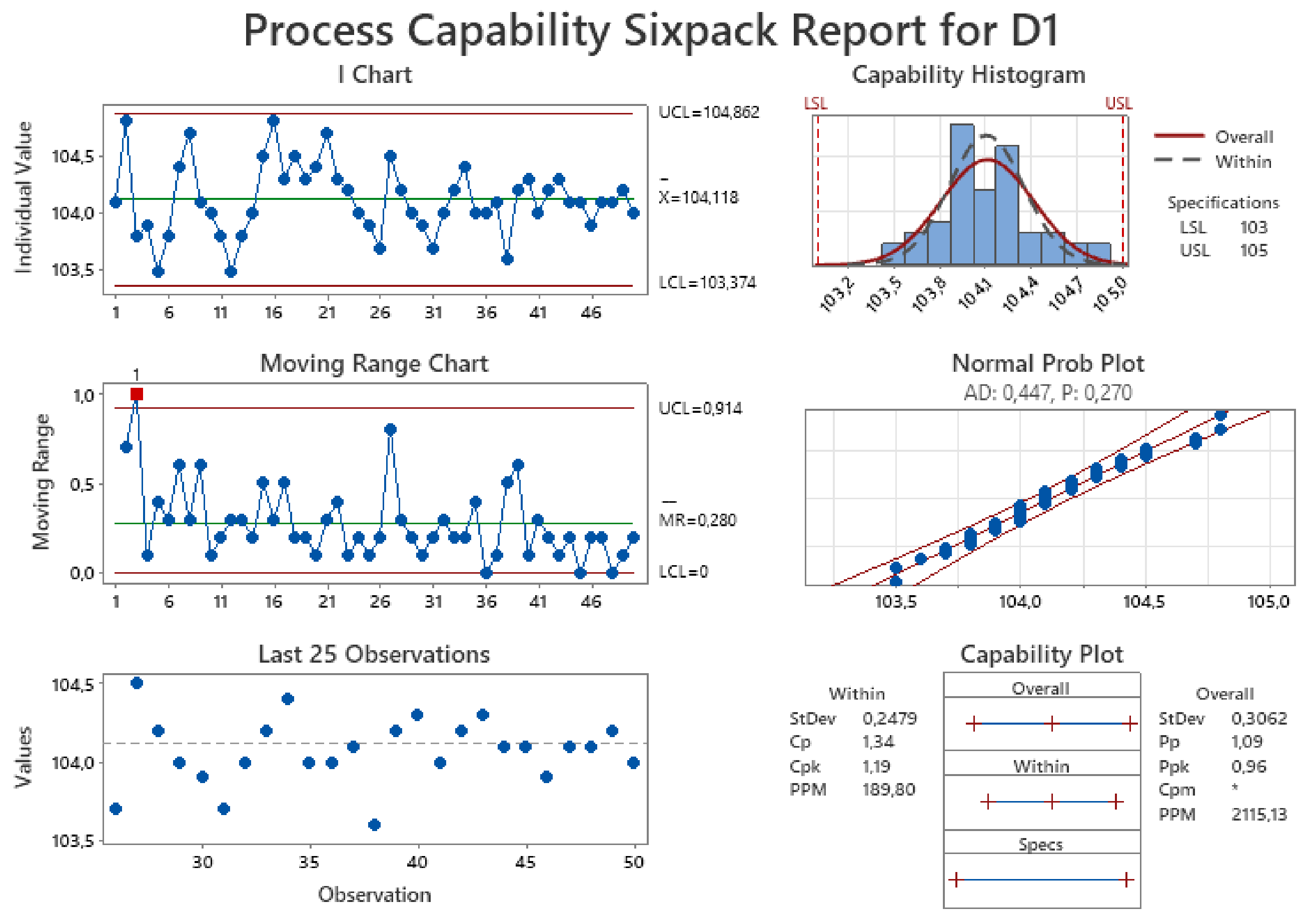


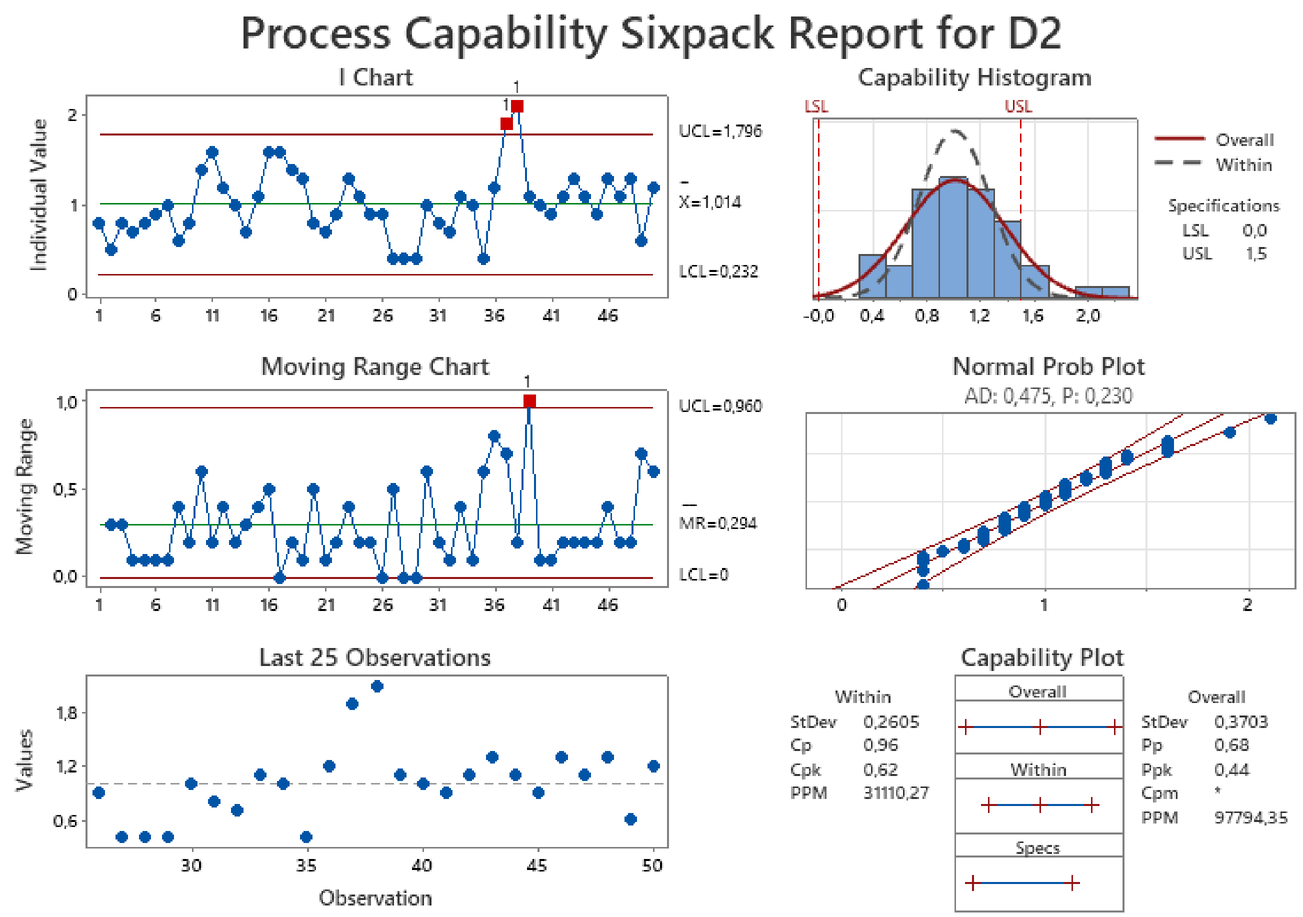


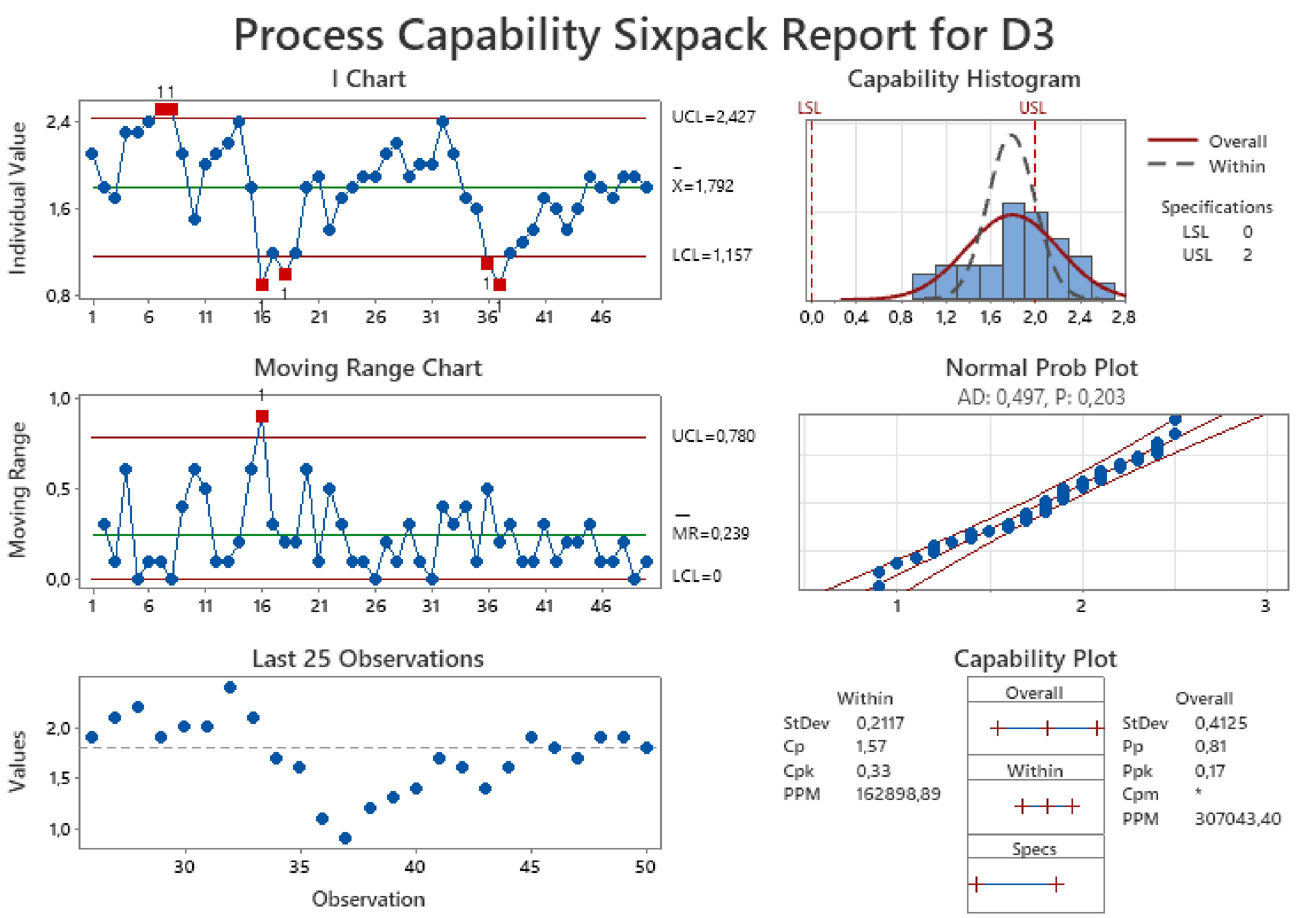


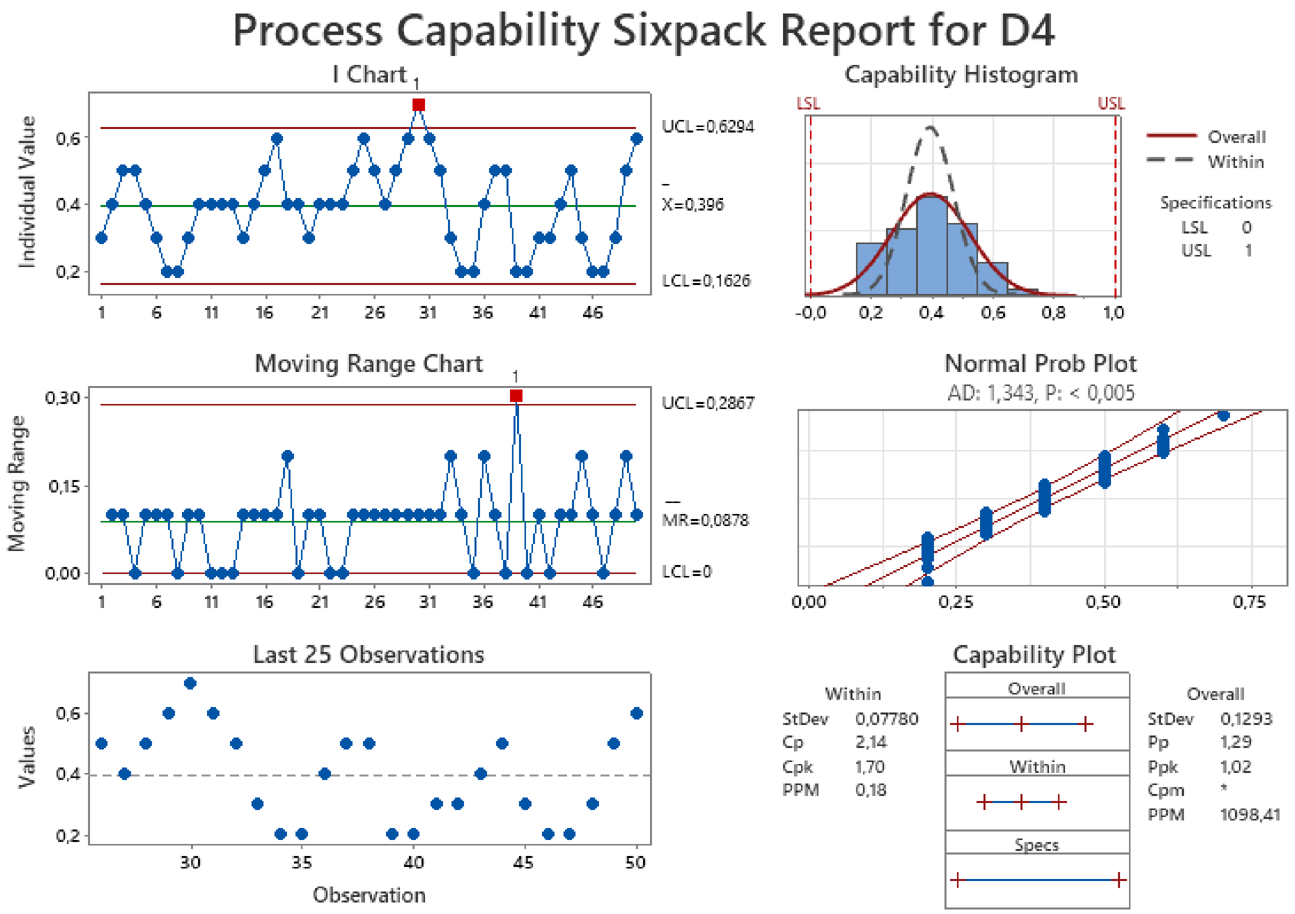


Appendix F.2 Updated capability analysis









Appendix G Failure mode occurence

Table 24: FMEA measurements

Base	
Measurement	Occurrence
Total	220
Yield	45
