

# DEVELOPING AN IMPROVED LASER WELDING MACHINE

*By: J.F. Heiner*





# Final report on the bachelor's assignment

**A research on how to improve the human-machine interaction of the laser welding machine of BW-TEC AG**

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BW-TEC AG  
Hofstrasse 1  
CH 8181 Höri  
+41 44 863 70 70

Student  
J.F. Heiner  
s1086103

Coordinator BW-TEC:  
Mr. M. Wegmann

Bachelor Coordinator  
Ir. M. E. Toxopeus

Project Coordinator  
Dr. Ir. G. M. Bonnema

University of Twente  
Faculty of Engineering Technology (CTW)  
Industrial design

## Preface

For this project I was given the opportunity to work at BW-TEC in Switzerland. I have never been to Switzerland before, so it was a complete new adventure and experience for me. However, I soon felt at ease, because of the comfortable ambience at BW-TEC. Therefore I am very grateful to all my colleagues and my employers I worked with. They gave me many opportunities to support me with my research, they were very flexible and open, and they made me feel at home.

I would like to offer my sincere gratitude to the following people, for investing their time in me and supporting me with my research on how to improve their laser welding machine.

First of all, Michael Wegmann, one of the mechanical engineers of BW-TEC, for coaching me during the project. I was able to discuss every detail of the project with him, whereupon he gave valuable feedback. His mechanical point of view helped me a lot with elaborating my ideas to a certain level.

Mathias Heller and Ben Koch for advice and guidance during my project. I could knock on their doors whenever I liked to appeal to their expertise and point of view.

Josia Pantli, Jakob Willi and Werner Christl in the first place for giving me the opportunity to do my internship at BW-TEC. Besides that, they gave me the opportunity to join Compamed, one of the biggest medical trade fairs in Europe, which I am very thankful for.

All coworkers for their help with my usability test, their help with building the prototypes and for being good company.

All in all, I enjoyed my time at BW-TEC. It was a great learning opportunity for me. I hope that during this project I have shown my capabilities as an industrial designer and that my research will be of value for their future development of laser welding machines.

## Abstract

BW-TEC AG in Switzerland produces several machines for the medical devices industry. This bachelor assignment focuses on their laser welding machine that are designed to weld rotation symmetrical connections of plastic tube and other materials. The laser is used for distal and proximal welding of balloon catheters and for tip forming.

This research report will focus on the human-machine interaction of the laser welding machines type 1244 and 1410.

First, an in-depth analysis of the machine will be executed. This analysis consists of a technology-, product-, market-, and target group analysis. The output of this analysis will be a final set of requirements and wishes. These requirements will form the criteria for suggestions for several possible solutions. These suggestions are further developed into several concepts that consist of solutions on how to improve the human-machine interaction of the laser welding machine. Finally, a chosen concept will be detailed, after which various conclusions will be drawn and recommendations will be proposed. During the development of an improved laser welding machine a distinction can be made between the machine and the HMI.

The outcome of this research is a innovative design for the HMI and for the machine. The HMI is consistent with the style of BW-TEC, but works with icons instead of words. The new designed HMI was tested by use of an extensive usability test which resulted in an intuitive redesign of the HMI. The design of the machine consists of several features that are optimized towards the interaction between the user and the machine. Besides that, several shape studies have been executed that resulted in a final concept proposal. Some of the features have been tested and some prototypes have been manufactured to investigate if they are realizable for future development.

The interfaces between the human and machine could be improved by the proposed designs of the machine itself and the HMI. Several features that meet the set of requirements have been detailed and recommended and could contribute to the future development of the laser welding machine. All the features together result into one design proposal for an improved laser welding machine concerning the human-machine interaction.

## Samenvatting

BW-TEC AG produceert in Zwitserland verschillende machines speciaal voor de medische industrie. Deze bachelor opdracht concentreert zich op de laser las machines die zijn ontworpen om rotatie symmetrische verbindingen van kunststof buizen en andere materialen te lassen. De laser wordt gebruikt om de distale- en proximale zijde van een ballon katheter te lassen en om de uiteinden te voorzien van een zogenaamde tip.

Dit onderzoeksverslag zal zich richten op de mens-machine interacties toegepast op de laser las machines type 1244 en 1410.

Allereerst, zal een uitgebreide analyse van de machine worden uitgevoerd. Deze analyse bestaat uit een technologie-, product-, markt-, en doelgroep-analyse. Deze analyses zullen leiden tot een uiteindelijk programma van eisen en wensen. Deze eisen zullen het criteria vormen voor verschillende ontwerpvoorstellen voor mogelijke oplossingen. Deze suggesties zullen zich gedurende het verslag verder ontwikkelen tot verschillende concepten die bestaan uit oplossingen voor verbeteringen aangaande de mens-machine interacties van de laser las machine. Uiteindelijk zal er een concept verder worden uitgewerkt, waarna er conclusies worden getrokken en verschillende aanbevelingen worden gedaan. Tijdens de ontwikkeling van een verbeterde versie van de laser las machine zal er een onderscheid worden gemaakt tussen de machine en de HMI (Human Machine Interface).

Het resultaat van dit onderzoek zal een innovatief ontwerp zijn voor zowel de HMI als de machine zelf. De HMI is consistent met de stijl van BW-TEC, maar werkt met illustraties in plaats van met woorden. De vernieuwde versie van de HMI is getest met behulp van een uitgebreide gebruikstest. Uit deze test kwamen verschillende verbeteringen voort, waarna de HMI herontworpen is. Het ontwerp van de machine bestaat uit verschillende eigenschappen die geoptimaliseerd zijn met betrekking tot de interactie tussen de gebruiker en de machine. Daarnaast zijn er verschillende vormstudies uitgevoerd die hebben geleid tot een uiteindelijk concept voorstel. Een aantal eigenschappen zijn getest en er zijn een aantal prototypes gemaakt om te onderzoeken of ze realistisch zijn voor verdere ontwikkeling.

De interfaces tussen de mens en de machine kunnen verbeterd worden met de ontwerpen van de HMI en de machine die zijn voorgesteld. Verschillende eigenschappen die voldoen aan het programma van eisen zijn uitgewerkt en worden aanbevolen om bijdrage te leveren aan verdere ontwikkelingen van de laser las machine. Al deze eigenschappen zijn samengevoegd in één uiteindelijk ontwerpvoorstel voor een verbeterde laser las machine met betrekking tot de mens-machine interactie.

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# 1 BW-TEC

## History

The history of BW-TEC started with two men: Jakob Willi and Werner Christl. They worked for many years for Schneider Medizintechnik in Bülach/Switzerland. Schneider Medizintechnik worked closely with Dr. Andreas Grüntzig, a pioneer of Cardiovascular Balloon dilatation. Mr. Willi and Mr. Christl were involved in the development of equipment and got to learn the process of PTCA production first hand. After Schneider was sold to the Pfizer Group and finally got transferred into Boston Scientific in Galway, the time for a new beginning had arrived.

BW-TEC was founded in 1999 by Jakob Willi. After first requests came in from former colleagues, the first machine was built in the garage of his private home. In these exciting pioneer days, Werner Christl joined in and the workshop got moved to the Oertli Building at Hofstrasse 1 in Höri.

In the beginning the two entrepreneurs did everything themselves. Daniela, the daughter of Jakob, helped part time to take care of the administration and international communications. Rumors quickly spread out that there is a Swiss equipment provider in the field of balloon catheters, so thereafter, purchase orders for the development of many different applications were signed. Soon enough Automation and Mechanical Engineers were hired to meet the growing demands. By being present on the annual Medtec Europe event in Stuttgart, and by building solid quality equipment, BW-TEC became known internationally. Especially the CO<sub>2</sub> Laser Welding Machine 394 accelerates the growth of this new enterprise. Companies from around the globe became interested in this technology and within a few years BW-TEC became the benchmark for distal and proximal welding of balloon catheters.

In the last few years, the company grew steadily. Today there are more than 20 people working for BW-TEC. The facility accommodates about 1000 square meters. BW-TEC has customers on six continents and with 85% export share, became an important partner for the Swiss economy.

## Products

Since the beginning of the history of BW-TEC, many different types of machines have been developed to high quality machines. BW-TEC designed machines for the following different applications:

- Laser applications
- Balloon forming applications
- Necking applications
- Test and other applications

*Figure 1 in appendix A* shows the different machines BW-TEC has developed for the accompanying application. The numbers of the machines indicate the version of the machine. A lower number stands for an older machine and a higher number stands for one of the latest machines.

Beside the machines, BW-TEC has also developed a new HMI that is applicable on all of their machines. HMI stands for Human-Machine-Interface and is the user-interface where interactions between humans and machines occur. The user gives the input by pressing for example on a touch screen and simultaneously the machine gives feedback that supports the decision making process of the user.

The BW-TEC HMI has been programmed for Windows and optimized for Touchscreen-applications. The HMI can easily be translated into any language, without any programming expenses.

The user-interface is designed for intuitive and simple interaction. Even recipes with many parameters are clearly displayed and easily administered. With its numerous open interfaces, the HMI can be integrated in company-wide ERP- and MES- systems.

## **Services**

The main services of BW-TEC consist of three different categories: engineering, automation, and consulting.

### ***Engineering***

BW-TEC produces high-quality machines to manufacture medical devices. Their machines are tailor-made for each customer's requirements and can thus be optimally integrated into production processes. Their engineers develop these machines with know-how and professionalism.

### ***Automation***

BW-TEC automates current as well as new processes and procedures with precision and to specification. They always try to find the best division between automation and manual processing to produce high-quality products with very low chance of failure by operator involvement.

### ***Consulting***

BW-TEC supports customers with process design and product development during all phases of a project with foresight and efficiency.

## 2 Laser welding machines



Fig. 1: The laser welding machines type 1410 (left) and type 1244 (right) of BW-TEC.

BW-TEC has developed several laser welding machines over the years for the same application: the assembly of balloon catheters. The latest versions of laser welding machines are the type 1244 and the type 1410.

The machines work semi-automatically and are designed to weld rotation symmetrical connections of plastic tube and other materials. The laser is used for distal and proximal welding of balloon catheters and for tip forming. The distal end of the balloon has a smaller diameter than the proximal end and therefore the parameters of the welding process that have to be filled out by the user are slightly different. The formed tip functions as a smoother guidance when the catheter enters the vascular system of the patient (fig. 2).

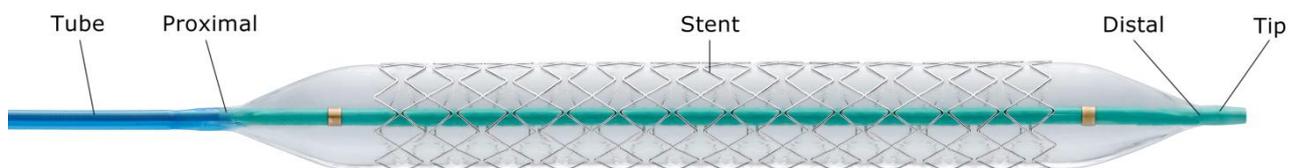


Fig. 2: A balloon catheter surrounded by a stent.

The user loads and unloads the product onto a rail, clamp and collet before he/she can fill out the parameters on a touch screen. The process is monitored by a camera and displayed on another screen. The axis is movable over a certain distance to allow length -and point welds. The difference between the mentioned types is the way of rotational welding. The type 1410 actually rotates the product and the laser beam is applied from above, while the type 1244 makes use of a mirror around the product and the laser beam is applied from the side, so the product does not rotate. They both make use of a CO<sub>2</sub>-laser which has a wavelength of 10.600nm and provide the same quality.

Technical specifications	Type 1244	Type 1410
User-interface	BW-TEC HMI Touchscreen	BW-TEC HMI Touchscreen
Parameters to set	Power, welding time, rotation, radius, feed rate	Power, welding time, rotation speed, focus position, distance
Welding	Asymmetric welding at any angle around the product	Rotation symmetrical welding
Laser type	Water cooled CO <sub>2</sub> -laser	Air cooled CO <sub>2</sub> -laser
Wavelength	10.57 to 10.63 μm	10.57 to 10.63 μm
Power output	10 W	5/10 W
Camera	Digital camera with line generator, photo- and film capacity	Digital camera for active inspection, screenshots, and film of production process
Length of products to weld	Max. 300 mm	Max. 350 mm
Dimensions LxWxH	1000x600x1000 mm	1000x504x860 mm
Weight	110 kg	100 kg
Power	100-230 VAC, 50/60 Hz, 700 W	100-230 VAC, 50/60 Hz, 700 W
Air pressure	6-10 bar	6-10 bar

Table 1: The technical specifications of the latest versions of the laser welding machines of BW-TEC.

### 3 Assignment

#### Laser welding machine

BW-TEC produces several machines for the medical devices industry. This research focuses on their laser welding machines, that produce welds onto balloon catheters. These machines work semi-automatically and therefore require the involvement of the user. For this reason, the interaction between the user and the machine, between the manual and automatic part of the machine, should be optimized. This research will point out on how to improve the human-machine interaction between the user and the laser welding machine.

There are different interfaces that are used during the process. The user has to give the input through one of the interfaces and, thereafter, the machine has to give the corresponding feedback or perform the required action (fig. 3).

While developing an improved laser welding machine, some important factors have to be taken into consideration. For instance, the machine should be safe to operate, so the user could not be exposed to the laser beam. The interfaces should be easy to use and understand to improve the performance of the process. Besides that, the total process time is a key factor that plays a role during the development of an improved machine.

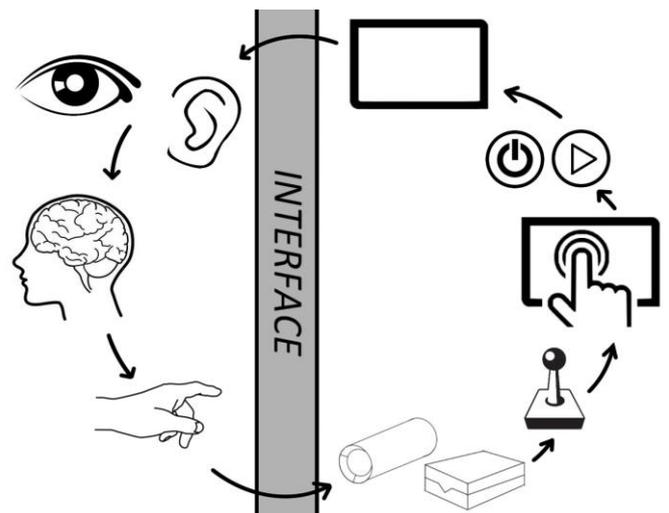


Fig. 3: A visualization of the human-machine interaction of the laser welding machine

The current laser welding machines of BW-TEC already take these factors into account. However, the operation procedures are not optimal and some small problems might occur. Therefore several improvements can be applied to the machine to improve the human-machine interaction. These improvements will be proposed during this report.

The development of the solutions for the improvements should always take the following factors into account:

- Ease of use
- Interaction between user and machine
- The improvements have to be cost efficient
- Possible solutions have to be realistic and easy to integrate

## **Design brief**

For formulating the final set of requirements for the development of an improved laser welding machine, a research towards the customers, competitors and other stakeholders of BW-TEC has been executed. Different questionnaires have been made and the results have been taken into consideration when formulating the final set of requirements. A distinction can be made between the machine itself and the user-interface.

### **Machine**

*Functional requirements:*

1. The machine has to be adaptable to its working environment
2. The machine has to provide visual, auditory and physical feedback to the user
3. The machine has to be operational by use of an interactive device and a monitor
4. A database of at least 100 recipes has to be provided
5. The overall process time has to be optimized
6. The machine has to allow to produce innovative designs and therefore it has to be customizable, but still be economically beneficial for the company

*Non-functional requirements:*

1. The machine has to be reproducible so every manufactured machine delivers the same output
2. The machine has to be cost efficient
3. The machine has to have a more user-friendly look

### **User-interface**

*Functional requirements:*

1. The recipe developer has to fill out the parameters more easily
2. Functions in the user-interface have to be grouped together in a logical manner
3. The user-interface has to provide a way out of the different menu's at all time
4. The user-interface has to provide shortcuts to the operator
5. The user-interface has to provide feedback to the user
6. The end of the process must be indicated

*Desires:*

1. The machine should prevent errors by detecting errors in a early stadium of the process
2. Help buttons should be provided that show short explanations
3. The administrator should be able to customize the menu's in the user-interface
4. A database with different welding strategies should be provided
5. A cooling system should be provided once the weld has been made
6. Different informative charts should be provided in the interface
7. Different sensors should be built in the machine to provide valuable feedback

## 4 Analysis

During this phase of the bachelor's assignment, different analysis have been executed to research on how the laser welding machine of BW-TEC can be improved. First the technology behind the laser welding process has been researched. Different welding techniques will be researched. Secondly, the product will be analyzed. Hereby, a distinction can be made between the machine and its functions and the user-interface.

### 4.1. Laser technology

Over the past few years, lasers have evolved with the speed of light. The possibilities of applications with laser technologies is widespread. Lasers are used in fields like communication, manufacturing, and in medical industries. Because the laser weld machine of BW-TEC makes obviously use of a laser, it is important to understand the technology of lasers.

Laser stands for Light Amplification by Stimulated Emission of Radiation. Lasers have characteristics that differ from natural light. They have a small focal point and therefore the ability to travel great distances. For these reasons they can be used in several applications in a wide variety of fields. (Keyence Corporation, 2015)

An extensive explanation of laser technology can be found in appendix A. In this chapter only the technology that concerns the laser welding machine will be discussed.

#### Types of lasers

Nowadays many different types of lasers are available in the market. Each laser makes use of a different medium and has different wavelengths. The laser medium is the source that is used to emit the laser light and for which the laser is named. *Table 2* gives an overview of different types of lasers that exist.

Type	Medium	Wavelength (nm)
Solid state laser	YAG, ND:YVO <sub>4</sub>	1064
Gas laser	CO <sub>2</sub>	10600
Semiconductor laser	AlGaAs, AlGaInP, GaN	Various
Fibre laser	Nd/Yb doped fibre	1000 to 1150

*Table 2: Different types of lasers*

### **Gas laser**

The laser welding machines of BW-TEC make use of a gas laser. The medium for this laser is CO<sub>2</sub>. Electrodes are arranged in an enclosed tube filled with CO<sub>2</sub> gas. Electrode plates are connected to external elements in order to apply high-frequency electric power that acts as the excitation source. Performing an electrical discharge between the electrodes causes plasma to be generated within the gas, which causes the CO<sub>2</sub> molecules to change to their excited state. This is the laser that BW-TEC uses for their machines.

### **Welding techniques**

Process engineers seek value added efficiencies in selecting equipment solutions for balloon catheter production. The main goal is to achieve the most efficient cycle times.

Currently used technologies feature touch screens, high resolution cameras, precise weld alignment, adding operator visibility, and ease of setup. To prevent warping of balloon cones or damage to external components, the heat to the welding area is localized.

The most expensive component in a balloon catheter is often the balloon. So special caution has to be taken during the welding process, regardless of the method.

We can distinguish three different kinds of welding methods when we look to the specific laser welding methods for balloon catheters: hot air, laser, and thermal compression. Heat migration can lead to balloon defects and influence for instance the burst strength and tensile strength.

### **Laser bonding**

With laser welding a laser beam is directed to the welding area on the balloon catheter while it is rotating. However, with the technology of BW-TEC, the product does not necessarily have to rotate. When the balloon catheter is rotating, the laser beam gives heat to the polymers. The laser bonding machine tend to be very expensive, but delivers high quality welds. The cycle time of a laser bonding machine can be short depending on the expertise of the operator.

## **4.2. Product analysis**

The laser welding machine and the HMI will be analyzed during this chapter. The analysis will start with the history of the laser welding machine. Next, the machine will be analyzed more in detail. Primary -and secondary functions will be researched and a distinction will be made between the human -and machine interactions. Besides that, the work environment of the machine will be analyzed. The focus with this analysis will be on the user-interface with its in- and outputs.

Several problems will be mentioned and ideas for solutions will be provided in the idea generation chapter.

## 4.2.1. Process description

### Function structure

To analyze and develop a function structure, the method of the function analysis is used. A function structure is an abstract model of the new product. This function structure describes the functions of the product and its parts and indicates the mutual relations. The principle of function analysis is first to specify what the product should do, and then to infer from there what the parts should do.

A distinction between main -and sub functions has been made considering the laser welding machine.

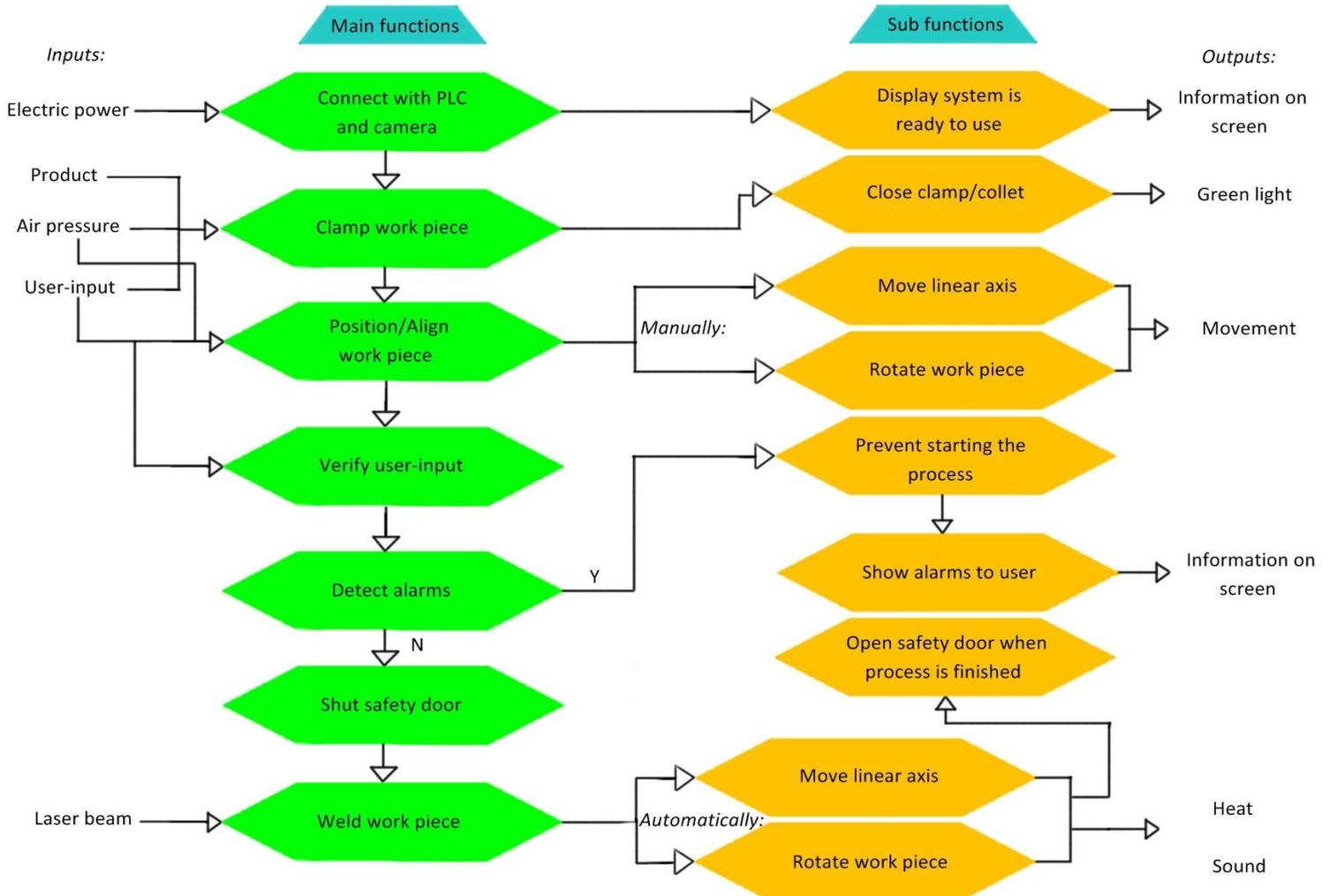


Fig. 4: The function structure of the machine

The functions can be categorized into two major groups, namely the actual machine functions and the user-interface functions. These functions are displayed in *table 5* which can be found in *appendix K*. After all the main -and sub functions were drawn up, a function structure could be made. This function structure can be viewed in (*fig. 4*). The sort of input can vary between energy, material or information as well as the output. The interrelations are displayed by use of several connection lines.

# Sequence diagram

The sequence diagram principle is based on the inputs from the user followed by a response of the system. The user gives inputs through a user-interface and the system uses software and hardware components to react to these inputs to create outputs. As a reaction on the outputs, the user can execute the next task. The sequence diagram can be viewed in *figure 5*.

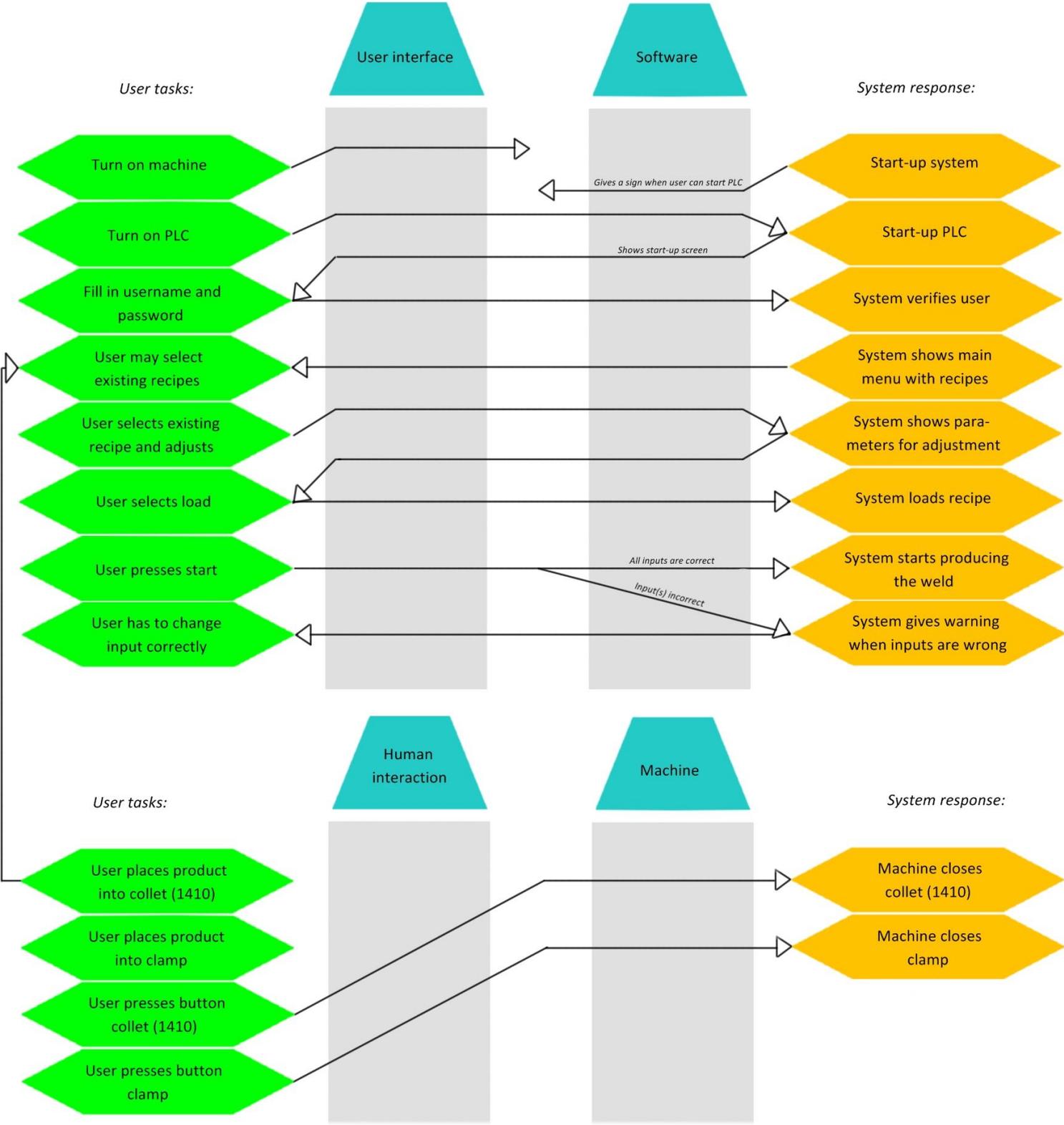


Figure 5: A sequence diagram to analyze the inputs and outputs between the user and the system

## Time studies on the laser welding machines type 1410 and 1244

To analyze the total process time of welding a balloon catheter on the laser welding machine type 1410 and type 1244, two time studies (*table 6 and 7, appendix K*) have been executed. A division between the manual load time and the machine time was made to determine which part of the process is automated and which part is not. Later on, it would be recommended to compare this time study with other time studies on the same machine with different operators and with time studies on a redesigned machine. Eventually, the different time studies can conclude whether the different operators have influence on the process time and to see whether the redesigned machine has improved the total process time.

The different job elements consist of several (manual) actions which will be explained.

For the *preparation of the product* you need a mandrel, which is a supporting wire for the catheter, an inner and outer tube, a balloon and a shrinking tube. The balloon has a proximal and a distal side which are relatively the larger and smaller openings at both ends of the balloon. The shrink tube has special material properties, heat makes it reduce in diameter and this applies radial pressure to the weld. The shrink tube has to be assembled on the position where the weld has to be applied. The preparation of the product consists of the assembly of all the previous parts.

The *start-up of the machine* consists of the start-up of the machine itself followed by the start-up of the PLC. These two components cannot be started at once. After that, the user has to fill out the correct username and password.

The *placing of the product* consist of the placement onto the clamp and into the collet.

The balloon catheter must be positioned precisely and repeatable underneath the laser. All the clamps and Supports must be adjusted to different products. the collet chuck rotates the work and on the type 1410 machines can be exchanged to fit different mandrel diameters.

The engineer can *fill out* a certain amount of *parameters* to make the required weld. These parameters consist of the laser power, start position, delay, rotation speed, weld length, and feed rate. Besides that, the engineer can add a line on the camera screen to align the product with the laser.

To make the required weld, the product should be *aligned* with the laser *by use of the camera*. The product can be moved over an axis. The time required for this step depends on the previous position of the axis.

To *start the process*, the operator has to press the start button. The total machine process time will be measured. This time varies with the set parameters. (e.g. welding time, delay, etc.)

After the weld has been made, the operator has to *check* the weld. This can be done with the camera, but to have a closer look, a microscope has to be used. With this job element, only the camera check will be taken into consideration. The camera makes recordings of every weld that has been made, so the operator can review the weld on the machine itself.

To *unload the product* the operator has to press the button of the collet, so it releases the mandrel.

Finally, the shrinking tube and mandrel have to be removed from the balloon catheter.

For the time study on the type 1244, the same job elements apply as in the time study of the type 1410. However, the placement of the product on the 1244 is different than on the 1410, because the product does not have to rotate, a collet is not necessary. Therefore an action has been eliminated from the total process.

## Conclusion results time study

All in all, the manual load time of the total process is more than three times as long as the machine time (*table 6 and 7, appendix K*). This is remarkable for an automated process. Besides that, the time to fill out the recipe parameters contributes the most to the total process time. This issue should be taken into account when redesigning the user-interface. Finally, starting the machine takes twice as much time than shutting down the machine. There might be a solution to influence the start-up of the machine in a positive way to make it possible to start the machine and the PLC at the same time.

## Scenario analysis

After the time study was executed, the whole process of welding a balloon catheter was analyzed by occurred scenario's. There are different scenario's in which the operator can operate the machine in a wrong way. It is important to highlight these scenario's to get a better understanding of how errors occur and accordingly to search for solutions to prevent possible errors (*appendix E*). Several scenario's emerged during an experiment with welding balloon catheters and can be viewed in *table 3*.

Scenario	Appearance	Solutions
Incorrect alignment	No straight alignment of the balloon on the mandrel resulted in asymmetric weld	Careful attention when assembling the catheter System detection Feedback to the operator
The weld is too long	Wrongly filled out parameters	Feedback or feedforward
The power of the laser is too long	Wrongly filled out parameters	Feedback or feedforward Different shrinking tube
The focal distance is too short	Wrongly filled out parameters	Feedback or feedforward
Wrong movement of the axis	Wrong interpretation of axis movement	Congruous user input with actual movement Display the actual movement
The laser destroys the balloon catheter	Combination of previous errors	Warning system Simulation

*Table 3: Different appeared scenario's with possible solutions*

## Conclusion scenario analysis

From the scenario analysis can be concluded that a lot of errors still occur when operating the laser welding machine. These errors consist of a wrong alignment, a too long weld duration, too much power input for the laser, a too short focal distance, and an incongruous movement of the axis. The worst case scenario analyzed was when the operator destroyed the balloon. All these errors have in common that they are dissolved by use of a trial and error method.

Several solutions are considered: system detection, system feedback, system feedforward, tolerance areas, other materials (with other properties), and simulation of the process. These solutions will be discussed later on in this report.

# FMEA

Failure Mode and Effect Analysis is used to analyze the possible failures of the human-machine interaction between the laser welding machine and the operator. It reviews the different process steps the operator has to take to produce a weld on a balloon catheter. Besides that, with FMEA it is possible to identify failure modes, and their causes and effects.

Process Function or Step	Potential Failure Mode	Potential Effects of Failure	S E V	Potential Cause(s)/ Mechanism(s) of Failure	O C C	Current Process Controls	D E T	R P N	Recommended Action(s)	Responsibility and Completion Date	Actions Taken	Action Results				
												S E	V	O C	D E	T P
Turn on machine	Start the PLC too early	Black screen or lost of information on screen	7	Lag between start-up time PLC and Computer	7	Blinking light of the stop button	3	147	Start Computer when stop button is blinking	21-9-2015	Yes	5	5	2	50	
Fill out user-name and password	Wrong user-name or password	User-Interface will not start	9	Loss of memory of the user	2	Pop-up with message that user-name or password is invalid	1	18	Reset user-name and password or remember by writing down	21-9-2015	No	7	1	1	7	
User places work piece in clamp and presses button	Work piece is not clamped correctly	Wrong alignment with the laser: bad weld	8	User wants to work too fast	6	Special V-grip of the clamp prevents wrong alignment	2	96	Training of the user to place work piece correctly in the clamp	21-9-2015	No	6	4	2	48	
User places work piece in collet and presses button	Work piece does not rotate correctly	Wrong alignment with the laser: bad weld	8	Wrong type of collet is used (wrong diameter)	7	User checks diameter mandril with diameter collet and verifies	3	168	User should know the details of the work piece so he can easily select the right collet	21-9-2015	Yes	6	5	2	60	
User selects existing recipe	User selects wrong recipe	Wrong recipe will result in a wrong weld and will possibly destroy the balloon catheter	8	User wants to work too fast or does not recognize the recipe	5	When the process has started and the user for example detects a wrong movement of the axis	3	120	User checks recipe parameters and verifies	21-9-2015	Yes	6	4	2	48	
User selects existing recipe and adjust	The recipe cannot be adjusted	The user has to select another recipe or create one	3	The engineer has not allowed the user to adjust the parameters of the recipe	8	User detects when recipe is not adjustable	1	24	The engineer should make more parameters adjustable	21-9-2015	No	3	6	1	18	
User selects load	The recipe will not be loaded	User has to reload the recipe	2	The software does not respond with the user-input	1	Information will be displayed in the user-interface	1	2	User has to reload the recipe	21-9-2015	No	2	1	1	2	
User presses start	The machine will not start	Process will not start	9	Clamp/collet is not closed or an alarm occurred and has to be solved	6	Alarms and warnings will be displayed and start button will not blink	2	108	User solves alarms and warnings and closes clamp/collet	21-9-2015	No	7	5	2	70	
Machine shut safety door	Safety door does not shut	User gets exposed to the laser beam: skin burn, eye damage	10	Failure of hardware of the machine	2	Alarms and warnings and emergency button can be pressed	1	20	Machine will not start when safety door is not closing	21-9-2015	No	7	2	1	14	
Machine welds work piece	Wrong movement axis; laser beam too strong/weak; asymmetric rotation	Destroying work piece	9	Wrong programmed recipe or wrong selected recipe	7	User detects and interferes with machine	7	441	Machine simulates selected recipe and gives alarms and warnings	21-9-2015	Yes	5	5	2	50	

Table 4: The Failure Mode and Effect Analysis of the human-machine interaction of the laser welding machine type 1410.

## Conclusion FMEA

From the FMEA table (table 4) can be concluded that the Risk Priority Number (RPN) of a wrong user-input is relatively high considering the other failure modes. Furthermore, the lag between the PLC and computer, a wrong alignment of the work piece, and a wrong recipe selection have large RPNs. Almost all of these failure modes have in common that they are caused by a wrong user-input. Therefore special caution has to be taken when redesigning the user-interface. Mistakes of the user-input have to be prevented and solutions have to be presented to the user. Different ideas and solutions to the main failure modes will be provided later on in this report.

