TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
DEPARTMENT OF MECHANICAL AND INDUSTRIAL ENGINEERING

DEVELOPMENT OF THE STANDALONE PRESSING STATION FOR ASSEMBLING PRINTED CIRCUIT BOARDS

TRÜKKPLAATIDE KOOSTU KOKKUPANEKU TÖÖJAAMA ARENDAMINE JA PROJEKTEERIMINE

MASTER THESIS

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Tallinn 2024

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THESIS TASK

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Thesis topic:

(in English) DEVELOPMENT OF THE STANDALONE PRESSING STATION FOR ASSEMBLING PRINTED CIRCUIT BOARDS

(in Estonian) TRÜKKPLAATIDE KOOSTU KOKKUPANEKU TÖÖJAAMA ARENDAMINE JA PROJEKTEERIMINE

Thesis main objectives:

1. Research possible pressing solutions
2. Develop concept based on project specification
3. Design a solution for pressing printed circuited board together

Thesis tasks and time schedule:

No	Task description	Deadline
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2.	State of art	16.02.24
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CONTENTS

PREFACE

The given master is going to provide a solution for one Estonian manufacturing company which has a potential safety and quality problem in the current manufacturing process for assembling printed circuit boards. The thesis provides and evaluates three possible concept ideas in order to solve the issues. The most suitable solution is developed further and a special workstation is designed. The author shows that it is possible to design an affordable solution which increases the safety of the assemblers and solves the raised issues with the quality. The author would like to thank supervisor of the thesis Margus Müür.

List of abbreviations and symbols

ESD	Electrostatic discharge
EU	European Union
HMI	Human-Machine Interface
IGBT	Insulated-gate bipolar transistor
ISO	International Organization for Standardization
PC	Polycarbonate
PCB	Printed circuit board
PLC	Programmable logic controller
VDC	Volts Direct Current

INTRODUCTION

Well-known manufacturing companies always focus on satisfying customer needs, offering them the best possible products on the market which requires meeting high quality standards in the product manufacturing process. Negative feedback can break customers' trust and loyalty which may decrease the advantage in the market. This is the main reason why production companies actively invest in manufacturing equipment to ensure availability of advanced technology and processes that can consistently produce high-quality products. One of the benefits would be that the funding supports making the production environment safer and lowering the risk of damaging the product.

The given master's thesis is going to propose a solution for an Estonian manufacturing company which has problems with one of their products. The potential issues were noticed after the product was released to the market on the hyper care phase. The raised issues are related to the product quality and assembly process which are more thoroughly described in the following chapters. Based on the information described in the problem statement, the project specification defines the goal and criteria of the project.

The market research is going to be conducted to discover all possible technologies used for pressing the parts together to make the electrical connections between the assemblies. The gathered information is going to be analysed to develop different concept solutions for the project, after which the best idea is selected and developed further. A new process flow will be proposed for the selected solution and a preliminary risk assessment is made to evaluate the safety measures of the system. The development and the design of the machine is going to be described and the cost calculations are made to estimate the overall cost of the project.

Keywords: pressing station, printed circuit boards, product assembly, safety, master thesis

1. THE PROBLEM

The upcoming master's thesis aims to present a solution for an Estonian company, which has a potential safety and quality problem in the current manufacturing process. The company uses manual labour for assembling the product where one subassembly operation consists of assembling several printed circuit boards (PCBs) together. The electrical connections between the boards are made with the pin headers. Currently the PCBs are connected manually by pressing the boards together.

The conducted measurement shows potential quality issues which the PCBs can have if too much force is used while the production worker is pressing the PCBs together. One potential issue involves micro cracks between PCB layers, which can damage signal tracks and lead to short circuits. Micro cracks might also pose a significant threat to the mounted components. Ceramic capacitors are recognized for their vulnerability to stretching and pressing forces, making them prone to cracking with ease (see Figure 1.1).

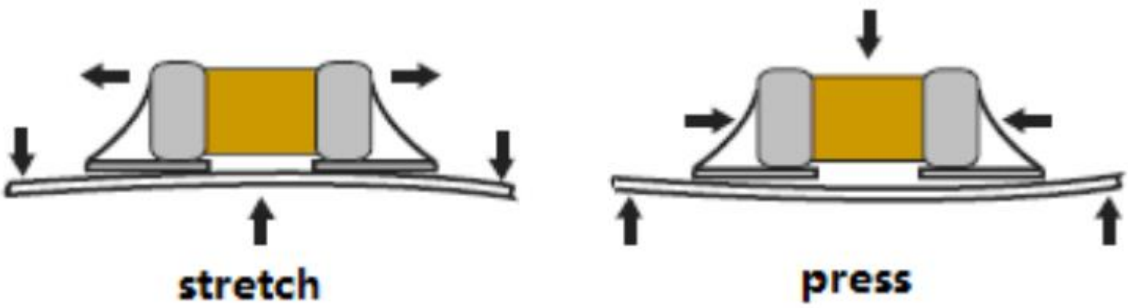

Figure 1.1 Stretching and pressing forces affecting the capacitor [1]

Additionally, there is a possible hazard for the production worker of developing occupational disease caused by using excessive force with hands long term. Although proper personal protective equipment is used and the risk assessment has been done, the company still wants to reduce risks. The welfare and safety of the employees are of utmost importance to the company.

As the PCBs assembly is assembled as a sandwich, there is an additional problem related to the pin headers alignment specially related to the most upper one on the left. The board called as Charlie has two 2x20 (two parallel twenty-pin header rows) 38 mm long pin headers which must be connected to the bottom PCB. The production worker must always check that the pin headers are properly attached to the socket and aligned.

The given product has already been introduced to the market and redesigning it is no longer an option, therefore product improvements are not going to be considered in this master’s thesis. The results of the current master’s thesis are used internally to study the possibility of pressing the boards together by a fully automated solution in the future.

The company has set three targets which the given master thesis follows:

- The proposed solution has to be safe to use
- The solution lowers the possibility of damaging the PCBs during the assembly
- The cost of the system should be under 15 000 €

1.1 Overview of the current manufacturing process

The make to order production technique is used in the given manufacturing line. The area is considered to be electrostatic discharge (ESD) safe and all ESD rules are followed. The product is manufactured by one production worker and the materials are located on the nearby shelf. The assembly takes place on the table and a tailor-made production jig is used to manufacture the product. The production jig must be used as the product cannot be assembled otherwise. The purpose of the assembly jig is to make pin headers and the PCBs alignment more accurate, reduce the pressing force to the bottom PCB (Alfa) and generally make the assembly process more convenient for the worker. All the standoff holes are not used for positioning, instead bolts are secured at a later stage to attach the PCB subassembly to the base plate. The tightening operation is not covered in this master thesis.

The assembly process starts when the largest PCB (Alfa), is placed into the jig and three long standoffs are added on top of it on the left (see Figure 1.2). The long standoffs are placed manually because they are too big for the surface-mount technology line and cannot be placed in advance. The other option was press-fitting standoffs to the Charli PCB, however, this was not proceeded during the product development phase.

Figure 1.2 Bottom PCB (Alfa) positioned in the jig

The Bravo board has four standoff holes where only one is used for guidance and the board has male 2x20 17mm pin headers connector (see Figure 1.3). After the Bravo board has been added on top of the bottom PCB, the production worker places fingers on top of the connectors and checks the pin header alignment from the left before pressing the two boards together.

Figure 1.3. The Bravo PCB is added on the top of Alfa PCB

The third PCB (named Charlie) is added on top of the second PCB and the worker picks up the assembly to check the connector alignment and uses the hands to press the two PCBs together (see Figure 1.4). The third PCB has two 2x20 38 mm long pin headers and three standoffs which all have to align perfectly. Even the smallest mismatches can cause significant malfunction to the board’s functionality.