C1	125
C3	1
C4	35
C5: 50	11
C6: 20	2
C7	1
Adjustment #1	
Measurement	Occurrence
Total	323
Yield	224
C4	83
C6: 20	5
C7	6
C8: 35	5
Adjustment #2	
Measurement	Occurrence
Total	234
Yield	172
C1	1
C3	50
C4	2
C6: 20	6
C6: 80/85	3
Adjustment #3	
Measurement	Occurrence
Total	291
Yield	272
C3	12
C4	4
C6: 20	3

Appendix H Root cause analysis measurement

Table 25: Measurements module 90

No/batch	1	2	3	4
1	12,55	12,4	12,45	12,4
2	12,4	12,45	12,6	12,5
3	12,35	12,5	12,45	12,6
4	12,45	12,8	12,45	12,5
5	12,55	12,4	12,35	12,45
6	12,65	12,5	12,45	12,4
7	12,7	12,5	12,5	12,55
8	12,7	12,6	12,45	12,6
9	12,65	12,45	12,6	12,3
10	12,6	12,5	12,4	12,4
11	12,65	12,35	12,5	12,35
12	12,7	12,5	12,45	12,5
13	12,6	12,45	12,35	12,7
14	12,5	12,5	12,4	12,5
15	12,6	12,55	12,55	12,4
16	12,55	12,4	12,65	12,45
17	12,5	12,55	12,5	12,3
18	12,55	12,5	12,45	12,6
19	12,4	12,6	12,6	12,35
20	12,7	12,45	12,5	12,5
21	12,65	12,5	12,45	12,4
22	12,5	12,45	12,35	12,6
23	12,55	12,5	12,5	12,55
24	12,5	12,45	12,45	12,5
25	12,4	12,35	12,35	12,4