## 4.2.2. Analysis of the interfaces

The physical user-interface (fig. 6) of the laser welding machine type 1244 and type 1410 and the graphical and functional design of the HMI of both machines (fig. 7) have been analyzed. Both machines make use of the same graphical interface. The HMI consist of different graphical designs for different

users. (e.g. engineers versus operators)

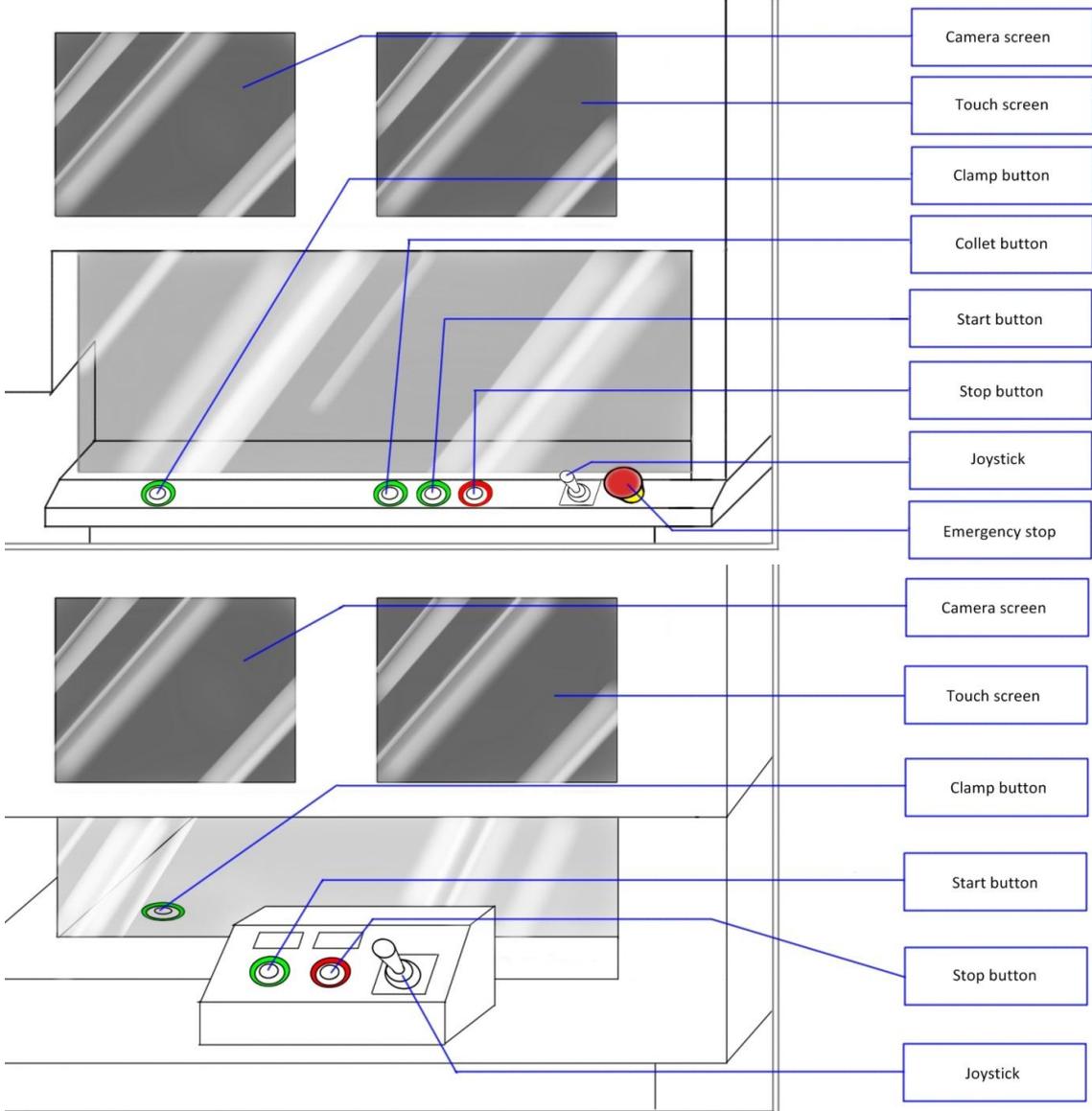


Fig. 6: The physical user-interface of the laser welding machine type 1410 (above) and type 1244 (beneath).

Some differences between the user-interface of the 1410 towards the 1244 can be noticed. First, the movable console is gone, therefore there is more space to operate. The clamp button is brought to the front, so the button is better reachable. The 1410 has a collet button, because the product has to rotate. With the 1244, the product does not rotate because the laser beam is reflected on a round mirror. The 1410 has relatively more process space than the 1244.

From the graphical design of the recipe menu can be concluded that a lot of information is displayed at once to the operator. Many different options are possible to chose from and therefore the decision making process is slow. Instead of displaying all the possible process information at once, the process steps should be subdivided into several steps, so the operator will run through a certain menu. This will improve the decision making process.



Fig. 7: The recipe menu in the HMI of the operator (left) and of the engineer (right).

### Background information

The HMI of all the machines of BW-TEC is designed for intuitive and simple interaction. The HMI can be integrated in company-wide ERP- and MES- systems, because of its open interfaces. The HMI can be translated into many languages, without programming expenses.

Recipes for specific welds can be generated offline or directly at the machine. It is also possible to import/export recipes as XML-File or with a recipe database.

A distinction can be made between the users of the machine, namely between the engineers and the actual operators. The engineers are authorized to make recipes, while the operators just can load the recipes and adjust some parameters that are made adjustable by the engineer. To support this distinction, two different user-interfaces are mainly used (Fig. 7).

The protocol and process documentation are the same in both user-interfaces. The protocol will show important events, such as process-start, process-end, logins, alarms and warnings. At the end of a process, all the data, such as parameters, results and user, will be saved in an excel- or XML-file or sent to a printer.

## 4.2.3. Heuristic evaluation user-interface

A heuristic evaluation has been executed towards the user-interface on the laser welding machines of BW-TEC. The heuristic evaluation is an usability inspection method for computer software. By use of a heuristic evaluation, it is possible to identify usability problems in the user-interface design. The heuristic evaluation makes use of the 10 usability heuristics for user interface design of Jakob Nielsen. (Wickens, C.D. and Lee, J., 2013). These heuristics are mentioned in *table 1 of appendix C*. Every single principle is applied to the corresponding design applications of the user-interface of the laser welding machines of BW-TEC. The results can be viewed in *table 2 of appendix C*.

### **Conclusion on heuristic evaluation**

The design applications of the user-interface are not optimized yet. Therefore the shortcomings should be taken into consideration when redesigning the user-interface. The applications that could be improved are summarized below:

- The user can only switch between German and English in the user-interface
- The user cannot collapse the different menu's by pressing it
- Some functions are not grouped in a logical manner
- There is no status information directly provided to the operator
- There is no temporary feedback provided to the operator
- There is only one way to move through the different menu's
- The errors that occur, are not prevented
- The operator does not get feedback from errors while filling out the parameters
- The recipe loading button is well hidden
- There is no shortcut from the creating of a "new recipe" to "the loading of the recipe"
- Nothing is done with often used options
- The system is not very efficient

### **Work environment analysis**

The actual work environment of the laser welding machine has to be investigated to better analyze the human-machine interaction. This analysis was executed during a visit to Company A and Company B, two customers of BW-TEC. The analysis focuses on how the operator works with the machine to produce a high quality product and consists of a questionnaire (appendix A) and an observation.

#### **Conclusion work environment analysis**

From the work environment analysis can be concluded that the machines are used in a clean room. This work environment consists of different rooms with their own climate regulation systems, where special procedures are executed. A clean room is a very expensive work environment, because a large air flow system has to be built in. The air in a clean room has to be continuously refreshed. This is done by circulating the air from the ceiling through the tiles and thereafter through many different air-filters. Other precautions to sterilize the environment have to be taken as well, but the extent to which a company takes these precautions differs. For instance, it was obliged to wear two kinds of shoe protection, a protection suit, a protection hat, protection gloves, and even a protection mask. The most remarkable aspect of the total welding process, was the process time. The operator works with fully assembled balloon catheters which are placed easily in the machine. The operator presses the clamp/collet button and thereafter presses start. The operator almost never has to interfere with the process, because nothing can really go wrong, because the engineer has made fully tested recipes. Mostly, no parameters are made adjustable for the operator. Therefore, the production steps are reduced and the process time is much shorter.

Company A works also with the laser welding machine type 1244, the one with the round mirror. They experienced some problems with this machine, because the mirror quality reduces by every weld you make. After a certain amount of welds produced, the quality is so, that the mirror has to be cleaned. A dirty mirror is caused by smoke that appears when the weld is produced, because of a too high laser

power. This smoke can leave a coating on the mirror. This coating disturbs the laser beam from producing a good weld.

The most interesting comment for the research was, that not every filled out parameter works the same on similar, or other machines. Every machine has its own properties and characteristics, even if it is of the same type.

At Company B, I worked with an engineer on the balloon forming machine of BW-TEC, so we did use the engineer's interface. The engineer was really satisfied about the interface, because it was ideal for his trial and error method, to find the right recipe for the product. The interface consisted of charts to display the total process and to give feedback to the engineer. Nevertheless, the interface did not give feedback to the engineer on which parameter to adjust to get the right recipe. Therefore, it is required to have the knowledge about the physics of the materials and the process.

## 4.3. Market research

This chapter analyses the competitors and the target group and gives an overview of the results of the questionnaires that have been executed.

The competitors and their machines have been compared to the machines of BW-TEC. The results of this comparison show several features that are interesting for improvement.

Various requests and wishes of the customers of BW-TEC have been listed in this chapter and they will be the main focus for improving the human-machine interaction of the laser welding machine.

### 4.3.1. The market

#### Competitors

The collage in *fig. 9, appendix D* shows all the laser welding machines of the direct competitors of BW-TEC. The collage is meant to analyze the different aspects that have direct relations to the human-machine interaction. The aspects that are remarkable of this collage are compared to the laser welding machine of BW-TEC and are given a gradation towards this laser welding machine (*table 5*). Features are graded positive when BW-TEC already has integrated them and graded negative when BW-TEC did not integrate them and therefore should be taken into consideration when redesigning the machine.

Feature	Negative	Neutral	Positive
Size		In general the size of the machines is large	
Size	One of the machines is very compact		
Working position		Mainly the operator has to stand to operate the machine	
Working position			Some of the machines allow little space to operate
Working position	Some machines do not need an additional table to be operative		
Interface			More than half of the machines only have one screen to operate the machine, so the operator has to switch between the input screen and the camera screen

<i>Interface</i>		All the machines make use of a touch screen to operate the machine	
<i>Mobility</i>	Half of the machines is mobile because they have rollers		
<i>External look</i>		A lot of the techniques of the machines are well hidden	
<i>External look</i>		You cannot see the functionality of the machine directly	
<i>External look</i>		All the machines are consisting of straight lines, this gives an industrial look to the machines	
<i>External look</i>	Some of the machines are colorful		
<i>Visibility</i>		The visibility of the emergency button is very clear and therefore easy to reach	
<i>Visibility</i>			Some of the screens are very small

Table 5: A comparison of different features of competing machines

From table 5 can be concluded that the laser welding machine from BW-TEC could be more compact, more mobile and have a more user friendly look. On the other hand, the machine of BW-TEC provides a large operational area and more control of the process by use of two screens and a high resolution camera.

## Comparative machines

The collage in fig. 10, appendix D shows a certain amount of comparative machines towards the laser welding machine of BW-TEC. These machines make use of semi-automation processes too. This collage is meant to analyze the human-machine interaction as well. The aspects that are remarkable of this collage are compared to the laser welding machine of BW-TEC and are given a gradation towards the laser welding machine (table 6). The gradation works the same way as the previous table.

Feature	Negative	Neutral	Positive
<i>Size</i>		In general the size of the machines is large	
<i>Size</i>	Some machines are very compact		
<i>Working position</i>		Mainly the operator has to stand to operate the machine	
<i>Working position</i>		Some machines need a additional table to be operative	
<i>Working position</i>	Half of the machines do have enough operational space		
<i>Interface</i>			More than half of the machines only have one screen to operate the machine, so the operator has to switch between the input screen and the camera screen
<i>Interface</i>		All the machines make use of a touch screen to operate the machine	
<i>Mobility</i>	Half of the machines is mobile because they have rollers		
<i>External look</i>	The technique of most of the machines is visible		
<i>External look</i>	The machines show a lot of		

	functionality		
External look		All the machines are consisting of straight lines, this gives an industrial look to the machines	
External look	Some of the machines are colorful		
Visibility		The visibility of the emergency button is very clear and therefore easy to reach	
Visibility			Some of the screens are very small

Table 6: A comparison of different features of comparative machines

Conclusions that can be drawn from *table 6* are that the machines displayed in *figure 23* show the technique of the machine and for this reason a lot of functionality. The functionality of the laser welding machine of BW-TEC is well hidden, mainly because of safety reasons.

## Atmosphere collage

An atmosphere collage gives a better insight on the environment in which the machine will be used, what people are involved with the machine, and which colors are used in this kind of industry. From the atmosphere collage in *figure 26* can be concluded that the environment in which the machine will be used is clean, sterile, and spatial. The operators are highly skilled to operate the machine. The main colors used in the medical industry are white, blue, and grey. The operator is highly involved in the process and makes use of accurate devices and materials. Information is displayed on large monitors and parameters are filled out by use of a touch screen.



Fig. 8: An atmosphere collage of the medical industry

## 4.4. Target group analysis

To better understand the needs and desires of the customers of BW-TEC a target group analysis has been executed. This analysis focuses on the main goals, values, and product deliverables of the companies. By use of these descriptions, it is possible to conclude a set of requirements in the perspective of the customers of BW-TEC. Eventually, the results can be compared with the possibilities of the laser welding machine and to what extent they meet the customer's requirements.

A detailed description of the values, goals and deliverables of each customer can be found in appendix F.

From the descriptions of the several companies an overall set of requirements can be concluded. In *table 4* the general goals, values, and product deliverables are mentioned. From this table a conclusion can be drawn for creating the final set of requirements from the customers point of view. The table does not show any interrelations between the goals, values, and product deliverables, but displays the most important goals, values, and product deliverables.

<i>Goals:</i>	<i>Values:</i>	<i>Product deliverables:</i>
Continuous investment in R&D	Enhance knowledge	High quality product
Pursuing technological innovations	Innovative design	Innovative medical devices
Reduce overall costs	Effectiveness and Efficiency	Meet the needs of the clients
To be a market leader	Flexibility	Provide sustainable products
Improve the treatment of patients	Innovative technologies	Flexible adaption to their customer needs
Provide the clients with the highest quality possible	Customer satisfaction	Continuous improvement of the several phases of the product life cycle
Enhance the team of professionals	Dedication	Provide high performance of products and services
Enhance long term strategic plans for growth	Quality	Bringing new technologies and exceptional products to the market
Continue to introduce new products to the market	Integrity	
Innovate products to help patients live longer, healthier and more productive lives	Service	
Work to enhance the quality life for their patients and family	Responsibility	

*Table 7: The general goals, values, and product deliverables of the customers from BW-TEC*

### Conclusion customer goals, values, and deliverables

From *table 7* the following set of requirements can be drawn of the analysis of the customer goals, values, and deliverables for the laser welding machine of BW-TEC.

**Requirements:**

- The machine has to produce consistently high quality welds
- The machine has to be customizable, so innovative products can be produced
- The machine has to be effective
- The machine has to be efficient
- The machine has to be operational for different people
- The machine has to reduce the costs of the total process

**Desires:**

- The machine should produce the highest possible quality of welds available
- The machine should be adaptable to the newest technologies
- The machine should be operational with exceptional products
- The machine should be customizable in a way that it could always allow fast product changes

## 4.4.1. Results questionnaires

Two different questionnaires have been executed. One for the customers of BW-TEC and one for other interesting companies. The results of these questionnaires are highly valuable for the research and will contribute to the final set of requirements.

All of the results can be viewed in appendix B. Next, some of the most important aspects that came forward will be mentioned which will contribute the most to the final set of requirements and which will be discussed during the idea generation:

- The flexibility of the machine
- The size of the process area
- The customization of the HMI
- The adaptability of the machine
- The cooling system in the machine
- The welding of different spot sizes
- The reproducibility of the machine

## 5 Concept development

During this chapter several ideas will be worked out. First, the final set of requirements will be drawn. Second, some ideas for solutions will be proposed. In the end, these ideas will lead to several concepts. A distinction is made between the hardware -and the software part of the machine.

## 5.1. Final set of requirements

The final set of requirements will be the basis for as many as possible ideas for the improved laser welding machine, a final set of requirements has been drawn up. The total set of requirements consists of functional -and non-functional requirements and desires. Only the most important requirements have been selected out of the total set of requirements (*appendix D*). A distinction can be made between the machine itself and the user-interface.

### Machine

#### *Functional requirements:*

- 1) The machine has to be adaptable to its working environment
- 2) The machine has to provide feedback to the user
- 3) The machine has to be operational by use of an intuitive screen and monitor
- 4) A database of recipes has to be provided
- 5) The machine has to allow to produce innovative designs and therefore it has to be customizable, but still be economically beneficial for the company
- 6) The end of the process must be indicated
- 7) A cooling system has to be provided once the weld has been made

#### *Non-functional requirements:*

- 1) The machine has to be reproducible so every manufactured machine delivers the same output
- 2) The machine has to be cost efficient

### User-interface

#### *Functional requirements:*

- 1) The recipe developer has to fill out the parameters more easily
- 2) Functions in the user-interface have to be grouped together in a logical manner
- 3) The user-interface has to provide a way out of the different menu's at all time
- 4) The user-interface has to provide shortcuts to the operator
- 5) The user-interface has to provide feedback to the user
- 6) The end of the process must be indicated

#### *Non-functional requirements:*

- 1) The user-interface has to be consistent with the style of BW-TEC

#### *Desires:*

- 1) The machine should prevent errors by detecting errors in a early stadium of the process
- 2) Help buttons should be provided that show short explanations
- 3) The administrator should be able to customize the menu's in the user-interface
- 4) A database with different welding strategies should be provided

## 5.2. Idea generation

An overview of the brainstorm (fig. 1, appendix G) has been made to display all the ideas that were drawn up from the set of requirements. The brainstorm can be divided into ideas for the laser welding machine and for the user-interface. To improve the human-machine interaction, both components should be taken into account when redesigning the laser welding machine. The ideas will be discussed later in this chapter.

### Morphological scheme

For generating more ideas on how to improve or redesign different features, a morphological scheme has been made. It represents the different functions between the human and the machine coupled with their solutions. The morphological scheme can be viewed in figure 9. The green line represents the most ideal solutions that would improve the human-machine interaction. These different solutions should be taken into account when developing a concept. The blue line represents the 'out of the box' ideas that are creative, but not very realistic to integrate. However they could improve the human-machine interaction, so it is worth to consider these ideas and develop them as far as possible. The red

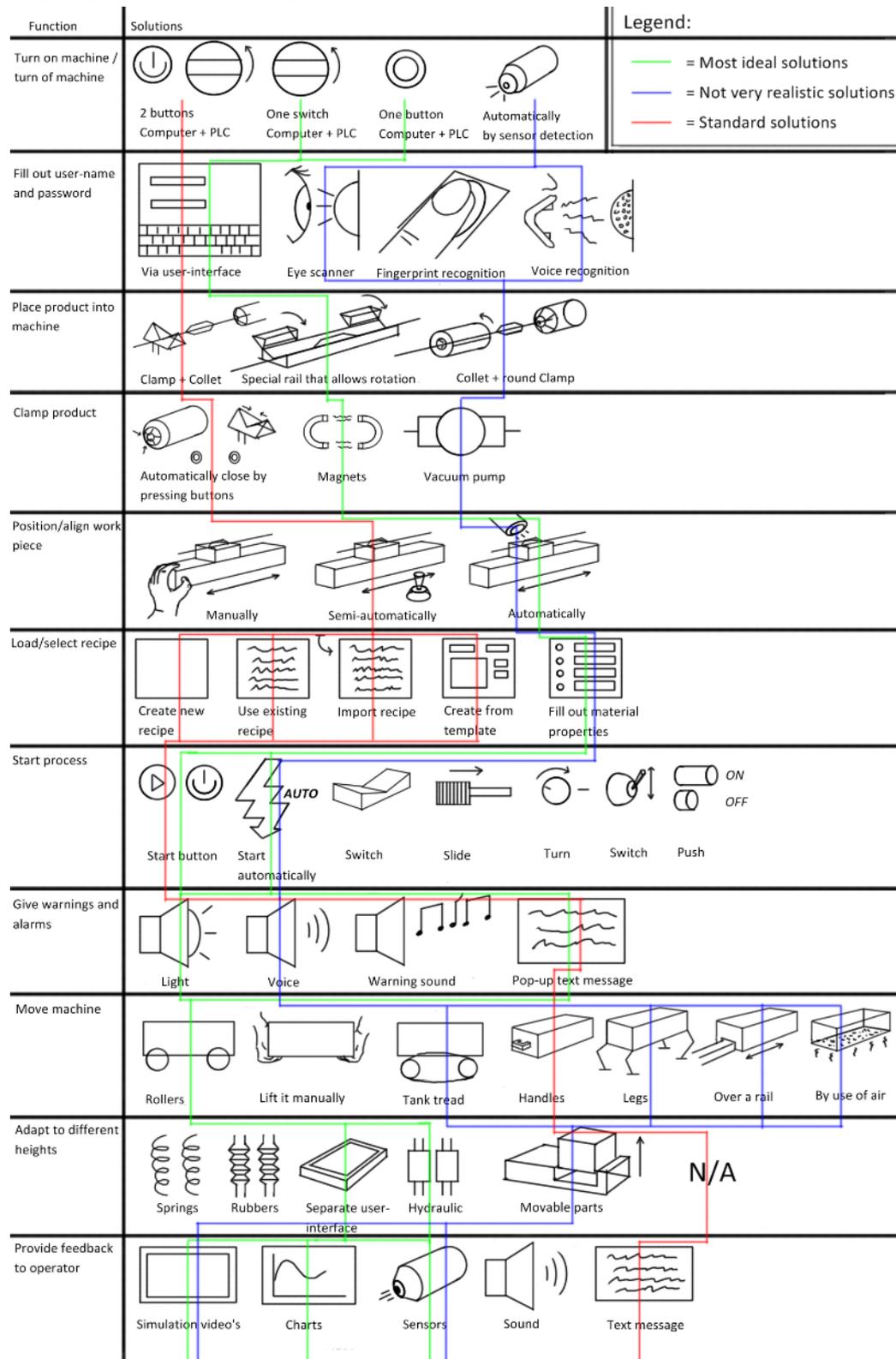


Fig. 9: Morphological scheme.

line represents the solutions that the machine already has. These are the most standard ideas and they still could be valuable to improve the human-machine interaction, but they might have to be adjusted in a certain way. For example, to move the machine, the people involved have to lift the machine by its handles onto a trolley. The lifting is very heavy, but could be improved by making the machine lighter or add a tool to make the lifting easier like a pump handle.

## The user-interface

To analyze the navigation of the user-interface of the operator, the diagram in *figure 3, appendix G* has been made. The diagram shows the different menu's (green), the different buttons (blue), and the different parameters the operator has to fill out (orange).

The several steps to start the process and the different menu's can be derived from this diagram. Concerning improving this user-interface, some menu's could be integrated into one menu. The alarm history could be integrated in the alarms and warnings menu and be visualized as a button in this menu. Besides that, the protocol menu could be integrated in the process overview menu, because the protocol is more or less a process overview.

The list of menu's could be more decreased by integrate the exit option into the log off button. The operator has first to log off and after that he can shutdown the machine.

Nowadays, the menu buttons look like this. The total of menu buttons can be reduced by three, so there will be only four menu's left as can be viewed right next to it. This will improve the decision making process.

Furthermore, the icons used to display the menu's can be improved, because a small research pointed out that the icons used are not commonly used icons. Besides that, they do not show much consistency. This could lead to misunderstanding the function of the menu. Moreover, when the user-interface consists of clear icons, space could be saved, because the icons do not necessarily have to be explained with words.

The new menu proposal would look like the menu displayed in *figure 11*.

At the top the process overview menu is displayed. This is actually the most used menu during the production process. Therefore this menu could also be visualized as the home menu.



Fig. 10: Reduction of menu's

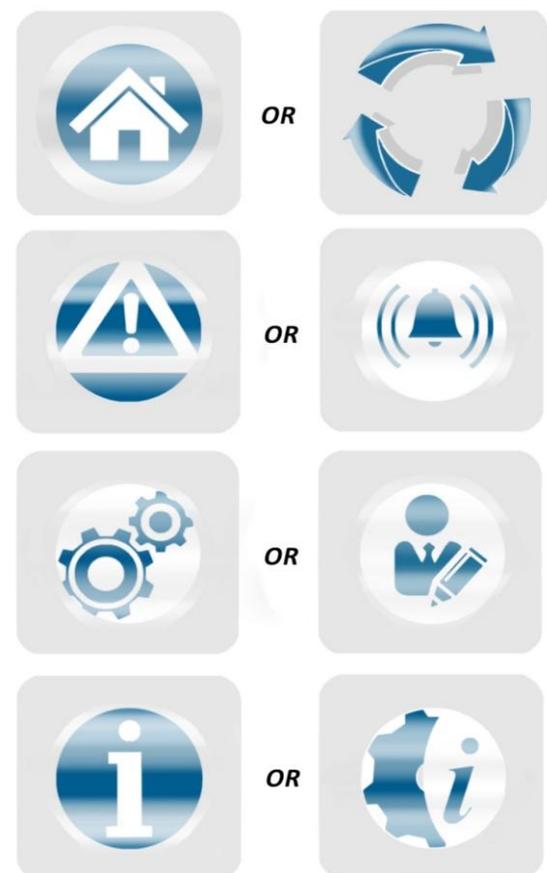


Fig. 11: Proposed new menu's

The lamp of the alarm and warnings menu should indicate an alarm, however, this symbol is not commonly used for this function. The commonly used symbols for warnings and alarms are also displayed in *figure 28*.

The user settings icon could also be visualized as a more commonly used icon for settings. This will prevent confusion and the words "user settings" do not have to be used anymore.

The machine information menu icon is fine, but if the icon is like the one in the right corner of *figure 28* the words "machine information" do not have to be used anymore.

The user-interface of the engineer is different compared to the user-interface of the operator. There are no icons shown in the menu's of the interface of the engineer and a menu collapses by clicking on it. The navigation is quite similar to the interface of the operator, however, more options to adjust are presented to the engineer. An engineer could additionally create a new recipe, fill out parameters concerning the system, and search through the process history.

### **Conclusion user-interface**

Possible solutions for the proposed ideas will be mentioned in this chapter. During the concept development, these solutions will be detailed.

No escape button is provided in the different menu's. To give the user more freedom of control, such a button should be provided.

The run-through the different menu's could also be improved, because in this moment, the user-interface contains many different options that can be selected at any time. The decision making process therefore is slow and could be improved by introducing a step-by-step method. When a step is finished, the user will go to the next step and so on. Obviously, this method should consist of as few steps as possible. To improve the decision making process the user-interface should contain different shortcuts. The shortcuts can be used by the expert user, that has worked several times with the same interface. Eventually the shortcuts will result in a shorter process time.

Right in this moment, the buttons to operate the machine are all physically integrated in the operating panel. It might save space to integrate all these buttons in the user-interface. Besides that, the machine will even be more intuitive than before when the buttons are all integrated in the user-interface.

Instead of filling out a specific number, the value of a specific parameter should be adjustable by making use of scale of a minimum and a maximum value. This means that the value of the parameter should have tolerances. One way of adjusting the value of the parameter could be swiping over a line with a finger.

## **Feedback**

Feedback is the most important aspect of the total process. When the user gets "quality" feedback, the total process will be very time efficient. Quality feedback is feedback that communicates errors to the user and shows the user on how to respond to these errors.

The laser welding machine does not provide enough feedback to run smoothly as can be concluded from the market research results. Nowadays, it is required of the user to understand the physics behind the weld to know which parameters to adjust, like material, power, focus distance, speed, time, etc. The expert user has no problems with these data, but a novice user might. Therefore, it is proposed to have a

database of created recipes with the new HMI and so this will be time saving. However, more feedback could be provided to ensure the process is running more smoothly.

### ***Welding strategies***

The database could be improved by proposing different welding strategies. The strategy with the best results could be selected from a list. The different strategies can be focused on for example the reduction of process time, the repeatability of minimum stress in the surrounding material or the minimum power input.

### ***Visualization of the timing***

What also could be very useful, is a visualization of the timing during the process and combining this with a video for fine-tuning. Hereby, the user could time the position of the product or the time when the shutter opens. Besides that, a little chart, which shows the power over time, would be interesting. When creating a recipe, the engineer has to work with a trial and error method to find the correct parameters. A chart will then be very useful to better understand which parameters should be adjusted to create a good recipe.

### ***Camera detection***

The camera recordings help the user to see and study the effects of the programmed parameters and to understand how the product behaves during the laser welding. Moreover, they are useful for documentation to improve the process development. However, in the R&D phase, it is still hard to check with the camera if the weld has been made. To do so, the user needs to remove the heat shrink tube to check. Therefore the camera should detect if the weld has been made instead of the user.

### ***Quality recipe***

One of the other ideas is to allow the user to checkmark if a process made a good weld and not just if the process was successfully completed by the machine. Each recipe can the display the percentage of good welds. With this feature, the operator can select more easily a successful welding process and does not have to apply a trial and error method.

### ***Simulate movement***

From the market research results can also be concluded that it is difficult to understand the setting of the displacement of the motor axis to the left or right. If the weld should be propagated to the right, the motor should move left. The feedback on this process step is not well enough underpinned and for this reason it should be improved. For improvement, the machine could digitally simulate the movement of the axis on the screen or by actual moving the axis. In other words, the parameters should be verified before running them.

### ***Simulations***

More simulations should be provided on a screen to better understand the quality of the weld. These simulations need beforehand information to give valuable feedback to the user. The information can be extracted from different sensors that are built in the machine. Normally, the machine makes only use of a high resolution camera that displays the up-close look of the balloon catheter. To improve the feedback of the machine, more information collecting resources should be installed.

The machine needs to detect the balloon catheter and should get the material properties, the wall thickness of the tube, the temperature of the weld, and the alignment of the work piece automatically. To get all this information, the machine could make use of different sensors like, a thickness measuring sensor, a smoke detector, and a temperature sensor. In the next paragraphs some devices will be proposed to install on the machine to acquire the valuable feedback from.

## Temperature sensor

An infrared temperature sensor (*fig. 12*) consists of a lens to focus the infrared energy on to a detector, which converts the energy to an electrical signal that can be displayed in units of temperature. This temperature measurement is possible from a distance and is contactless. An infrared thermometer is usually used in applications where a fast response is required, so this could be a good solution for the laser welding machine. (Omega, 2013)



*Fig. 12: infrared temperature sensor*

For an accurate noncontact infrared temperature measurement the engineer has to take into account the different aspects like, distance to target ratio, field of view, environmental conditions, ambient temperatures, and emissivity.

The distance to target ratio comprises the infrared energy to a spot on the work piece which is focused on the detector. "Optical resolution is defined by the ratio of the distance from the instrument to the object, compared to the size of the spot being measured." (Raytek, 2015)

The target should at least be twice as large as the spot size, considering the field of view. The smaller the target, the closer you should be to it.

Considering environmental conditions, smoke, dust and steam could prevent accurate measurement by obstructing the unit's optics. Other conditions that should be taken into account are vibrations, electromagnetic field, and noise. To protect the sensor from environmental conditions, a water -or air cooling mechanism or a protective housing could be installed.

The ambient temperature, or the surrounding temperature, has also an effect on the quality of the measurement of the sensor. For every different kind of ambient temperature a specific temperature sensor should be installed.

Emissivity is about an object's ability to emit infrared energy. The emitted energy indicates the temperature of the object. All values of emissivity fall between 0.0 and 1.0. (Raytek, 2015)

For the temperature measurement of the laser weld, the best sensor to be used would be a fiber optics sensor. They are effective for environments that are hazardous or where there could be regular electromagnetic interference. They are able to transmit data over long distances with little or no loss in signal integrity. (National Instruments Corporation, 2015)

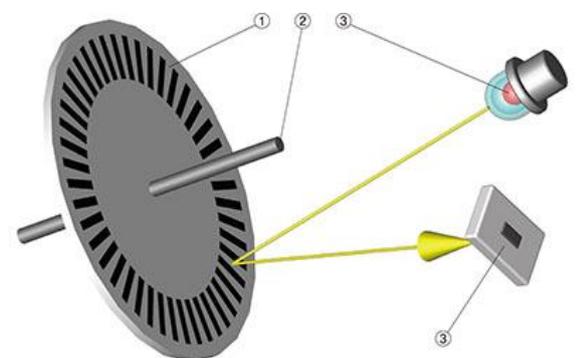
## Optical sensor

To measure the layer thickness of the tube, an optical sensor is needed. When the material properties are known, the following aspect to know is the layer thickness of the material. Besides that, the machine has to detect if the work piece is aligned correctly, so the displacement has to be measured.

The most important factors in selecting a position sensor are excitation, filtering, and environment.

For the position and displacement measurement the best sensor to be used is an optical encoder (*fig. 13*).

This sensor can determine speed, direction,



*Fig. 13: The principle of a rotary optical encoder*

and position with fast, high accuracy and can either be linear or rotary. The sensor uses light to determine position.

## Smoke detector

When the laser beam is too powerful or focused too strong on the work piece, it could damage the balloon catheter. When this occurs, you can see smoke coming of the work piece. For this reason, smoke is an indicator of a bad laser weld and therefore should be detected by the machine. So, the machine should have a smoke detector to detect the smoke coming of the work piece and immediately react to this by shutting down the process.

For smoke detection, an end-to-end optical beam

(fig. 14) smoke detector could be used. This detector

works on the principle of light obscuration. When a certain amount of the transmitted light is blocked, the smoke is detected. This smoke detector is small and consists of a separate light transmitter and receiver. Two wavelengths of light (UV and IR) are used to detect smoke. UV and IR respond differently to for example fog, steam, and other things that cause false alarms. Therefore the two wavelengths of light are used together to detect smoke accurately.



Fig. 14: An end-to-end optical beam smoke detector

## Material properties

The material properties should be filled out by the engineer. The engineer has to develop several recipes for different kind of balloon catheters with different material properties, so the operator only has to select the right recipe from the menu. Therefore, the recipe has to have an understandable and obvious name, so the decision making process of the operator will be short.

## User demands and wishes

From the market research results some user demands and wishes can be concluded. Some of the customers of BW-TEC still miss or do not understand features on the machine that might or could improve the product quality and overall process.

### *Flexibility*

The accessibility of all the important components to control the machine is depending on the environmental conditions and use of the machine. Some customers found it useful to have a flexible input panel, because some products lay in front of the machine. While operating the laser welding machine type 1244, the integrated input panel is obstructing the process area. The input panel of the laser welding machine type 1410 is already integrated into the front and thereby it created more operating space. However, the input panel is still in front of the machine and some customers do want an input panel that is flexible and can be operated from another position.

### *Process area*

One of the wishes of the customers was to have a built-in z-axis. The z-axis allows the product to move towards the user. In this way, the user could load and unload the product more easily. This feature will be a challenging one, because an additional z-axis will result in a deduction of operational space. Another way to improve the process area is, to reduce the depth of the machine. Right now, a lot of space in the

machine is unused, especially in the depth. When the process space is moved more forward, it will be easier for the user to load and unload the product.

### ***Customizable menu's***

Considering the user-interface, it would be great when the administrator could customize the menu's. For instance, the administrator would be able to change the order of the menu's, to change the content of the menu, or to change which menu can be used by each different kind of user. Nowadays, the user-interface of the machine is standardized for every customer of BW-TEC, but not all of the customers of BW-TEC produce the same products. Therefore this feature might be interesting for some companies.

### ***Adaptability***

The machine should be more mobile and adaptable to better integrate into the production line of the customers of BW-TEC. In this moment, the machines are placed on movable and adaptable tables which the company arranged by themselves. Therefore it might be an improvement when the laser welding machine is movable and adaptable by itself. For example wheels and hydraulic pumps could be installed on the machine to realize these features.

Nevertheless, the most important feature is to have a stable and robust machine. Therefore, the movability and adaptability should not keep the machine from being stable and robust.

### ***Camera lines***

The camera lines, the user can add, are only used to measure the placement of the balloon catheter and the welding distance, but the lines are not actually used for the length of the weld. It would be a great feature when the engineer could add one line with the camera and set this line as the starting point of the weld, followed by setting another line as the end point of the weld. Hereby the engineer could eliminate the thought on how the axis will move (left/right) and the engineer does not have to estimate and manual fill out the weld length anymore. Moreover, this allows a more precise weld length than filling out this parameter manually.

### ***Cooling system***

One of the demands of the customers of BW-TEC is to have an integrated cooling system that cools down the weld afterwards. In this moment the weld produced is still warm and it takes time to cool down. When the cooling down process is increased, for example by use of a nozzle with cool air, the total process time will be decreased.

### ***Spot size***

Another feature that would be interesting to improve is to weld with different spot sizes that are changeable with the HMI. This is already possible with the laser welding machine type 1410, but the type 1244 has difficulties with this feature. The different spot sizes are adjustable by changing the focus distance of the laser beam. When the laser is placed further from the product, the spot size will be bigger and the power of the laser beam will be less powerful. The focus distance of the laser beam can be automatically adjusted through the HMI on the type 1410, but unfortunately only manually adjusted on the type 1244. Also, this manual adjustment is not very precise and therefore it is not recommendable to adjust on the type 1244. Some customers that have the type 1244 want to automatically adjust the focus distance to create recipes that allow high process times.

### ***Reproducibility***

The biggest challenge with the development of the balloon catheter is to duplicate machines that can use the same recipe and have the same output. Unfortunately, nowadays the machines of BW-TEC do not always deliver the same output. The engineer has to design recipes for every single machine for the same

product. The parameters that vary with the machine are spot size, energy power, speed, rotation, displacement, etc. It would save a lot of time when the engineer only has to design the recipe once for the same product for the same machine.

## 6 Concepts

The following concepts came forward from the analysis and idea generation for the development of an improved machine considering the human-machine interaction.

### **Existing machine with minor improvements**

- Basic features
- Which features could be easily improved in a few years to meet some requirements
- Minimal cost
- Optimized HMI

### **Comfortable machine with optimized interface**

- Features that satisfy the customer demands
- Realistic machine
- Semi-automation
- Optimized HMI

### **SciFi machine with all available techniques possible**

- High-tech features
- No budget limit
- Automation
- Optimized HMI

In this chapter, the development of the concepts will be divided into two different aspects. Namely the software part (HMI) and the hardware part (actual machine) of the machine. Every concept has its own specific set of requirements that were derived from the analysis phase. Several features have been elaborated and are finally integrated in the new design of the machine.

## 6.1. Functional machine

The first concept machine is a functional machine that consists of only basic functions to produce the required weld. Therefore it functions the same as the existing machine, but it has some improved features. The production cost of the machine should be low and the cycle time of the process should be cost efficient. To improve the human-machine interaction, a new HMI has been developed. Because of the new HMI, some functions and components of the machine have to be adjusted. For the development of this machine, a specific set of requirements has to be met.