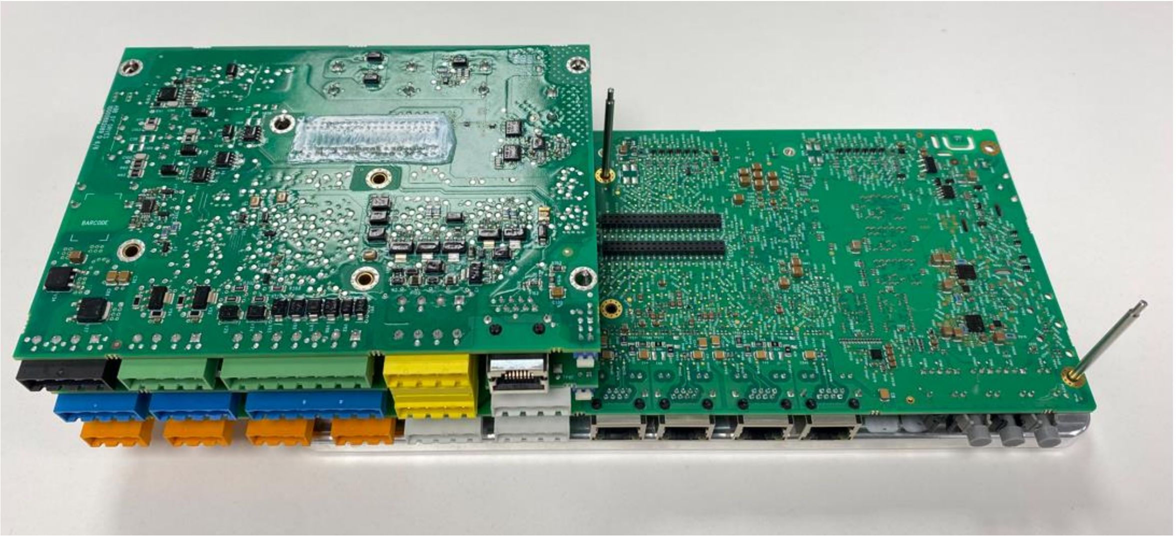

Figure 1.4. The Charli PCB is added to the assembly

The simplest PCB assembly is represented in the Figure 1.4, where three PCB boards are stacked on the left. The base unit has two stacked blind covers (type 1), type 2 has one PCB and the blind cover, whereas type 3 has two PCBs stacked on top of each other on the right side of the unit. The manufacturing process of the left side of the unit is always the same but the right side is configured based on the clients' needs. The PCBs on the right side look similar to each other and they all have two 2x40 17 mm male pin headers.

1.2 Legislation overview

The significance of workplace safety has seen a considerable increase in recent times. Legislators have been establishing legal frameworks and regulations to ensure safety standards. Therefore, a review of directives and laws is necessary to ensure the best compliance. These standards and legislations are developed based on past experience and the best practices, ensuring safety in the workplace.

The European Union (EU) has issued Regulation 2023/1230/EU – the machinery which establishes the health and safety standards for the design and manufacturing of the machinery that is introduced to the European market. The machinery is defined as a collection of parts or components, intended to be equipped with a drive system that does not rely on direct human or animal force, which has at least one moving part and these parts are interconnected for a particular purpose. The manufacturer of the machinery or a related product is required to conduct a risk assessment to identify the fundamental health and safety requirements applicable to the machinery or related product. The regulation describes all aspects of the machinery which have to be considered during the risk assessment, for example the immediate safety of the operator, ergonomics and operating positions. Additionally, it is mentioned that every workstation must be equipped with a control mechanism capable of halting either some or all operations of the machinery or the related product when the risks arises. The machinery should then be designed and built to eliminate hazards or if not feasible, to reduce all pertinent risks to a minimum, considering the findings of the risk assessment. Manufacturers are also tasked with the creation of the necessary technical documentation and the execution of the appropriate conformity assessment process. Once the machinery's compliance with the essential health and safety requirements has been proved through the appropriate conformity assessment procedure, the manufacturers are obligated to prepare the EU declaration of conformity and attach the CE marking [2], [3].

The International Organization for Standardization (ISO) 13850:2015 Safety of machinery – Emergency stop function – Principles for design has some correlation to EU Regulation 2023/1230/EU. The design principles and functional requirements for emergency stop functions on the machinery are described in a greater detail in the ISO 13850:2015. The idea of the emergency stop function (or E-stop) is to lower the hazards to person or machinery and it could be activated by a single action performed by a person. The emergency stop devices can be the following types: pushbuttons, wires, ropes, bars, handles and foot-pedals without a protective cover. The locations of the devices are brought out in the standard. The emergency stop should operate based on one of the given stop categories: category 0 or category 1. The power to the machine's actuators is immediately cut off in the category 0 and in the category 1 the power is turned off after the machine stops the movement [4].

The ISO 16092-1:2018 standard outlines the technical safety requirements and measures that should be followed by those responsible for designing, manufacturing, and supplying presses which are used for working with cold metal or partially cold material, but which can also be utilized similarly to process other types of sheet materials [5]. The standard is studied as it covers different press systems and defines the safeguards considered in this master thesis. The ISO 16092-1:2018 standard brings out general safety requirements separately for each system (hydraulic, pneumatic and electrical press system) which they have to comply with. One or more safeguarding measures described in the standard have to be applied to all systems, the most known measures are the two-hand control device and the safety light curtains. Additionally, the standard gives an overview of all aspects of the press system which should be considered during the design phase [5].

The previously mentioned ISO standards have many references to the ISO 12100:2010 which are all related. It outlines the fundamental terms, principles and a strategy for ensuring safety in the design of the machinery. It lays out the principles of the risk evaluation and mitigation to aid designers in achieving this objective. These principles are grounded in the knowledge and experience of the machinery design, usage, incidents, accidents and associated risks. It details the procedures for hazard identification and the estimation and evaluation of risks during pertinent stages of the machine's lifecycle as well as for hazard elimination or adequate risk reduction. It provides guidance on the documentation and verification of the risk assessment and the risk reduction process [6].

1.3 Project specification

The purpose of the project specification is to define technical requirements which are used to select and develop the best possible solution.

Technical requirements:

- The pressing force should be 110 N
- The system should be easy to use
- The system should be poka-yoke
- The system should comply with electrostatic discharge (ESD) requirements
- The press should be able to press three different locations and two different heights.
- The process of manufacturing should remain the same
- The general pressing machine safety standards should be followed

The maximum force is 110 N which also includes some buffer, the exact measured force is not published due to confidentiality. The new system should be easy to use for the worker to avoid any special supervision and training. The poke-yoke (failsafe system) approach is used in all company's projects to avoid any mistakes and therefore only the right process sequence can be used. This ensures that the operators cannot harm themselves and the product. This is one of the LEAN tools which the company uses in their everyday work. The electrostatic discharge has to be considered to meet the set production standards and to not damage the boards. The opposite side of male pin headers has been selected for a suitable pressing location as the force is the highest there. There can be four boards in total which can be added on top of the bottom PCB, therefore different pressing areas are needed (see Figure 1.5). Two pressing areas are located on the left side of the assembly and only one of them is on the right, because the third layer board pin headers are located in the same place as the headers on the second layer board. Also, two different pressing heights are used as two different layers are added on top of the Alfa board. The system must prevent a situation where the wrong height and location are used for pressing. One of the aims is not to change the current manufacturing process to avoid any additional trainings, layout changes or investments outside the scope of the project. The design of the machine should follow the general pressing machine safety standards described in chapter 1.2.