Table 26: Measurements module 30/35

No/batch	1	2	3	4
1	12,4	12,5	12,5	12,4
2	12,6	12,6	12,3	12,45
3	12,6	12,5	12,5	12,4
4	12,5	12,5	12,5	12,5
5	12,5	12,45	12,55	12,45
6	12,45	12,5	12,4	12,55
7	12,5	12,5	12,5	12,5
8	12,55	12,4	12,5	12,5
9	12,3	12,55	12,55	12,45
10	12,6	12,5	12,4	12,5
11	12,4	12,4	12,5	12,4
12	12,55	12,55	12,5	12,6
13	12,5	12,4	12,3	12,4
14	12,55	12,4	12,4	12,55
15	12,45	12,45	12,4	12,5
16	12,5	12,55	12,55	12,55
17	12,55	12,45	12,5	12,55
18	12,4	12,5	12,5	12,45
19	12,55	12,5	12,4	12,4
20	12,6	12,6	12,4	12,4
21	12,5	12,4	12,6	12,5
22	12,4	12,5	12,45	12,4
23	12,4	12,5	12,5	12,55
24	12,3	12,45	12,4	12,5
25	12,4	12,55	12,5	12,5

Appendix I FMEA Tables

Table 27: FMEA Occurence

Failure mode	Number of errors per 1000 tea infuser	Occurrence value
C1	1	4
C2	0,5	3
C3	44	7
C4	15	6
C5 - 20	0	1
C5 - 30/35	4	5
C5 - 40	0	1
C5 - 50	1	4
C6 - 20	11	6
C6 - 80/85	6	5
C7	8	6
C8	5	5

Table 28: FMEA Severity

Failure mode	Critical failure	Harm user	Tea infuser useable	Severity value
C1	1	1	3	6
C2	1	1	3	6
C3	3	3	1	8
C4	3	3	1	8
C5 - 20	1	0	3	5
C5 - 30/35	3	0	3	7
C5 - 40	1	0	3	5
C5 - 50	3	0	3	7
C6 - 20	1	3	1	6
C6 - 80/85	1	3	1	6
C7	0	0	0	1
C8	0	0	0	1

Table 29: FMEA Detection

Failure mode	Top	Bottom	Individual	Detection value
C1	3	2	4	10
C2	3	1	2	7
C3	0	0	0	1
C4	3	1	2	7
C5 - 20	0	0	0	1
C5 - 30/35	0	0	0	1
C5 - 40	1	0	0	2
C5 - 50	0	0	0	1
C6 - 20	1	1	2	5
C6 - 80/85	1	1	2	5
C7	1	0	0	2
C8	0	0	0	1

Table 30: FMEA initial

Failure mode	Occurrence	Severity	Risk	Detection	RPN
C1	2	5	10	9	90
C2	1	8	8	3	24
C3	7	3	21	4	84
C4	6	5	30	8	240
C5 - 20	1	6	6	1	6
C5 - 30/35	2	8	16	1	16
C5 - 40	1	8	8	3	24
C5 - 50	1	10	10	2	20
C6 - 20	6	6	36	4	144
C6 - 80/85	3	6	18	6	108
C7	2	4	8	2	16
C8	2	2	4	3	12

Table 31: FMEA determined

Failure mode	Occurrence	Severity	Risk	Detection	RPN
C1	4	6	24	9	216
C2	3	6	18	3	54
C3	7	8	56	4	224
C4	6	8	48	8	384
C5 - 20	1	5	5	1	5
C5 - 30/35	5	7	35	1	35
C5 - 40	1	5	5	3	15
C5 - 50	4	7	28	2	56
C6 - 20	6	6	36	4	144
C6 - 80/85	5	6	30	6	180
C7	6	1	6	2	12
C8	5	1	5	3	15

Appendix J Bill of materials module 30/35

Table 32: BOM of parts to go into the machine

In	Amount	Total
Module_30_Air_Endstop_Bracket	1	2
Omron Through Beam Photoelectric Sensor EE-SX4009-P1	1	2
Module_30_Air_Heatseal_Assembly_Bracket	1	2
Module_30_Air_Cylinder_Bracket	1	2
Air cylinder AEVC-25-25-P-A	1	2
Air Speed Control 360 Swivel Valve	1	2
2/3 Pneumatic Valve	1	2
Pressure Regulator	1	1 (Shared)
Solid State Relais (amount of free relais switches)	1	2
Thermistor PT1000	1	2
Connector pieces	**Amount**	**Total**
Alan Bolt M4 x 10mm	1	2
Alan Bolt M5 x 8mm	4	8
Hex Bolt M4 x 35mm	2	4
Hex Bolt M5 x 35mm	4	8
Hex Bolt M5 x 50mm	6	12
Set Screw M4 x 8	2	4