### Requirements:

- 1) The machine has to be cost efficient
- 2) Process with minimal functions
- 3) Easy to use and understand interface
- 4) Easy to use and understand HMI
- 5) Provide minimal feedback to the user
- 6) The process information has to be displayed on a minimal 15 inch LCD monitor and touch screen
- 7) A database of recipes has to be provided in the user-interface

### Desires:

- 1) Starting the machine should be going faster
- 2) A flexible input panel should be provided

## Features

Some small improvement features have been applied to the existing machine to meet some easy to integrate demands of the customers of BW-TEC. The improvements can be subdivided into hardware - and software improvements

### Hardware:

After the production of the weld on the product, the weld will be cooled down by an integrated nozzle with cold air. This will decrease the production time, because the cooling down process is accelerated. The operator does not have to wait anymore on the product to cool down, so the operator can load and unload the products faster. Not only will the air cool down the product, but it will also blow away any possible created smoke from the product outside the machine. The smoke that could come of the product has a bad effect on the mirror of the type 1244. Namely, the smoke will create a coating on the mirror that eventually can disturb the laser beam. When the laser beam is disturbed, the machine cannot produce a good quality weld anymore, so this should be prevented.

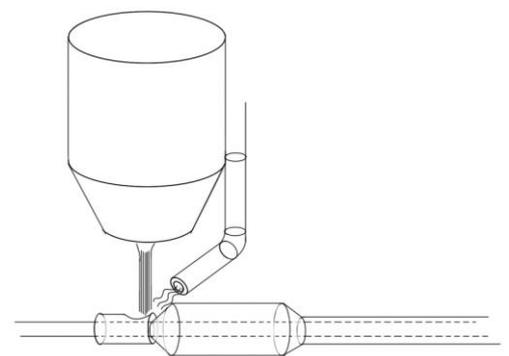


Fig. 15: Cooling system.

One of the customer's demands was to lock the safety door during the process. This feature is easily to integrate and therefore will be applied. The safety door will be locked automatically during the process by pushing two pins from the side into a small hole. Hereby the safety door cannot be moved upwards anymore. However, the cycle time will negatively be influenced by integrating a lock mechanism and therefore should be taken into consideration.

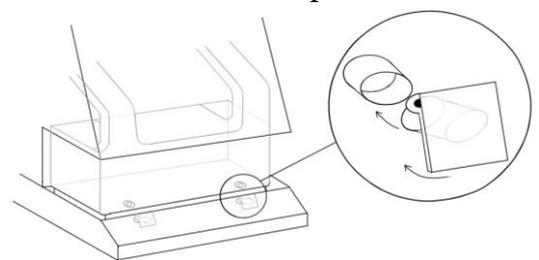


Fig. 16: Lock mechanism.

With the laser welding machine type 1244, the setup of the product could be improved. The product has to be placed in the center of the mirror and therefore should lay perfectly straight.

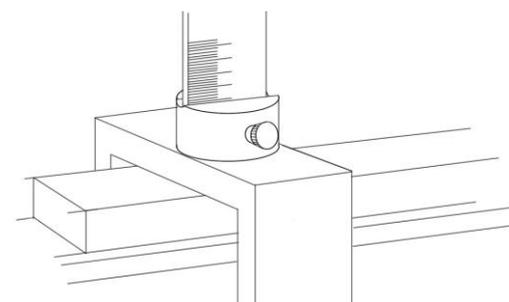


Fig. 17: Scale.

The straight alignment of the product is a difficult procedure, because the user has to manually adjust the height of three different standards. In this moment, the straight alignment is done by producing a weld on a shrinking tube and by afterwards checking if the weld is perfectly round or asymmetric.

When the weld is asymmetric, the standards have to be adjusted in height. After this is done, the user has to repeat the same procedure. This method is a trial and error method and could be improved. For the improvement of this method, a scale on the different standards is introduced. With this scale, the user can easily measure the height of every standard and it will become more easy to align the product in a straight way.

The start up of the machine is also improved. The machine used to have two buttons to start up the machine. One for the machine itself and one for the PC. Normally, the user had to wait for the machine to start, before he could press the button of the PC, which was indicated by a blinking stop button. That takes a little time and patience of the user. To eliminate this procedure, only one button is introduced to start up the whole machine. The PC will automatically start, when the machine is ready.

The laser welding machine should be adaptable to any work environment. To improve the flexibility of the machine towards its environment, some small adjustments can be made. For instance, to save operational space, the loading axis could be adjusted to a vertical position instead of the existing horizontal position. For long balloon catheters this could be very useful, because in horizontal position the operational space will be twice as wide as the machine itself. Usually, there is enough space in height in a clean room, so this adjustment should not give any problems.

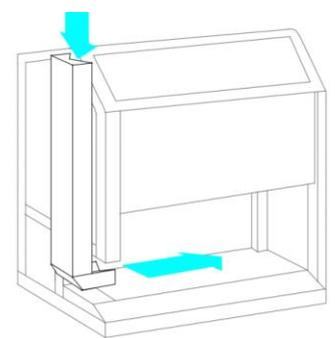


Fig. 18: Vertical guiding axis.

Another way to save work space is, to make the axis operational from both sides. Therefore the machine has to be open from both sides and the compartments, that have to hold the product, should be easily be removed and replaced to set-up the right working position. This principle is more easy to integrate in the 1410 than in the 1244, because the laser in the 1410 comes from the top. With the 1244, the laser comes from the side and therefore, the customer should indicate in which direction he wants to operate before the actual production of the machine starts, or the whole laser should be removable.

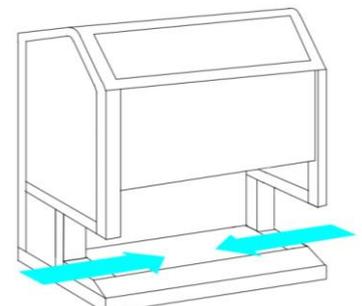
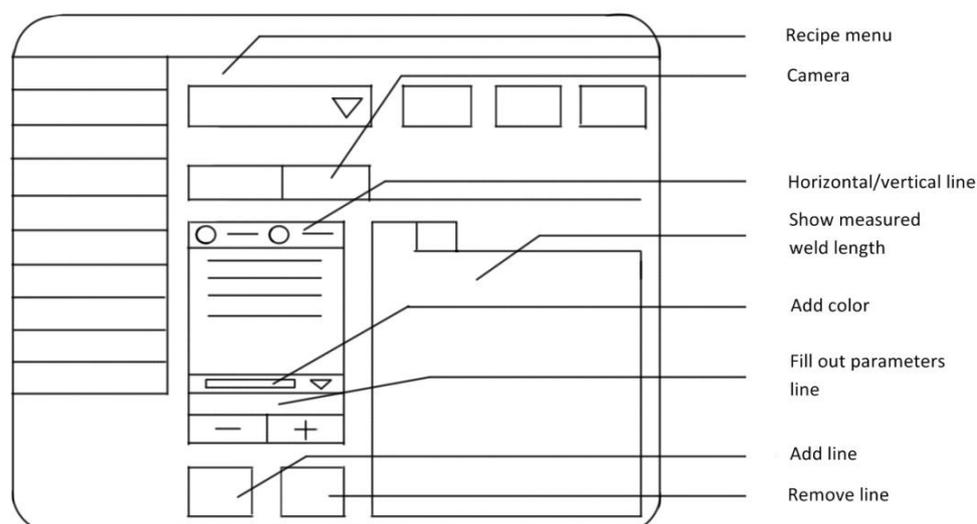


Fig. 19: Operational from both sides.

*Software:*

The camera lines that can be added through the touch screen, will be used to actual insert the weld length. Before, the lines were only used to measure certain distances, but it would be very helpful to directly visualize the weld



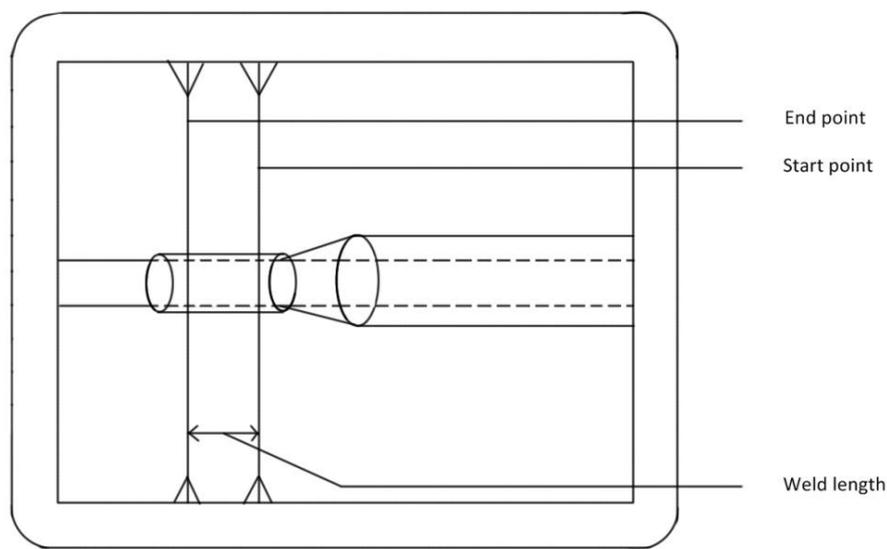


Fig. 20: Added camera lines.

length on the product. Not only will this method be more easy to use for the user, but it will also be more precise. With the old user-interface, the user had to estimate the weld length and there was a change of failure. With this method, the user can precisely insert the weld length and the machine will do the exact measurement. Furthermore, with this method, the machine determines in which direction the weld will be made. The first added line is the starting point of the weld and it will move to the second line. More lines could be added in the right order to be processed. Therefore the user does not have to think about in which direction the axis will move anymore by filling out the parameters. This will only work when the added steps will not overlap with each other in the process area on the product. The user just have to look on the camera screen and add the lines through the user-interface.

When the added steps will overlap with each other in the process area on the product, a small simulation will be provided when setting the parameters for the weld length. This simulation consists of a small pop-up box and visualizes the different steps and the direction of the movement of the axis.

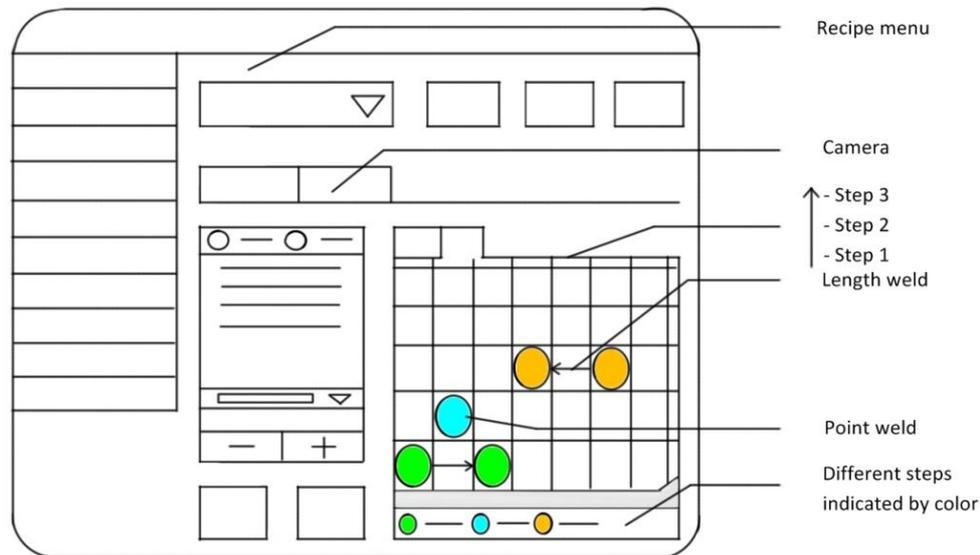
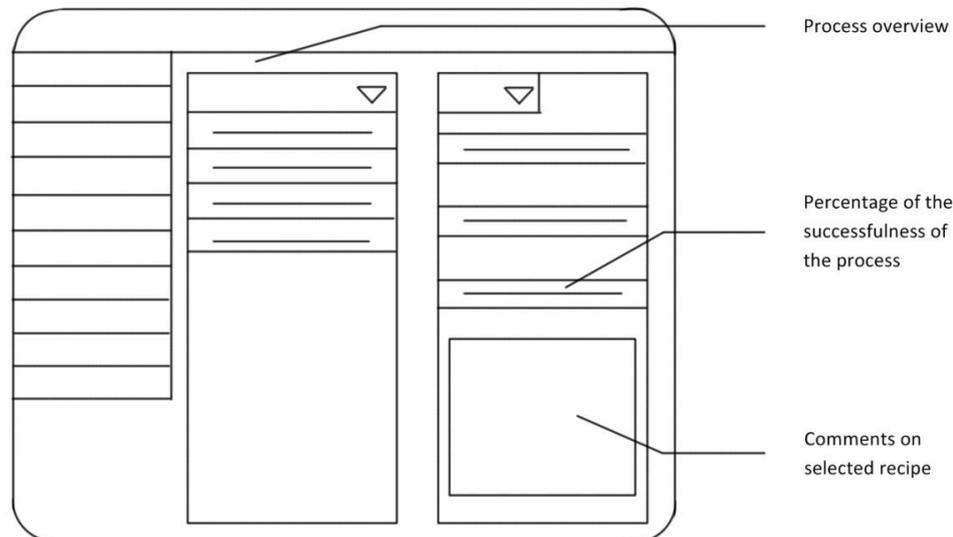


Fig. 21: Simulation welding process.

After a weld production has been done, the user can criticize the quality of the process. The user is allowed to checkmark if the process was successful and has produced a good weld. Each recipe can display a certain percentage of good welds. So, the user can select a recipe from the recipe menu based on the highest percentage. This method will increase the decision



making process and delivers the needed feedback to the user. The checkmark of the process can be done in the process history and after a checkmark has been filled out, it is automatically calculated with the other data of the same recipe and displayed in the recipe menu.

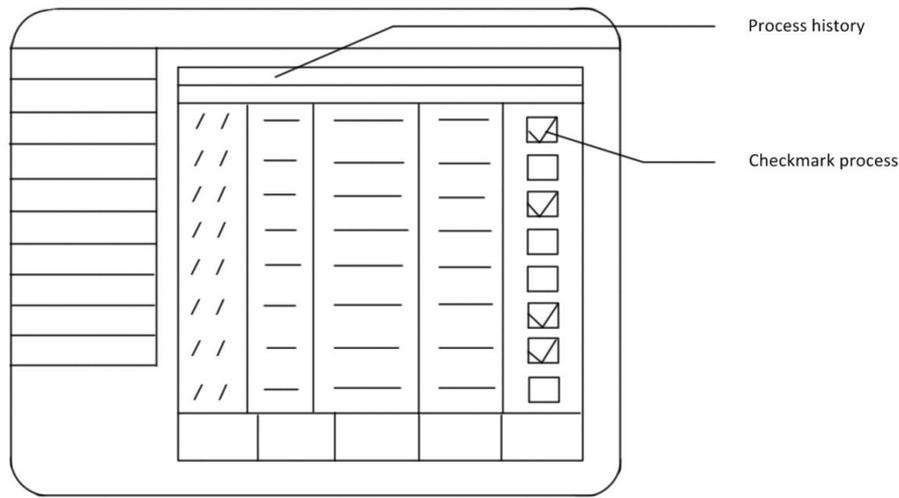


Fig. 22: Checkmark welding process.

To help the user better understand the parameters, help will be given by displaying a description of the concerning parameter. The user simply has to select the parameter and a small text message will pop-up. By clicking next to the textbox, the message will disappear again. The text message will consist of the characteristic and the function of the parameter. It might also give a tolerance area in which the parameter would work.

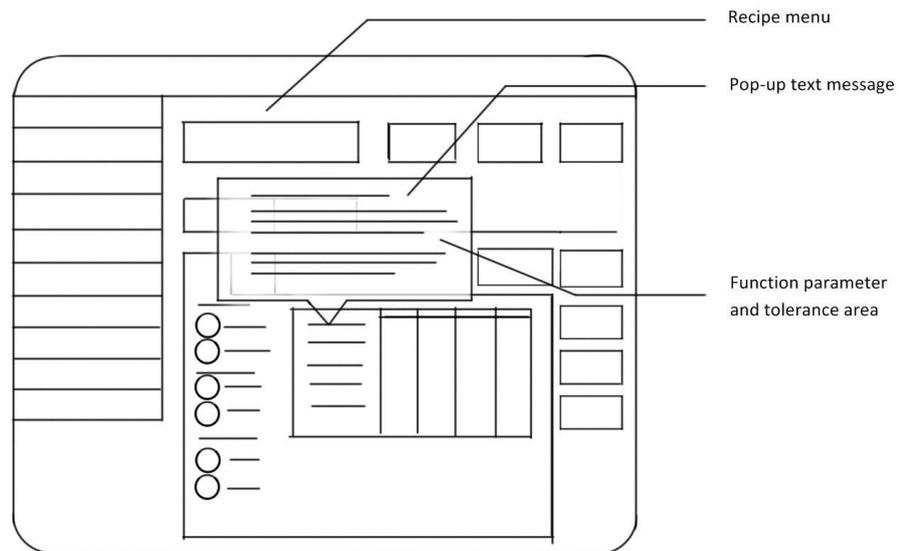


Fig. 23: Pop-up help message.

## The machine

To fit in all the different features that are mentioned before, the hardware of the machine has to be changed. Therefore a shape study has been made. This study consists of machines that look more user friendly, provide flexibility, and improve the interaction between the user and the machine.

The main new improved features of the machine are sketched below. The machine provides the ability to move the components in order to be operational from both sides. Besides that, the monitor of the camera and the touch screen can be placed to the front on a rail. Therefore the visibility of the process is improved and can easily be adjusted to the requirements of the user. When this feature is applied, the buttons and joystick are integrated in the HMI. To be operational from both sides, it will save space to load the product vertically, but this is not necessary. The user can also disassemble the arm to hold the product and reassemble it onto the other side.

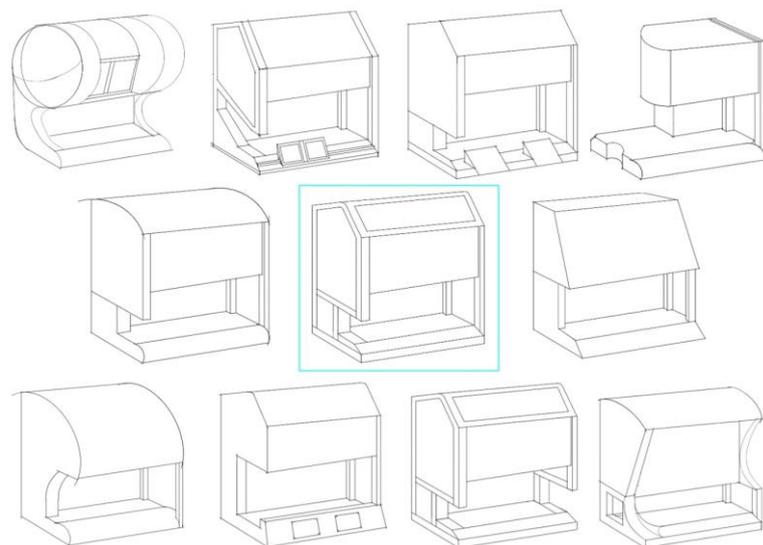


Fig. 24: Shape study.

When all the previous ideas are put together into one re-designed machine, it will look like this:



*Fig. 25: Final concept functional machine.*

## 6.2. Comfortable machine

The second concept is a comfortable machine that consists of convenience features and a optimized interface. The features generally satisfy customer demands in the best way possible. Here, the best way is defined as the way to provide the required features to the customer without resulting in economically disadvantages for the company.

This concept is the successor of the functional machine. The same set of requirements is applied to this machine plus some additional requirements and desires. The specific set of requirements for this concept consists of:

*Requirements:*

- 1) Provide valuable feedback to the user
- 2) The machine has to be flexible
- 3) The machine has to be adaptable to its working environment
- 4) The overall process time has to be optimized
- 5) Provide a user-friendly look

- 6) The machine has to be reproducible to allow standard production with the same recipes on every machine
- 7) Satisfy customer demands, but still be economically beneficial

*Desires:*

- 1) Allow software simulations without actually using the machine
- 2) Allow the administrator to customize the menu's of the user-interface
- 3) Provide more options to control the machine

## Features

To satisfy the customer demands in the best way possible, several features have been designed for the machine. The features are a little harder to realize than the features from the functional machine, but eventually, these features will better improve the human-machine interaction.

*Hardware:*

To be adaptable to the working environment, the machine is made adaptable in height. This is realized by a special designed table that makes use of hydraulic pistons in the table legs. Hydraulic legs are used by default with this kind of tables. With the buttons in front, the table could be raised or lowered. This makes it possible to vary in working position. When the user is tired, he can lower the table to sit and work, but when the level of attentiveness is too low, the user should stand while operating, because this keeps the user alert.

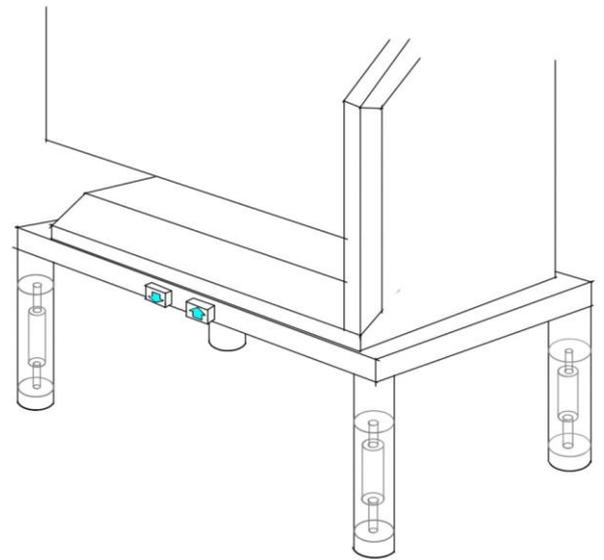


Fig. 26: Adaptable heights.

The laser does not necessarily have to come from the top towards the product. It could also be placed underneath the product as can be viewed in the picture beneath. When the laser comes from beneath, the machine could be smaller because you do not need the upper part anymore. Moreover, the process area will increase in size by removing the upper part and therefore the user can operate the machine more easily. A disadvantage might be that it is not possible to integrate the monitor for the camera and the touch screen anymore. They have to be additionally placed on the top of the machine or the side of the machine.

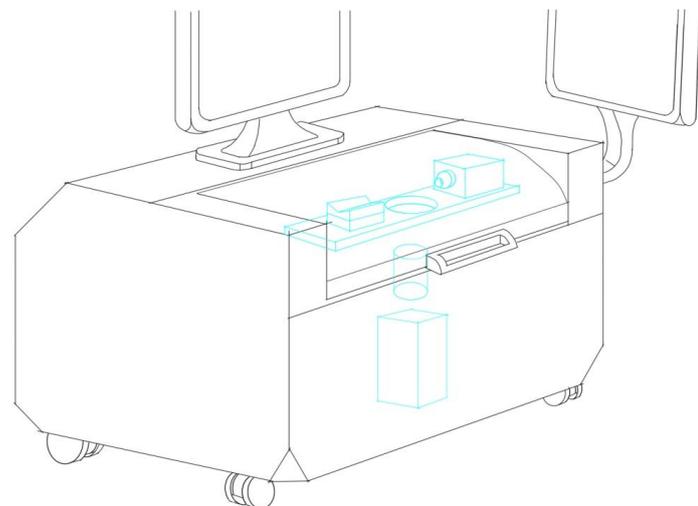


Fig. 27: Laser beam from beneath.

Another aspect that has to be taken into account, when the laser beam is applied on the product from beneath, is the safety of the user. The protection shield has to cover the whole process area, and the laser power should be absorbed completely to do no harm to the user.

When the machine is smaller, it will be easier to be moved. To increase the machine's movability, rollers have been applied. These rollers can also be applied to the previous adaptable machine. With the combination of the adaptable heights and an increased movability, the machine will be highly adaptable to its working environment.

Some customers want to have the freedom to redesign the machine themselves and to add specific features to the machine for their production line. To satisfy these specific customer demands, some parts of the machine are customizable. In this moment, the HMI is integrated in the body of the machine. The HMI could also be taken out of the machine and be provided on a tablet or an additional touch screen. For this reason,

not only the demands of the customers are met, but the flexibility of the machine increases as well. The buttons and the joystick in the current machine are integrated in front of the machine. The customer might find it useful to have all the buttons and the joystick integrated in the HMI. For this purpose, the HMI has to be adjusted. After the user has pressed "save and load" in the recipe menu, a screen will appear to control the process. Besides that, the movement of the axis can be done within the step-by-step menu and will be part of the second step (selecting or creating a recipe). Therefore, the buttons to control the axis will be provided in this step.

The emergency button however, should not be integrated in the HMI, because that will decrease the safety of the machine. The emergency button will still be provided on the front of the machine and it is easy to reach during the process.

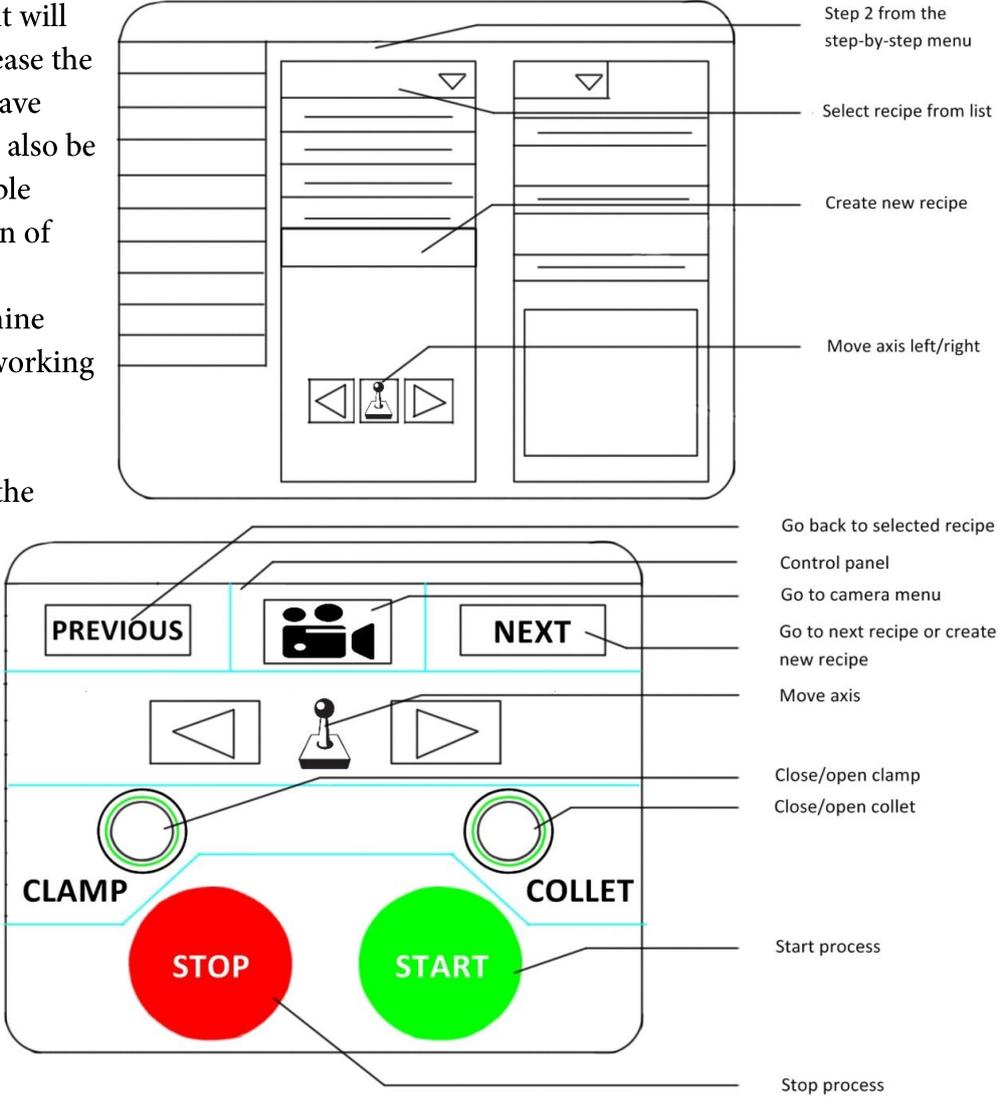


Fig. 28: Hardware interface integrated in HMI.

Furthermore, the customer might want to vertically load the product instead of horizontally. The realization of this feature was already explained with the functional machine.

To eliminate the problems with adaptable heights, the touch screen could also be replaced by a tablet. The user just has the tablet in his hands during the process and therefore the user can operate the machine from all different positions.

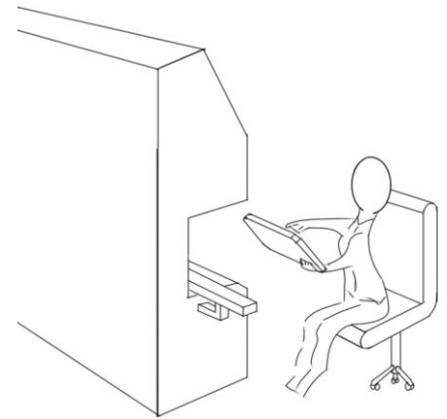


Fig. 29: Flexible tablet.

To measure the temperature, a temperature sensor has to be installed in the machine. The temperature sensor will be a precise IR sensor and will be placed next to the laser like is shown below. It measures the temperature of the weld and communicates this through the HMI to the user.

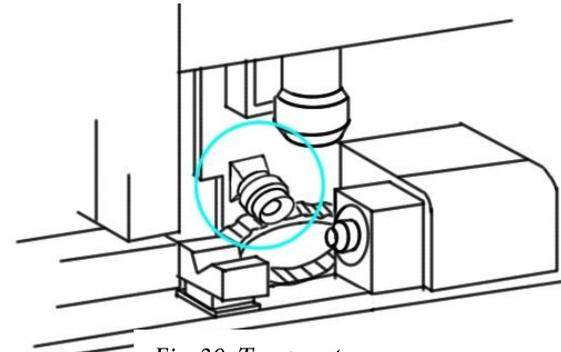


Fig. 30: Temperature sensor.

Some customers want to weld with various spot sizes. The spot size can be varied by adjusting the focus distance of the laser. On the laser welding machine type 1244, it is possible to move the mirror to create a different spot size.

Unfortunately, the mirror can only be manually moved to the desired position. This procedure is not very easy and takes a lot of time to be accomplished. Therefore, the mirror will be placed on an automated axis as well, so the mirror can move left and right by use of the joystick. For movement by use of the joystick, the user has to switch between axis. This can be done by pressing an additional switch-button.

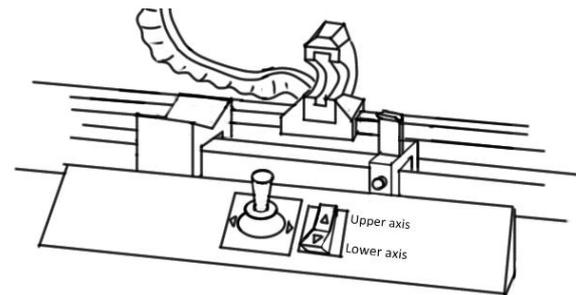


Fig. 31: Extra axis.

To improve the flexibility of the machine, some parts of the machine can be disassembled. For instance, the guiding axis can be disassembled from the one side and reassembled on the other side. This will provide the possibility to operate the machine from both sides.

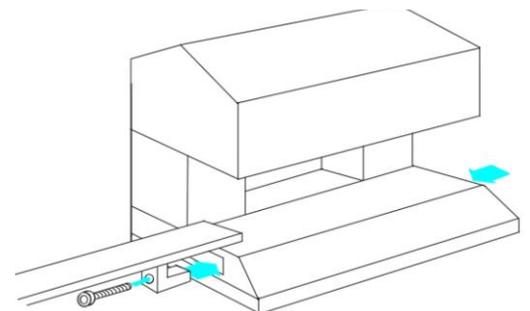


Fig. 32: Flexible axis.

Furthermore, the machine needs to have more easy to disassemble components to be operational from both sides. The clamp and the rotation mechanism have to turn with the direction that the user wants to weld with. An easy magnetic click-on system has been designed. Some hinges are built-in the different component's standards to allow them to click-on the rail.

The rail is magnetic and dependent on the magnetic field, the components are either attracted or repelled on the rail.

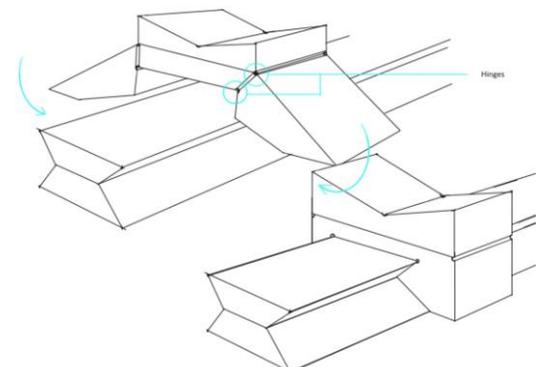


Fig. 33: Click-on system.

Besides the guiding axis and other components, the customer will also be able to choose whether he wants the monitor of the camera and the touch screen integrated in the upper part or in the front of the machine. The ease of use of the two screens is depending on the working position and for this reason is it related to the adaptability of the working environment.

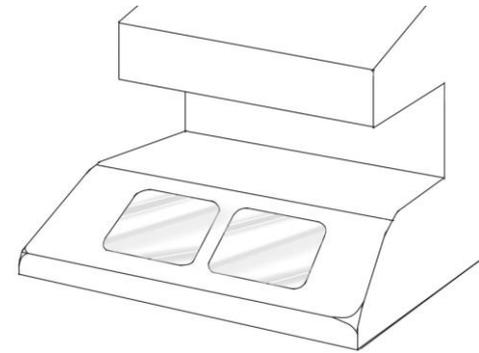


Fig. 34: Screens in front.

*Software:*

For the development of new recipes, it would be very useful to make use of simulations. These simulations can be provided on the machine before producing the actual weld, but this is not an optimal procedure. It would be an improvement for the engineer when he is allowed to develop new recipes without actually using the machine. This will be possible by new software that shows the precise simulation of the weld that has to be accomplished. The engineer fills out the material properties and the other required parameters in the existing HMI and thereafter he runs the simulation. The simulation shows whether it is a good weld or a weld that does meet the requirements. The advantages and disadvantages of this method are drawn up to give an overview of the possibilities.

*Advantages:*

- Saves loading/unloading time of the product
- No physical errors will appear (to the product)
- It will be more easy to adjust parameters
- No actual machine involvement during the development of the recipe

*Disadvantages:*

- Large database of compared material is needed
- Video's are difficult to simulate in the HMI

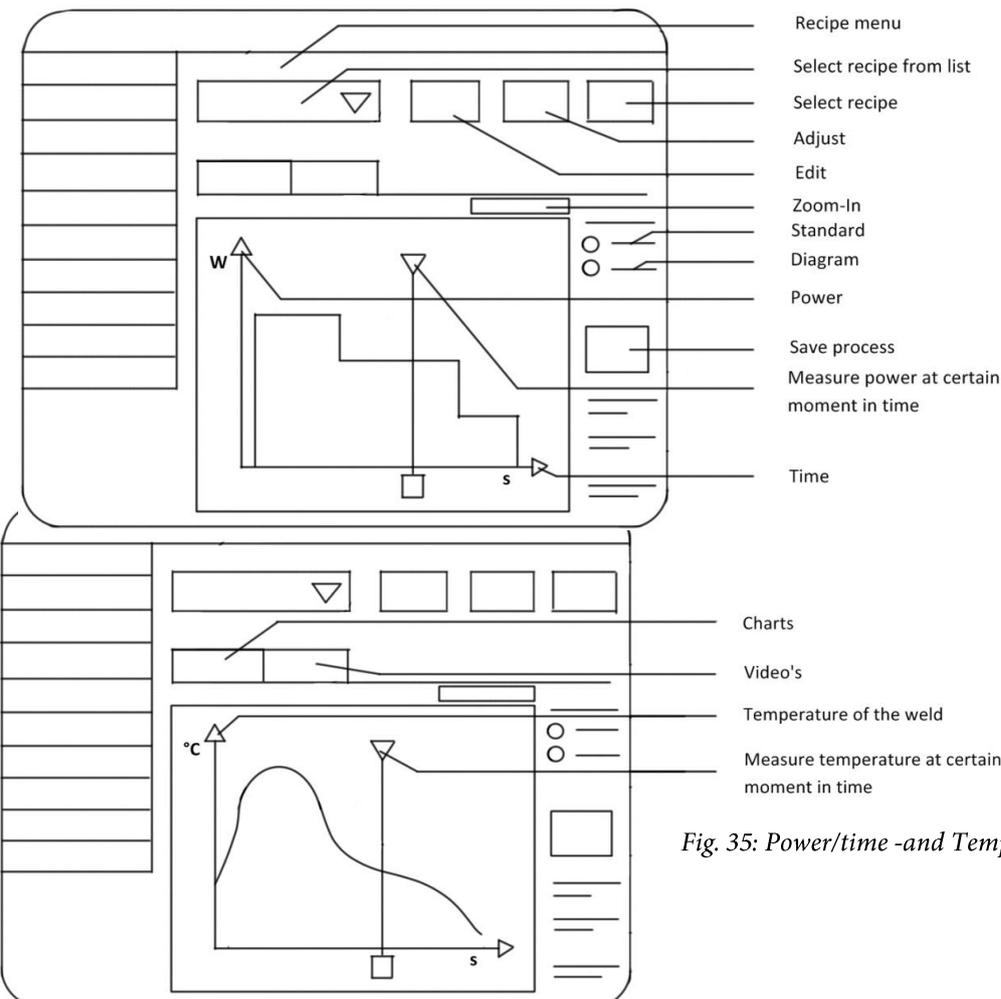


Fig. 35: Power/time -and Temperature/time chart.

Charts can be used to analyze the weld, so the user is able to vary between the parameters in an understandable way. Different charts were requested by the customers and therefore two examples of possible charts are given. The first one shows the power of the laser over time, and the second shows the temperature of the weld over time. Another way to provide feedback of the process, is by using a video that simulates the process. The video shows the actual welding spot and the direction in which the product will move. The shrinking of the shrinking tube will be simulated to check if the power that is applied is enough to

produce a good weld. Together with the charts, this will give clear feedback to the user to develop recipes without actually using the machine.