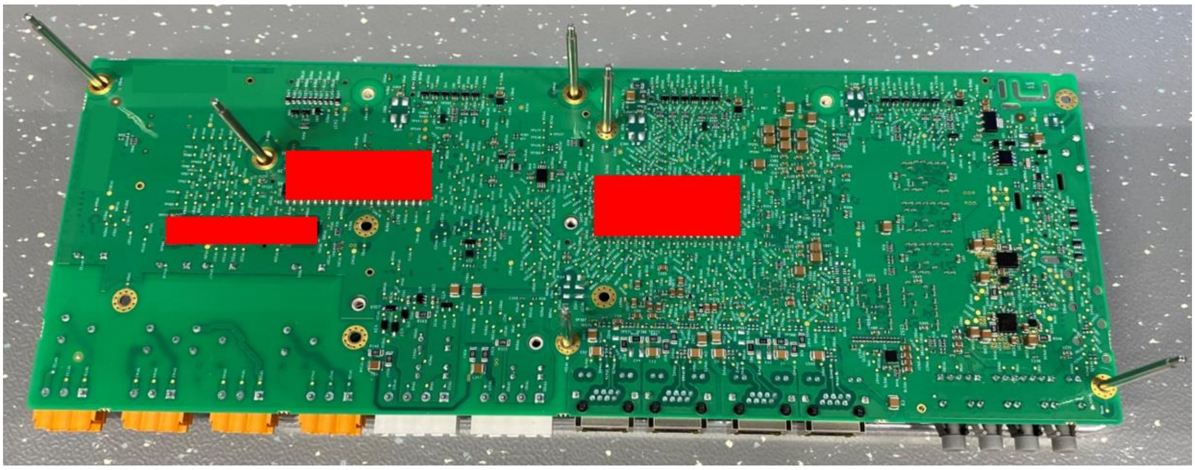

Figure 1.5 Pressing locations marked in red

2. STATE OF ART

There are many different possibilities for establishing board-to-board connections. Each of these methods come with its own set of advantages and considerations, allowing engineers to tailor their approach based on factors such as space constraints, signal integrity requirements, and environmental conditions. The choice of the board-to-board connection method plays a crucial role in the overall design and performance of electronic systems, making it essential for the designers to carefully evaluate and select the most suitable option for their specific application. However, the trend shows more and more applications shifting away from solder technology due to its harmful environmental impact and time-consuming nature. A research conducted on insulated-gate bipolar transistor (IGBT) modules utilizing solder-based construction indicates that the solder layers within these modules represent a significant vulnerability which is revealed by fatigue when subjected to both active and passive temperature cycling [7].

Frequency converters utilizing IGBTs within the voltage range of 1200 V to 1700 V are usually soldered to the printed circuit board. However, this process can pose challenges because of the substantial copper content in the PCB's power traces rapidly dissipate heat from the soldering zones. Consequently, achieving the necessary soldering temperature at the solder pin through holes can only be achieved by increasing the solder temperature to level that risk damaging portions of the PCB and its components, thereby significantly diminishing their lifespan [8]. A press-fit connection is a solderless electrical connection technology that relies on the mechanical contact force generated between terminals, slightly wider than the PCB through-holes, and the PCB itself. Press-fit technology has gained significant attention recently as a response to the "Lead Free Requirement" concerning materials used in electric and electronic devices. Additionally, this technology offers the following benefits: elimination of additional heating processes for surface-mounted devices and elimination of the necessity for heat-resistant plastics in connector housing due to the terminal insertion process being conducted at room temperature. [9]. Experiments have shown that the press-fit technology is very reliable regarding corrosion, vibration, and active thermal cycling [8]. However, the press-fit technology requires extremely precise alignment conditions, otherwise the PCB can get damaged because of the elevated stresses applied during the assembly process which may result in insulation failure occurring within the circuits [10].

Contact springs can be compared with other solder-free contacts such as screw terminals or plug connectors and they have many variation available which are used widely [11]. These connections are engineered to streamline and enhance the coupling of components that engage through sliding or rotational motion, rather than in an axial or vertical alignment. Upon engagement, the ball compresses and rolls, facilitating contact between mating surfaces, enabling smooth parallel movement while the spring force ensures consistent electrical contact is maintained. [12]. Gold-plated copper alloy wire spring contact is widely used in the electrical interconnection system of aviation and aerospace engineering due to its advantages of high quality, high reliability and long life [13]. Also, the contact spring technology can be found in the household equipment, the US10312623B2 patent describes a solution where electrical connection is made between the device and the power adapter [14]. Another approach in power electronic industry is to use contact springs for all of the auxiliary contacts where they enable a solder-free connection between the driver PCB and IGBT [7]. However, this requires a special process for assembling the two pieces together. Semikron proposes two different PCB mounting methods which the manufacturer can choose between. In the standard mounting, the driver PCB is positioned onto the module, and the screwing process draws the PCB towards the module until it securely fixed on top of the mounting domes. An alternative method employs a press mechanism to affix the PCB onto the top of the SKiM IGBT. This effectively secures the PCB in position, overcoming the spring force exerted by the auxiliary contact springs (see Figure 2.1) [11].

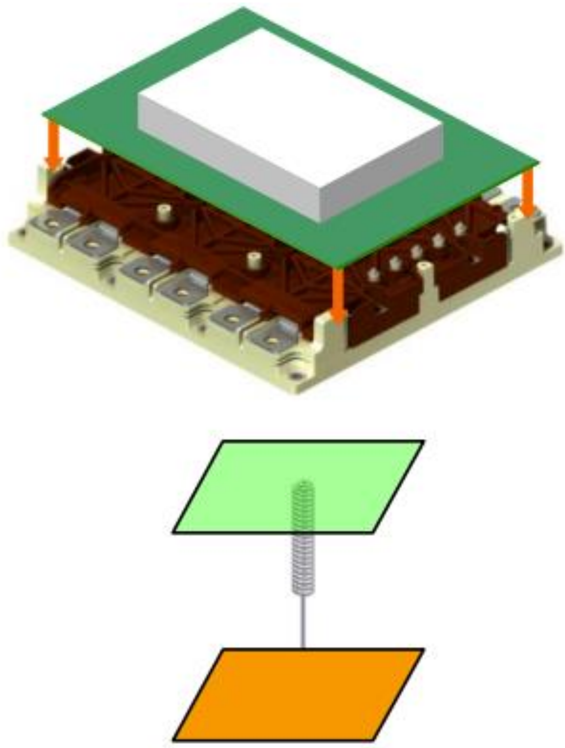

Figure 2.1 SKiM IGBT spring contacts [7]

A pin header functions as a bridge, serving as the connection point between a PCB and external wires, cables or other PCBs. This enables to transfer signals, power, and ground in and out of a PCB. The pin headers are used in complex industrial products or do-it-yourself projects, also making it a good solution for rapid prototyping. The pin header is designed to connect to the female connector offering a secure and reliable electrical connection. The header usually consists of plastic which surrounds and isolates metal pins in one or more rows and has different configurations available, such as single-row or dual row and straight or angled [15]. Additionally, the pin header pitch spacing can vary from 0,64 to 11 mm and is chosen based on application requirements and available space on the board [16]. A well-known pitch spacing size is 2.54 mm which is used in general purpose applications, for example microcontroller such as Arduino or Raspberry Pi. The insertion force can be 1,39 N per single contact, hence theoretically the 2x40 pin header’s combined mating force is 111,2 N [17].