Table 33: BOM of parts to go out of the machine

Out	Amount	total
Module_30_Guidance_Endstop_Bracket	1	2
Omron Through Beam Photoelectric Sensor EE-SX4009-P1	1	2
Trapeze nut 8	2	4
Trapeze axle 8 x 50mm	2	4
Stepper motor NEMA40	2	4
Stepper driver TB6600	1	2
O-ring D=5mm	2	4
K-type Thermocouple	1	2
Thermocouple driver Max6675	1	2
Connector pieces	**Amount**	**Total**
Alan Bolt M4 x 8mm	4	8
Alan Bolt M5 x 10mm	4	8
Hex Nut M5	4	8

Appendix K Updated code module 30/35

Code pneumatics

```
// INDICATE ACTIVITY
  Serial.println("Active...");
  digitalWrite(ledPin, HIGH);
 digitalWrite(stepper1DirectionPin, 0);
   for (int i = 0; i < 20; i++) {
  digitalWrite(stepper1StepPin, HIGH);
  delayMicroseconds(2500);
  digitalWrite(stepper1StepPin, LOW);
  delayMicroseconds(2500);
  }
  while (digitalRead(endStop1) == LOW){
  digitalWrite(stepper1StepPin, HIGH);
  delayMicroseconds(2500);
  digitalWrite(stepper1StepPin, LOW);
  delayMicroseconds(2500);
  }
  for (int i = 0; i < 20; i++) {
  digitalWrite(stepper1StepPin, HIGH);
  delayMicroseconds(2500);
  digitalWrite(stepper1StepPin, LOW);
  delayMicroseconds(2500);
  }
 while (digitalRead(endStop1) == HIGH) {
  digitalWrite(stepper1StepPin, HIGH);
  delayMicroseconds(2500);
  digitalWrite(stepper1StepPin, LOW);
  delayMicroseconds(2500);
 }
  // PUSH DOWN AIR CILINDER
  digitalWrite(airPin, HIGH);
  // STAY DOWN
  delay(sealTime);
  // PULL UP AIR CILINDER
  digitalWrite(airPin, LOW);
  // FINISHING UP...
  timeFinishedStart = millis();
  stopFlag = true;
```

Code Thermistor

```
//-----------------------------------------------------------------------------
// FUNCTION TO CONTROL HEATERS PER TIME INTERVAL
//-----------------------------------------------------------------------------
void heaterCalculate()
{
 if (millis() > tempReadMillis)
 {
  // Temp1
  tc1 = Thermistor1.calcTemp();
  tempSwitch(setTempHeater1, tc1, relaysHeaterPin1);
  // Temp2
  tc2 = Thermistor2.calcTemp();
  tempSwitch(setTempHeater2, tc2, relaysHeaterPin2);
  // Temp3
  tc3 = Thermistor3.calcTemp();
  tempSwitch(setTempHeater3, tc3, relaysHeaterPin3);

  // LCD
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("Temp1,2:");
  lcd.setCursor(9, 0);
  lcd.print(tc1);
  lcd.setCursor(13, 0);
  lcd.print(tc2);
  lcd.setCursor(0, 1);
  lcd.print("Temp3:");
  lcd.setCursor(7, 1);
  lcd.print(tc3);
  tempReadMillis += 2000;
 }
}

//-----------------------------------------------------------------------------
// FUNCTION TO SWITCH HEATERS DEPENDING ON DELTA. RE-
TURNS LATEST TEMPERATURE
//-----------------------------------------------------------------------------
void tempSwitch(double setTempHeater, double tc, byte relay-
sHeaterPin)
{
 if (tc < setTempHeater)
 {
  digitalWrite(relaysHeaterPin, LOW);
 }
 else if (tc < 5)
 {
  digitalWrite(relaysHeaterPin, LOW);
 }
 else
 {
  digitalWrite(relaysHeaterPin, HIGH);
 }
}
```


Appendix L Bill of materials module 20

Table 34: BOM module 20

In	Amount
Module_20_Frame_Left	1
Module_20_Frame_Right	1
Module_20_Frame_Front	1
Module_20_Frame_Back	1
Module_20_Brackets_Knife	1
Module_20_Brackets_Knife_Connector	1
Module_20_Brackets_Pusher	1
Module_20_Pusher	1
Module_20_Countershape	1
Module_20_Knife_V3_ML10	1
Linear bearing LMT8	2
Linear bearing LMT12	2
Axle bracket SHF8	2
Axle bracket SHF12	4
Axle D=12mm L=174mm	2
Axle D=8mm L=90mm	2
Axle D=6mm L=60mm	2
Air cylinder DSNU-25-50-P-A	1
Air cylinder ESNU-10-10-P-A	1
Air Speed Control 360 Swivel Valve	4
5/3 Pneumatic Valve	2
Valve bracket	2
Pressure Regulator	2
Tubing (m)	3
Solid State Relais (amount of free relais switches)	2
Connector pieces	Total
m5x8	20
m4x8	2
m3*20	4
nut m3	4
m5*35	4
m5*50 half	3
nut m5	12