In the HMI, the menu's can be adjusted by the administrator in any way he likes. The basic functions still have to be provided in the menu's, but secondary functions can be added or left out of the menu's. Furthermore, the administrator determines which parameters can be adjusted by other users. For this reason, the operator cannot adjust the power of the laser or the engineer cannot adjust the order of the menu's.

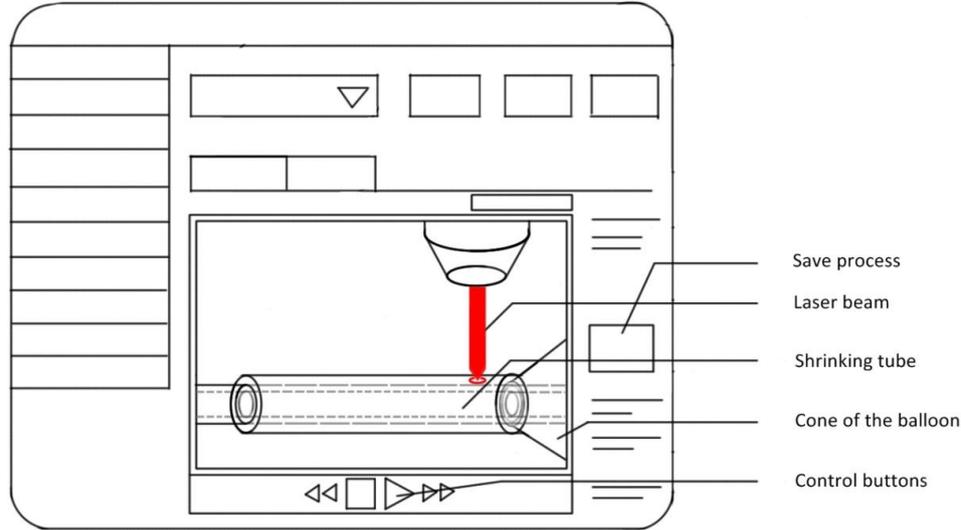


Fig. 36: Video of simulation welding process.

## The machine

A shape study has been made to determine the shape of the machine. The height of the machine, reachableness of the touch screen and the working position have been taken into consideration when doing the shape study.

The machine is reduced in size, so it does not have the higher part anymore. The machine is also placed on rollers, so it is easy to move around. For these reasons, the user will produce the weld more easily. A touch screen is integrated in the front of the machine and the monitor, to watch the camera images, is placed on top. The laser will be applied from beneath to the product through an opening in the axis. A temperature sensor is integrated to get the temperature of the weld and thereafter to simulate the temperature over time in a chart. The product can be loaded through the hole in the side of the machine and can be placed on the clamp and into the collet. The clamp and the rotating mechanism are placed on standards that are easy to click-on the axis by use of magnets. Furthermore, an emergency button is placed on a remarkable position, so it is easy to reach.

After a short evaluation of this concept, some adjustments have been made to make the machine even more comfortable. To improve the ease of use, the axis is not only moveable in the x-direction, but also in the y-direction. In other words, the axis will move towards

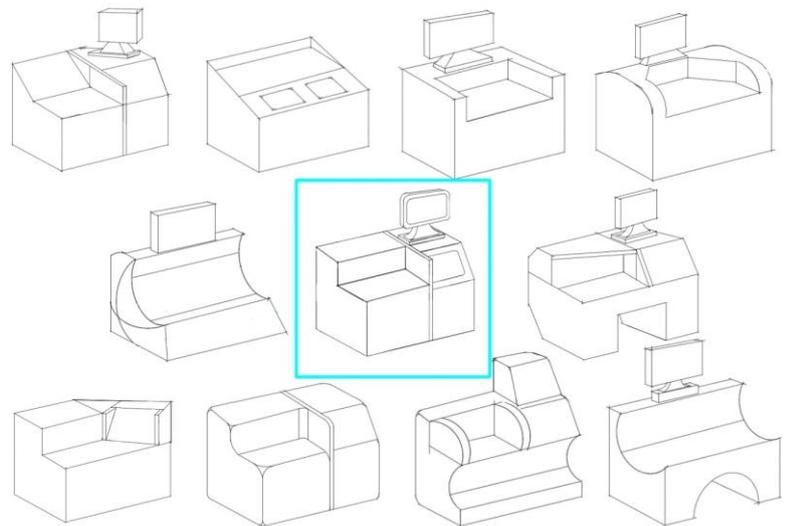


Fig. 37: Shape study.

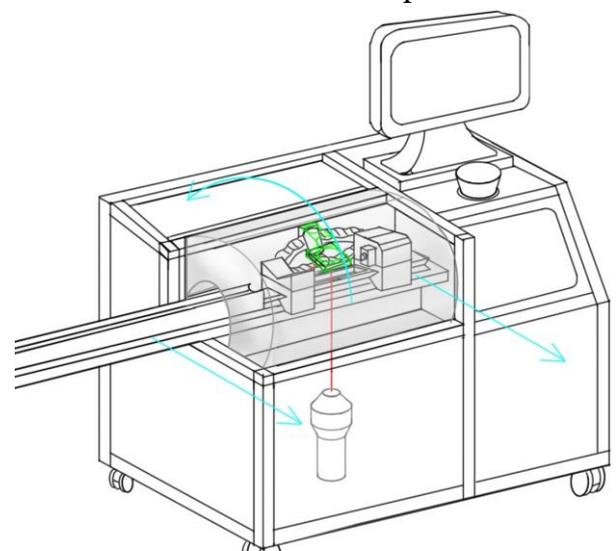


Fig. 38: Adjustments concept comfortable machine.

the user to provide the ability for the user to load and unload the product more easily. The safety door will automatically move into the machine when the process is finished. Highlighted with green, a mirror can be viewed. It is installed to reflect the laser beam under an stable angle towards the product. The mirror will move upwards when the process is finished, so it will not obstruct the axis to move towards the user. To create different spot sizes, the focus distance can be changed by moving the laser upwards or downwards.

An additional tablet can also be provided instead of the integrated touch screen. Besides that, the customer can chose whether he wants the interface (start/stop button, collet/clamp button and joystick) integrated in the software or integrated on the machine itself.



*Fig. 39: Final concept comfortable machine.*

To ensure the user's safety, the emergency button is placed closer to the safety door. Therefore, when the user got stuck between the machine and the safety door, he can more safely interrupt the process.

The laser shoots from beneath through a hole in the rail onto the mirror. Thereafter, the mirror reflects the laser beam onto the product. A camera, nozzle, and temperature sensor are pointed to the weld, so they can deliver the essential feedback.

## 6.3. Sci-Fi-machine

The third concept is a machine that consists of all high-tech features, and therefore it is called a science fiction machine. The main characteristics of this machine are that it meets the most of the customer demands and that it works almost completely automatically.

This concept is the successor of the comfortable machine. The same set of requirements is applied to this machine plus some additional requirements and desires. The specific set of requirements for this concept consists of:

### Requirements:

- 1) Provide as many feedback as possible
- 2) The process needs minimal user input
- 3) Satisfy all customer demand in the best way possible
- 4) Occurred errors from the past have to be prevented by automatically recognizing the errors and communicate these errors to the user

### Desires:

- 1) A database with different welding strategies should be provided
- 2) The machine should prevent errors in a early stadium

## Features

To satisfy all kind of customer demands, several features have been designed to improve the human machine interaction in the best way possible. All kind of available techniques are applied to perform different functions.

### Hardware:

The alignment of the product can be improved by using magnets instead of the clamp. The alignment will be based on the principle of magnetic levitation. The user loads the product through two rings that are attached to two different magnets. The magnets are levitated by a coil. The current in the electromagnet is regulated using a digital sensor controller and the vertical position of the magnet is measured using a linear Hall effect sensor. The position of the product can be stabilized by an up -and down push button to adjust the controller parameters. The left -and right alignment can be accomplished by moving the coils automatically. The magnets will move with the position of the coils.

To provide all the necessary feedback to the user, different kinds of sensors are installed in the machine.

A smoke detector will detect the smoke coming of the product when the laser power is too strong or the focus distance is too short. When this occurs, the machine will automatically shut down the process and will indicate the problem to the user. Moreover, it will provide a suggestion to the user on how to correct the parameters of the applied laser beam to produce an accurate weld.

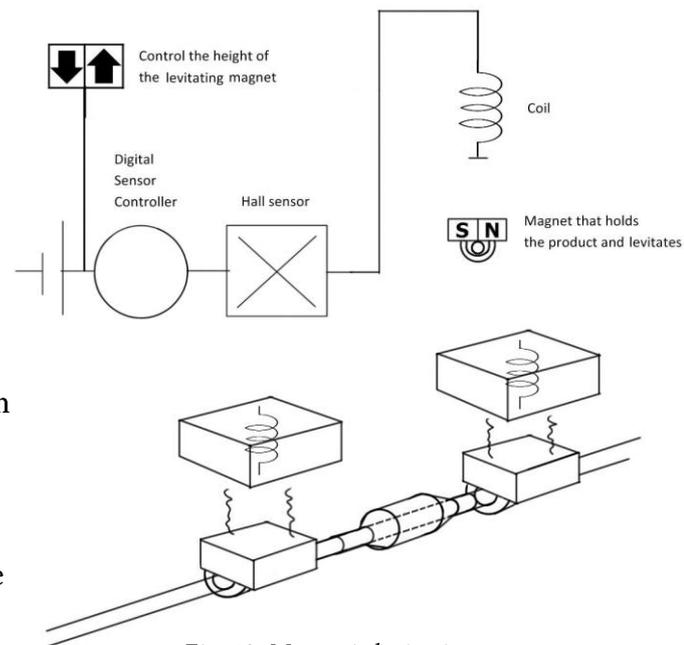


Fig. 40: Magnetic levitation.

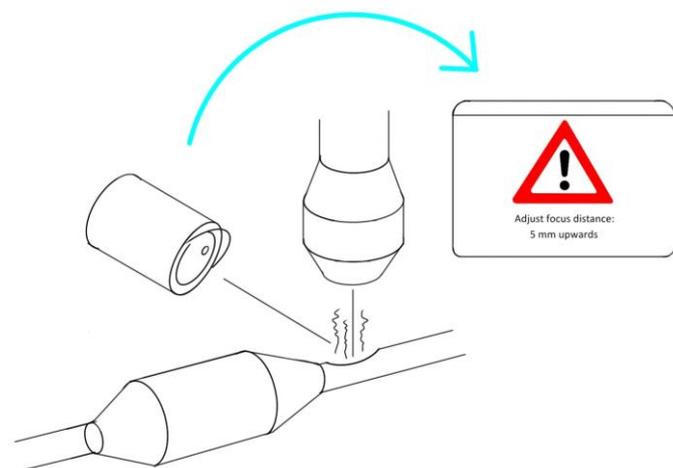


Fig. 41: Smoke detection.

An optical sensor will be placed into the machine to measure the layer thickness of the balloon, so the power of the laser can be determined. Furthermore, the optical sensor is used to determine if the product is aligned correctly and afterwards it can be used to perform a quality control.

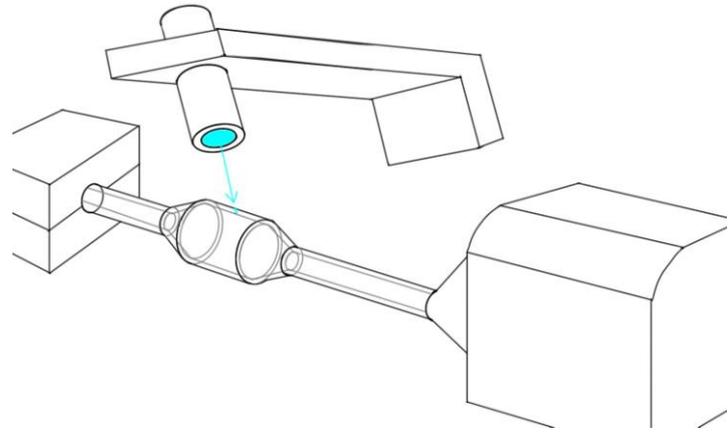


Fig. 42: Quality control.

This process is not ideal, because the process takes a lot of time to succeed, but it works very precise. The process consists of the following steps:

- The product is first positioned underneath a vision system
- Two perpendicular images are made and the position of the balloon is determined
- The interferometry sensor is exactly positioned over the surface of the balloon. The sensor is always kept perpendicular to the surface
- A flexible number of points can be programmed to be measured
- The measurement position and balloon contour are indicated on the screen, so deviations can be detected

The optical sensor is not the only solution for measuring the dimensions of the balloon catheter. Another way to measure the dimensions is by use of light. The product is aligned between a light transmitter and a receiver. The light transmitter sends green LED light onto the product and receives this light on the other end. All the light that has been obstructed by the product is not received, and therefore the diameter of the balloon can be measured.

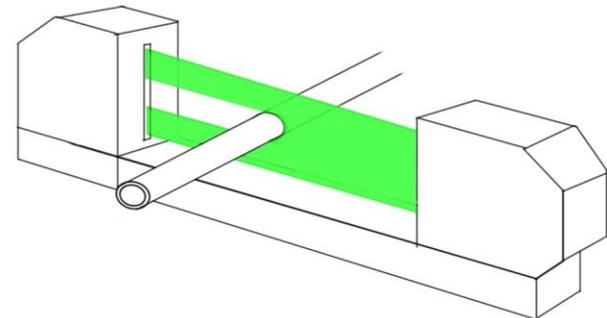


Fig. 43: Measuring diameter.

This process can be executed in only a few seconds, but is very expensive.

In fact, the device can recognize the diameter of a specific balloon catheter. Therefore, one of the applications of this process could be recognizing the balloon catheter to subsequently automatically load the corresponding recipe.

This procedure can also be executed by using barcodes. This process is much cheaper, but the user has to give a barcode to every different kind of balloon catheter. That means, before assembling, every tube, balloon and mandrel have to be matched and coded. Therefore, this procedure is time spending.

To detect if the laser has produced an accurate weld, a camera, with a higher resolution than the existing one, is installed in the machine. This will improve the quality control process while the user does not have to take out the product and watch the accuracy of the weld underneath a microscope anymore.

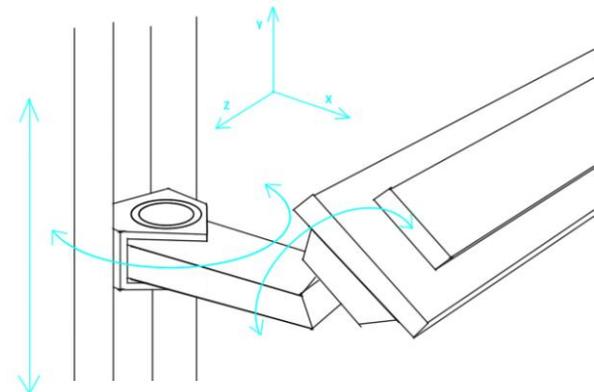


Fig. 44: Flexible axis.

For providing minimal effort for the user to load and unload the product, the axis, that holds the product, moves in all directions (x-, y-, z-direction). In other words, the axis moves like a robot arm.

The movability of the machine could still be more improved compared to the comfortable machine. Available techniques allow it to move the machine with minimal human input. For instance, the machine could be movable by the principle of a hovercraft. Hovercraft use blowers to produce a large volume of air, that is above atmospheric pressure, below them. The pressure difference between the higher pressure air below the hovercraft and lower pressure ambient air above it produces lift. This causes the hovercraft to float above the surface. The same principle can be applied to the laser welding machine.

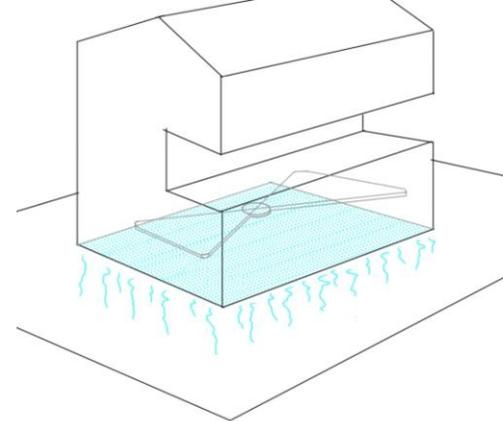


Fig. 45: Floating machine.

To keep the operator up-to-date, a light stroke with different colors is applied above the screens. The different lights are used to indicate how far the user is in the process, so they are linked to the different steps in the menu. When the light turns green, the user can start the process.

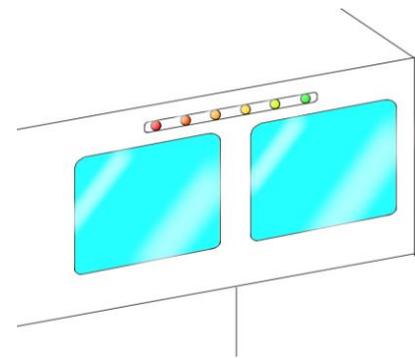


Fig. 46: Process indication.

*Software:*

When the diameter of the balloon catheter is measured, the details are communicated to the PLC. The PLC automatically loads the corresponding recipe. To start the process, the user has to verify that the PLC has loaded the right recipe. To load the right recipe, a database of all different kind of recipes has to be present. All the details of every different weld ever made can be saved on a drive. Recipes can easily be added or removed from this database and they can also still be adjusted. With the SciFi-machine, a step-by-step menu is used as will be proposed with the new user-interface. Two features are added to the second step of the step-by-step menu: a button to start the measuring process and four checkmark boxes with different process strategies.

The introduction of different strategies was one of the desires of the customers and should be taken into consideration.

The strategies are provided to the user, to provide more freedom of control towards the user. The four strategies consists of time efficiency, minimum stress in the surrounding material, repetitive focus, and quality control. Only one strategy can be selected to proceed with the process.

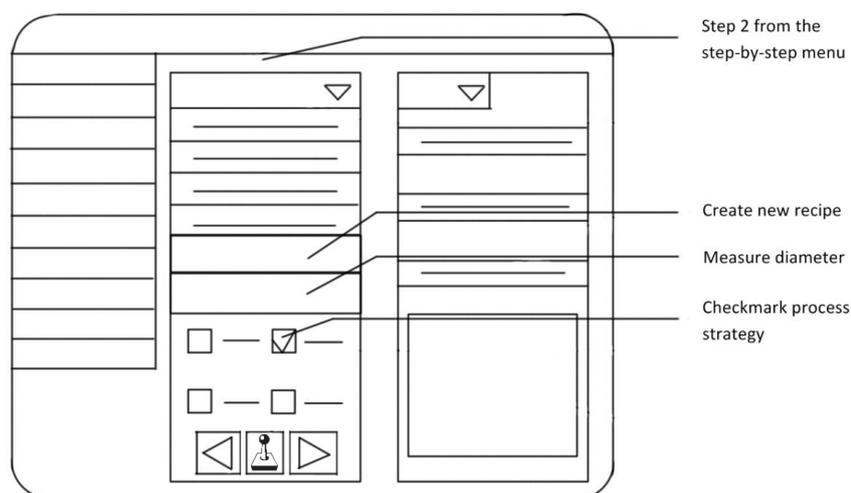


Fig. 47: Welding strategies.

The time efficiency strategy aims at reducing the process time in the most efficient way. Therefore, the less important steps of the process will be eliminated and other steps will go faster. This might result in a loss of the required quality of the product, but will save cost.

The minimum stress in the surrounding material strategy will focus on the material of the product, and the laser power, focus distance, and rotation speed of the machine. It will optimize these parameters to result in minimum stress in the surrounding material. The repetitive focus strategy will focus on a standard production process for every weld to make. Every loaded product will take the same time to be processed and the same quality will be reached for every weld made. This strategy will be the standard selected strategy in the step 2 menu.

Finally, the quality control strategy will focus on the quality of the product. This process is time consuming, but guarantees the best quality of the product. After the weld has been produced, the weld will be checked by the high resolution camera and the optical sensor.

When a recipe of a weld is selected, the machine automatically loads the tolerances for the parameters. The user can change the value of a selected parameter between a minimum and a maximum value. To make this go easier, the new parameter adjustment consists of a line where the user has to swipe over to adjust the parameter. The value of the parameter is displayed in the triangle.

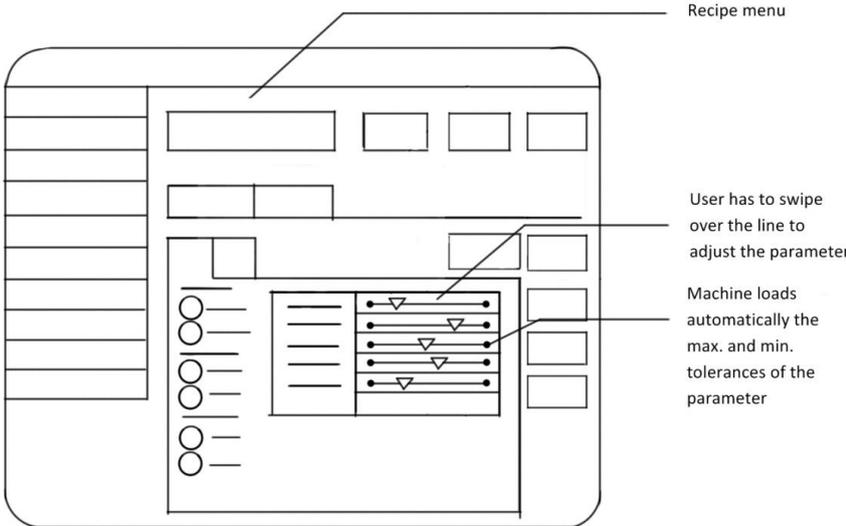


Fig. 48: Swipe over line.

When smoke is detected during the process, the process will shutdown automatically. A screen will pop-up on the touch screen with the type of warning and the feedback on how to solve the problem. Suggestions will be provided in the user-interface. For instance, the user-interface shows that the user has to adjust the focus distance to decrease the applied power onto the product.

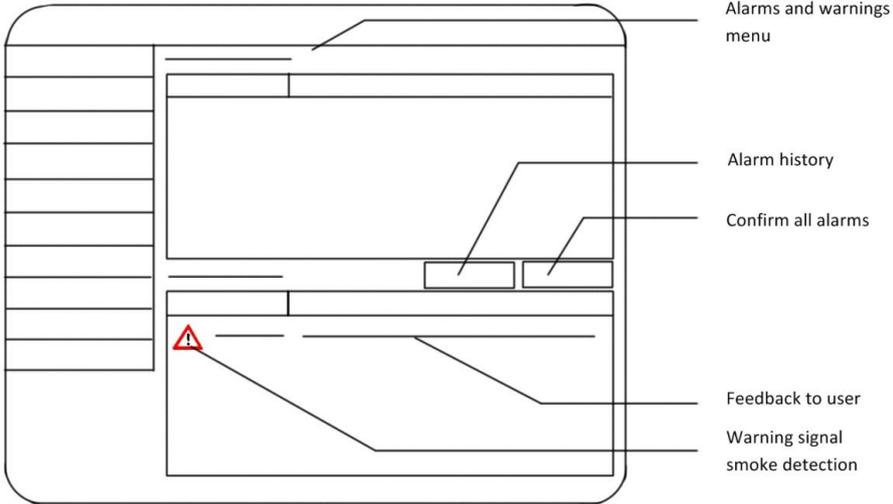


Fig. 49: Pop-up warning message.

When the machine runs a simulation of the weld to be made (as was introduced with the comfortable machine), the machine will detect problems automatically. When this happens, the previous screen will also pop-up with the certain warning of the problem with the according feedback.

## The machine

When just the essential process features are applied to the machine to successfully proceed a weld, the machine could be much smaller. In fact, in the future, the whole "machine" could be a device that the user simply could hold in his hands. Therefore a diode laser is needed which can create a laser beam with the specific wavelength for welding a balloon catheter. It will be applied from beneath the product. Furthermore, magnets are used to position the balloon catheter precisely in the middle of the device. The laser beam will be applied when the user activates it by pressing the handle on the grip. The device might look like this:

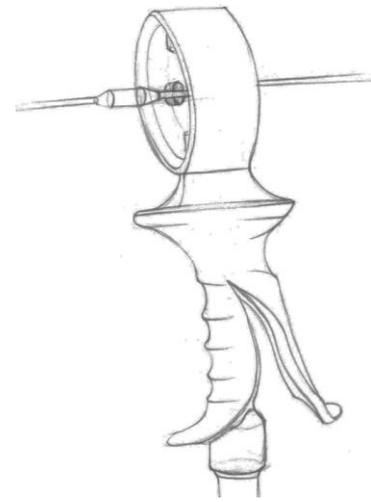


Fig. 50: Futuristic device.

The ultimate machine, would be a machine that automatically does the assembly, welding and quality control of the balloon catheter. Therefore, the different departments are build in the machine and the product has to be rotated through these departments, so the only thing the user has to do is load and unload the components of the product and press start.

On the left picture, the laser welding and the control process are displayed. An optical sensor checks the quality of the product directly after the weld is produced. The table turns clockwise.

On the right picture the assembly, the next station, can be viewed. All the different subcomponents are loaded from the top and automatically loaded onto the rail before they are move to the welding station.

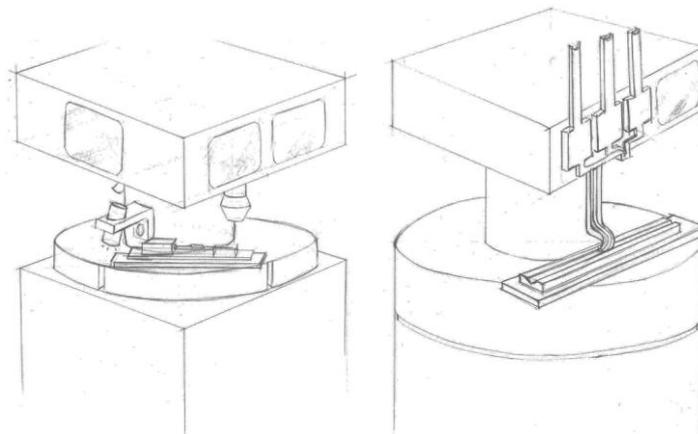


Fig. 51: Fully automated process.

A shape study has been executed to find a futuristic form that fits the machine. The size of the machine does not necessarily has to be reduced, because all the high-tech components have to fit in.

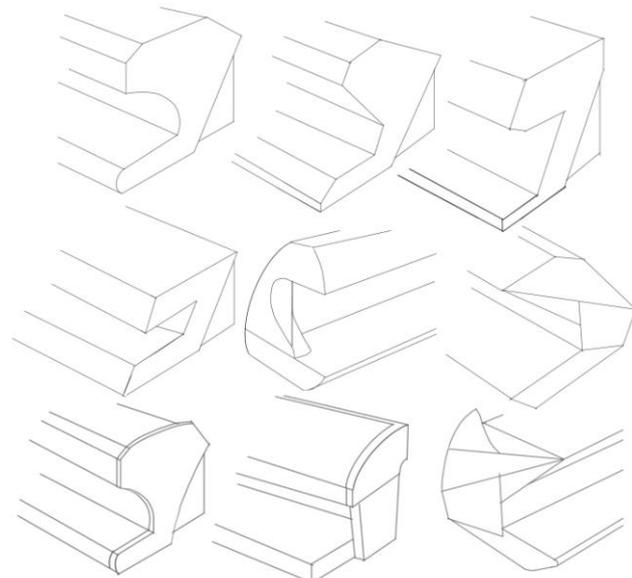


Fig. 52: Shape study.

The concept of the Sci-Fi machine contains most of the high-tech features that are described. The most important feature of this machine, is the axis that can move in all possible directions. The safety door will automatically fall around the process area.

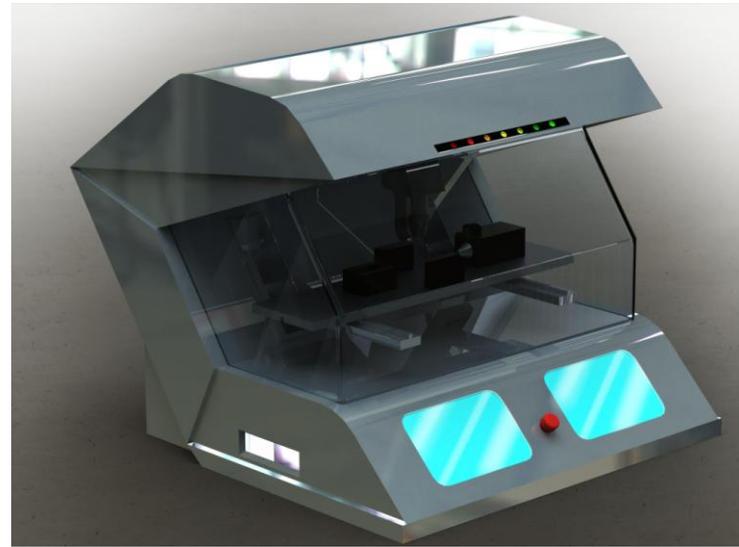
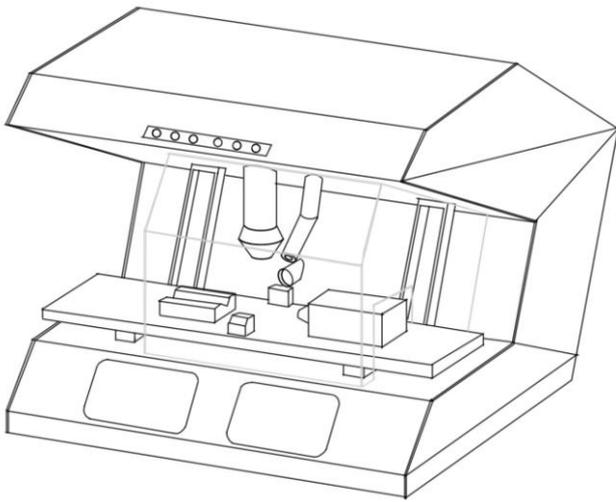


Fig. 53: Final concept Sci-Fi machine.

## 6.4. User-interface

To improve the run-through and the decision making process of the process, a new user-interface has been developed. The main requirements for the new user-interface were:

1. The recipe developer has to fill out the parameters more easily
2. Functions in the user-interface have to be grouped together in a logical manner
3. The user-interface has to provide a way out of the different menu's at all time
4. The user-interface has to provide shortcuts to the operator
5. The user-interface has to provide feedback to the user
6. The end of the process must be indicated

The new user-interface of the engineer will consist of only 4 different main menu's instead of 5. Moreover, a step-by-step interface (fig. 72) is introduced to improve the decision making process of the engineer. The engineer will more easily run-through the recipe menu by filling out the parameters and thereafter pressing the next button. The step-by-step menu will consist of the following steps:

- 1) Log-in
- 2) Select recipe or Create new recipe
- 3) Adjust recipe or Create new recipe/Create recipe from template

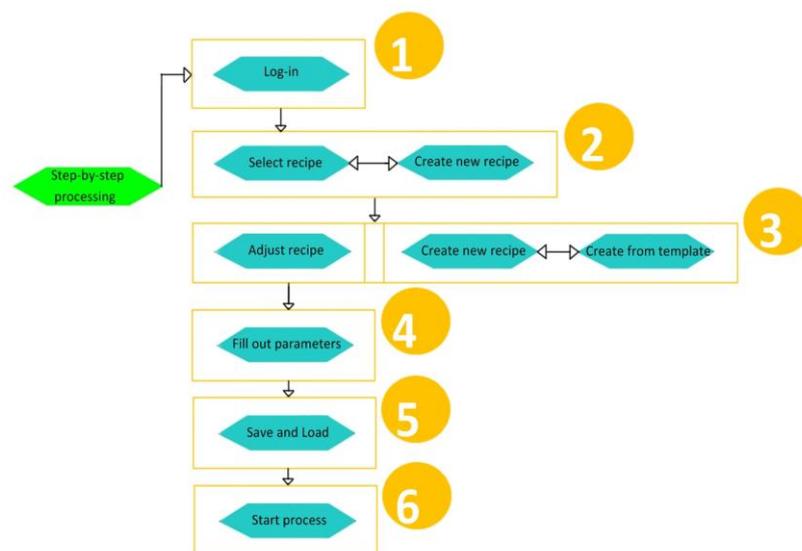


Fig. 54: The new step-by-step interface.

- 4) Fill out parameters
- 5) Save and Load
- 6) Start process

The engineer could also start the process in only 4 steps by logging-in, selecting an existing recipe and instantly pressing the "Save and Load" button followed by pressing start. In other words, the engineer could move from step 2 to step 5. The user can move back and forward through the step-by-step menu by pressing the previous button and by pressing the correct button to go to the next step. Besides that, the previous button functions as a "cancel"-button to give the user a way out of the menu.

When the recipe is saved and loaded, the user can select the simulate process button to simulate the process, so errors can be detected.

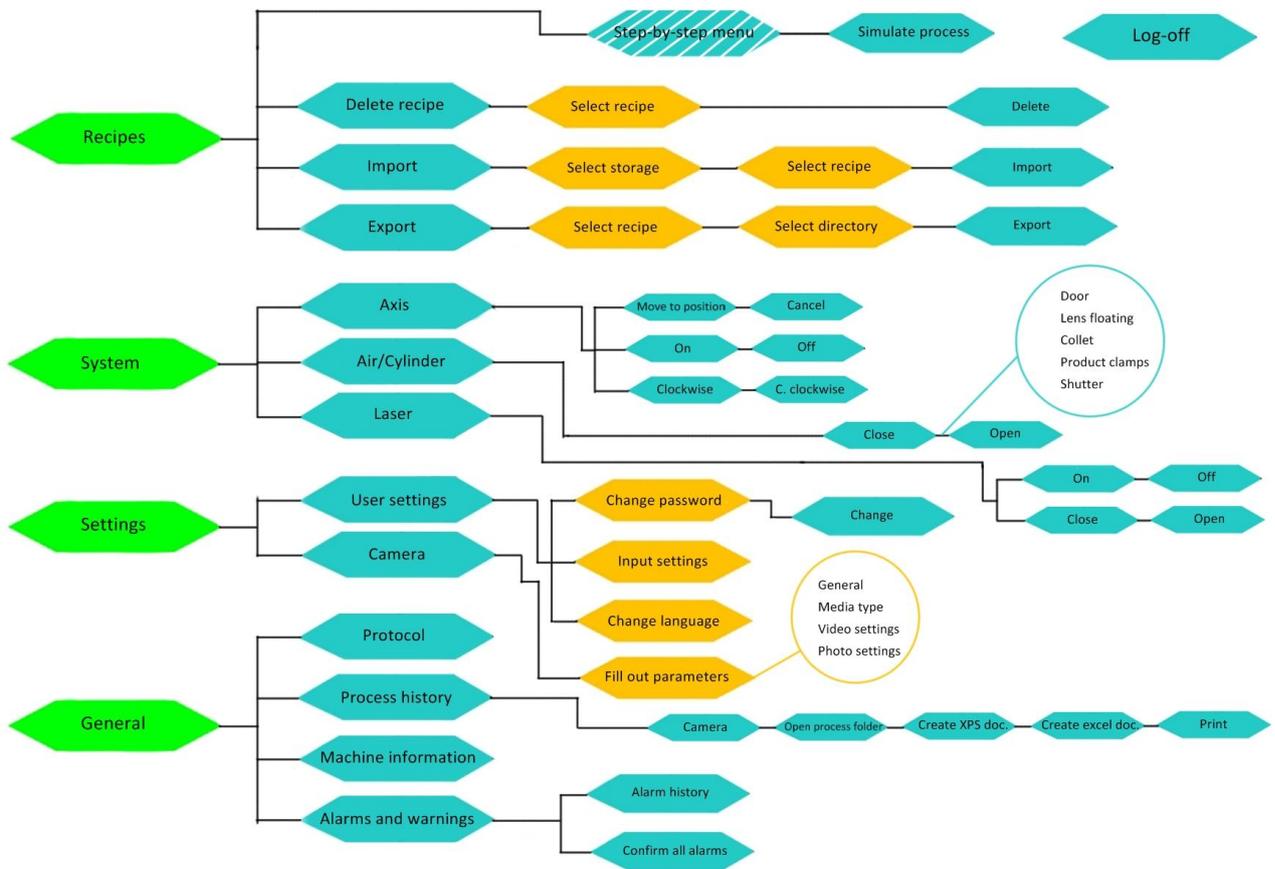


Fig. 55: The navigation of the new user-interface of the engineer.

In figure 73 the green balloons represent the different menu's, the blue balloons represent the buttons that could be pressed, and the orange balloons represent the parameters that have to be filled out by the user.

The user does not have to set the settings of the machine every time he uses the machine, therefore the user could use the step-by-step menu to operate more efficient.

The log-off button is present at all times. To shutdown the machine, the user first needs to log-off. Thereafter, the user can press the exit button to shutdown the machine.

The most important feature of the new user-interface will be the feedback that it could offer to the user. For help when needed, the user is allowed to get a description on the selected parameter. A little text message with the concerning information will pop-up and is easy to

minimize when the information is not longer needed. Furthermore, the user could run a simulation of the process. The filled out parameters of the recipe will be verified and the machine will display a short simulation of the process. This simulation will visualize possible errors and failures of the weld that will be made. This will reduce the costs of the total process, because the product is prevented from damaging.