2.1 Available pressing solutions

Different board to board connection technologies have multiple technical solutions available which the manufacturer can choose from. However, every application has its own unique distinct requirements which have to be considered when selecting the optimal solution. Additionally, it has to be pointed out that generally the design and used technologies in tailor-made production lines or workstations are considered as confidential and not advertised publicly. Also, the developed solutions are not covered with patents which would reveal essential production information.

2.1.1 Manually operated press

There are three types of manual presses available on the market: rack-and-pinion, toggle and toggle with pneumatic assist [18]. They are relatively affordable compared to other options, the simplest KIPP toggle press (push-pull type) costs around 220 € [19]. A rack-and-pinion press generates a steady linear force throughout the entire stroke. Typically, a rack-and-pinion press is favoured for pressing and forming tasks, whilst a toggle is chosen for riveting, punching and flaring. Additionally, the toggle press is used for crimping wires to terminals and connectors. In a toggle press, the ram is linked through a toggle mechanism and the lever action of the toggle exponentially amplifies the force exerted by the ram. The press initiates with minimal force at the beginning of the stroke, but delivers peak force at the end, similar to the act of fastening a substantial pile of paper with a staple. The press has to be properly selected and have the right tooling to maintain productivity and avoid any risks to the worker. Process monitoring is frequently used with powered presses to confirm the correct tooling force and stroke distance during an assembly process, ensuring its repeatability. This technology is rarely used with manual presses due to its relatively high cost and therefore the control relies on the operator to visually check if the operation was done properly. Manual control poses a high risk of damaging the board or connectors due to the excessive pressure applied [18], [20].

Additionally, there are specialized manually operated mechanical press fixture kits available on the market. They operate through a lever-actuated vertical clamping press mechanism which multiplies the force exerted by the operator, allowing large forces to be applied without causing operator fatigue. The kits are made of durable aluminium and steel construction, precision bearings and hardened steel rods for accuracy and repeatability [21]. Such solutions are only suitable for applications where consistent force and fixed height are utilized.

2.1.2 Pneumatic press solution

A pneumatic system, versatile and useful across a wide range of applications, employs compressed air as its working medium to transmit and regulate energy. This system harnesses energy from compressed air which is stored in a reservoir under pressure, ready to deliver near-instant force upon valve operation. The system requires a compressor for air compression, an actuator for task execution, a circuit for air transfer and a valve for air control. These components work together to make the pneumatic system an efficient tool in various fields. They are extensively used in various domains where they are an optimal selection for simple applications and motion tasks such as controlling train doors, managing automatic production lines and operating mechanical clamps. Many industries utilize pneumatic presses due to their efficiency and adaptability. For instance, the automotive industry shows a preference for toggle presses. Another significant application of pneumatic systems is in custom steel stamping, which can reshape dozens of units within a reasonable timeframe. These stamps are particularly useful for marking brand names and other essential details on products. This wide range of applications showcases the utility and versatility of pneumatic systems [22], [23], [24], [25].However, whilst pneumatic drives may initially appear to be the most cost-effective choice in terms of investment, it’s vital to also consider the overall expenditure, namely, the total cost of ownership [25]. The system can be used only if the manufacturing unit has compressed air capability and it meets set quality air standards. Maintaining the smooth operation of pneumatic components is vital for ensuring process reliability in the production. Moreover, different industry segments and specialized applications demand specific standards for the quality of compressed air [26]. It is important to emphasize that the technology and operational costs of a system reach their optimum efficiency only when every component receives a sufficient supply of compressed air. That is why the system must have sufficient flow rate (l/min) and pressure. Each pneumatic consuming device is calibrated to operate within its optimal pressure range. If the operating pressure falls below this range, system efficiency is compromised, often leading to malfunctions. Conversely, excessive operating pressure accelerates wear on seals and other components, heightens energy consumption and results in an undesirable noise level [26].

2.1.3 Electrical press solution

Electro-mechanical presses represent a significant and promising advancement in press technology which offers processing accuracy, improved tool life, increased productivity and noise reduction [27]. Also, the ability to halt the press cycle midway in case of errors significantly reduces or eliminates the need for rework [20]. The main part of the electro-mechanical press system is an electric motor which operates in tandem with a drive. The motor is responsible for moving the load and components and is equipped with position detection, for instance, encoder. The drive, often considered the central component of any motion control system, modifies controlled parameters such as position, speed or torque, based on a set target value (command value) to precisely control machine operations. A system consists of drives and motors controls motor operations in a closed loop and is utilized when high precision is necessary. The actual position, speed or torque of the motor is fed back for comparison with the command value and to calculate the errors between them. Using this error information, the drive makes real-time corrections to the motor’s operations, ensuring that the system can deliver the required performance [28, 29]. The most frequently used motor is an industrial servomotor which utilizes brushless motors. The rotor is equipped with a strong permanent magnet. The stator consists of several conductor coils, and the rotor rotates when the coils are energized in a specific sequence. The rotor’s movement is dictated by the stator’s frequency, phase, polarity and current when the correct current is delivered to the stator coils at the right moment. The drive follows set parameters and regulates the output torque, rotational speed or the position of motors. The position, speed and torque are managed based on inputs from a motion controller, feedback encoder and the motor itself and the drive provides the suitable amounts of power to the motor at the correct times [29].

Many researches and use cases have been published where servo electric press solutions are implemented and tested in the steel industry. One research proposes a case study for retrofitting a stamping industry machine by attaching a servo-drive and proportional–integral–derivative control to improve productivity. According to the research, the cost of transforming a traditional mechanical press into a hybrid servo-press using a proposed technique is around 20% of the cost of a direct drive servo-press. This makes it a cost-effective solution for manufacturers looking to upgrade their existing machinery without incurring the high costs associated with purchasing new equipment. In addition to the cost benefits, the research also discusses the potential productivity improvements such as manufacturers potentially achieving higher levels of precision and control, leading to improved productivity [30]. Festo has published two uses cases where their standard servo presses are used in production. The first study case describes a process where smartphone display and housing are pressed together by a fully automated pressing station. The system parameters are predefined and monitored during the process [31]. Another application developed by Festo uses their standard components in modular workstation concept where electrical connectors are produced. The servo press kit, offering a simple configuration for position- and force-controlled movement along the Z-axis, is utilized for press-fitting and bending contact pins. The modular servo press kit YJKP consists of a closed-loop servo motor, a mechanical axis, a motion controller, force detection and application software. This results in the accurate, robust, and delicate positioning of the pins. Evaluation functions like insertion or block force monitoring provided by the application software determine if the fit is within the acceptable range [32].

2.1.4 Pressing solution options

The Table 2.1 presents a comparison matrix between three types of press solutions: manually operated presses, pneumatic press, and electrical press. A weighted decision matrix is a good tool for selecting a suitable solution which takes into account criteria weight and the received score of the solution. The weights and scores are multiplied and the final points summed up to have the final results. Four different criteria with a five-point weighted score system are used based on the importance for the selection process. A five-point system is used for scoring the solutions, 1 being the lowest possible score and 5 the highest. The weight score for both the accuracy and force control is 5 as they are crucial aspects of the system. The weight score of the maintenance requirements is 3 as the requirements for the machine life cycle need to be considered. The weight score of the ease of the setup is 2 points. The setup includes the design and assembly of the system.

The manually operated press scored 1 point in accuracy and force control as these aspects are challenging to monitor and control. The operator would be responsible for manually operating the tool and visually verifying the quality of the connection. The process would not be poke-yoke. The ease of setup scored 4 points, due to the solution being ready to be used instantly (it would only require some minor tuning). The maintenance requirements scored 4 points as the manually operated press is relatively maintenance free. The combined score of the manually operated press is 30 points.