Appendix M Updated code module 20

```
// INDICATE ACTIVITY
 Serial.println("Active...");
 digitalWrite(ledPin, HIGH);
 // PUSH DOWN KNIFE
 digitalWrite(airPin, HIGH);
 delay(1000);
 // PUSH DOWN PUSHER
 digitalWrite(airPin, HIGH);
 delay(750);
 // PULL UP AIR PUSHER
 digitalWrite(airPin, LOW);
 delay(750);
 // PULL UP KNIFE
 digitalWrite(airPin, LOW);
 delay(1000);
 // FINISHING UP...
 timeFinishedStart = millis();
 stopFlag = true;
```


Appendix N Measurements evaluation

Table 35: Measurements D1-D5 evaluation

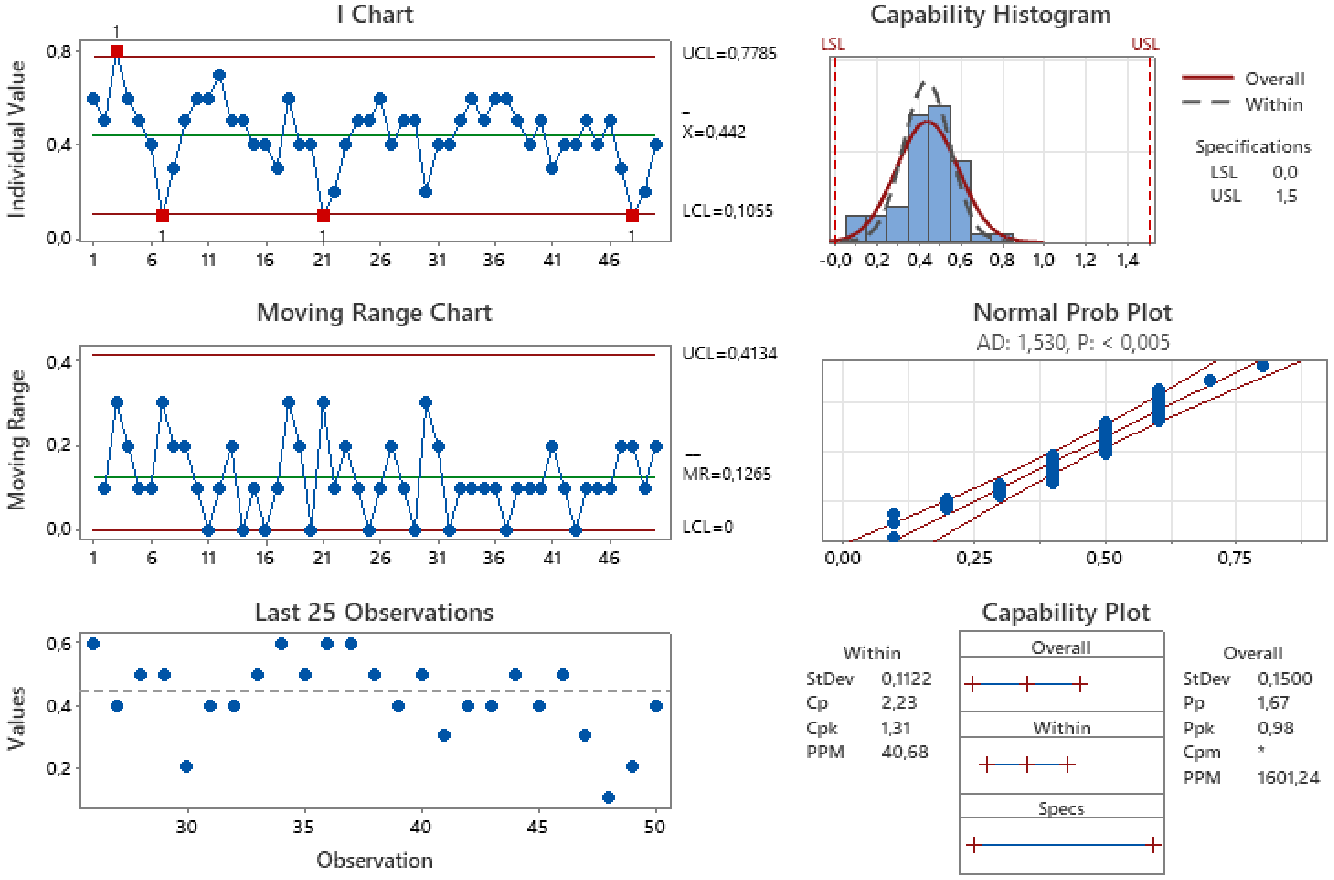
Nr.	D2	D3	D4	D5
1	0,6	0,5	0,6	4,4
2	0,5	0,7	0,6	4,3
3	0,8	0,5	0,5	4,4
4	0,6	0,3	0,6	4,3
5	0,5	0,7	0,5	4,2
6	0,4	0,6	0,4	4,2
7	0,1	0,7	0,4	4,2
8	0,3	0,9	0,5	4,3
9	0,5	0,8	0,4	4,4
10	0,6	0,6	0,2	4,5
11	0,6	0,3	0,3	4,5
12	0,7	0,4	0,3	4,4
13	0,5	0,5	0,2	4,4
14	0,5	0,5	0,3	4,6
15	0,4	0,8	0,2	4,6
16	0,4	0,8	0,3	4,5
17	0,3	0,5	0,2	4,5
18	0,6	0,4	0,2	4,4
19	0,4	0,4	0,2	4,2
20	0,4	0,7	0,1	4,3
21	0,1	0,6	0,2	4,2
22	0,2	0,5	0,2	4,2
23	0,4	0,8	0,3	4,6
24	0,5	0,7	0,4	4,4
25	0,5	0,5	0,5	4,5
26	0,6	0,5	0,5	4,2
27	0,4	0,8	0,4	4,4
28	0,5	0,6	0,3	4,4
29	0,5	0,6	0,4	4,3
30	0,2	0,8	0,2	4,2
31	0,4	0,5	0,3	4,2
32	0,4	0,7	0,4	4,2
33	0,5	0,6	0,4	4,5
34	0,6	0,7	0,5	4,5
35	0,5	0,6	0,6	4,3
36	0,6	0,6	0,3	4,3
37	0,6	0,7	0,2	4,4
38	0,5	0,6	0,3	4,4
39	0,4	0,6	0,4	4,4
40	0,5	0,7	0,4	4,5
41	0,3	0,8	0,4	4,2
42	0,4	1,0	0,2	4,5
43	0,4	0,8	0,3	4,2
44	0,5	0,7	0,4	4,3
45	0,4	0,6	0,5	4,4
46	0,5	0,6	0,6	4,5
47	0,3	0,7	0,3	4,6
48	0,1	0,8	0,2	4,5
49	0,2	0,7	0,3	4,4
50	0,4	0,6	0,4	4,3