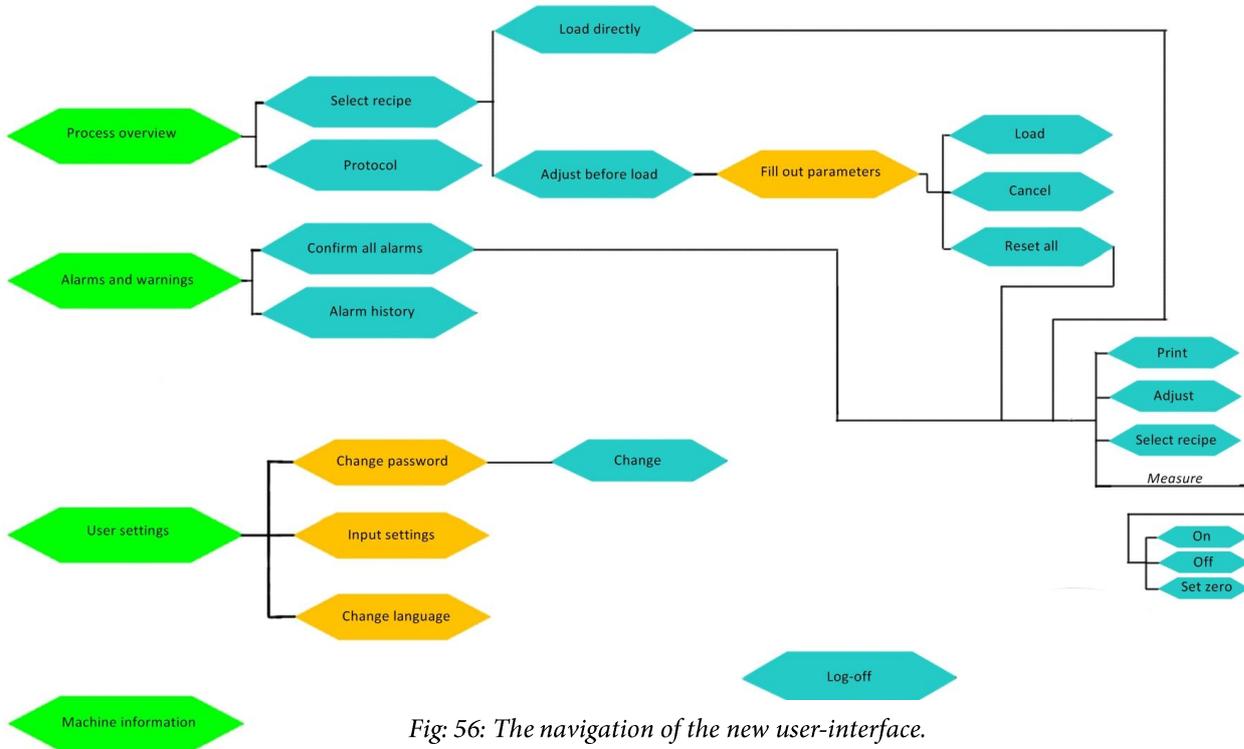


Fig: 56: The navigation of the new user-interface.



Fig: 57: The new icons for the menu's.

Besides the help function and the simulations, the user-interface will also indicate when to start the machine and when the process is finished. The start indicator will consist of a "please press start" pop-up text message and a blinking start button. The end of the process is indicated by a beep and by a "process finished" pop-up text message that will minimize automatically after 2 seconds.

The user-interface of the operator could also be improved. The navigation of the new user-interface is displayed in figure 74. The interface consists of only 4 different menu's. Shutting down the machine goes in the exact same order as through the interface of the engineer. The icons of the new user-interface of the operator are adjusted compared to the old user-interface and are displayed in figure 75. The walk-through the menu's is already made very easy to understand, so no large improvements have to be applied.

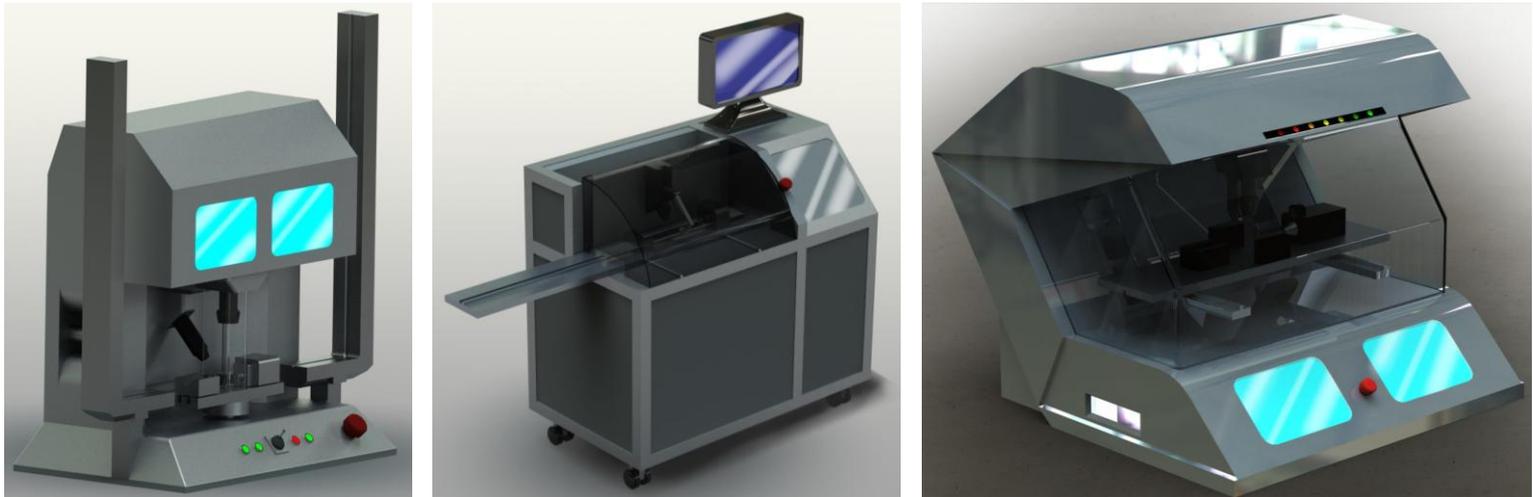
## The software

As was mentioned before, the menu now only consists of 4 different menu's. The top one represents the process overview. In this menu, the operator can select the recipe and subsequently load, or adjust before loading, the recipe. Besides that, it is possible to watch the protocol of the previous processes. The protocol shows a table that consists of the time, action and details of the previous processes. The operator can easily move backwards through the different menu's, since a button for this action is always present. The second menu shows the

occurred alarms and warnings of the active process. If a alarm arises, the operator first needs to confirm all alarms to proceed with the process. In this menu, the alarm history can also be viewed. The alarm history shows a table that consists of the activation time, deletion time and an alarm message. The third menu is the user settings menu. It consists of the same settings as the old user-interface. For the operator, only a few adjustable settings are provided. The final menu shows the machine information. The same information is provided as in the old user-interface.

## 7 Concept choice

This chapter describes the decision making process on which concept to develop into a final concept proposal for a future laser welding machine. All the different concepts show different aspects that will be taken into consideration when developing the final product, but one concept has to be chosen to be the initial concept.



*Fig. 58: Concepts to chose.*

### Pros and cons

To make an educated decision about which concept fits the stated requirements best, a short list of all positive and negative elements of the proposed concepts was made:

#### Functional machine:

- + Easy to produce and adapt in production line of BW-TEC
- + Low cost
- + Save space by vertically loading product
- + Minimal improvements
- Requires still a high involvement of the user
- + Minimal feedback to the user

**Comfortable machine:**

- + Easy to use
- + Flexible and adaptable to environment
- + Satisfies most customer demands
- + Feedback by simulations
- + Provides customer's freedom
- Additional monitor is required
- Horizontal loading requires more operational space
- Only operational from one side

**SciFi-machine:**

- + High-tech features
- + - Minimal involvement of user (automatic)
- + Provides as many feedback as possible
- + Satisfies all customer demands
- + Movable axis
- Not very adaptable to environment
- Expensive
- Difficult to manufacture

To further ground the decision of the concept to develop the following table plus *table 10, appendix I* has been made. The table in appendix I describes all of the main tasks that have to be performed by the laser welding machine. Besides that, it describes on how the tasks are performed by each concept. The table below (*table 8*) shows the grading of the efficiency in fulfilling the intended tasks. The grading scale varies from "--", which symbolizes 'not efficient', to "++", which symbolizes very efficient.

Aspect	Functional machine	Comfortable machine	SciFi-machine
Manufacturing	++	+	-
Cost	++	+	-
Efficiency	+ -	++	++
Flexibility	-	+	+
User friendliness	+ -	++	++
Interaction	-	+	++
Reproducibility	++	+	--
Automation	-	+	++
Feedback	+ -	+	++
Customer satisfaction	+ -	+	++
<b>Total</b>	<b>3</b>	<b>12</b>	<b>9</b>

*Table 8: The assessment of the performance of every concept*

According to the previous tables and when the pros and cons are taken into consideration, the comfortable machine shows the greatest potential compared to the functional -and SciFi-machine. However, when creating the final concept, value is provided by combining convenient or more effective aspects of the three concepts into one hybrid machine.

# 8 Concept detailing

Now that a concept has been selected, a table can be drawn up that consists of the main requirements with their possible features and the way on how to realize these features. (table 11, appendix I) After discussing this table, the most interesting features could be specified. These features that were introduced by the concept phase, can be subdivided into four main categories. Namely, the HMI usability, the clamp system, the physical ergonomic design of the machine and the sensors and other devices that can be integrated on the machine.

## 8.1. HMI usability

A new HMI has been designed. An interactive software model has been made and tested to investigate whether the new designed HMI is an improvement compared to the old one or not.

The new HMI works with images and supporting words instead of only words. When images contain a clear message, images will be recognized and processed more quickly by the brain than words. One of the principles of the theory of heuristic evaluation of cognitive ergonomics states that 'recognition rather than recall' should be applied to an interface. Recognition is easier than recall because it involves more cues. All the cues spread activation to related information in memory, raise the answer's activation, and make the decision making process more easy. An image provides a richer context to the user than a word and therefore makes the memory retrieval easier. Besides that, images are commonly used world-wide and therefore comprehensible no matter the language.



Fig. 59: The modified icons for the new HMI.

Several icons that were designed for the specific menu's can be found in appendix H. The surrounded icons were selected to be modified to the style that fits the HMI the best. These modified icons are displayed below (fig 76). The icons show a lot of consistency and make use of the colors of BW-TEC. Furthermore, the logo of the company is used in the background of the icons to provide a watermark to make it more proprietary.

## Usability test

The usability test focuses on the ease of use of the different menu's and buttons and the total run through the HMI to eventually start the process. It will be compared to the old HMI and the results will be used to improve the redesigned HMI. The subjects are varying from novice users to experts.

First the subject will be asked to perform some specific tasks that will be provided to him/her. After the tasks are completed, the subject will be asked to fill out some evaluating questions. Every participant will be given a short explanation of the main focus of the research and the procedure of the usability test. During the test, the total time it takes for a subject to perform all the tasks will be measured. The answers to the questions as well as extra remarks and observations will be written down.

## Results

Table 1 in appendix L shows how much time it took for the subject to fulfill the usability test successfully and it shows which tasks are performed good (*green*) and which ones are completed below the average (*red*). The performance of the tasks that are completed below the average will be explained.

*Task 3:* The step-by-step-menu is a new feature in the HMI and therefore is not recognized by the subjects.

*Task 4:* The same applies to the simulating process-menu.

*Task 5:* Also the different charts in the simulating process-menu are new to the subjects.

Therefore it was hard to understand the different icons in this menu, like the chart that shows the power over time.

*Task 7:* The loading button was disabled, the subject did not find it logical that you first had to save the recipe before you can load it.

*Task 8:* The distinction between creating a new recipe and creating a new recipe from template was not well understood. However, when labels are used to describe the function, the similarities of the icons will not cause confusion anymore.

*Task 9:* The subjects tried to fill out the parameters, but this could not be realized with the software that was used for this prototype. Of course, this will be possible in the final HMI.

*Task 10:* The subjects struggled with the selection of the cases, something that is caused by the program Axure. The cases will not be provided in the final HMI.

*Task 17:* The settings -and system icon are too similar, and therefore they caused confusion to the subjects whereupon the subjects chose the wrong intended menu.

*Task 19:* The subjects did not understand the shutdown-icon and some subjects did not find it very logical that you first have to logoff in the HMI before you can shutdown the machine.

### **General conclusion**

The new introduced features like the camera lines, the step-by-step-menu, and the simulating process are successfully integrated in the different menu's. Their added value was accepted by the subjects.

One of the main concerns of the subjects was that a process overview or an overall map should be provided at any time when the user is navigating through the different menu's, so the user knows where he/she is during the process in the HMI. Moreover, this will provide more freedom of control for the user, because the user is allowed to switch menu's at any time during the process.

When an alarm appears, it should pop-up in the HMI. When the user confirms the alarm, it should be redirected to the menu he/she was working in.

The colors used in the new HMI are similar to the company's colors. One of the subjects mentioned that it would be better looking when the HMI has a total intuitive interface. Therefore, the top bar should be deleted from the interface, so the whole space of the interface is used.

### **Icons**

In general, the most icons (menu's and buttons) are understandable by its own. However, some icons need words or a help message that describe their functionality.

For example, the system-icon is confused for the settings-icon, but with the describing words this problem will be solved. The same applies to the camera settings-icon. The descriptive words could be used or the icon could be replaced by an actual camera icon to better understand its functionality. Besides that, the shutdown-icon is not clear enough without the describing words. Many subjects thought it was the login button. The shutdown-button should be provided at all time in the HMI. Some subjects find it understandable that the user first has to log off before shutting down the machine. Others found this extra step to shut down the machine not very logical and time consuming.

### **Buttons**

The save-before-load- function was not clear to the subjects. Therefore it would be better to have one button that saves and, thereafter, loads the recipe automatically.

It is necessary to have disabled buttons in some menu's, because the HMI is operational for different users that are allowed or forbidden to adjust different parameters. When a button is disabled, the user should get information about why the button is disabled and feedback on how to act to enable the button when possible. This could be provided by, for instance, an hovering help message.

Furthermore, a home-button should be provided in all of the menu's, because the user should have the freedom to navigate through the different menu's at any time. The back-button

could be left out of some menu's when the home-button is provided. However, the back-button is very useful in the recipe menu.

Finally, the button for the joystick in the camera-menu is very useful, but should be left-out in the select recipe-menu, because this causes confusion with the functionality of this menu. It would be a good idea to integrate the button for the joystick in the system-menu, because the user might have to move the axis to a certain position when adjusting some parameters in this menu. The user then could vary between big -and short movements of the axis by holding the arrow buttons for a relatively longer or shorter time. When the joystick is totally taken out of the physical interface of the machine, a shortcut to move the axis should be provided at any time in the HMI. It was also noticed that it will save money when the joystick is provided in the HMI.

### Simulation process

In this moment, it would be very hard to realize the simulation of the temperature over time, because it is very hard to precisely check the temperature of the weld with the sensors that are available on the market. Therefore, this simulation chart might be left out of this menu.

It would be great when more simulated information is displayed in one screen. For example the chart that shows the power over time and the video of the welding process should be displayed in one screen, so the charts and video's are more related to one another.

Concerning the quality control, it would be great to check the quality of the weld on the machine itself instead of checking the quality underneath a microscope. Moreover, it might be possible to do a complete quality control on the machine. For example, the pressure test could be installed on the machine to check if the balloon catheter is leaking. To realize a quality control on the machine, a focus lens is needed that is able to zoom on the spot and for the leaking test, the machine needs some mechanical adjustments.

Finally, one of the subjects mentioned that the simulation process only works when a real picture of the product has been made. So the camera should be able to make a snapshot of the product before running the actual simulation.

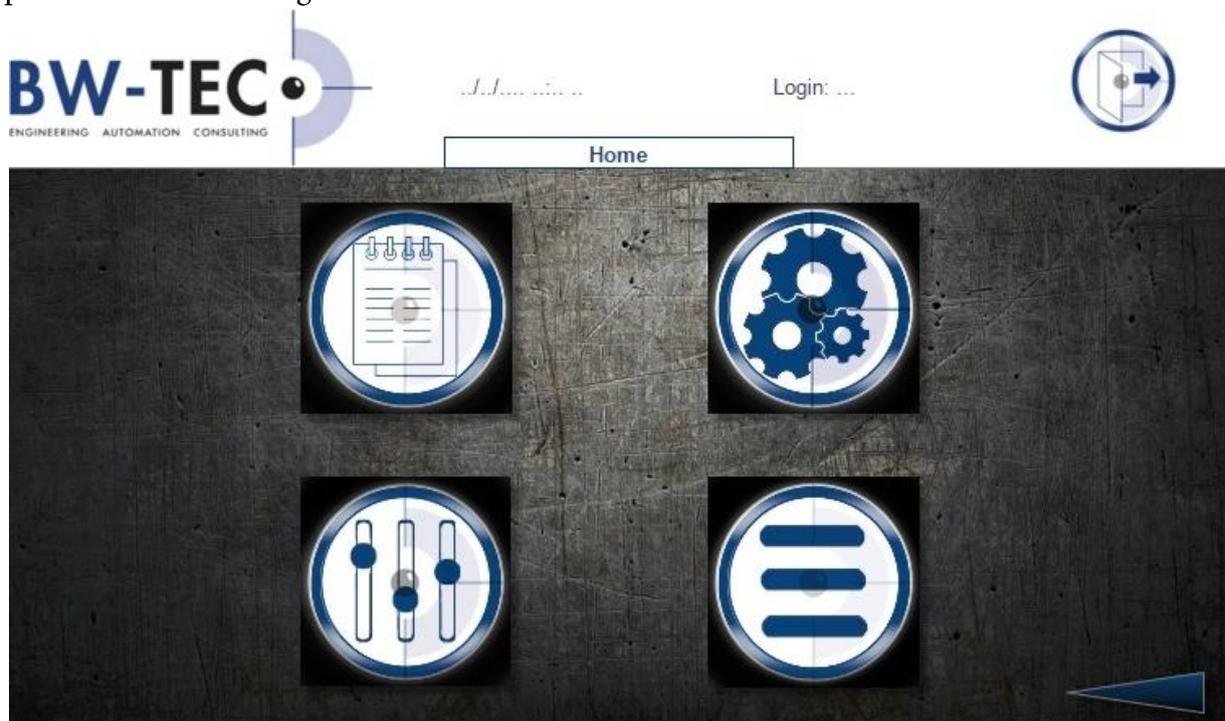


Fig. 60: The home menu of the new HMI that was tested.

## Adjustments HMI

After the usability test has been executed, the results were analyzed. Some icons were not immediately clear to the subjects. Therefore, these icons have been redesigned. It was also mentioned that the total interface did not fit the style of BW-TEC. Therefore the HMI has been adjusted with a more consistent overall graphical design (fig. 78).

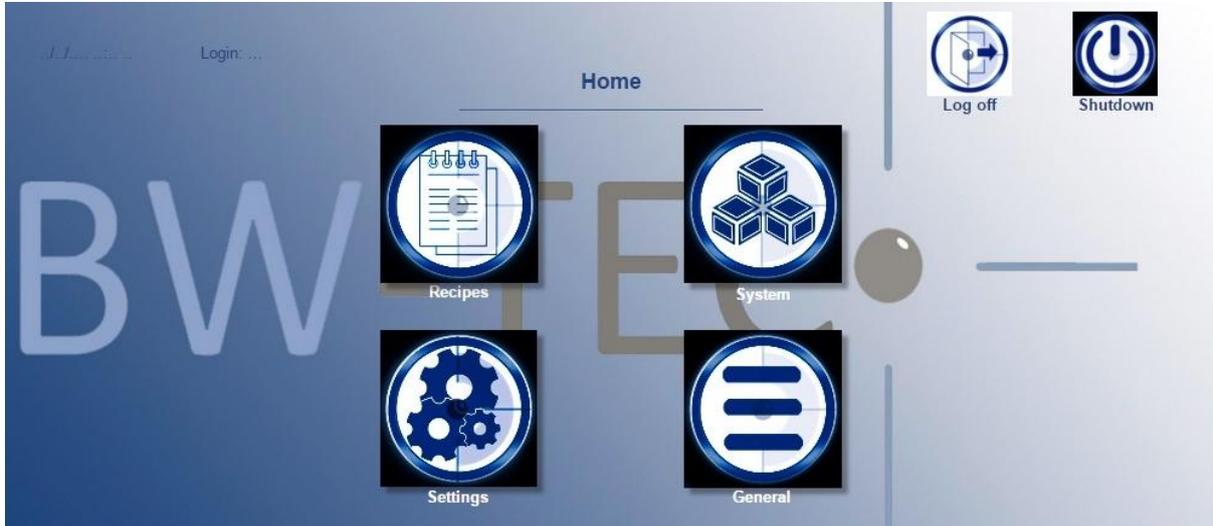


Fig. 61: The home menu of the redesigned HMI.



Fig. 62: The process-menu of the redesigned HMI.

In fig. 79 the process-menu is displayed. A home- and back-button are provided in the user-interface. These can be eliminated because in the final HMI, the overall map will be interactive. Therefore, the user only has to press on the label of the desired menu, so the user will automatically be directed to this menu. When the overall mapping is introduced, the width of the screen could be reduced by one-third.

The developer of the existing HMI was also asked to his opinion of the redesigned HMI and gave the following feedback which will be taken into consideration and be applied in the final redesign of the HMI:

- BW-TEC uses 800x600 12" screens, because these screens are cheap and easy to install.
- The right panel uses too much space of the total HMI.

- The BW-TEC background should only be provided in the login-menu, because it might be confusing in the other menu's.
- The parameter table is too small, because BW-TEC normally uses 8 parameters to be filled out. Therefore a scroll bar should be introduced in this table.
- The process time should be displayed to give more feedback to the user.

## 8.2. Clamp system

A research has been executed to find out which clamp system is suitable for the laser welding machine. The most important requirements of this clamp system are:

- The product must be aligned exactly in the centre of the clamp.
- The clamp has to allow rotation of the product.
- The clamp must not damage the product.

Besides these requirements, the clamp and rotation mechanism should be easy to disassemble and the height of the product should be indicated on the clamp to provide more control to the user. Moreover, the user should be able to load and unload the product more easily than on the existing machine.

With these requirements and other aspects, some ideas for an improved clamp system were created (*fig. 80*).

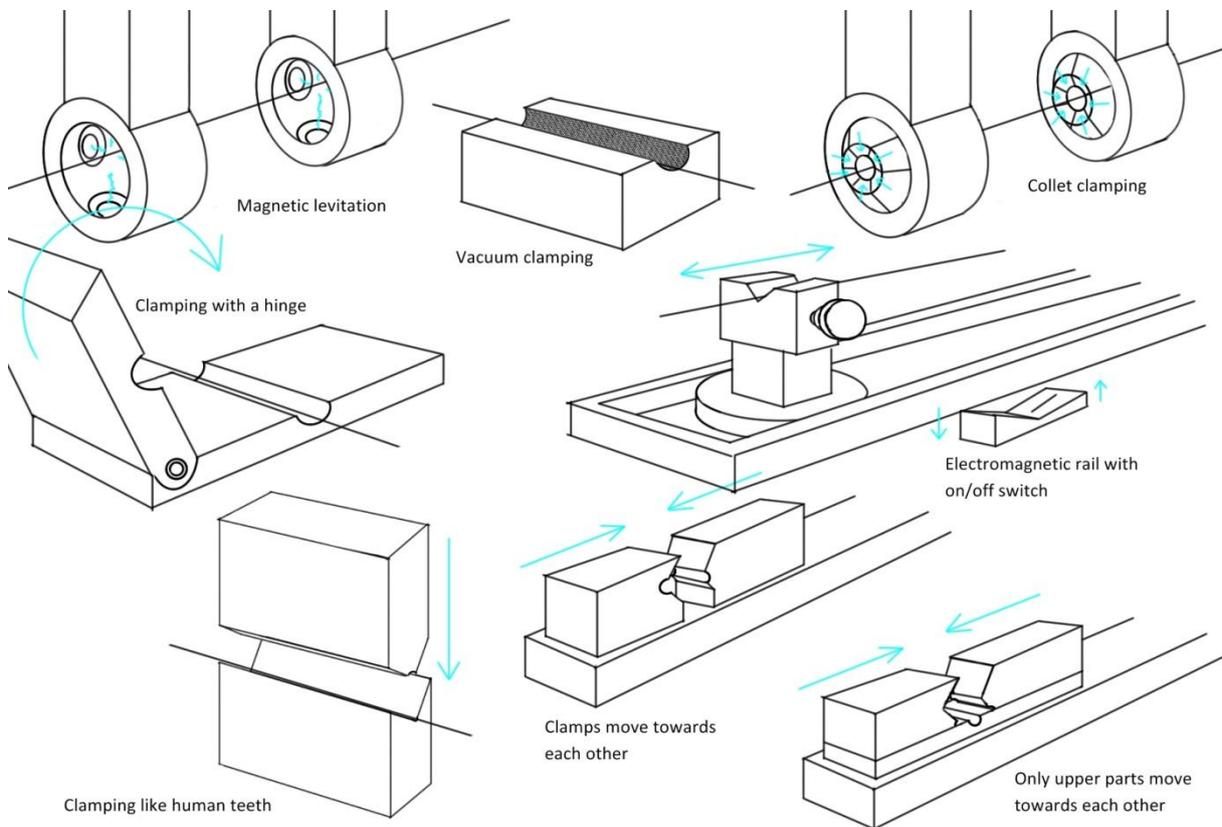


Fig. 63: Multiple ideas for the clamp system.

The clamp system could make use of different mechanisms. For a futuristic way of holding the product it could make use of magnetic levitation. Several coils are installed surrounding the product, keeping it precisely in the centre. The problem with this way of holding the product is the vibrations that the rotation mechanism may create. Because the product is light weighted, vibrations could easily ensure that the product is not aligned correctly anymore and this will cause a bad weld.

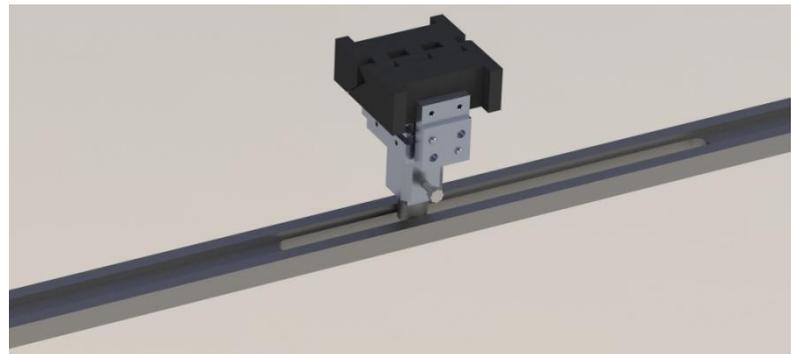
The clamp system could also consist of a clamp with small holes that creates a vacuum. The balloon catheter will be sucked onto the clamp. This way of clamping has several problems. Namely, the diameter of the balloon catheter varies, so you will need a different clamp for each possible diameter and again a straight rotation is hard to realize.

In the existing machine, the product is aligned between a clamp and a collet. This collet makes use of different inserts for every different mandrel diameter. To install these inserts into the collet takes time. Therefore the collet can automatically or manual be closed to the required diameter.

The other ways of clamping the product that were drawn, do not meet the first requirement: they cannot align the product exactly in the centre.

For the movement of the different components on the axis, a electromagnetic rail has been designed. On the existing machine, the user had to screw and un-screw the different components on the rail to move them. With the electromagnetic rail, the user only has to switch the magnetic field on or off to move the components.

This, in combination with the existing way of clamping the product, will deliver an improved clamp system that will look like the *figure 81*.



*Fig. 64: The new clamp system.*

The clamp system has a scale (in mm) on the side so the upper part is easy to set to the required height. By pressing the switch that is displayed, the electromagnetic field can be switched on or off. When the magnetic field is turned off, the user can move the component to the required position. The component will not be movable when the magnetic field is on.

## 8.3. Physical Ergonomic Design

This research also focuses on the physical ergonomic design of the machine to improve the human-machine interaction. Several aspects of ergonomics have been taken into account while designing the final concept of a future laser welding machine.

Dan MacLeod (1990), pointed out ten principles of physical ergonomics which will be described and subsequently applied to the final concept design. These principles can be found in appendix J.

Besides these principles, some specific dimensions will be applied to the design of the final concept as well. For precision work involving fine visual details, the work surface should be

set just above elbow height and support for the elbows should be provided. The seat height should vary between 40,6 cm to 52,1 cm which will accommodate most users. The seat height should allow a 90 degree angle at the elbows. The seat width of 43,5 cm to 50,8 cm suffices most people. The backrest of the seat should offer firm support and should be 30,5 cm to 48,3 cm wide and make an angle with the seat of 90 degree. (NS State University, 2015) These and other dimensions are displayed in the next figure.

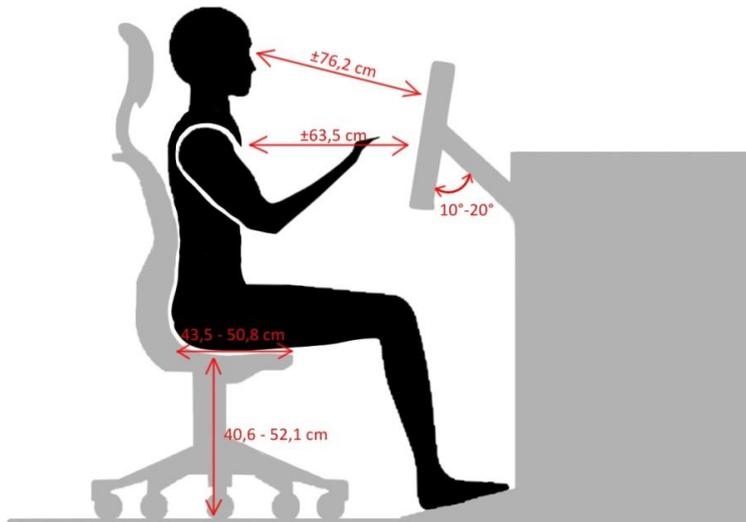


Fig. 65: The dimensions of the ideal working position.

For pushing and pulling the machine some calculations have been done to check if the machine is easy to move with the rollers (*appendix J*).

#### Conclusion calculations physical ergonomic design

From founded results (Ergonomic design for people at work, 1986) we can conclude that the maximum allowed force that should not be exceeded while horizontally pushing an object is 110 N when the primary arm and shoulder muscles are used and the arms are fully extended. The calculated force falls easily in this tolerance area and therefore the wheels will be installed on the machine. When the wheels will not be installed and the user has to push the machine the friction coefficient will be much higher and therefore the force to push the machine will also be higher. The friction coefficient will be around 0,04, so the  $F_{push}$  will be 134,22 N. This force will exceed the allowed force, so for this reason the wheels have to be installed on the machine.

## 8.4. Sensors and other devices

For realizing the new introduced simulation process, different sensors and other devices have to be installed on the machine. The simulation process needs input information from different components on the machine. For instance, it has to measure the power, temperature, time and quality of the process. Not all of these aspects can be optimized by use of a sensor, but a proposal will be done for possible sensors in this chapter.

For the simulation of the process the following division between the different input components can be made:

- Power over time chart
  - Timer (already integrated in the machine)
  - Power measuring device
- Temperature over time chart
  - Timer (already integrated in the machine)
  - Temperature sensor
- Quality of the weld
  - Camera
  - Air nozzle to provide air to cool down the weld
- Detection
  - Smoke detection sensor
  - Optical sensor for diameter detection
  - Detection sensor that locks safety door when it is closed
  - Safety sensors (already integrated in the machine)

## Temperature sensor

The most common material of the product is PLA. Its melting point lies between 150-160 °C. To determine which temperature sensor will be selected to be integrated on the machine, the maximum temperature of the weld has to be calculated. This maximum temperature should not exceed the melting point of the material. All the parameters that can be filled out by the engineer that influence the temperature have been taken into account. The calculation of the maximum temperature consists of the maximum value of those parameters.

The calculations and a small market research can be found in appendix K.

For selecting a proper temperature sensor that is able to measure the temperature of the weld, the following criteria have to be taken into account:

- The temperature range
- The spectrum sensitivity
- The accuracy
- The response time

With this criteria, a table with different temperature sensors has been made. (*table 12, appendix K*)

One of the most important requirements for an accurate measurement of the spot of the weld is a high response time. Therefore the PyroCube (Calex Electronics, 2015) will be recommended. The calculated temperature fits in the minimum and maximum values of this temperature sensor. Furthermore this temperature sensor is ideal for small targets, because the measurement area is as small as 1.6 mm diameter. Because this temperature sensor is very accurate, the cost price is high as well. The total price of the PyroCube is £723,50.



Fig. 66: The PyroCube.

## Camera

The camera that has to be integrated in the machine has to fulfill the following functions:

- The camera should have a focus lens to zoom in on the spot of the weld
- The camera should be able to take a snapshot of the product to run the simulation over this snapshot
- The camera should be able to film the process
- The camera should be able to check if the product is aligned correctly

*Table 13 in appendix K* gives an overview of the available camera's that meet the specific set of requirements.

The existing camera had a frame rate of 87.2 fps and a resolution of 752x480 with 0.36 MPixel. From the table can be concluded that the camera that fits the stated requirements the best, and has a higher performance than the existing camera, is the Q-12A180. (Adimec, 2010) This camera is actually meant for the manufacturing and inspection of electronic systems, but can also be used to inspect the quality of the weld on the laser welding machine. A consistent and precise sensor alignment is thoroughly embedded in the camera. The images that can be made, could be easily used for simulating the process, because they have a high resolution and therefore are realistic.



*Fig. 67: Q-12A180.*

## Air nozzle

The selection specifications for an air nozzle to cool down the product are not very important, because the air nozzle just has to produce a cold air flow and should not obstruct the other components in the machine. Therefore the air nozzle should be small in size. There are many different air nozzles available and they all have similar specifications, however they vary a lot in price. Therefore a specific air nozzle can be recommended based on the price.



*Fig. 68: Nex Flow Model 47001.*

From *table 14 in appendix K* can be concluded that air nozzles can vary a lot in price while they are able to provide the same compressed air pressure. Therefore the Nex Flow Model 47001 (NexFlow, 2015) is selected to be integrated on the machine, because it is the cheapest and it is small. It has a sound level of 74 dBA and is mainly used for blow-off applications.

Besides that the air from the nozzle has to be cold, the air also should be de-ionized, because ionized air might cause sparks in combination with fast rotating plastics. Therefore an ionizer can be installed in line with the nozzle. Before the cold air reaches the nozzle, it travels

through the ionizer that charges the air molecules (negatively). These molecules will interact with other molecules in the surrounding air due to an electric attraction. In other words, the ionizer eliminates the static electricity of the air. The ionizer that is recommended is the Ionizer Nozzle Type IZN10. (SMC, 2015)



Fig. 69: Ionizer Nozzle Type IZN10.

For the detection of electrostatic air molecules, an electrostatic sensor has to be integrated in the machine. It detects a point  $r$  in a static electric field  $E$  which has a specific electrostatic potential value that can be measured and that can be compared with other values. To realize this detection, the IZD10 electro static sensor is recommended. This sensor is also from SMC and therefore can be easily combined with the ionizer.

## Lock mechanism

The lock mechanism of the safety door will work with a pin that is inserted in a hole in the safety door. This lock is activated when the safety door falls into a slot with a pressure sensor where the pins are located. The pins are automatically released when the welding process is finished. The pins are inserted and removed by use of an air cylinder. The operation of the lock mechanism is illustrated below.

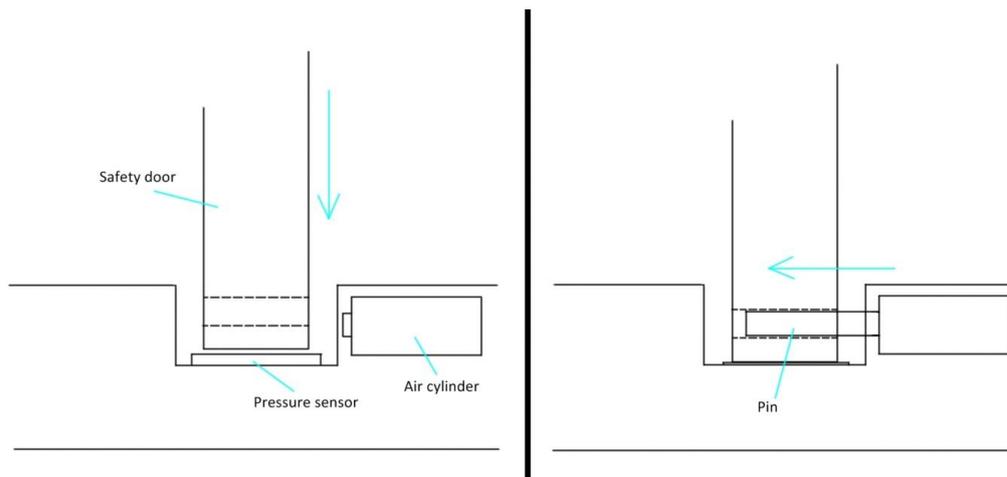


Fig. 70: The operation of the lock mechanism.

## Shape study

A final shape study has been executed (fig. 88). The shapes are all based on the shape of the comfortable machine. The main components that the machine should consist of are two screens to view the welding process and give the input for the process, a

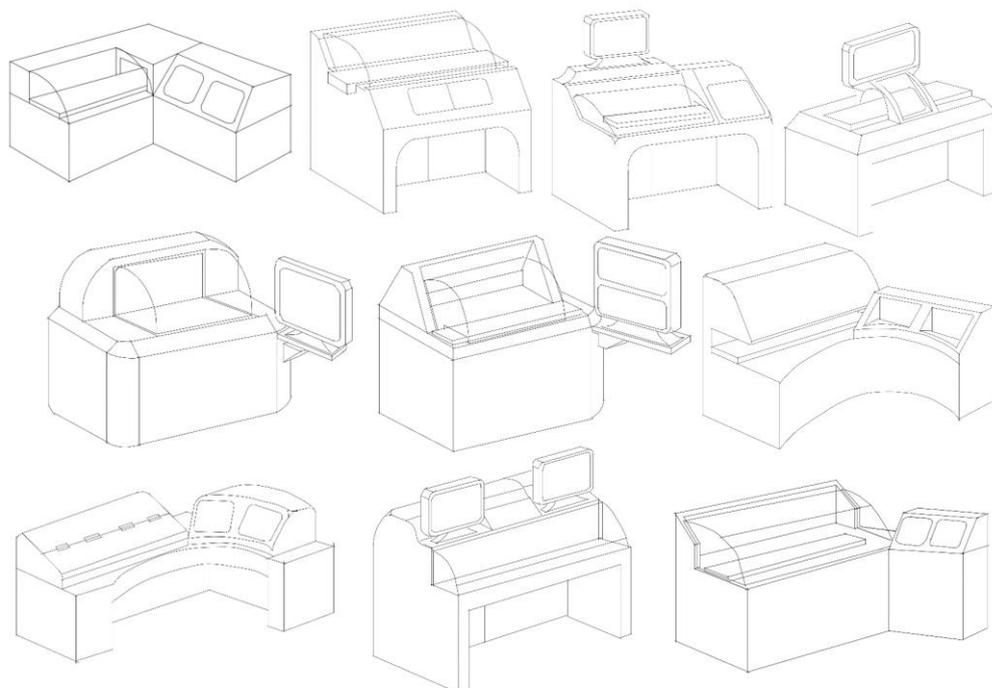


Fig. 71: Shape study final concept.

mechanism that protects the user against reflections of the laser beam, and enough space to be ergonomically operational.