The pneumatic press solution received 3 points in accuracy as it might be affected by the factory's pneumatic system. It could be prevented by adding additional sensors and actively monitoring the overall system. However, it would make the pressing system much more complex and is reflected in ease of setup which scored 2 points. Additionally, the annual maintenance plan would be needed for the pneumatical parts to ensure the high accuracy and reliability of the system. The maintenance requirements scored 3 points. The force control would be automatic, but it would depend on the overall performance of the pneumatic system and the latter might affect the accuracy of the force control. These factors would be compensated by the sensors and force control limits. Therefore, the system scored 4 points in force control. The pneumatic press solution received 48 points in total.

Electrical press solution scored 5 points in accuracy, force control and maintenance requirements. The system would have high accuracy and force control which could be easily monitored and corrected if needed. The electrical press received 5 points in maintenance requirements as it is considered to be maintenance free. The system setup would be less complicated than the pneumatic setup, but still it would require a tailor-made design. The system setup scored 3 points. The electrical press solution received 71 points in total which is the highest result out of the three options. The electrical press solution is therefore the most suitable pressing technology.

Table 2.1 Comparison between three different pressing technologies

Criteria	**Weight**	**Manually Operated Press**		**Pneumatic Press Solution**		**Electrical Press System**	
		Score	Total	Score	Total	Score	Total
Accuracy	5	1	5	3	15	5	25
Ease of Setup	2	4	8	2	6	3	6
Maintenance Requirements	3	4	12	3	9	5	15
Force Control	5	1	5	4	20	5	25
	Total	30		48		71	

3. CONSEPT GENERATION

Concept generation is an important stage in the design process which enables to explore a wide range of ideas while taking into account the technical requirements of the project. This phase is also crucial for risk management, as it allows the comparison of multiple design concepts. Concept generation also includes stakeholders, making sure their needs and expectations are considered in the design. Additionally, this process contributes to cost efficiency by identifying potential design issues early on.

3.1 Three-dimensional gantry YXCR

A three-dimensional gantry YXCR solution (see Figure 3.1) from Festo is considered for positioning the electrical press to the right location. Such comprehensive system is ready for installation and includes energy chains for cables or tubes, suitable motors and drive packages. This system allows for a flexible working area due to the scalable strokes in the X, Y, and Z directions and enables three-dimensional movements in horizontal work areas [33]. The user defines the size and parameters of the gantry YXCR solution on the Festo website. The initial design is proposed and modelled while a standalone Festo gantry solution is used to move the press head to the right location. The system is intended to be a separate pressing workstation with minimal user interaction. The solution is fully automated, choosing the right pressing locations and offering a user a safe and comfortable working environment. The system features laser curtains to maximise user safety and prevent the operator from getting hurt while entering the working zone. The system also has Minitec electrically height-adjustable lifting columns which are used for adjusting the workstation to ensure workplace ergonomics. Minitec 45x45 and 45x90 aluminium profiles are used for making the frame. Human-machine-interface (HMI) screen is fitted on the left side of the assembly for operator interaction. The screen enables the operator to the select correct program and follow the work instructions. Additionally, HMI can be used for troubleshooting and analysing the system in case of unexpected occurrences. The only responsibility of the operator is to add the PCBs to the assembly and check the pressing quality.

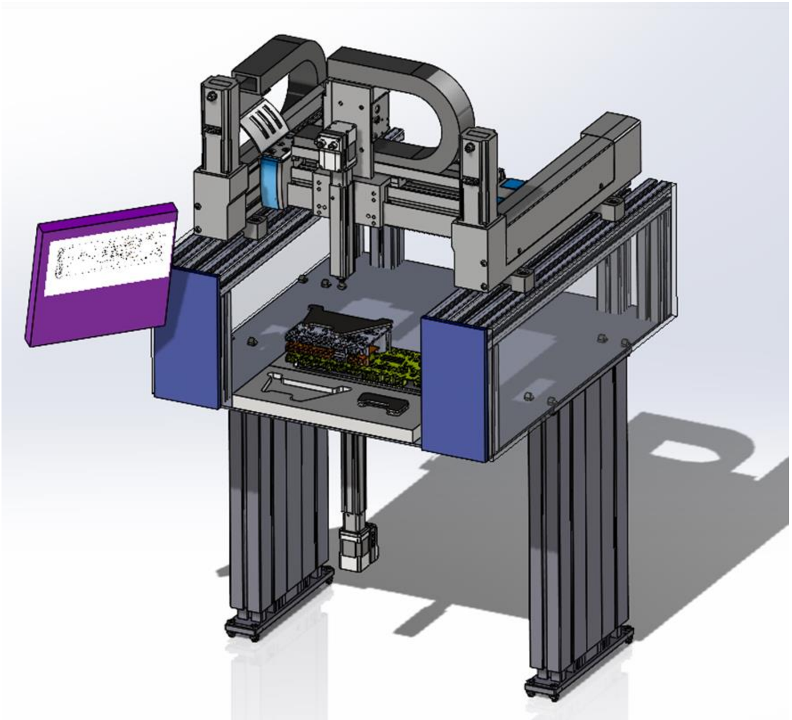

Figure 3.1 Concept solution of the tree-dimensional gantry YXCR

3.2 Table mounted press solution

An alternative design is considered where the pressing station is located on the assembly table (see Figure 3.2). The system has an electrical press solution which is mounted on a frame made from Minitec parts. A manual slider solution is proposed which requires the user to move the product to the right location manually after which the pressing operation is activated. The system features two slider systems, one of which is used for moving the product in and out from the pressing area (y-axis) and the second slider is used for positioning the pressing location (x-axis). When the product is in the right location then the user manually fixes the slider system to prevent any unnecessary movements which could damage the PCB. If the right procedure is followed and the checked by the sensors' system it enables the operator to initiate the pressing mechanism. The table mounted press is more cost efficient compared to the Festo gantry solution but it requires a sensors' system which checks the slider system positioning to ensure that the product is in the right location.

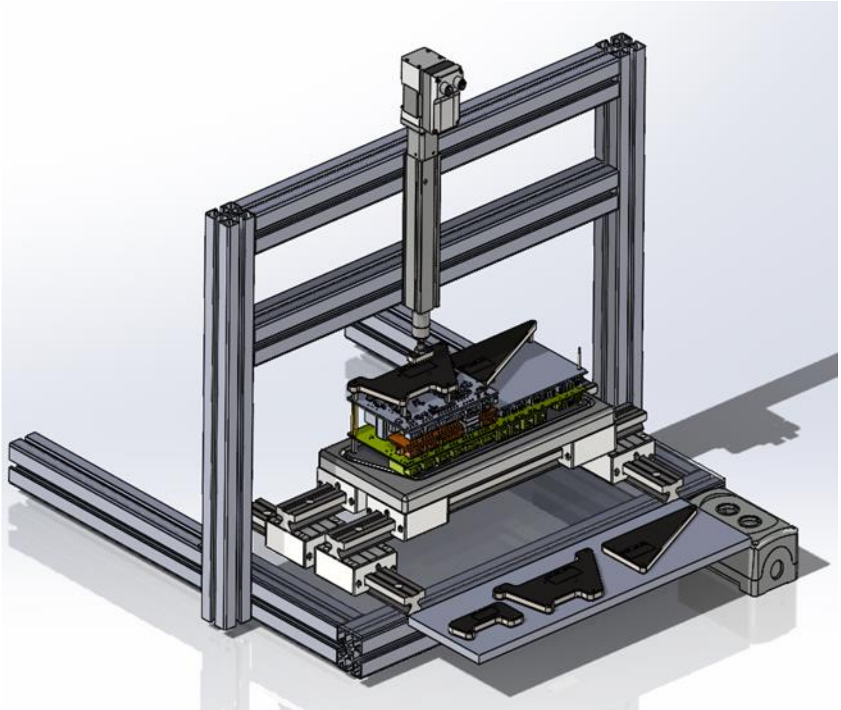

Figure 3.2 Table mounted press solution

The initial design shows that the pressing station would require at least 700x600mm space from the production table. As the current production table is 1500x800 mm, the pressing station take ups most of the space on the table in which case there is not enough space for the next production steps. The station should be secured to the top of the table to prevent any movement. Moreover, the integration of all the sensors and safety features is challenging due to the lack of space. There is also a need for housing all the electrical components separately. A permanently fixed station would be makes it challenging to relocate the setup if necessary.