Table 36: Failure mode occurence evaluation

Failure mode	0-200	200-400	400-600	600-800	800-1000	Total
C1	0	0	0	0	0	0
C2	0	0	0	0	0	0
C3	0	1	1	0	1	4
C4	0	0	0	0	0	0
C5 -20	0	0	0	0	0	0
C5 -30	0	0	0	0	0	0
C5 -35	0	0	0	0	0	0
C5 -40	0	0	0	0	0	0
C5 -50	0	0	0	0	0	0
C5 -60	0	0	0	0	0	0
C6-20	0	0	0	0	0	0
C6-80/85	1	0	0	0	1	2
C7	0	0	1	1	0	2
C8	0	0	0	0	0	0
P1	0	0	0	0	0	0
P2	0	1	0	0	0	1
P3	0	0	0	0	0	0
P4	0	0	0	0	0	0
P5	0	0	0	1	0	1
P6	0	0	0	0	0	0
P7	0	0	0	0	1	1
P8	0	0	0	0	0	0
P9	0	0	0	0	0	0
P10	0	0	0	0	0	0
H1	0	0	0	0	0	0
H2	0	0	0	0	0	0
H3	0	0	0	0	0	0
H4	0	0	0	0	0	0
H5	0	0	0	0	0	0
H6	0	0	0	0	0	0
H7	0	0	0	0	4	4

Appendix O Capability analysis evaluation

Process Capability Sixpack Report for D2



Process Capability Sixpack Report for D3