Based on all the features that were mentioned during the concept development- and concept detailing chapter, the following concept has been designed and will be recommended to BW-TEC to be their future machine:

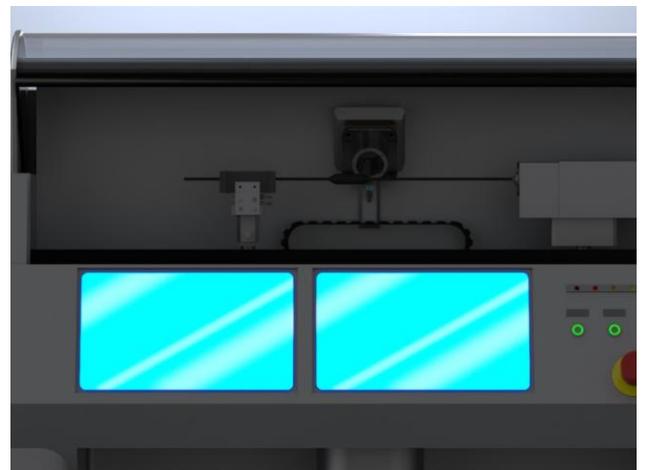
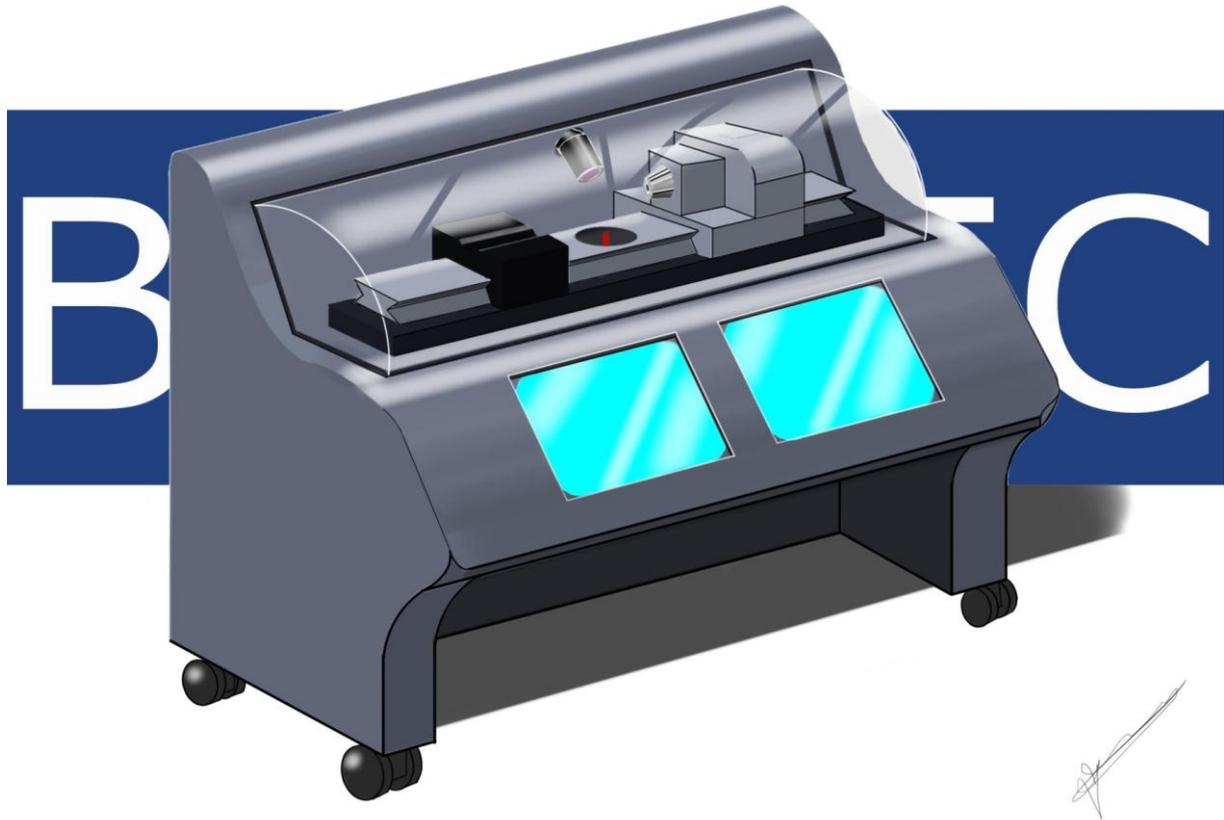


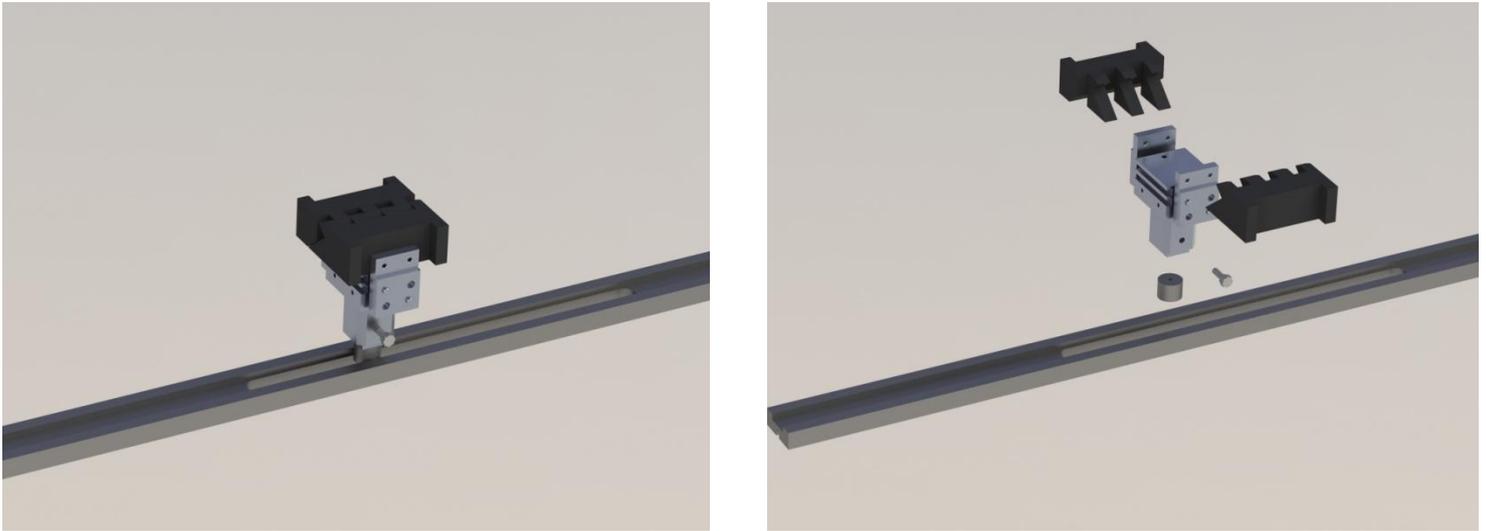
Fig. 72: Final concept..

## 8.5. Prototypes and testing

During the last two weeks of the bachelor's assignment different prototypes have been made to demonstrate some of the designed features. Furthermore, different sensors and devices have been tested to check if they are easy to integrate on the machine and if they work properly.

### Clamp system

The clamp system consists of a rail, stand, electromagnet, switch, and the existing clamping device. The SolidWorks model is displayed beneath.



*Fig. 73: The SolidWorks assembly and exploded view of the clamp system.*

The actual prototype is displayed beneath here. It looks quite similar to the SolidWorks model, however some adjustments had to be made. The rail is simplified, therefore it does not have the hole in the middle and it also does not have the extruded cut on the bottom.

The electromagnet has been connected to a switch to switch on or off the power of the magnetic field. When the power is switched on, the magnet is 'active' and the clamp is fixed on its position. When the power is switched off, the magnet is 'passive' and the clamp can be moved to the required position. Possibly, a scale on the rail, like the scale on the clamp itself, can be applied to set the clamp in the correct position.

To improve the movement of the clamp over the rail, a piece of PE tape was added onto the rail. Now the clamp moves more easily, but the magnetic field is too weak, so it cannot be ensured that the clamp is fixated during the weld. Therefore the tape should be removed or a stronger magnet should be installed.

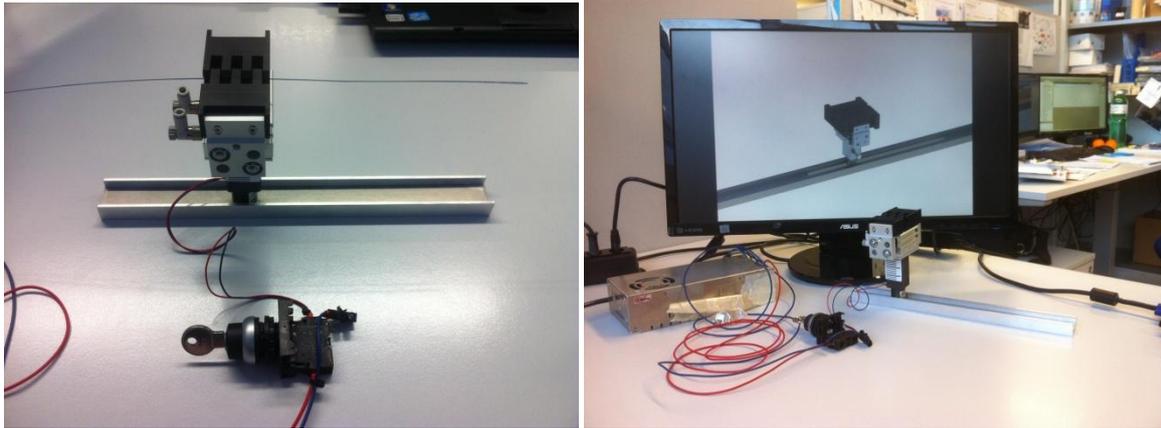


Fig. 74: Left, the prototype of the clamp system and right, the setup of the test of the prototype.

## Ionizer and detection sensor

The company SMC offered to come by to do some testing with the ionizer (IZN10) and the corresponding sensor (IZD10). After this test can be concluded that the static electric field of the surrounding air in the machine is only 0,5 kV. With this air, a spark could never appear because the voltage is too low. Therefore the ionizer and the sensor are not required to safely operate the machine and for this reason they will not be recommended to install on the machine.

## Temperature test

BW-TEC had one IR temperature sensor available to do some tests to measure the spot of the weld. Unfortunately, this IR temperature was not accurate enough to measure the actual temperature. However, it still gives an indication of the variances between the temperature when the user fills out different parameters. This is what the test consists of; testing the differences in temperature by adjusting some of the parameters. The test only focuses on a point weld, while that is the easiest way to measure the temperature on the spot. Table 1 in appendix M shows the parameters that were adjusted and the corresponding temperature that was measured. Different materials were tested and it was tested if the temperature of the weld varies when you rotate the product or not. The test material consisted of different shrinking tubes on a mandrel. The temperature sensor was placed in a 45 degrees angle in the back of the machine.

The various temperatures that were measured are far too high, because the technical specifications of the temperature sensor used, show that it is only possible to measure temperatures up to 180 °C. This inaccuracy is caused by the small spot size to measure. However, the measured temperatures still give information about the variances when the parameters are adjusted. For this reason, the test is still valuable and some conclusions can be drawn.

## Conclusions temperature test

When the power increases, the temperature of the spot of the weld also increases. Obviously this can be explained by the formula for the heat input:  $Q_{\max} = ((P_{\max} * 60) / (S_{\max} * 1000)) * \text{Efficiency}$ . When S and the Efficiency factor are constant and P increases, the heat input increases because the fraction will be a higher number.

It is hard to draw a conclusion about the influence of the rotation, because the results vary in temperature. Sometimes the temperature decreases when the rotation parameter is switched on, and sometimes it increases. It even did occur that the rotation parameter had no influence at all on the temperature of the weld.

The material of the shrinking tube has a huge influence on the temperature of the weld. This can be concluded from the following charts. The different diameters are related to their corresponding temperatures. The charts are based on the following parameters from the table:

Power: 0,5 W

Focus Position: 10 or 20 mm

Rotation Speed: 1000 rpm

Weld Duration: 10 s

The hypothesis was that a smaller diameter would result in a higher temperature.

However, with a focus distance of 10 mm, the temperature is the highest with a diameter of 2,5 mm instead of 1,2 mm. Therefore can be concluded that another factor must have a huge influence on the temperature and this will be the material of the shrinking tube.

Concerning the weld duration can be concluded that a longer time to weld the shrinking tube will result in a higher average temperature. This meets the hypothesis, because it is logical that a longer time to weld will result in a higher average temperature, because the shrinking tube is exposed to the laser beam for a longer time the temperature increases.

The temperature sensor that was recommended, the PyroCube, is more accurate than the temperature sensor used for this test. Therefore it is recommended to do this test once more with the PyroCube if possible to see if the temperature of the weld could precisely be measured.

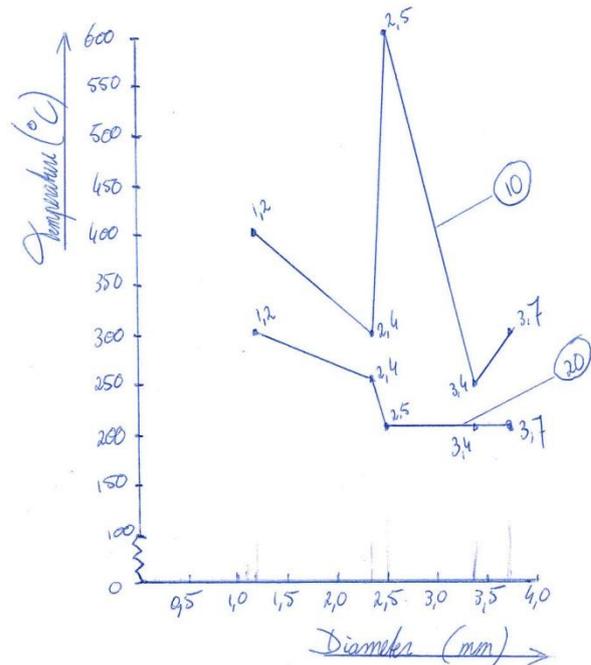


Fig. 75: Chart diameter over temperature.

# 9 Conclusions and Recommendations

## Conclusions

Several innovative solutions for different features have been found and even some have already been integrated in the new designs of the machines. BW-TEC could benefit from some of these solutions when they apply them on their future laser welding machines. It was hard to find comparing material for improving the laser welding machine, because BW-TEC does not suffer from hard competition in their market. Besides that, the customers and users of the laser welding machine are commonly very satisfied with their machines. Moreover, the process time is near to optimal. Different analysis have pointed out some problems and some reasons for improvements. The main improvements are solutions for problems that are based on the fact that the mainly used method to dissolve problems on the machine is a trial and error method.

## Recommendations

All the recommendations of the research are listed below:

- More feedback to the user should be provided to improve the human-machine interaction.
- Several sensors and devices are recommended to install in the machine to realize this feedback.
- The HMI could be improved by the use of the proposed icons and words instead of only words.
- In the HMI, it would be helpful to integrate the recommended simulation process to provided valuable feedback before welding.
- The recommended simulation process should minimally consist of charts and video's that show valuable information.
- A visualization of the several welding steps should be provided in the HMI.
- The proposed functionality of the camera lines is recommended to integrate in the HMI.
- It is recommended to fill out the quality of the recipe after the weld has been produced.
- The machine could be smaller and it could be more adaptable to its work environment by applying the laser beam from beneath.
- To improve the flexibility of the machine, an easy to assemble and disassemble axis is recommended and the machine should be operational from both sides.
- An ideal working position concerning the physical ergonomics has been recommended. The screens should be in a 10-20° angle and the operating height should be at elbow height when seated.
- The clamp system could be improved by use of electromagnets onto a rail.

- A scale should be provided onto the stands to align their height and a scale should be provided onto the rail to align the stand horizontally.
- The PyroCube temperature sensor is recommended to install in the machine to give the user feedback about the temperature of the weld.
- The NexFlow air nozzle should be installed to cool down the product after the weld has been produced to provide a shorter process time.
- The Q-12A180 high resolution camera is recommended to integrate in the machine because it has better technical specifications than the existing camera.
- It is **not** recommended to have an ionizer and a corresponding detection sensor integrated in the machine due to a low static electric field.
- It is recommended to install a lock mechanism to lock the safety door during the process to ensure the safety of the user.

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# A. Products of BW-TEC

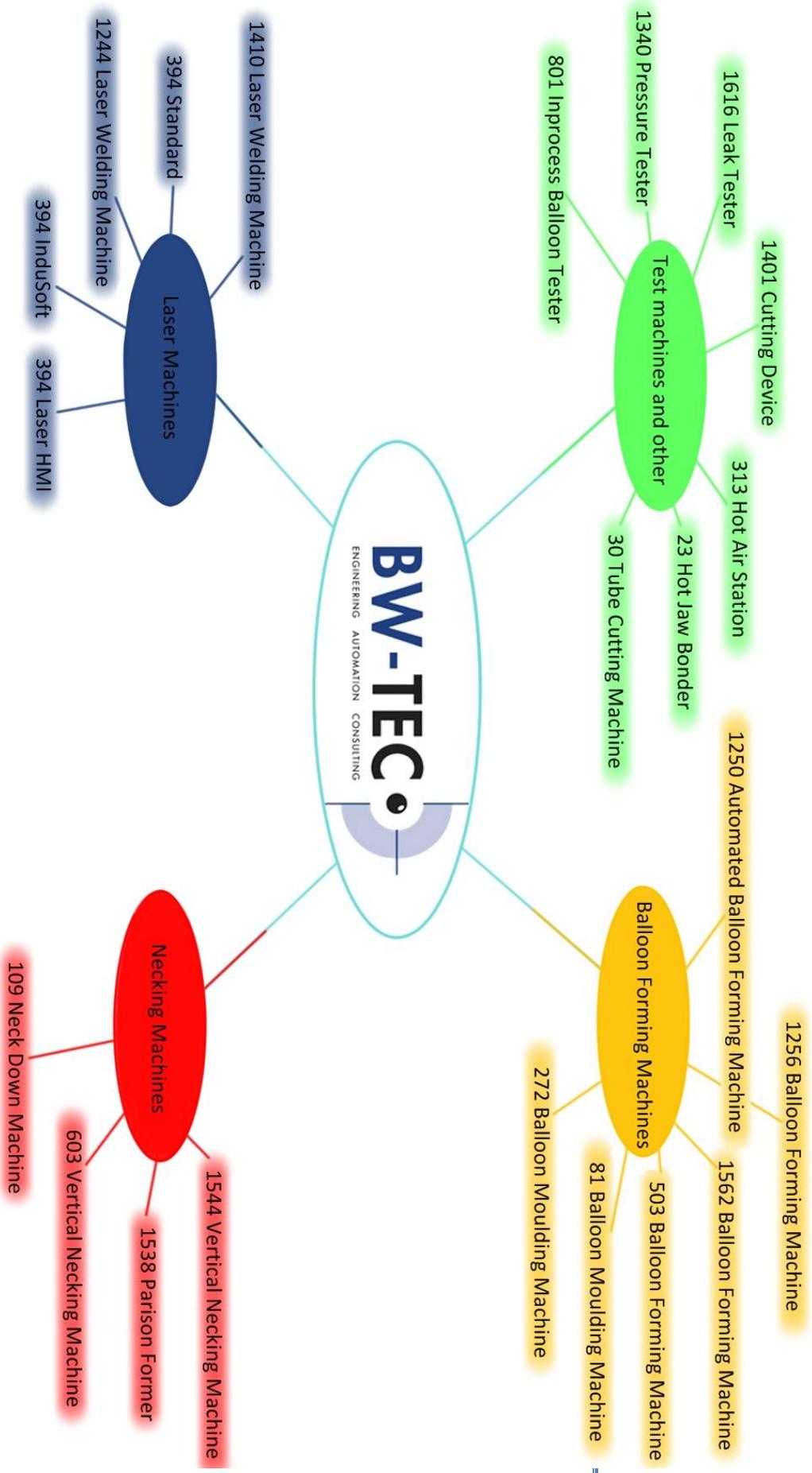


Fig. 1: An overview of all of the machines that BW-TEC has produced.

## B. Laser Technology

### Laser characteristics

#### Monochromaticity

Natural light includes a variety of wavelengths. A laser beam consists of light with a single wavelength. This characteristic is called monochromaticity. The advantage is the increased flexibility of optical design that it enables.

#### Directionality

Directionality is the property of maintaining the direction of sound or light as it travels through space. Natural light has waves that propagate in all directions. Laser light has high directionality so it can travel over long distances.

#### Coherence

Coherence describes the degree to which light interferes with itself. The more uniform the phase of the light, the higher the light's coherence. Because the wavelength, phase, and direction of laser light is the same, it is possible to maintain a strong wave without suffering diffusion.

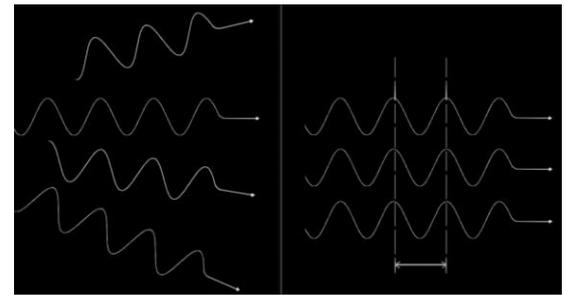
#### High energy density

Because lasers have excellent monochromaticity, directionality and coherence, they can be concentrated into an extremely small beam spot, which makes it possible to create light with a high energy density.

### Create a laser beam

#### Excitation

To generate a laser beam, a medium is required consisting of atoms or molecules. When this medium is exposed to external energy, the atoms change from their ground states to their excited state. In the grounded state they have low energy levels, while in the excited state they have high energy levels. When the atoms are in the excited state, their electrons move from the inner shells to the outer shells.



Various wave lengths

Uniform wavelengths

Fig. 2: Difference between the wavelengths of natural light and laser light.

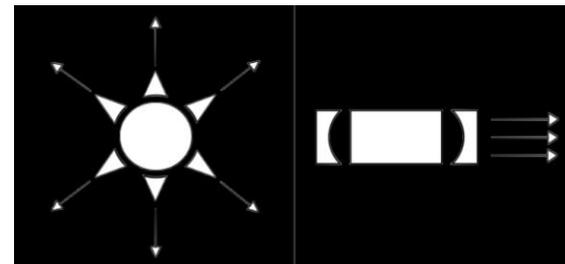


Fig. 3: Difference between the directions of natural light and laser light.

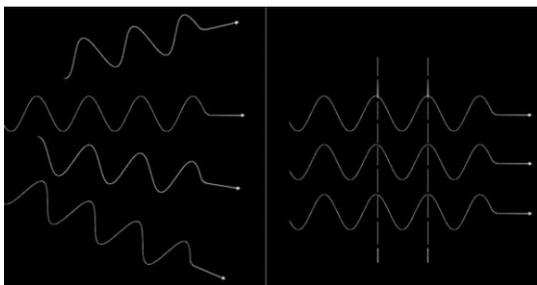


Fig. 4: Difference between the coherence of natural light and laser light.

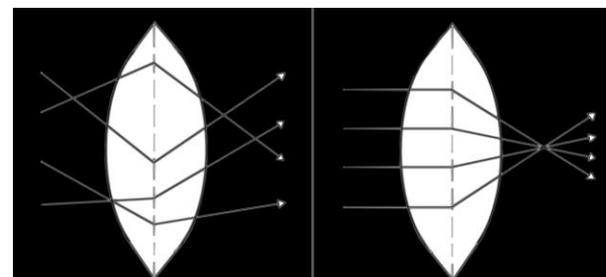
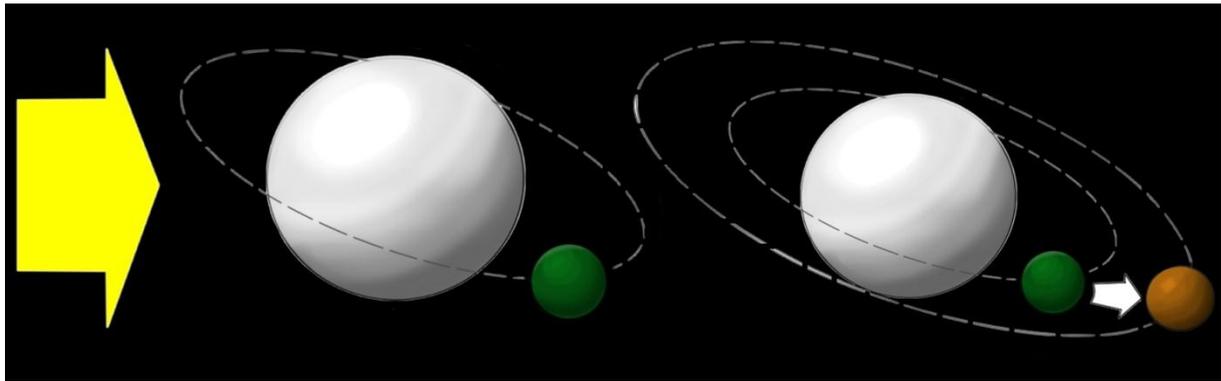


Fig. 5: Difference between the density of natural light and laser light.



Pumping in light

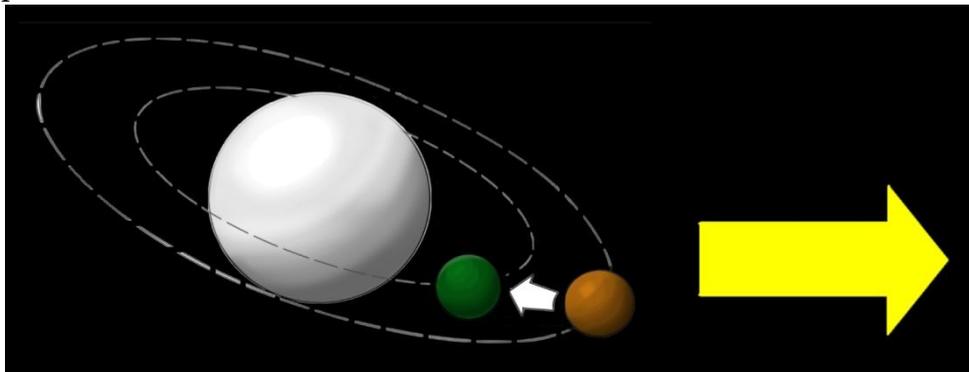
Atom in grounded state

Atom in excited state

Fig. 6: Atoms change from the ground state to their excited state.

### Natural emission

After a certain amount of time of being in the excited state, the atoms will return to the ground state. The energy that was given to the atom, to move from the ground state to the excited state, is emitted as light with a predetermined wavelength. So, to create laser light, the process of excitation and natural emission is used.



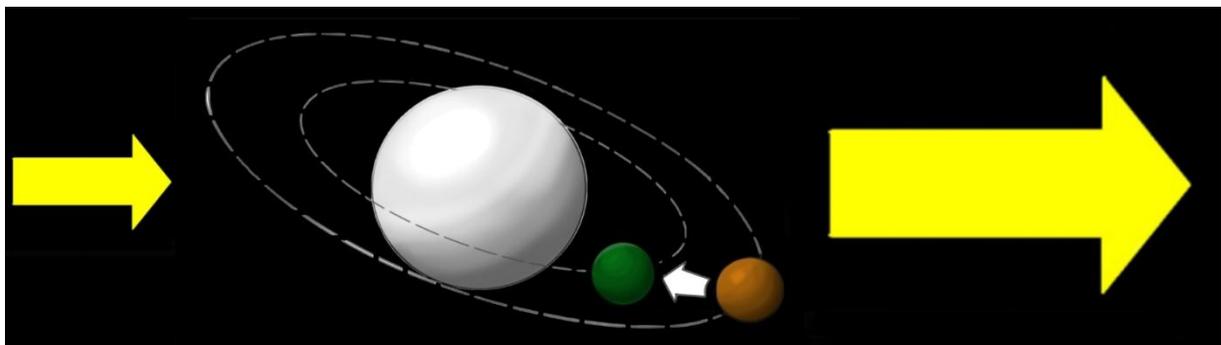
Atom returns to grounded state

Emitted light

Fig. 7: Natural emission.

### Laser amplification

To use naturally emitted light as a laser, the naturally emitted light must be amplified. When the pumping light, the external energy, is strengthened, the number of atoms in the excited state as well as the amount of naturally emitted light increases. This leads to stimulated emission.



Incident light

Atom returns to grounded state

Stimulated emitted light

Fig. 8: Stimulated emission.

## **Types of lasers**

### **Solid state laser**

This laser is also called a YAG laser, because this one is the most common solid state laser. YAG is a crystal that is doped with Nd (neodymium). The oscillator is constructed with pumping laser diodes arranged parallel to each side of the axis of the YAG crystal. The resonator is constructed with a pair of mirrors and a Q-switch arranged between them. A Q-switch is an element that can change the direction in which light propagates. The pumped light is applied to a wide area, making it possible to apply a high amount of energy, and therefore obtain high output. These lasers are typically used in marking, engraving, and welding of metals.

### **Semiconductor laser**

Semiconductor crystals with different materials are layered on top of each other to construct the active layer. The light generated in this layer is made to travel back and forth between a pair of mirrors constructed on both ends, which amplifies the light and generates the laser.

### **Fibre laser**

Fibre laser use fibres as their medium and have long-distance communication relay amplification technology that has been developed for high-output lasers. Optical fibre as are composed of a core that propagates the light along the centre of the fibre and cladding that concentrically wraps the core. Fibre lasers use this core as the laser medium to amplify the light. The core is doped with Yb (Ytterbium). In the general composition of a fibre laser, a laser diode is used to generate the pulse light known as the seed light. Fibre lasers have a higher oscillation efficiency and lower power consumption than solid state lasers and gas lasers.

## **Other welding techniques**

### **Thermal compression**

"Thermal compression provides a homogenous and consistent weld by encapsulating the specified weld area with uniformly heated dies." (Interface Catheter Solution, 2003, p. 3)

These precisely machined dies close around the weld area, isolating it from the external environmental changes. This leads to high repeatability from weld to weld.

The most advantageous aspect of this method is, that the technology allows for quick loading and unloading of the balloon catheter and therefore it has a very minimal setup time.

Thermal compression welding prevents movement during the fusing process, unlike laser welding. But, since the development of laser welding methods is going really fast, the movements during the weld are also minimized.

### **Hot air system**

Hot air bonding works by directing a stream of hot air to a weld area. The polymers will then be welded together. The process is easy to run and requires a minimal training level of the operator.

Hot air systems deliver less precision with difficulty to any degree of accuracy. Environmental changes contribute to the inconsistencies with air flow disruption and thermal pockets relative to thermodynamic entropy.

### Laser welding compared to conventional welding methods

There are many different advantages of laser welding compared to conventional welding methods. That is one of the main reasons that BW-TEC makes use of a laser in their machines. Some of the advantages are listed below: (ROFIN, 2015)

- Contact-free processing
- Diverse materials and different thicknesses are weldable
- Easy conversion to automatic operation
- High flexibility in terms of process and geometry
- High welding speed
- High welding seam quality, resulting in little need for rework steps
- Low thermal material influences
- Adjustable energy supply in relation to the material
- Highest reliability at maximum flexibility
- Save operation by proven beam guiding systems
- Adjustment to customized requirements and local conditions by modular design of the machine
- Simultaneous operation at different machines or different welding spots by beam deflectors or splitters
- Optimized nozzle geometries for best application results
- Availability of further options like quality monitoring or documentation of the process data
- When we look more to the specific laser welding methods that are available for the application of medical devices, we can make a distinction between two interesting welding methods: ultrasonic welding and laser welding. The advantages and disadvantages are displayed in *table 3*. (Engineerlive, 2013 and Brown, J., 2011)

	Advantages	Disadvantages
<b>Laser welding</b>	Direct laser welding	Initial capital investment
	Welding of thin films	Tight part tolerances
	The radiation is readily absorbed by the plastic	Special plastics characteristics required
	Flexible	
	Process monitoring	
	Minimal part stress	
	Short cycle times	
	Low total cost of ownership	
<b>Ultrasonic</b>	Very short cycle times	Maximum joint length of 250mm

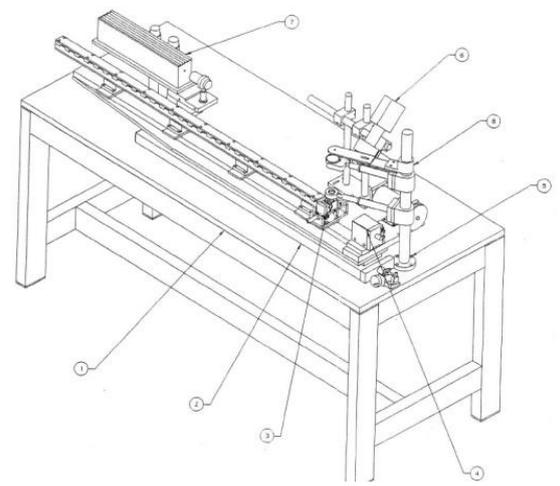
<b>welding</b>		
	Limited 3D contours	Welding of membranes to other components
	Low maintenance costs	Require to separate generator for each welding head
	Clean process	Lower accuracy
	Little or no flash	High mechanical load
	High-volume production	Particulate development

*Table 1: The dis -and advantages between laser -and ultrasonic welding methods*

## C. Product development

### Laser welding machines

BW-TEC has developed several laser welding machines over the years (*table 3, appendix E*). The new technology of laser welding was first applied in a machine that was designed for Schneider and functioned as a lab application (*fig. 11*). It was produced in 1992, and it was just an assembly of basic parts to laser weld the distal and proximal ends of a balloon catheter. It consisted of a table, a laser, a button to regulate the power of the laser, a digital timer, a start/stop button, and an analog camera. There was no software involved, so the parameters were all manually inserted. The safety regulations were also poor for this machine e.g. the operator had only to wear protective eyewear instead of that the whole process area was covered by a safety shield.



*Fig. 9: The first laser welding machine.*

The next generation of laser welding machines, of the type 03 (*fig. 12*), looked far more useable than the lab application. More parts on the machine worked automatically, because software was introduced by adding a PLC. PLC stands for Programmable Logic Controller which contains a microprocessor that controls its different outputs on the basis of the information from the inputs. Through the interface of the PLC, the operator could set-up different parameters in different menu's. This machine also had a manual movable axis, and additional buttons for start/stop, setting zero, close/open clamp, and close/open collet. The safety of the machine also improved compared to the lab application by introducing a cover over the laser assembly, but still the machine was not completely safe to operate, because the process area is not covered.



*Fig. 10: The laser welding machine type 03.*

The following generation of laser welding machines, of the type 083 (*fig. 13*), looked more like the design of the newest laser welding machines. It was produced around the year 2006, and it is the first machine with a fully enclosed work space area. Furthermore, the machine works with a PLC software system that allows to visualize more data to the operator on the screen. The interface consists of different gages for pneumatics like the air pressure of the clamp and collet, a clamp and collet button, a start and stop button and a joystick to move the axis. The x-axis could now be moved automatically to precisely align the product. Moreover this improvement allowed to produce not only point welds automatically, but also length welds.



*Fig. 11: The laser welding machine type 083.*

The laser welding machine type 394 is the following generation of laser welding machines and can be divided into three different kinds of machines: the 394 standard (fig. 14), the 394 with InduSoft (fig. 15), and the 394 with HMI (fig. 16). The 394 standard has only PLC software to operate the machine. The interface consists of the standard buttons, a joystick to move the axis horizontal, a LCD screen, and a PLC button-interface. Also the emergency button had been moved to a better, reachable place.

The 394 with InduSoft makes use of a PC with custom made software: InduSoft. This software is only used on this machine and has a relatively hard to understand user-interface. The machine has an additional touch screen and makes use of two camera's to control the weld. Besides that it contains a barcode scanner to scan every product that runs through the machine.

The 394 with HMI makes use of a PLC in combination with HMI software. The HMI software is custom made by BW-TEC, because they want to improve the user-interface of the InduSoft. It can be regulated by use of an integrated touch screen. It only uses one camera, but the camera in this machine is the first digital camera.

The main improvement for these types of machines was the standardization of all the different components. This allowed higher production output, easily assembly, and reduction of the total process time. All the machines have a fully enclosed process area and the safety door closes automatically when the process starts.



Fig. 12: The laser welding machine type 394 standard.



Fig. 13: The laser welding machine type 394 with InduSoft.



Fig. 14: The laser welding machine type 394 with HMI.

The laser welding machine type 400 (fig. 17) was specially made for one client. The main demand of the client was to produce a compact laser welding machine with the same functions as the type 394 standard laser welding machine. Therefore it has the exact same interface and camera as the standard 394. Its main deliverable was the spatial specifications in the height and the footprint.

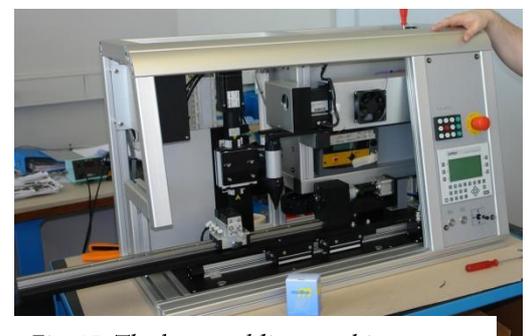


Fig. 15: The laser welding machine type 400.