3.3 Standalone press solution

The third concept solution (see Figure 3.3) is developed combining the two formerly proposed solutions. The table mounted press solution proves to be too big for the table and an initial standalone solution is developed. The latter is inspired by the Festo gantry solution which is designed as a separate workstation. The standalone station enables to have more flexibility with the size and design without compromising the operator comfort. It is equipped with wheels which make it easier to move it around in the production. Similarly to the table mounted press solution, the press mechanism is secured to the frame and the double axis liner slider system is used for positioning the assembly to the right location. The operator manually fixes the assembly location with the ball lock pins. This solution requires a separate control program on the PLC which uses sensor input to control the position of the assembly. The station would consist of three levels: the assembly and PCB pressing at the top, electrical compartment in the middle and on the bottom level for storage. All necessary control buttons are located on the top level including the emergency stop button. The PLC, power supply unit and other electrical components are securely located in the middle section of the station with limited access. The idea is to have side panels from three different sides and access door in the back. The last level could be used for storing necessary production equipment or some critical spare parts. This approach makes the system more compact and enables to add all necessary safety features.

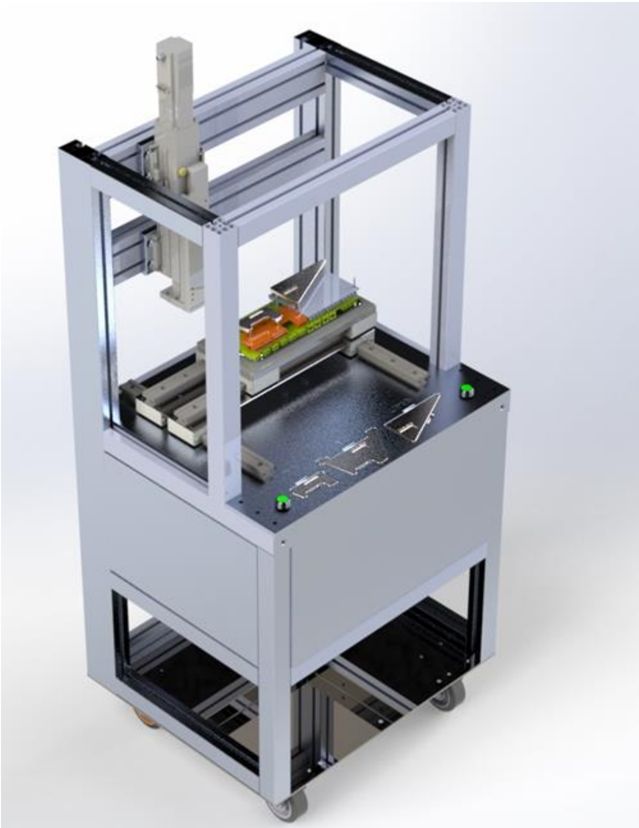

Figure 3.3 Standalone pressing station

3.4 Solution comparisons

Three different concept solutions are developed and proposed for evaluation. A weighted decision matrix (see Table 3.1) is used in the selection process to proceed the most suitable solution for this project. Five different criteria are considered with a five-point weighted score system which are ranked based on their importance. The weights and score are multiplied and the final points are summed up to receive ultimate results. Every solution is scored in a five-point system, one is the lowest possible score and five the highest. The weight score for the compliance with the technical specification and estimated cost is 5 as they are two most critical aspects of the selection process. The weight score for the space usage is 3 as it is important to use minimal space. The weight score is 1 for the design complexity as it indicates how much time would be required for developing the solution. User friendliness scores 1 as demonstrates how little the operator needs to interact with the station and the safety and ergonomics are already covered in the technical specification.

The three-dimensional gantry YXCR scores 5 points for meeting the technical requirements. The solution receives only 1 point in cost estimation as it is considered to be the most expensive solution out of the three. The gantry YXCR scores 3 points in space usage as it would be a separate workstation which gives more room for the operator to carry out the procedures. However, the usage of the area of the system is bigger compared to the standalone press station. The gantry YXCR scores 2 points in development complexity as there would be a need for a lot of resources to design and program the three-dimensional system for the station. The user friendliness scores 5 points because the proposed solution would have minimal human interaction. The three-dimensional gantry YXCR scores 46 points in total.

The table mounted press solution receives 5 points for being in accordance with the technical requirements. The estimated cost of the system is considered to be the most affordable out of the three solutions, hence scoring 5 points. The table mounted press receives 2 points for space usage as it would use the current production table and therefore limit its usage. The solution scores 3 points for development complexity as the integration of the necessary equipment proves to be challenging. The user friendliness scores 2 points as the solution would use the current production table and the space for the operation would be limited. The table mounted press solution receives 59 points in total.

The standalone press solution meets all set technical requirements scoring 5 points. The solution is predicted to be reasonably cost effective, scoring 3 points. The solution scores 4 points for space usage as it would require a standalone operating area which would be considerably smaller than the three-dimensional gantry YXCR. Additionally, it would not use the existing table, giving the operator more room to work. The development complexity receives 4 points as it would be simpler to develop than gantry YXCR and the standalone station enables to have more flexibility with the size and design. The solution scores 4 points for user friendliness as it would require operator interaction. The standalone press solution receives 64 points in total. The evaluation matrix shows that the most promising and suitable solution is the standalone press which is going to be selected and developed further.

Table 3.1 Comparison table between three different solutions

Criteria	**Weight**	**Three-dimensional gantry YXCR**		**Table mounted press solution**		**Standalone press solution**	
		Score	Total	Score	Total	Score	Total
Meets set technical requirements	5	5	25	5	25	5	25
Estimated cost	5	1	5	4	20	3	15
Space usage	3	3	9	2	6	4	12
Development complexity	2	1	2	3	6	4	8
User friendliness	1	5	5	2	2	4	4
	Total	46		59		64	

3.5 New process flow

The new process flow for the pressing station should be as similar as possible to the exiting process to avoid additional training and increasing the process time. The idea with the standalone pressing station is for the operator to use the developed solution only for pressing the two boards together. The production jig still has an essential role in the manufacturing process. The operator prepares the PCB assembly for the pressing operation on the jig and then selects the right product type from the pressing station HMI where the operator can also see the next process steps. The jig is placed to the designated slot on top of the multi axis linear slider system which is moved to the intended location and secured in place under the electrical press. As one of the goals is to keep the design and operation of the press station as uncomplicated as possible and hence the separate press heads are going to be developed for each board. The idea of the press head is to press the board from the right location and minimize potential bending. The design and usage of the press are described in greater detail in chapter 4.2.2. The production worker takes the correct press head and places it on top of the PCB assembly, this is verified by sensors which also detect the usage of the right press head and the location of the multi axis linear slider. If the process is carried out properly and verified by the PLC, the operator is able to press the push-buttons to start the pressing operation. The pressing quality is assessed by the electrical press through measuring the torque and distance. If the values are within the defined limits, the operator takes the assembly, visually checks the pin header alignment and starts preparing the next board. If the measured values are not within the defined limits, an error message is shown in the HMI describing the problem. As measurements done by the electrical press and final visual inspection by the operator are considered to be sufficient, a camera system is not used in the new process. The described process steps are repeated when other PCBs are installed. A simplified process logic is presented in Figure 3.4 which shows the flawless process flow.