Nowadays BW-TEC produces mainly the laser welding machines of type 1244 and of type 1410 which were mentioned in chapter 2. Both machines work with the latest technologies and have the highest human-machine interaction of the machine production history of BW-TEC. The software on both machines consists of a PLC software and an self-designed HMI software. The PLC software interacts with the HMI software. The user-interface consists of the standard buttons, a digital camera screen, a touch screen, and a joystick.

The technology of the type 1244 differs from the one of the type 1410, because the product in the type 1244 cannot rotate. For this reason the machine does not need a collet to rotate the product and therefore it does not have a button to open/close the collet. Basically, the type 1244 uses a round mirror that reflects the laser beam all around the product.

The type 1244 was designed with high customer involvement during the process. The type 1410 was designed in an innovative point of view. The main deliverable of this machine was to re-design the standard laser for improvement on as many (mechanical) points as possible. Besides that, the type 1410 has the ability to keep records of every weld made.

## D. Description Scenario's

### **The product is not aligned correctly on the axis**

*Appearance:* This error occurred on the laser welding machine type 1410. The balloon catheter was not aligned straight on the mandrel. Therefore, when the machine started rotating the product, the weld was asymmetric.

*Solutions:* The operator should have taken more careful attention to the assembly of the total product. The cut of the balloon could have been asymmetric, so the alignment was not straight.

The system should detect incorrect alignment of the product and should give a warning. Moreover the system should give feedback through the user-interface to the operator on how to align the product in the correct way.

### **The weld is too long**

*Appearance:* This error occurred on the same laser welding machine. The parameters of the weld duration were set to long. Therefore the laser almost touched the cone of the balloon. The operator had to interfere with the process.

*Solutions:* The system should give feedback or feedforward through the system. By feedback is meant that the system should provide information to the operator on how to adjust the weld duration to make a correct weld. By feedforward is meant that the system should give information to the user based on the product properties and the other parameters. In that way, the right weld duration can be calculated, so no problems will occur with welding over a too long distance.

### **The power of the laser is too long**

*Appearance:* The operator had set the parameter of the power of the laser too high. Therefore the shrinking tube completely melted.

*Solutions:* Here the system also should give feedback or feedforward. The system could allow the operator to change the power of the laser, but with a tolerance, so the laser will not destroy the balloon catheter.

The operator could also apply another shrinking tube with different material properties. Specifically a shrinking tube with better temperature resistance.

### **The focal distance of the laser is too short**

*Appearance:* The operator had set the parameter of the focal distances too short. Therefore the distance from the laser to the product was too short, so the intensity of the laser beam on the product increased. This led to the melting of the shrinking tube in an unwanted way.

*Solutions:* The system should also give feedback or feedforward. The power of the laser and the focal distance of the laser should be optimized and linked together, so no errors can occur.

### **The axis moves in the wrong direction**

*Appearance:* The operator filled out the parameters for the length duration and thought the axis would move right, but instead the axis moved left.

*Solutions:* Apparently, the movement of the axis is not displayed in an obvious way through the user-interface. Therefore the user-input should be more congruous with the actual movement of the axis. This could be done by programmatically running a simulation of the axis to see in which direction the axis will move after the operator has filled out the parameters.

The interface should be congruous with the movement of the axis by displaying a left or right movement of the axis when the operator has filled out the parameters.

### **The laser destroys the balloon catheter**

*Appearance:* This appearance was a combination of the previous errors. The weld duration was too long and the laser power was too strong. This led to destroying the balloon catheter.

*Solutions:* This is the worst case scenario and should be prevented at anytime. Fortunately, the operator can interfere the process by pressing the stop button. The system will stop immediately and the balloon catheter has been saved. But actually, you do not want to interfere with the process, you want the process to go smooth. Therefore a better warning system should be provided. The system should check before the process starts whether the balloon catheter will be save or will be damaged. This can also be provided with a short programmatically simulation where the systems detect errors and shows them to the operator.

## E. Questionnaires

### Questionnaire customers

My name is Jorrit Heiner. I study Industrial Design at the University of Twente in the Netherlands. Right now I am doing an internship at BW-TEC in Switzerland. I am doing a research on the human-machine interaction of the laser welding machines that BW-TEC has produced over the years. For this research I require some feedback information from every source available.

All the questions are mainly based upon the human-machine interaction. Therefore the main question of this interview is: "How could BW-TEC improve the human-machine interaction of their laser welding machine?"

The results of this interview will be used for the development of an improved concept of the human-machine interaction of a future laser welding machine.

### Effectiveness of the operation

- Do you find it easy to accomplish a drawn up goal? (e.g. a weld connection) What do you find hard about accomplishing goals?
- Do you find it easy to break down this goal into logical steps? If not, could you explain why?
- What do you think of the easiness of doing one step during the process and then go to the next step?
- Did you do an operational time study on the laser welding machine? Could you provide this information for my research?
- What job elements did you test with your time study? Is your time study comparable with the time study I did?\*

### Control of the machine

- Do you think you are in control of the machine when you are using it? In what way do you think you might lack control?
- What do you think of the user-interface of the machine?
- Do you find it easy to understand the user-interface? Which parts are more difficult to understand?
- What do you think of the accessibility of all the important components to control the machine?

### Machine feedback to the user

- Do you think the machine gives you enough feedback to operate the machine in a good way? What feedback does the machine lack in your opinion?
- What do you think of experimenting with new recipes?
- Should there be a database of recipe templates? Why do you think that?
- Which parameters aren't clear and should give you more feedback?
- What kind of data is useful for each production cycle?
- What do you think of the alarm and warnings?
- In what way do the camera recordings help you to better understand the way of welding?

### Decision making process

- What do you think of the several menu's of the user-interface?
- What do you think of the easiness of running through the user-interface?
- Do you think there are too many or too few parameters to consider? Which parameters should be eliminated or be added in your opinion?
- Do you think the buttons on the machine are placed in a logical manner? In what way would you place the buttons more logical?
- Are there things which could be done to change the decision making process if necessary?

### Ease of use

- What do you think of the ease of use of the machine?
- In what way does working with the machine satisfy your requirements?
- Do you think some steps could be eliminated from the process? Which steps should be eliminated in your opinion?
- What is your opinion about the flexibility of the system of the machine?
- Could you use the machine successfully every time you use it?

### Work environment

- What do you think of the brightness and visibility of the user-interface in your working environment?
- Should the machine be more mobile?
- What do you think of the required working position?
- What do you think of the size of the machine?

### Usability features

- Are you satisfied about all of the features on the machine? Which features could be improved in your opinion?
- What features do you miss on the machine?
- Are you able to use the machine for different products? (geometry/materials)
- In what way is the machine adaptable to your products?
- In what way could the machine be easily integrated into your production line?

### Process speed and setup time

- What do you think of the process speed of the machine?
- Should the machine operate in a faster way? What process steps should be going faster?
- What do you think of the setup of the product into the machine?
- Does it take too much time to setup the product into the machine?
- Could some steps be eliminated from the setup process?

### Safety of the machine

- What do you think of the safety of using the machine?
- Have you ever experienced unsafe situations during the operation of the machine? What kind of situations? And whose fault was that? (e.g. machine or human)
- What do you think of the placement of the emergency button?

### Future development

- Are there design or utility features you have seen on other machines that you would like to have integrated in the laser welding machine?
- With the development of the balloon catheters, what are the biggest challenges you see for working with laser or other bonding machines?

\*These are the results of my time study I did on the BW-TEC laser welding machine type 1244.

Job Element	Manual Load (sec)	Machine Time (sec)	Manual Load (sec)
Prepare product			
Start-up machine		57.50	
Place product	18.20		
Fill out parameters	185.55		

Align product by use of the camera	18.30			
Start process		11.14		
Check results	25.70			
Unload product			38.44	
Turnoff machine		24.92		
<b>Total process time</b>	<b>247.75</b>	<b>93.56</b>	<b>38.44</b>	<b>379.75</b>

## Questionnaire other interesting companies

My name is Jorrit Heiner. I study Industrial Design at the University of Twente in the Netherlands. Right now I am doing an internship at BW-TEC in Switzerland. I am doing a research on the human-machine interaction. For this research I am looking for some information from as many sources possible.

All the questions are mainly based upon the human-machine interaction.

The results of this interview will be used for the development of an improved concept of the human-machine interaction for future machines.

### Control of the machine

- In what way do you provide control to the user of your machine?
- What is in your opinion the best division between the automated part of the process and the manual part of the process?
- In what way is the operator involved in the process? How do you make sure that the operator will be kept in the loop?
- Through what user-interfaces can the user operate the machine?

### User-interface

- In what way do you provide an effective user-interface?
- In what way do you provide an understandable user-interface?
- What are your minimal standards for an user-interface? (e.g. visibility/brightness)
- How should the operator interact with the user-interface?
- In your opinion, how many menu's should an user-interface consist of?
- In your opinion, how many steps should be taken through the user-interface to finally start the process?
- What should be the maximum amount of parameters that can be manually inputted?
- What should be the maximum amount of buttons on the machine?

### Machine feedback to the user

- Do you find it important to give feedback to the operator of the machine? Why?
- In what way does the machine give feedback to the user?
- To what extend does the machine give feedback to the user? (e.g. does it give feedback after each single step or only when the process has been finished?)
- Do you provide a database with standard programs or recipes the operator can easily select?
- In what way(s) does the machine give alarms and warnings to the user?

### Usability features

- How do you meet the requirements of your customers?
- Do you provide the machine to be customizable? In what way is the machine customizable?
- In what way do you provide a flexible system for the machine to be operated?

- In what way do you ensure the machine is easily adoptable in the customer's production line?

### **Working environment**

- What should be the required working position to operate the an industrial machine?
- In what way do you provide mobility of the machine? (e.g. is it possible to move the machine or is it possible for the operator to move around the machine?)
- In your opinion, how important is the size of the machine? (e.g. is the functionality more important than the size?)
- How do you provide the safety of the machine?

### **Questionnaire work environment**

- Of what parts does the machine set-up consists?
- How much time does the machine set-up take? (compared to own time study)
- How do the employers work with the machine? (remarkable aspects)
- How do the employers handle the product?
- Through what interfaces do the employers communicate with the machines?
- How much room is there to operate the machine?
- What are the characteristics of the operation room?
- What is the total operation time of one product? (compared to own time study)

## F. Results Questionnaires

### Questionnaire customers BW-TEC

#### Effectiveness of the operation

Programming the older machines of BW-TEC is more uncomfortable, because you cannot jump freely forward and back in the Steps and Saving-Problems. (e.g. you have 4 Steps, when you change a Parameter in the second Step and then press "Save," you will lose the other two Steps.)

To confirm accuracy and stability of parameters like rotation, displacement left/right up/down, and speed an operational time study has been done. The challenge that Company J encounters is to measure the rotation of the mirror.

The user-interface requires trials and errors until finding the right setting (e.g. for a robust weld connection) Step by step programming makes it simple.

#### Control of the machine

The membrane keyboard of the Jetter-OP is problematic for a fast workflow. The newest generation of laser welding machines provides a much better HMI than the old ones.

The calibration process is not well communicated through the HMI. It is not clear what the user can change and for what purpose.

When the user does not change the register values everyday with the old generation of laser welding machines, the user needs to use the manual to do so.

The accessibility of all the important components to control the machine is depending on the environmental conditions and use of the machine. The employees of Company C found it useful to have a flexible input panel, because some products lay in front of the machine. The newer machines have an integrated input-panel on the front.

The new machines allow more control of how and whom used the machine.

The control of the location of the mirror can be improved and provide more options to control the machine.

The focus of the laser changes sometimes if the program is stopped.

It is confusing at the beginning that the menu to edit recipes is not the same as the one to select a recipe to run.

#### Machine feedback to the user

The experimenting with new recipes is much more satisfying with the new HMI in comparison to the old HMI. There should be a database of recipe templates, because the processes to weld a distal assembly do not change so drastically. To start with a template can save a little time during developing a new process on a new product.

To visualize the timing during the process and combining this with a video is very useful for fine-tuning. (e.g. at which time/position does the shutter open?) Besides that, a little graph, which shows the power over time would be interesting.

For each product cycle the following are useful data: worker, product, lot-nr., name of the recipe, date/time, machinenr., power/position/shutter over time

The camera recordings help the user to see and study the effects of the programmed parameters and they are useful for documentation.

The equipment should have side port where the user can confirm all the parameters in use (e.g. speed, mirror rotation, etc.)

The "swing" parameter is unclear on how to use or to measure it.

It would be great to know/estimate the temperature inside the material you want to weld or in the vicinity, but this depends on so many parameters, and it is very difficult to implement.

For process development, the camera recordings are great. The video helps to understand how the product behaves during the laser welding.

A database could be an advantage to propose different welding strategies. Which strategies offers the best results (time, repeatability minimum stress in the surrounding material, etc.

It would be nice to have the code verified before running the code (e.g. will it reach axis limits)

It is difficult to understand when setting the displacement of the motor axis to left or right. If the weld should be propagated to the right, the motor should move left.

It would be nice to have the code verified before running the code.

In the R&D phase, it is still hard to check with the camera if the weld has been made. You need to remove the heat shrink to check.

### **Decision making process**

It is good to have the menu's on the left and the rest is used for interfacing with machine.

To ramp up the z-axis would be a nice feature. (e.g. like a robot arm)

The buttons on the machine are placed in a logical manner and the user-interface did not cause any problems yet.

It would be interesting when the administrator could customize the menu's in some sort of way.

The "swing" method is never used.

What could be confusing is that the menu to edit recipes is not the same as the one to select recipe to run.

It requires a good understanding of the physics behind the weld to know on which parameters to play. (like material, power, focus, speed, time, etc.)

### **Ease of use**

The new HMI of the machine goes in the right direction. It allows easy programming and maintaining the parameters and recipes.

The machine can be used successfully, without any problems.

The machine does what it supposed to do.

### **Work environment**

Sometimes the glare of sunlight makes problems to read the user-interface.

Company C solves the mobility problem of the machine by themselves by putting the machine on a table with wheels. They also have tables with adjustable heights and therefore they can regulate the working position themselves.

The size of the machine is OK.

The machine should be more mobile.

The depth should be reduced, to improve the preparation area.

It is more important to have a stable and robust machine.

### **Usability features**

Different lengths of balloon catheters can easily be produced on the same machine.

Company C only needs the clamps and sometimes a new circuitry (air).

The cooling system could be improved, because you cannot say it is a table top machine.

A chiller is a feature that is missed on the machine.

Also, to be able to have different spot sizes just using the HMI would be great.

The flexibility of the machine is good, but compare to the other models it is not able to change the spot size in the same recipe.

A better way to verify the parameters should be provided.

It might be nice to have different field of view (zoom) on the machine to accommodate different diameters.

A cooling system once the weld has been produced is missed.

The machine is not designed to perform longitudinal weld.

### **Process speed and setup time**

The process speed is fine for Company C.

The clamps to hold the product is not robust enough during the setup one got separate the glue was not the best way to construct parts that will be with a lot of handling.

The clamps are not adequate.

It is not necessary to operate faster. The design of the parts to weld, of mandrel or heat shrink tubing are the key points for a fast operating cycle.

### **Safety of the machine**

The safety of the machine is found OK. The accessibility of the emergency button is OK.

The safety of the machine is adequate.

The protective glass can be raised during the process. Therefore there should be a lock.

You have to rely on the "transparent" front window.

### **Future development**

The biggest challenges for working with a laser welding machine are the stability of the laser power and the beam hitting the product in the middle.

It is a must to have different spot sizes.

The biggest challenges with the development of the balloon catheter are to duplicate machines that can use the same recipe and have the same output (e.g. spot size, energy, speed, rotation displacement)

The machines of Company A did not work reliably at the moment.

## **Questionnaire other interesting companies**

### **Control of the machine**

A touch screen interface is primarily used to provide control to the user of the machine. Sometimes a PC using a LabView based software is used.

The economically aspect of the division between the automated part of the process vs. the manual part of the process is the most important.

The operator prepares, loads products, while the engineer develops process recipes. To keep the operator in the loop, current active functions, upcoming functions, current parameter settings, and current process values are displayed.

### **User-interface**

The focus on the user-interface is to keep it simple and clear. Calibrations are designed to be very easy and foolproof. Help buttons leading to short explanations are associated with most functions.

The operator should interact by touch with the user-interface.

The user-interface should consist of as few as possible menu's while clearly separating very different functional environments. (e.g. "manual mode" for development and "run mode" once the process is defined.)

The process should only consist of two steps to be started.

### **Machine feedback to the user**

The operator must be aware of the operating conditions like errors, so feedback is important.

Feedback is provided by use of pop-up error messages, continuous display of current process values, and a beep at the end of the process.

The machine gives warnings and alarms by giving red pop-up windows that must be acknowledged to proceed.

### **Usability features**

The customer can do whatever they want to a machine. Therefore it is highly customizable, but it should still be economical for the company.

The focus for a flexible system is on a easy to use interface. There is a less change for errors if the interface is kept simple.

To ensure the machine is easily adoptable in the customer's production line, standard fittings, connections, and machine inputs are provided. Sometimes to help ensure success, special trainings are done.

### **Working environment**

The required working position should be one that does not cause the operator to have short or long term pain. One that does not put the operator in harm's way. It should allow efficient use of the machine and not contribute to mistakes being made.

When the machines are kept as small as possible, the mobility of the machine will increase.

The size of the machine is extremely important to most customers, but especially those in the medical device industry. Most machine are placed in clean rooms which are very expensive to build and maintain. There are often flow-benches and other equipment which limit the size of the machine.

The safety of the machine is provided by an emergency button, finger guards, proper electrical design, software based safety features, interlocks, training, and well written user manuals.

## G. Heuristics

Heuristic	Description
<i>Match between system and the real world</i>	<ul style="list-style-type: none"> <li>- Speak the language of the user</li> <li>- Use familiar conceptual models and metaphors</li> <li>- Group tasks into user goals</li> </ul>
<i>Consistency and standards</i>	<ul style="list-style-type: none"> <li>- Do the same thing as through the interface</li> <li>- Use the same color codation</li> <li>- Use the same input syntax (same actions, same functions)</li> <li>- Functions should be grouped in a logical manner</li> </ul>
<i>Visibility of system status</i>	<ul style="list-style-type: none"> <li>- Keep the user up to date with the status information during the process</li> <li>- Show that the input has been received</li> <li>- Show temporary feedback for all actions</li> <li>- Show progression in task performance</li> <li>- Use visual objects/results</li> </ul>
<i>User control and freedom</i>	<ul style="list-style-type: none"> <li>- Clear option to cancel, re-do or undo input</li> <li>- Clear marked exits</li> <li>- Allow the user to perform actions</li> </ul>
<i>Help users recognize, diagnose, and recover from errors</i>	<ul style="list-style-type: none"> <li>- Prevent the errors</li> <li>- Use clear/obvious/explicit error messages</li> </ul>
<i>Recognition rather than recall</i>	<ul style="list-style-type: none"> <li>- Use see-and-point instead of memorize-and-type</li> <li>- Make possible actions remarkable</li> <li>- Provide visual objects and visible choices</li> </ul>
<i>Flexibility and efficiency of use</i>	<ul style="list-style-type: none"> <li>- Give/provide shortcuts</li> <li>- Often used options should run faster by giving options</li> <li>- The system should be efficient</li> </ul>
<i>Aesthetic and minimalistic design</i>	<ul style="list-style-type: none"> <li>- Should have a simple graphical design</li> <li>- Eliminate uncommon words or graphics</li> <li>- Present all information in a logical order</li> </ul>
<i>Error prevention</i>	<ul style="list-style-type: none"> <li>- Eliminate error-prone conditions</li> <li>- Present the errors to the users with a confirmation option before the commit the action</li> </ul>

Table 2: The description of the 10 heuristics of Nielsen.

Heuristics	Design applications
<b><i>Match between system and the real world</i></b>	The user can switch between German and English, but no more languages
	The menu is very straightforward with familiar models
	You cannot collapse the menu by pressing it
<b><i>Consistency and standards</i></b>	The tasks are grouped well in user goals
	The colors used in the interface are consistent with the company colors
	The same input syntax is used (e.g. create recipe from "create new" gives same result as create recipe from "create from template")
<b><i>Visibility of system status</i></b>	The functions are not always grouped in a logical manner (e.g. "save" should not be right next to "close")
	There is no status information directly provided to the operator (e.g. the operator does not know how far he is in the process)
	The menu's stay highlighted when operating in the corresponding menu
<b><i>User control and freedom</i></b>	There is no temporary feedback provided to the operator (e.g. operator has to experiment)
	Operator can use the camera to align the product with the laser
	Many menu's provide a clear option to cancel
<b><i>Help user recognize, diagnose, and recover from errors</i></b>	There is only one way to move through the menu's
	The log off button is well displayed
	Errors are not prevented, but they are recognized as soon as the operator starts the process
<b><i>Recognition rather than recall</i></b>	The errors are diagnosed and are messaged to the operator in a clear manner
	The operator does not get feedback from errors while filling out the parameters
	The loading button is well hidden (e.g. it is not very logical to go from a just created recipe to the process overview menu to load this recipe)
<b><i>Flexibility and efficiency of use</i></b>	Possible actions are made remarkable
	For creating a new recipe, "create from template" is a positive shortcut
	There is no shortcut from the creating of a new recipe to the loading of the recipe
<b><i>Aesthetic and minimalistic design</i></b>	Nothing is done with often used options (e.g. often used recipes are not made remarkable)
	The system is not very efficient (e.g. the operator has to fill out a lot of parameters)
	The graphical design of the interface is simple and good to understand
<b><i>Error prevention</i></b>	The information is presented in a logical order
	The system does not prevent errors
	Errors are displayed in the user-interface and explained to the operator

Table 3: The 10 usability heuristics with their corresponding design applications.

## H. Product Collages



Fig. 16: Collage competing machines.



Fig. 17: Collage comparative machines.

# I. Conclusions and Total Set of Requirements

## Conclusion on analysis

A final conclusion on all the analysis has to be made to put forward a set of requirements for the improvement of the human-machine interaction of the laser welding machine of BW-TEC. Therefore the final conclusions on every single analysis will be summarized below.

The following can be concluded from the **market analysis**:

- The machine is very large in comparison with some of the competitors' machines
- The machine is not very mobile in comparison with some of the competitors' machines
- The machine is only operational in a standing position
- The machine has a very industrial look
- The colors used in the medical industry are mainly white, blue, and grey
- The environment of the machine is clean, sterile, and spatial
- Therefore the machine has to be clean and sterile as well
- Therefore the machine has to have a spatial process area
- The user-interface should be easy to interpret by the operator
- The machine has to produce a high quality product with high operational accuracy
- The information of the total process has to be displayed on a large enough screen to be easy readable
- The parameters have to be filled out by use of a touch screen or another interactive user-interface to improve the human-machine interaction

*Conclusions from the questionnaire:*

- The HMI of the new machine has improved substantial
- Calibration process is not well communicated through the HMI, therefore not clear what the user can do and for what reason
- Flexible input panel could be useful
- A database of recipe templates should be provided; save time during developing a new process or product
- Visualize timing during the process and combining this with video is very useful for fine-tuning
- Chart which shows power over time is interesting
- Ramp up the z-axis like a robot arm
- HMI is not good readable when sunlight is shining on it
- Movability is provided by adaptable tables
- Stability of the laser power
- Hitting the product right in the middle
- The economically aspect of the division between manual and automatic is the most important

- Current active function, upcoming functions, current parameter settings, and current process values should be displayed
- Keep the user-interface simple and clear
- Provide help buttons with short explanations
- Separate the different functional environments (e.g. "manual mode" and "run mode")
- Beep at the end of the process
- Acknowledge alarm and warning pop-ups to proceed
- Machine should be customizable, but still be economical for the company
- The size is extremely important in the medical industry
- The size of the machine is limited, because of its environment (clean rooms)
- The user-interface requires trials and errors until finding the right setting (e.g. for a robust weld connection)
- The control of the location of the mirror can be improved and provide more options to control the machine
- The focus of the laser changes sometimes if the program is stopped
- It is confusing at the beginning that the menu to edit recipes is not the same as the one to select a recipe to run
- The camera recordings help the user to see and study the effects of the programmed parameters and they are useful for documentation
- The equipment should have side port where the user can confirm all the parameters in use (e.g. speed, mirror rotation, etc.)
- It would be great to know/estimate the temperature inside the material you want to weld or in the vicinity, but this depends on so many parameters, and it is very difficult to implement
- A database could be an advantage to propose different welding strategies. Which strategies offers the best results (time, repeatability minimum stress in the surrounding material, etc.)
- It would be nice to have the code verified before running the code (e.g. will it reach axis limits)
- It is difficult to understand when setting the displacement of the motor axis to left or right. If the weld should be propagated to the right, the motor should move left
- It would be interesting when the administrator could customize the menu's in some sort of way
- It requires a good understanding of the physics behind the weld to know on which parameters to play. (like material, power, focus, speed, time, etc.)
- The machine should be more mobile
- The depth should be reduced, to improve the preparation area
- It is more important to have a stable and robust machine, than having a mobile machine
- The flexibility of the machine is good, but compare to the other models it is not able to change the spot size in the same recipe

- It might be nice to have different field of view (zoom) on the machine to accommodate different diameters
- A cooling system once the weld has been produced is missed. The machine is not designed to perform longitudinal weld
- The clamps are not adequate
- It is not necessary to operate faster. The design of the parts to weld, of mandrel or heat shrink tubing are the key points for a fast operating cycle
- The protective glass can be raised during the process. Therefore there should be a lock
- You have to rely on the "transparent" front window
- The biggest challenges with the development of the balloon catheter are to duplicate machines that can use the same recipe and have the same output (e.g. spot size, energy, speed, rotation displacement)

The following can be concluded from the **product analysis**:

- The manual load time of the total process is relatively long compared to the machine processing time
- Filling out the parameters contributes the most to the total process time
- Starting the machine takes relatively more time than shutting down the machine
- The laser welding machine has been developed to a high quality level, but there is still room for improvement
- Many different improvements have been applied to the machine (e.g. safety aspects, setup, user-interface)
- The machine can still be optimized on certain aspects (e.g. size, ease of use, setup time)

*Conclusions on the user-interface:*

- The user can only switch between German and English in the user-interface
- The user cannot collapse the different menu's by pressing it
- Some functions are not grouped in a logical manner
- There is no status information directly provided to the operator
- There is no temporary feedback provided to the operator
- There is only one way to move through the different menu's
- The errors that occur, are not prevented
- The operator does not get feedback from errors while filling out the parameters
- The recipe loading button is well hidden
- There is no shortcut from the creating of a "new recipe" to "the loading of the recipe"
- Nothing is done with often used options
- The system is not very efficient

*FMEA:*

- The main failure modes are:
  - A wrong user input
  - The lag between the PLC and the computer
  - A wrong alignment of the work piece

- A wrong recipe selection
- Mainly the user-input is a failure mode and therefore user mistakes should be prevented and solutions to problems should be provided by the system

The following can be concluded from the **technology analysis**:

*Laser characteristics:*

- A laser is monochrome
- A laser is directional
- A laser is coherence
- A laser has a high energy density

*Laser welding characteristics:*

- Laser beam is directed on welding spot on rotating product
- Quite expensive method
- Short cycle times possible
- High quality products

*Laser welding advantages:*

- You have contact-free processing
- Diverse materials and different thicknesses are weldable
- Easy conversion to automatic operation
- High flexibility in terms of process and geometry
- High welding speed
- High welding seam quality, resulting in little need for rework steps
- Low thermal material influences
- Adjustable energy supply in relation to the material
- Highest reliability at maximum flexibility
- Save operation by proven beam guiding systems
- Adjustment to customized requirements and local conditions by modular design of the machine
- Simultaneous operation at different machines or different welding spots by beam deflectors or splitters
- Optimized nozzle geometries for best application results
- Availability of further options like quality monitoring or documentation of the process data

The following can be concluded from the **target group analysis**:

- The customers of BW-TEC have some goals, values and product deliverables
- Their main goals are reduce overall costs, provide the highest quality possible, and innovate products to help patients live longer, healthier and more productive lives
- Their main values are innovative design, quality, flexibility, customer satisfaction, effectiveness, and efficiency

- Their main product deliverables are produce a high quality product, meet the needs of the clients, provide sustainable products, bringing new technologies and exceptional products to the market, and provide continuous product improvement

*Scenario analysis:*

- A lot of errors still occur on the machine when operating
- These errors consist of a wrong alignment, a too long weld duration, too much power input for the laser, a too short focal distance, and an incongruous movement of the axis
- The worst case scenario is when the operator destroys the product in any kind of way  
Several solutions are considered: system detection, system feedback, system

feedforward, tolerance areas, other materials (with other properties), and simulation of the process

## Set of requirements

*Functional requirements:*

- ✓ The machine has to be moveable
- ✓ The machine has to be smaller considering the footprint of the machine
- ✓ The machine has to operational from adaptable heights (e.g. sitting and standing)
- ✓ The machine has to have enough space to operate, this will be the same as the size of the machine in the horizontal position
- ✓ The machine has to provide a stable laser power
- ✓ The machine has to provide feedback to the operator
- ✓ The information of the total process has to be displayed on a minimal 15 inch LCD monitor to be easy interpretable
- ✓ The parameters have to be filled out on a touch screen or another interactive user-interface
- ✓ A database of recipe templates has to be provided
- ✓ The operator has to be kept in the loop by providing continuous process information
- ✓ The manual setup and load time has to be decreased (this is product specific)
- ✓ The recipe developer has to fill out the parameters more easily
- ✓ The user-interface has to be more corresponsive with the real world (e.g. collapsing menu)
- ✓ Functions in the user-interface have to be grouped together in a logical manner
- ✓ The user-interface has to provide a way out of the different menu's at all time
- ✓ The operator has to get feedback while filling out the parameters
- ✓ The recipe loading button has to be more remarkable
- ✓ The user-interface has to provide shortcuts to the operator
- ✓ Often used options have to be displayed in a more remarkable way in the user-interface
- ✓ The machine has to allow to produce innovative designs and therefore it has to be customizable

- ✓ Occurred errors from the past have to be prevented by delivering feedback to the operator
- ✓ The calibration process has to be better communicated through the HMI
- ✓ The HMI has to be better readable
- ✓ Alarms and warnings have to be acknowledged in order to proceed
- ✓ Different functional environments must be provided (e.g. manual mode and run mode)
- ✓ The end of the process must be indicated
- ✓ The displacement of the motor axis has to correspond with the parameters on the user-interface
- ✓ A cooling system has to be provided once the weld has been made
- ✓ The clamps have to work accurate
- ✓ The protective glass have to be locked during the process
- ✓ ...

*Non-functional requirements:*

- ✓ The machine has to have a more user-friendly look
- ✓ The machine has to be cost efficient
- ✓ The machine has to have a efficient cycle time
- ✓ The machine has to be duplicable to allow standard production with the same recipes on every machine
- ✓ ...

*Desires:*

- ✓ Starting the machine should be going faster
- ✓ The operator should be able to switch between the Mandarin, English, Spanish, Portuguese, French, and German
- ✓ The machine should prevent errors by detecting errors in a early stadium of the process
- ✓ A flexible input panel should be provided
- ✓ The machine should visualize the timing during the process and combining this with video
- ✓ A chart which shows power over time should be provided
- ✓ Help buttons should be provided that show short explanations
- ✓ The machine should be customizable, but still be economically beneficial for the company
- ✓ Provide more options to control the machine (e.g. the location of the mirror)
- ✓ The administrator should be able to customize the menu's in the user-interface
- ✓ The temperature inside the material should be measured
- ✓ A database with different welding strategies should be provided
- ✓ The code has to be verified before running the code (e.g. will it reach axis limits)
- ✓ Different field of view on the machine should be provided to accommodate different diameters

## J. Tables

	Type	Lab app.	03	083	394 standard	394 with InduSoft	394 with own HMI	400	1244	1410
<b>Questions:</b>										
Through what interface had the operator to operate the machine? (e.g. screens, buttons, set-up)		Turning power button (manual) Digital timer	Line generator for the analog camera Distance measuring device PLC controller Manual axis	Gages for pneumatics for the lens/clamp/collet air pressure Jetter PLC	PLC button-interface LCD screen	Touch screen as an additional screen	Touch screen has been integrated in the machine One camera Touch screen replaces PLC	Jetter PLC interface	Own designed HMI software PLC software interacts with the HMI software	Own designed HMI software PLC software interacts with the HMI software
Of what important components did the user-interface consist?		Line generator for the analog camera Start/stop button	Start/stop button Setting zero button Close/open button Clamp/collet (one) button	Clamp and collet button Start and stop button Joystick to move axis	Normal buttons start/stop Button clap Joystick to move axis	Same as the standard 394	Same as the standard 394	Same as the standard 394	Same as the standard 394 Does not have the collet button	Same as the standard 394
How did the camera work? (e.g. digital/analog)		Analog	Analog	Analog	Analog	Analog	First machine with a digital camera	Analog	Digital	Digital
How did the software of the machine work? (e.a.)		No software was used in this	PLC based Jetter PLC Nano B: Interface	PLC based Jetter PLC Nano C: PLC allows to	Only PLC based	PC with custom software: InduSoft	Custom designed HMI	Only PLC based	PLC software interacts with HMI software	PLC software interacts with HMI software Quality
How did you provide the safety of the operator?		Eyewear: glasses	Cover over laser assembly, but still an open process area	Fully enclosed process area Safety door shuts automatically	Fully enclosed process area Safety door shuts automatically	Fully enclosed process area Safety door shuts automatically	Fully enclosed process area Safety door shuts automatically	Fully enclosed process area Safety door shuts automatically	Fully enclosed process area Safety door shuts automatically	Fully enclosed process area Safety door shuts automatically
Did the new machine arise from customer demands or from an innovative point of view? (e.g. market competence, new technologies available)		Customer demand	Customer demand	Customer demand	Customer demand	Customer demand	Customer demand	Customer demand	Combination of customer involvement and own design of the machine	Innovative point to improve their machine as good as possible

Table 4: An overview of the product development of the machines of BW-TEC.

Machine functions	
<b>Main functions:</b>	<b>Sub functions:</b>
Connect with PLC and camera	Show user when system is ready to use
Clamp work piece	Detect product
	Wait for user-input
	Deliver air pressure
	Close clamp/collet (only on the 1410)

Position product	Wait for user-input
	Move linear axis
	Rotate product (only on the 1410)
Detect alarms	Verify user-input (e.g. parameters)
	Prevent starting process
	Show alarms to user
Shut/open safety door	Wait for user-input and verify

	Open when process is finished
Weld work piece	Deliver laser beam
	Move linear axis
	Rotate product (only on the 1410)
<b>User-interface functions</b>	
<b>Main functions:</b>	<b>Sub functions:</b>
Process overview	Select recipe to load
Show alarm history	Show alarms
	Show warnings
	Show activation time
	Show detection time
	Show alarm message
Edit recipe	Select recipe
Create new recipe	Select storage
	Give name to new recipe
Create recipe from template	Select template for new recipe
	Select location for the new recipe
Delete recipe	Select recipe for deletion
Import recipe	Target storage for import
	Select recipes for import
Export recipe	Select recipe for export
	Select directory for export
Change user settings	Change password
	Change language
Select user accounts	Add user
Set settings for recipe storage	Manage recipe storages

	Fill out parameters for new storage registration
Set settings for administration	Reset HMI application
	Select directory to archive
	Set default settings
Set settings for process data	Select directory for data path
	Chose save mode option
Set settings camera	Select activation camera
	Select media type
	Select video settings
	Select photo settings
Set settings calibration	Manage laser power calibration points
Set settings setup	Chose mirror option
	Fill out laser position correction
	Fill out laser position test
Show protocol	Show time
	Show action
	Show details
Show process history	Show creator of process
	Show recipe name
	Show result
	Show operator
Show machine information	Show machine details
Exit machine/user-interface	Shutdown PC
	Close HMI

Table 5: Distinction between main -and sub functions of the machine and user-interface.

Job Element	Manual Load (sec)	Machine Time (sec)	Manual Load (sec)	
Prepare product	-	-	-	
Start-up machine		57.57		
Place product	10.07			
Fill out parameters	48.70			
Align product by use of the camera	10.00			
Start process		25.66		
Check results	17.50			
Unload product			7.43	
Turnoff machine		23.72		
<b>Total process time</b>	<b>86.27</b>	<b>106.95</b>	<b>7.43</b>	<b>200.65</b>

Table 6: Time study on the laser welding machine type 1410

Job Element	Manual Load (sec)	Machine Time (sec)	Manual Load (sec)	
Prepare product	-	-	-	
Start-up machine		57.50		
Place product	18.20			
Fill out parameters	185.55			
Align product by use of the camera	18.30			
Start process		11.14		
Check results	25.70			
Unload product			38.44	
Turnoff machine		24.92		
<b>Total process time</b>	<b>247.75</b>	<b>93.56</b>	<b>38.44</b>	<b>379.75</b>

Table 7: Time study on the laser welding machine type 1244

# K. Idea Generation

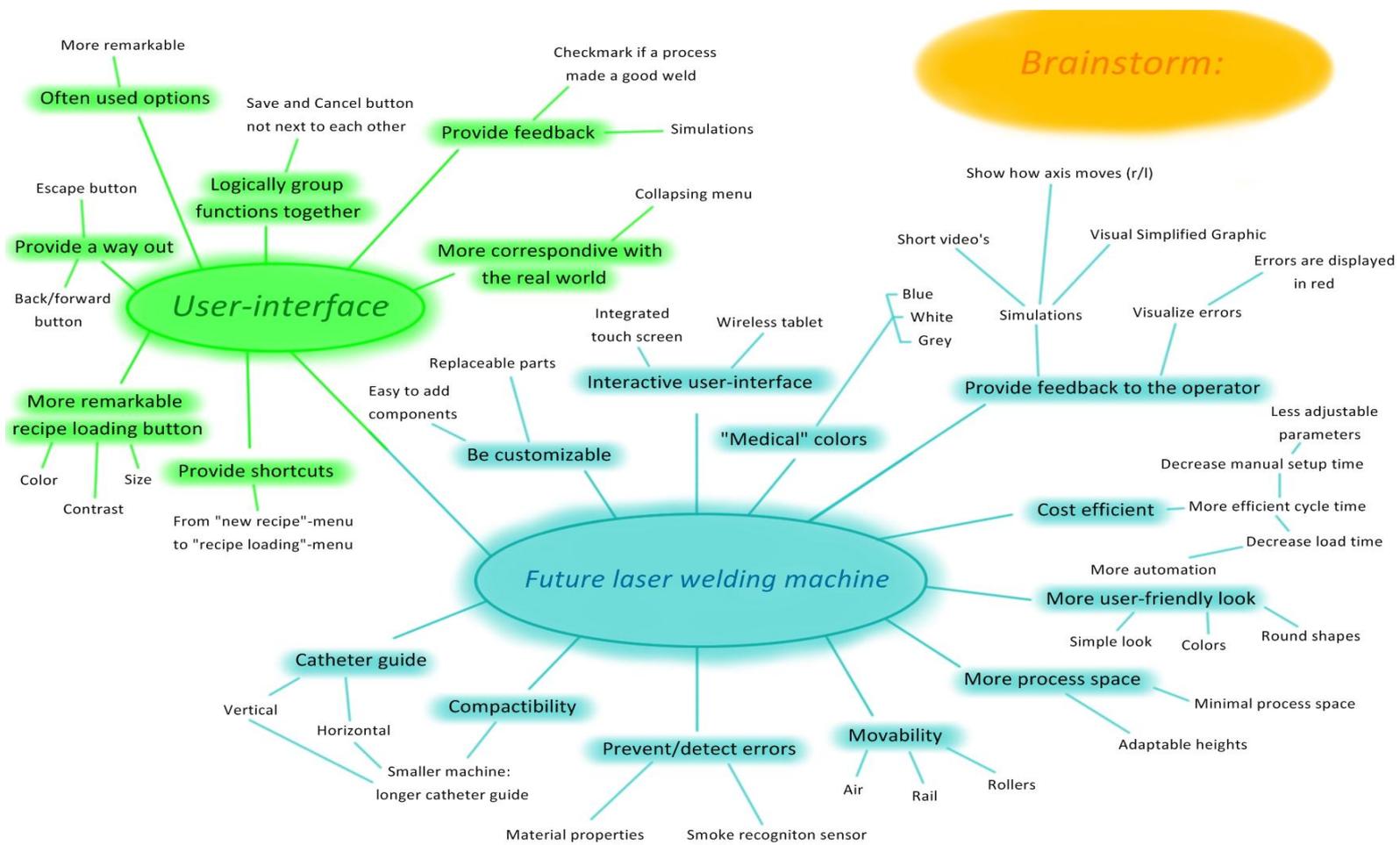


Fig. 18: A brainstorm to generate as many ideas as possible

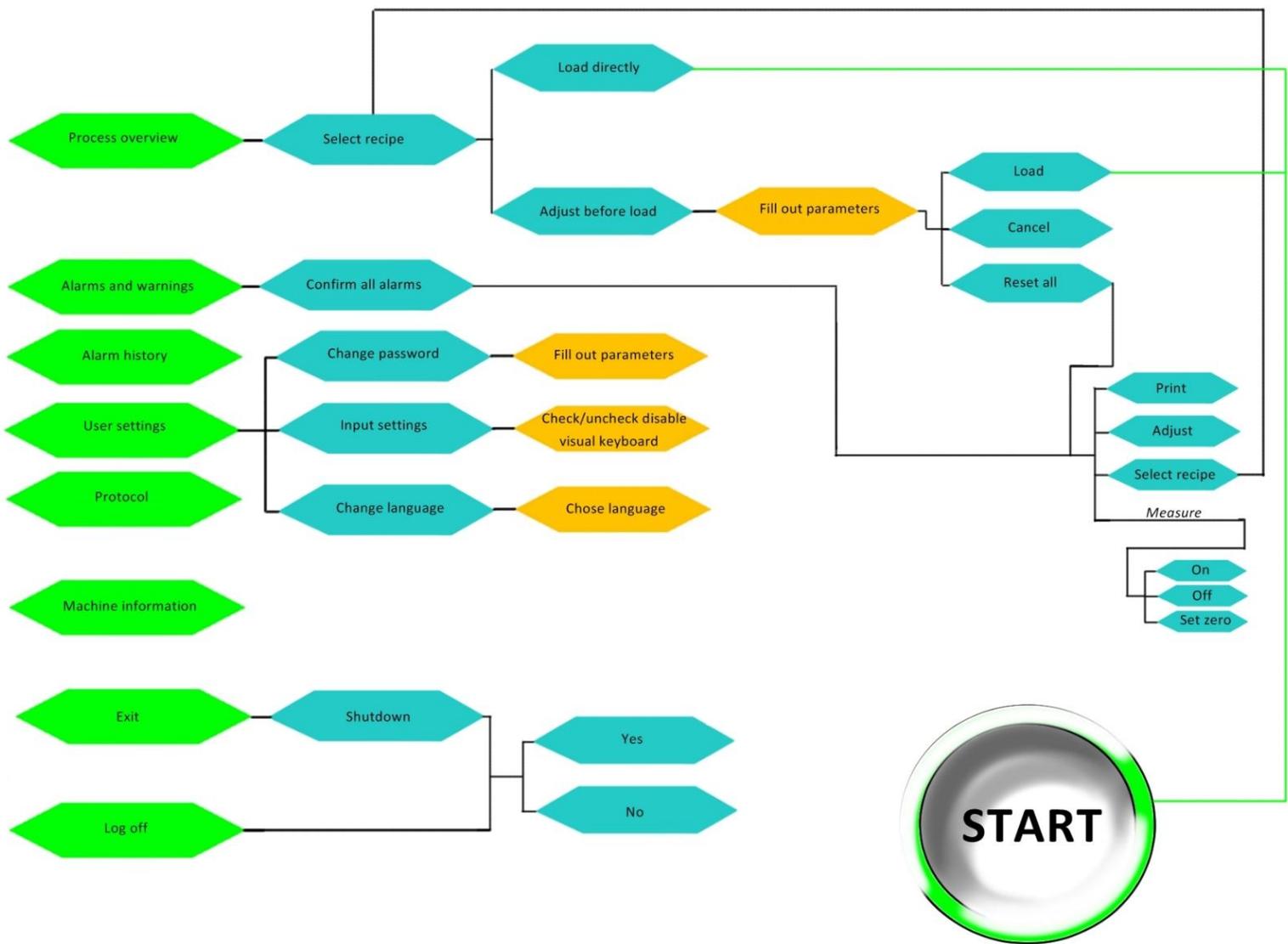


Fig. 19: The navigation in the user-interface of the operator.

# L. Sketches

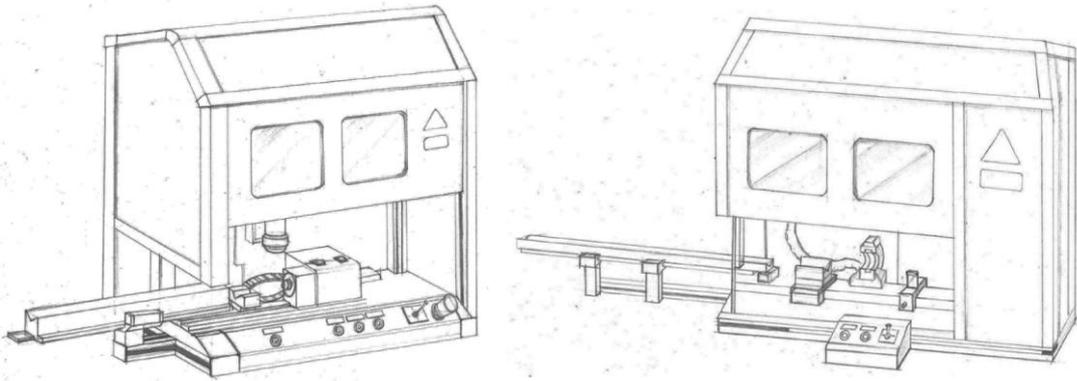


Fig. 20: Sketches of the laser welding machine type 1410 (left) and 1244 (right).

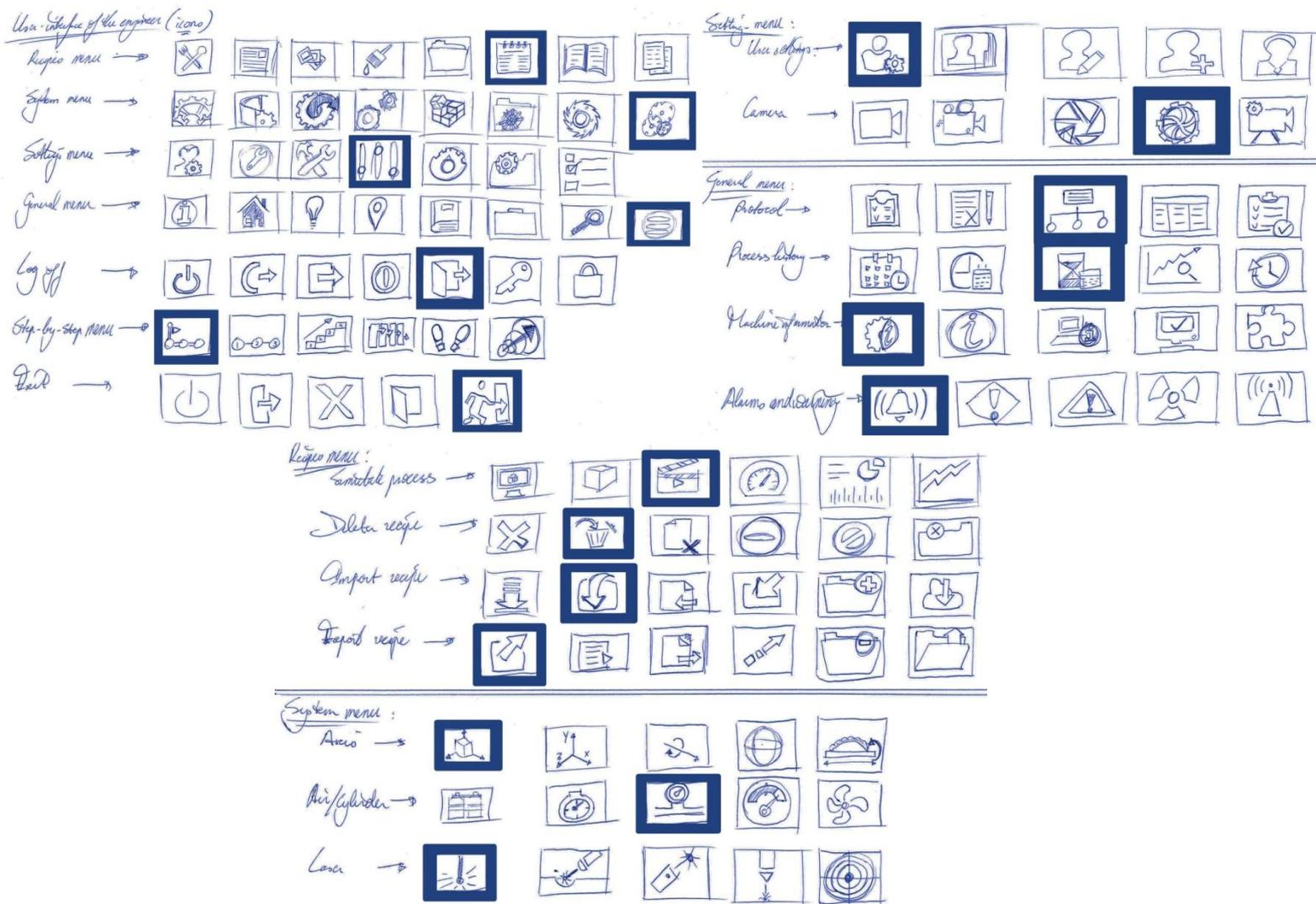
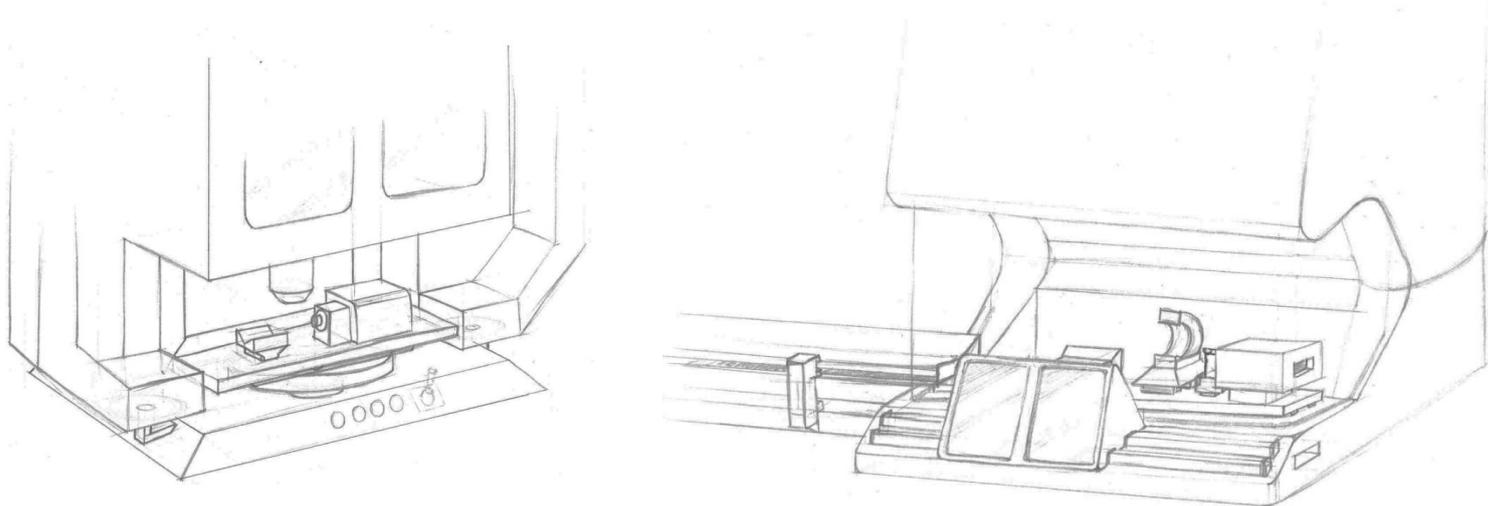


Fig. 21: Sketches of the several icons for the new HMI.



*Fig. 22: Sketches of the functional machine.*

## M. Concept Choice and Realization Table

Task	Functional machine	Comfortable machine	SciFi-machine
Turn on machine	One switch button	One push button	By touch
Load/unload product	Place product in collet and on clamp (existing system)	Axis moves towards user (x,y)	Axis moves towards user (x,y,z)
Clamp work piece	V-grip and different collets with different diameters	V-grip and one collet that changes the diameter	Magnetic levitation
Align product with laser and camera	Rotating axis plus movement in x-direction	Movable axis in x- and y-direction	Movable axis in x-, y- and z-direction
Fill out parameters	Existing system	Existing hardware buttons are integrated in the HMI	Swipe over line to adjust parameters
Detect alarms	Existing system	Existing system plus temperature sensor	Existing system plus temperature sensor, smoke sensor, optical sensor, simulations
Shut safety door	Small, only covers actual welding spot	Bigger, covers whole process area	Big, covers whole process area
Weld work piece	Laser from above the product, focus distance laser adjustable through interface	Laser from beneath the product, focus distance laser adjustable through interface	Laser from above the product, focus distance is determined by moving table instead of laser
Reach for emergency button	Right, next to the other buttons	Left from the user-interface, right from the process area	On the middle of the machine
Adjust to working environment	Vertical loading axis, in built handles to lift machine, can be placed on adaptable table	Rollers, horizontal axis	Can be placed on adaptable table, movable like hovercraft principle
Provide valuable feed back to user	Measuring camera lines, step display, checkmark process, help message	Temperature sensor, simulations	Smoke sensor, optical sensors, process indicator, automatically error detection

Table 8: Task fulfilling table.

Requirements	Features	Realization
Provide valuable feedback to the user	<ul style="list-style-type: none"> <li>- Simulations in the HMI</li> <li>- Sensors</li> <li>- Mechanical parts</li> <li>- Provide measurement scale on components</li> <li>- Show process status</li> <li>- Provide support when needed</li> <li>- Quality of the weld by check-marking the process</li> <li>- Insert weld length by camera lines</li> </ul>	<ul style="list-style-type: none"> <li>- HMI has to adjusted with an extra menu</li> <li>- New parameters have to be introduced in the HMI</li> <li>- Several sensors have to be installed in the machine</li> <li>- Sensor specification</li> <li>- Mechanical parts</li> <li>- Colored lights</li> </ul>

<b>The machine has to be flexible</b>	<ul style="list-style-type: none"> <li>- Adjustable menu's in the HMI</li> <li>- Assemble clamp and collet more easily</li> <li>- Flexible guiding axis</li> </ul>	<ul style="list-style-type: none"> <li>- HMI has to be adjusted to a flexible HMI</li> <li>- Click-on system (magnets)</li> <li>- Remove/assemble axis</li> </ul>
<b>The machine has to be adaptable to its working environment</b>	<ul style="list-style-type: none"> <li>- Movable</li> <li>- Adaptable</li> </ul>	<ul style="list-style-type: none"> <li>- Rollers</li> <li>- Smaller machine</li> <li>- Different working positions</li> </ul>
<b>The overall process time has to be optimized</b>	<ul style="list-style-type: none"> <li>- Quality control on the machine</li> <li>- Step-by-step-menu</li> <li>- Cool down the weld after production</li> </ul>	<ul style="list-style-type: none"> <li>- Optical sensor</li> <li>- Higher resolution camera</li> <li>- Introduce the step-by-step-menu in the HMI</li> <li>- Nozzle with cold air</li> </ul>
<b>Provide a user friendly look</b>	<ul style="list-style-type: none"> <li>- Round edges</li> <li>- Improve height of process area</li> <li>- Improve visibility of system status</li> <li>- Improve the position of the operating buttons</li> <li>- Axis moves towards the user</li> </ul>	<ul style="list-style-type: none"> <li>- New shape study results in new design</li> <li>- Research on ideal working height</li> <li>- Research on visibility/brightness of screens</li> <li>- Research on placement of buttons</li> <li>- Introduce axis in X- and Y-direction</li> </ul>
<b>The machine has to be reproducible to allow standard production with the same recipes on every machine</b>	<ul style="list-style-type: none"> <li>- Database of recipes</li> <li>- Manufacturing standards</li> <li>- Technological features</li> </ul>	<ul style="list-style-type: none"> <li>- Research on manufacturing procedures and assembly</li> <li>- Materials</li> <li>- Available techniques</li> </ul>
<b>Satisfy customer demands, but still be economically beneficial</b>	<ul style="list-style-type: none"> <li>- Different sources of feedback that can provide different feedback in the HMI</li> <li>- Allowance of welding with different spot sizes</li> <li>- Flexible integration of screens in machine</li> <li>- Lock safety door when process is started</li> </ul>	<ul style="list-style-type: none"> <li>- Designed charts with valuable feedback</li> <li>- Run simulation video's of welding process</li> <li>- Automatically move the mirror (1244)</li> <li>- Switch between axis to move</li> <li>- Position of screens adaptable</li> <li>- Research on how to lock safety door</li> </ul>
<b>Allow software simulation without actually using the machine</b>	<ul style="list-style-type: none"> <li>- Computer software simulation</li> </ul>	<ul style="list-style-type: none"> <li>- HMI for computer</li> <li>- Realistic simulations</li> </ul>
<b>Provide more options to control the machine</b>	<ul style="list-style-type: none"> <li>- 3 Dimensional axis</li> <li>- Measuring diameter and load recognized recipe automatically</li> <li>- Integrate control buttons in HMI</li> <li>- Introduce welding strategies</li> <li>- Fill out parameters more easily</li> </ul>	<ul style="list-style-type: none"> <li>- Research on robotic arms (3D)</li> <li>- Optical layer thickness sensor</li> <li>- Adjust HMI with control panel</li> <li>- Research on welding strategies</li> <li>- Swipe over line in HMI to adjust parameters</li> </ul>

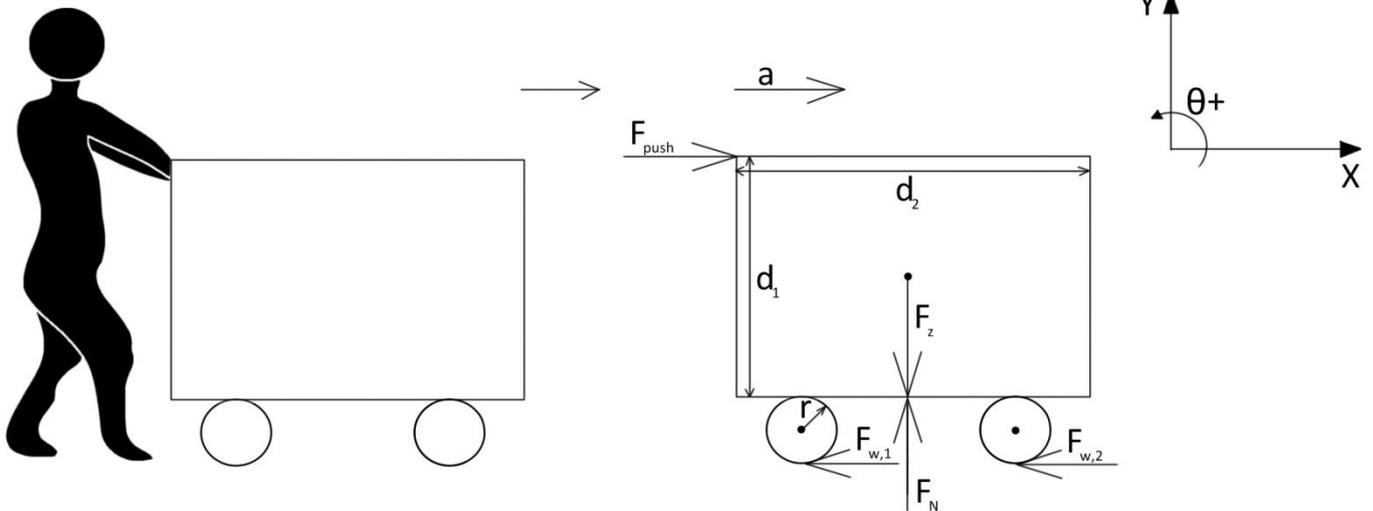
Table 9: Realization of different features concerning the final concept.

## N. Physical Ergonomic Design

### Ten principles of physical ergonomic design by Dan MacLeod (1990)

- 1) The first principle is about working in neutral postures. By neutral postures is meant that the user of the machine has to be able to maintain neutral positions while performing the tasks. This principle focuses on the shape of the curve of the back. To maintain the neutral S-curve is the most important. The way of operating should prevent the user to move its back into the C-curve or inverted V-curve which causes pain in the lower back. Also the neck should be kept aligned with the S-curve. Furthermore it is important to keep the elbows at sides, mostly in a 90 degree angle.
- 2) The second principle is about reducing the excessive force on the users joints. This principle is only applicable to the laser welding machine when it has to be moved, because other tasks with the machine do not consist of excessive force. For movement of the machine, the machine should have big enough rollers and good grips.
- 3) The third principle describes the ease of the reachableness of all the important components. The most important and the most used components should be easy to reach on the machine. Besides that, the work surface should be big enough to reach everywhere the user needs to reach from one single working position.
- 4) Working at proper heights is the fourth principle. One of the main rules with this principle is that most work should be done at elbow height, whether sitting or standing. Precision work or visually intense work is often best done at height above the elbow. Seat height should be pneumatically adjusted while seated.
- 5) Principle five is about reducing the excessive motions. The number of motions the user has to make to operate the machine during the day have to be taken into account. For this reason, many tasks will be automated on the machine to reduce manual repetitions.
- 6) The sixth principle describes the way of minimizing fatigue and static load. The static load is about holding the same position for a period of time which creates fatigue and discomfort. One possibility of a static load that can be experienced on the laser welding machine is one on the users legs. A footrest can permit the user to reposition its legs and will make it more comfortable to sit.
- 7) Principle 7 is describing the fact that a good ergonomic design has to minimize the pressure points. When the user is leaning forward onto the machine to load or unload the product for instance, the edges should not create painful pressure points. Also the pressure points that will be created while seated have to be taken into account.
- 8) The eight principle is about providing clearance for operating the machine. The user should have enough space to operate and therefore obstacles have to be eliminated from the machine. Furthermore, the important parts of the machine have to be visible.
- 9) The ninth principle explains that the user has to move, exercise, and stretch before, while or after operating the machine. If the user sits for long periods, he/she needs to shift postures. An adjustable seat would be helpful to provide the ability to the user to sit in different positions while operating the machine.
- 10) The final and tenth principle is about to maintain a comfortable environment in which the tasks have to be operated on the machine. One common problem is lightning. To increase the visibility of screens, the use of task lighting should be introduced on the machine.

## Calculations



*Known facts:*

$$m = 150 \text{ kg}$$

$$d_1 = 750 \text{ mm}$$

$$d_2 = 625 \text{ mm}$$

$$\mu_{rr} = 0,007 \text{ (estimated value from founded results)}$$

$$r = 40 \text{ mm}$$

$$v_{\text{end}} = 2 \text{ km/h}$$

$$t_{\text{end}} = 5,0 \text{ s}$$

*To determine:*

$$F_{\text{push}}$$

*Calculations:*

$$a_{\text{average}} = v_{\text{end}} / t_{\text{end}} = (2 / 3,6) / 5 = 0,11 \text{ m/s}^2$$

$$F_{w,1} = F_{w,2} = F_N \cdot \mu_{rr}$$

$$\Sigma F_X = m \cdot a_x \Rightarrow F_{\text{push}} - 2 \cdot F_w = m \cdot a_x \Rightarrow F_{\text{push}} = m \cdot a_x + 2 \cdot F_w$$

$$\Sigma F_Y = m \cdot a_Y \Rightarrow F_N - F_z = 0 \Rightarrow F_N = F_z$$

$$F_{\text{push}} = 150 \cdot 0,11 + 2 \cdot (150 \cdot 9,81 \cdot 0,007) = 37,10 \text{ N}$$

## O. Sensors and other devices

### Calculations for selecting the right temperature sensor

*Known facts:*

All parameters are retrieved from the existing machine.

The formula for the heat input is:  $Q_{\max} = ((P_{\max} * 60) / (S_{\max} * 1000)) * \text{Efficiency}$

$Q_{\max}$  = maximum heat input (kJ/mm)

$P_{\max}$  = maximum power of the laser (W) = 5 W

$S_{\max}$  = maximum welding speed (mm/min) = 50 / 60 mm/min

Efficiency = efficiency laser beam =  $\pm 0,8$

$d_{\max}$  = maximum distance (mm) = 600 mm

1 kJ = 1,899 °C

*To determine:*

$Q_{\max}, T_{\max}$

*Calculations:*

$Q_{\max} = ((5 * 60) / ((50/60) * 1000)) * 0,8 = 0,288 \text{ kJ/mm}$

Total energy of the laser beam =  $Q_{\max} * d_{\max} = 0,288 * 600 = 172,8 \text{ kJ}$

$T_{\max} = 172,8 / 1,899 = 91 \text{ °C}$

Temperature sensor	Temperature range	Spectrum sensitivity	Accuracy	Response time	Company
Pyrometer optris CT P7	0-710 °C	7,9 µm	$\pm 1,5 \text{ °C}$	150 ms	Optris Infrared Thermometers or Micro Epsilon
TMP 006	-40-125 °C	4-16 µm	$\pm 1,5 \text{ °C}$	200 ms	Texas Instruments
TPT 300 V IR Pyrometer	0-300 °C	8-14 µm	$\pm 3 \text{ °C}$	100 ms	Measurements specialities
ZIS 01 IR infrared sensor	0-200 °C	6,5-14 µm	$\pm 0,01 \text{ °C}$	100 ms	Ascon Technologic
PyroBus	-20-500 °C	8-14 µm	$\pm 1 \text{ °C}$	240 ms	Calex Electronics
PyroCube	0-500 °C	8-14 µm	$\pm 3 \text{ °C}$	10 ms	Calex Electronics

Table 10: Different temperature sensors with their specifications.

Camera	Resolution	Frame rate	Automatic focus lens	Snapshot	Film process	Product alignment	Company
UI-1460LE	2048x1536 3,15 MPixel	11.2 fps	V	V	V	V	IDS
Lynx-1024-CL	1024x1 50 MPixel/s	40000 lines/s	V	V	V	V	Xenics
Lynx-2048-CL	2048x1 50 MPixel/s	10000 lines/s	V	V	V	V	Xenics
Q-12A180	2352x1728 4 MPixel	187 fps	V	V	V	V	Adimec
SK2048VTDI-L	96x2048	...			V	V	Schäfter + Kirchhoff
C4080	4000x3000	max. 70 fps	V	V	V	V	Imperx

Table 11: Different camera's with their specifications.

Air nozzle	Compressed air pressure	Price	Dimension (length)	Company
Dual Nozzle CAG	80-100 psi	\$ 404,-	473 mm	Vortec
Whisperblast 600,623	100 psi	On request	19,5 mm	Lechler
Air Saver Nozzle 48004	40-100 psi	\$16,-	49,2 mm	AiRTX
Nex Flow Model 47001	80 psi	€16,-	25,4 mm	NexFlow

Table 12: Different air nozzles with their specifications.

## P. Usability test

The usability test will consist of three different HMI's that will be provided to the subjects:

- The existing one (refers to the old HMI)
- The redesigned HMI with only the images that are used for the different menu's and buttons
- The redesigned HMI with the images and supporting words that describe the function of the different menu's and buttons

The redesigned HMI with only the images that are used for the different menu's and buttons will be tested. The other two will be compared afterwards, because the most subjects already have the experience with the old HMI. Besides that, the other HMI will be the same as the tested HMI, except for the supporting words, and therefore will be only shortly provided to the subject to let him/her judge if the supporting words are needed to understand the HMI. In the end, all these different HMI's will be compared with each other and a final conclusion will arise from the results of the usability test.

### Setup

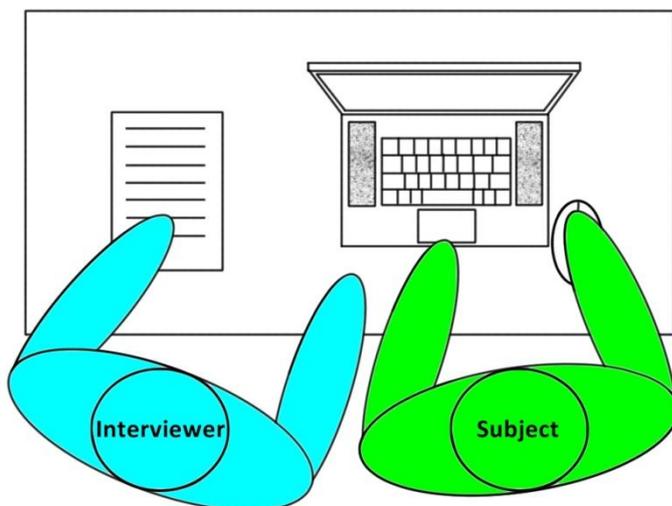


Fig: 23: The setup of the usability test.

### Run-through

The subjects will be asked to perform the following tasks in the presented order.

- 1) Please login.
- 2) In the Username text field, fill out: "Engineer" and press login.
- 3) Select a recipe 1 and adjust this recipe before loading.
- 4) Simulate the process before loading.
- 5) Check the chart that shows the power over time.
- 6) Check the simulated welding process.
- 7) Load the recipe from the 'simulate process'-menu.
- 8) Create a new recipe from template.

- 9) Create the recipe.
- 10) Add two steps to the recipe (*case 1 and 2*) and delete one afterwards. (*case 1*)
- 11) Check the camera menu and load the recipe.
- 12) Go to the 'home'-menu and select the 'system'-menu.
- 13) Move the axis to a distance of 5 mm and select counterclockwise.
- 14) Go back and fill out the new power of the laser and open the shutter.
- 15) Go to the 'home'-menu and select the 'general'-menu.
- 16) View the alarms and warnings and confirm all alarms.
- 17) Go to the 'home'-menu and select the 'settings'-menu.
- 18) Activate the camera and select "Use high quality streaming".
- 19) Go back and shutdown the machine.
- 20) You have finished the test successfully!

## Evaluation HMI

- 1) What do you think of the ease of use of the new HMI? Was it easy to run through the different menu's? What do you think of the reduction of main menu's?
- 2) What do you think of the used images for the different menu's and buttons? Are they clear enough to you and do you understand them without the help of words? Do you find the images logical for the function they represent?
- 3) What do you think of the 'step-by-step'-menu? Do the several steps follow one another in a logical order? Do you think the 'step-by-step'-menu will improve the easiness of selecting or creating recipes?
- 4) What do you think of moving the axis in the HMI?
- 5) Do you think it is useful to disable buttons when they are not useful and enable them when they could be used? Or should the buttons be available at any time in the HMI?
- 6) What do you think of the simulation process? Are there more aspects for simulating the process that have to be taken into account?
- 7) Do you think a quality control option on the machine is useful or do you prefer to check the quality of the weld underneath a microscope?
- 8) Do you think it is useful to have a 'back'-button at all time?
- 9) What do you think of the 'alarms and warnings'-menu? Do you find it logical that this menu is placed in the 'general'-menu? And what do you think about the alarm history?
- 10) When confirming all alarms, you will be directed to the 'adjust before load'-menu. Do you think this is logical or should you be directed somewhere else in the HMI?
- 11) What do you think of the fact that you first have to logoff in the HMI before shutting down the machine?
- 12) What do you think of the graphical design of the new HMI? Does it fit the style of BW-TEC?
- 13) What do you think of the new HMI compared to the old one? What do you think are remarkable aspects of the new HMI towards the old HMI? Which aspects are improved or unimproved concerning the old HMI in your opinion?

## Results

In the following table, the ease of use of the tasks that are completed can be viewed. The ease of use is represented on a scale varying from 1 to 5:

1. The subject could not complete the task without help
2. The subject could not complete the task without a small instruction
3. The subject completed the task, but it took some time to complete it
4. The subject completed the task without help
5. The subject completed the task with ease

### Usability test

Subject #	1	2	3	4	5	6	7	8	
Function in the company	Engineer Experienced	Automation Experienced	Automation Novice user	Automation Experienced	Automation Experienced	Sales Experienced	Tech. Manager Amateur	Engineer Amateur	Total points:
Task:	Without words	Without words	Without words	Without words	Without words	Without words	Without words	Without words	
1	5	5	5	5	5	5	5	5	40
2	5	4	3	4	3	4	5	5	33
3	2	3	2	4	3	4	4	5	27
4	4	4	3	4	3	4	3	3	28
5	5	4	3	3	3	3	4	4	29
6	5	5	5	5	5	5	5	5	40
7	3	3	3	4	3	3	3	4	26
8	2	4	3	3	2	2	2	4	22
9	2	4	3	4	4	3	3	5	28
10	4	5	4	3	4	4	3	4	31
11	5	3	4	4	4	4	4	5	33
12	5	5	5	3	4	4	5	3	34
13	5	5	4	5	5	5	5	5	39
14	5	5	5	5	5	5	5	5	40
15	3	5	4	4	5	5	5	5	36
16	5	5	5	5	5	5	5	5	40
17	4	3	5	5	3	4	2	3	29
18	4	4	4	5	3	5	5	4	34
19	3	3	3	4	3	4	2	2	24
20									Average: 32,26
Total points:	76	79	73	79	72	78	75	81	Average: 76,63
Measured time (min.)	12.14	8.37	11.37	11.56	11.37	12.24	14.52	10.35	Average: 11.49

Table 13: The results of the usability test.

The table content shows how much time it took for the subject to fulfill the usability test successfully and it shows which tasks are performed good (*green*) and which ones are completed below the average (*red*). The performance of the tasks that are completed below the average will be explained.

*Task 3:* The step-by-step-menu is a new feature in the HMI and therefore is not recognized by the subjects.

*Task 4:* The same applies to the simulating process-menu.

*Task 5:* Also the different charts in the simulating process-menu are new to the subjects.

Therefore it was hard to understand the different icons in this menu, like the chart that shows the power over time.

*Task 7:* The loading button was disabled, the subject did not find it logical that you first had to save the recipe before you can load it.

*Task 8:* The distinction between creating a new recipe and creating a new recipe from template was not well understood. However, when labels are used to describe the function, the similarities of the icons will not cause confusion anymore.

*Task 9:* The subjects tried to fill out the parameters, but this could not be realized with the software that was used for this prototype. Of course, this will be possible in the final HMI.

*Task 10:* The subjects struggled with the selection of the cases, something that is caused by the program Axure. The cases will not be provided in the final HMI.

*Task 17:* The settings -and system icon are too similar, and therefore they caused confusion to the subjects whereupon the subjects chose the wrong intended menu.

*Task 19:* The subjects did not understand the shutdown-icon and some subjects did not find it very logical that you first have to logoff in the HMI before you can shutdown the machine.

## Q. Temperature test

	1	2	3	4	5	6	7	8
<b>Parameters</b>								
Power (W)	0,5	0,5	0,5	1,0	0,5	0,5	0,5	1,0
Focus	10	10	10	10	20	20	20	20
Position (mm)								
Rotation Speed (rpm)	-	1000	1000	1000	-	1000	1000	1000
Weld Duration (s)	10	10	5	10	10	10	5	10
Rotation on/off	Off	On	On	On	Off	On	On	On
<i>Material</i>	<i>RNF-100-1/16</i>	<i>Diameter:</i>	<i>2,5 mm</i>					
Temperature ±(°C)	450	600	550	900	300	200	450	550
<i>Material</i>	<i>RNF-100-NR846-X-CS-34070</i>	<i>Diameter:</i>	<i>2,4 mm</i>					
Temperature ±(°C)	400	300	200	900	250	250	150	400
<i>Material</i>	<i>NFP 026-1500</i>	<i>Diameter:</i>	<i>3,4 mm</i>					
Temperature ±(°C)	250	250	150	300	200	200	100	400
<i>Material</i>	<i>FEP ID 3,15/1,94</i>	<i>Diameter:</i>	<i>3,7 mm</i>					
Temperature ±(°C)	150	300	200	250	150	200	200	200
<i>Material</i>	<i>FEP ID 1,07/0,69</i>	<i>Diameter:</i>	<i>1,2 mm</i>					
Temperature ±(°C)	300	400	350	400	300	300	300	400

Table 14: Results from the temperature test