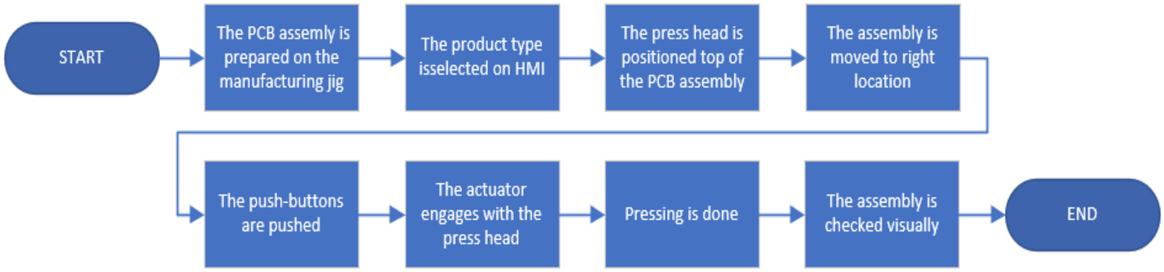

Figure 3.4 New process flow

3.6 Risk assessment of the solution

The risk assessment of the machine is conducted as required by the ISO 12000:2010 standard and is not only a regulatory requirement but also a proactive measure to ensure the safety. Also, this helps to analyse and evaluate the system's compliance with both the standards and the company's safety policy.

Table 3.2 is divided into two sections for ease of understanding and effective risk management. The left side of the table lists the possible hazards along with their potential consequences. This section demonstrates the nature of the hazards, their sources and the harm they can cause. The right side of the table presents the control measures. These measures are categorized into three groups: engineering design, workwear and administrative actions. The engineering design measures involve design solutions to the machine to eliminate or reduce the hazards. This is the first and the most crucial line of risk reduction. Workwear refers to the personal protective equipment that the operators have to wear to protect themselves from the hazards. Administrative actions include procedures, rules or regulations which must be followed to ensure safety.

The preliminary risk assessment is based on the company's risk assessment form and is carried out before the design phase begins. This proactive approach ensures that all aspects of the system are considered in the initial stages, thereby avoiding potential design errors. It allows for the identification and mitigation of risks early in the design process, leading to a safer and more efficient machine design. Additionally, the assessment is indicating that the operator’s safety is going to be improved significantly compared to the manual process.

Table 3.2 Possible risks and control measures of the pressing station

Hazard / Consequences	Control measures
Workplace safety – The hand of the operator is in the hazard zone The operator’s fingers might get crushed	**Engineering design**: • Two-hand control device • The access to hazard zone is only from one side covered with safety light curtains **Workwear**: The operator has to wear the required workwear(ESD gloves, footwear and coat) **Administrative**: The operator training
Workplace safety – The operator uses the wrong press head for pressing or the linear system is in the wrong location The board can get damaged	**Engineering design**: • Force control is applied • The proximity sensors are used to control the positions of the press heads and the linear system **Workwear**: The operator has to wear the required workwear (ESD gloves, footwear and coat) **Administrative**: The operator training
Electrical safety – Electrical shock due to the current leaking to the ground The operator can get an electric shock	**Engineering design**: • Residual-current devices and circuit breakers are used **Workwear**: The operator has to wear the required workwear(ESD gloves, footwear and coat) **Administrative**: The system is tested before operational use
Electrical safety – Electric discharge through the machine The operator can get an electric shock	**Engineering design**: • All parts of the machine are grounded **Workwear**: The operator has to wear the required workwear(ESD gloves, footwear and coat) **Administrative**: The system is tested before operational use

4. DESIGN OF MACHINE

The design of the machine is divided into two sections: the electrical design and the mechanical design. The electrical design process and component selection starts before the mechanical design and gives input about the size of the electrical parts. The measurements are needed for designing the size of the frame and other hardware parts. An overview of the electrical design of the standalone pressing station is presented in chapter 4.1 – 4.1.7 of the current master's thesis and the hardware design of the station is described in chapter 4.2–4.2.3.

4.1 Electrical design

The component selection is an important part of the design phase. All critical electrical parts are chosen and selected with care as they affect the hardware design. The Figure 4.1 presents a simplified overview of the electrical system. The most crucial components are shown in the rounded rectangles which are connected by lines. The orange line shows the estimated signal tracks and the green dashed line the biggest energy consumers. The PLC is running the program and is central to the system, monitoring the proximity sensors and the statuses of the push-buttons. The PLC also gives commands to the electromotor. The system has a signal tower for showing the status of the station, the HMI for selecting the programs and an emergency stop button as required by the machinery standard. All of this are powered by an electrical supply unit. The selections of the components are described more thoroughly in the following paragraphs.

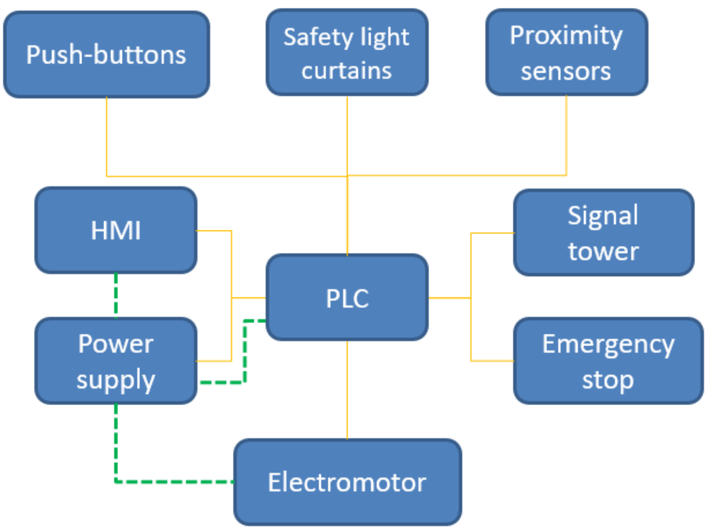

Figure 4.1 A simplified electronics system overview

4.1.1 Proximity sensor

Proximity sensors are used for monitoring the assembly of the PCB and the locations of the press heads. As described in the project specification, three different pressing locations need to be used. Also, the verification is necessary for choosing the correct type of the tailor-made press head. The sensors work in a specific combination, for example, the Bravo board press head sensor has to be low (no signal) and all other sensors of the press heads should be high (have a signal). Also, the Bravo board pressing location sensor has to be high and all the other signals of the sensors of the pressing location need to be low. The combination of the low signal of the press head and the high signal of the pressing location mean that the assembly is in the right location and the correct press head has been used. This combination enables the operator to start the pressing operation and if the combination is wrong, the pressing station program does not allow the operator to proceed.

The requirements for the proximity sensor are that the idle current should be ≤10 mA (the PLC detects the signal) and the operating voltage 24 volts direct current (VDC). It also needs to have a three wire system and it should detect the most common metals. For the testing purposes it would be beneficial if the proximity sensor had a status indication LED. Based on the described criteria and price of one sensor, the most suitable inductive proximity sensor is Festo’s SIEN-M8B-PS-K-L which meets all described criteria. SIEN-M8B-PS-K-L has operating voltage between 10-30 VDC and it detects aluminium, stainless steel, copper, brass and steel. Additionally, the sensors size is M8x1 and it is mounted with the lock nuts.

4.1.2 Electrical servo press

The servo electric press solution has been selected as the most promising solution for the current application. The recommended approach is to acquire the servo drive and motor with the linear actuator from one supplier as it guarantees the compatibility and availability of the product. The usage of the stock items lowers the development time and ensures there is enough information available about the products on the Internet. The marked research shows that there are only a few suppliers available, the most known is Festo which is also an approved supplier by the company.

Festo has developed a Simplified Motion Series which integrates the motor with a permanently attached drive unit and is available pre-mounted for a broad array of mechanical drives. The Simplified Motion Series facilitates both linear and rotary movements across a wide range of sizes. This design concept not only reduces the required installation space but also minimises the time and costs associated with installation in production processes. This feature is also extended to the control unit, combining software-free commissioning with cutting-edge control options. All settings can be directly adjusted on the motor using three buttons and a user-friendly LED menu. The speed and force can be configured for both directions [25]. However, the Simplified Motion Series is only suitable for simple applications where two end points and only one force are used. The task specification describes two different pressing heights which should be used. Also, the pressing force should not damage the boards. Another option is proposed which utilizes a programmable logic controller (PLC) with servo motor equipped with handling module and a drive for controlling the motor. The usage of the PLC enables to generate complex programs and monitor the position and torque of the handling module and motor. The downside of the PLC is that it requires knowledge of programming and the company has this know-how. The EMMS-ST-57-M-SEB-G2 stepper motor combined with the EHMZ-EGSC-60-BS-KF-12P-200-T-S1-W-X handling module has been selected as it offers a one-standard solution with high accuracy. The motor is equipped with an encoder and a brake and the handling module has a ball screw drive with a ball bearing guide. The selected motor with the combined handling module meets the requirements and offers a combined solution.

The nominal voltage of the motor is 48 V and the current is 5 A, the combined power can be calculated 4.1.

$$P = U * I \tag{4.1}$$

where *P* – power, W

U – voltage, V

I – current, A

The motor’s nominal power can be calculated as follows:

$$P = 48 * 5 = 240\ W$$

The motor nominal power is 240 W and this is later used selecting a suitable power supply unit. The repetition accuracy of the handling module is ±0,015 mm and maximum speed 0,6 m/s. A suitable servo controller CMMT-ST-C8-1C-MP-S0 is selected for controlling the motor and powering it. The I/O interface communication is used between the motor and the drive. The Festo Automation Suit can be used for programming the servo controller and the supported protocols for communications are: EtherNet/IP, EtherCAT, Modbus/TCP and PROFINET. Additionally, same protocols can be utilized for PLC communication.

4.1.3 Safety components

The safety components of the system are one of the most critical aspects of the design. The ISO 16092-1:2018 (described briefly in Chapter 1.2) give mandatory guidelines of the safety components which have to be present on the machine. One of the safeguard measures used is the two-hand control device which is installed to the workstation. Two ABB CP1-11G-10 push-buttons are used for this purpose and they are programmed to blink when the conditions are suitable for pressing operations. The operator has to press both push-buttons simultaneously to activate the process. The buttons are wired to PLC digital input/output (DI/DO) module. Additionally, the second layer protection is added to the system by utilizing safety light curtains. The selected Orion1-4-14-045-B safety light curtains cover the access area of the hazard zone which is considered to be the area where the operator can be harmed. The usage of the safety light curtains requires an additional safety module SM560-S to be integrated with the AC500 PLC [34], [35]. The Orion 1 base receiver can be directly connected to the safety module [36]. The Orion1-4-14-045-B has resolution 14 mm which can detect a finger placed in the sensing area. It has a total of 48 laser beams and the operating distance is between 0,2 to 6 m [35].

The emergency stop button is added to the station as required by the ISO 16092-1:2018 [5]. The button is easily accessible for the operator on the right front side. ABB Pilot devices series are offering a wide range of different push-buttons and emergency stop button solutions which the customer can choose and combine based on their specific needs. A twist release enclosure assembly (the emergency stop button) is selected as it is a ready-made solution which could be easily be added to the press station. The operator could use the emergency stop button if the potential danger situation occurs and the press needs to be stopped.

The Machinery Directive 2006/42/EC and the ISO standards require the machine to be equipped with a warning device [3], [5]. A Werma signal tower is chosen for the light signal as it has three different LED – green, yellow and red. The operating voltage is 24 VDC and the current consumption 100 mA [37]. The green light would symbolise normal operations, the yellow light indicates a warning and the red light shows danger. This colour schematic corresponds to ISO 11428:1996 standard and is used in the other workstations which are located in the production facility [38].

4.1.4 Programmable logic controller

The purpose of the PLC is to control the motor's drive and monitor the state of the sensors and the push-buttons. The PLC communication protocol has to comply with the protocols used by the servo driver. ABBs AC500 PLC series is considered to be a suitable option as it has appropriate protocols available and it has been used in the pervious projects in the company. Additionally, if there should be a problem with the AC500 PLC, it can be changed with the spare PLC which the company has for back up.

PM5630-2ETH process module has been chosen as it offers 8 MB memory and communication interfaces for 2 Ethernet, RS232/485 and CAN. The nominal operating voltage is 24 VDC. The maximum power usage of the PLC is 20,4 W. The EtherNET/IP protocol is considered to be the most suitable as it can be used for controlling and communicating with the electric motor controller and the HMI. In addition to the process module, the correct terminal base is needed as they act as a tandem together. The terminal base acts as a bridge between the process module and the optional modules to which several analog and digital option modules can be integrated. The selected terminal base has the same name as the process module PM5630-2ETH [34].

A separate DI/DO module is needed for monitoring the sensors and the push-button statuses and indicating the station status on the signal tower. All the signals are discrete and therefore there is no need for analog module. Similarly to the process module, the DI/DO module needs the terminal unit where the wires are going to be connected. The selected DI/DO module is DC532 which offers 16 DI at 24 VDC and 16 configurable DI/DO 24 VDC / 0,5 A [39]. A TU516 is a terminal unit used for connecting the wires and the TU516 supports the analog and the 24 VDC digital modules.

4.1.5 Human-machine interface

The HMI is used to improve the operator's interaction with the station and accessibility of information. It simplifies actions which the operator has to do such as selecting the pressing program, following work instructions, monitoring the status of the system. The operator has real time feedback from the system. Additionally, HMI can be used for troubleshooting potential issues. ABB CP600 series HMI panels are considered as they have been used previously in other projects of the company. The CP610 control panel is selected as it offers 10,1 inch thin-Film transistor touch screen, 64 K colours, 1024x600 pixel and IP66 (front). It has one industrial Ethernet and USB port and the supply voltage 18-36 VDC. The power consumption is 9,12 W [40]. This type of panel is selected as it can be easily integrated with the AC500 PLC and its price-quality ratio is considered to be optimal.

The home screen view of the HMI shows the user all pressing programs and an option to check the system's parameters (see Figure 4.2). Critical settings are password protected and this can be only accessed by the engineer. If the user selects a pressing program, a specific product view is opened. The work instructions are presented with status information. The system shows if the pressing is done correctly or it should be done again. If there are any problems with the product then the error messages are presented on the screen with possible causes. The program logic is developed in poka-yoke style which prevents possible errors in the manufacturing process.

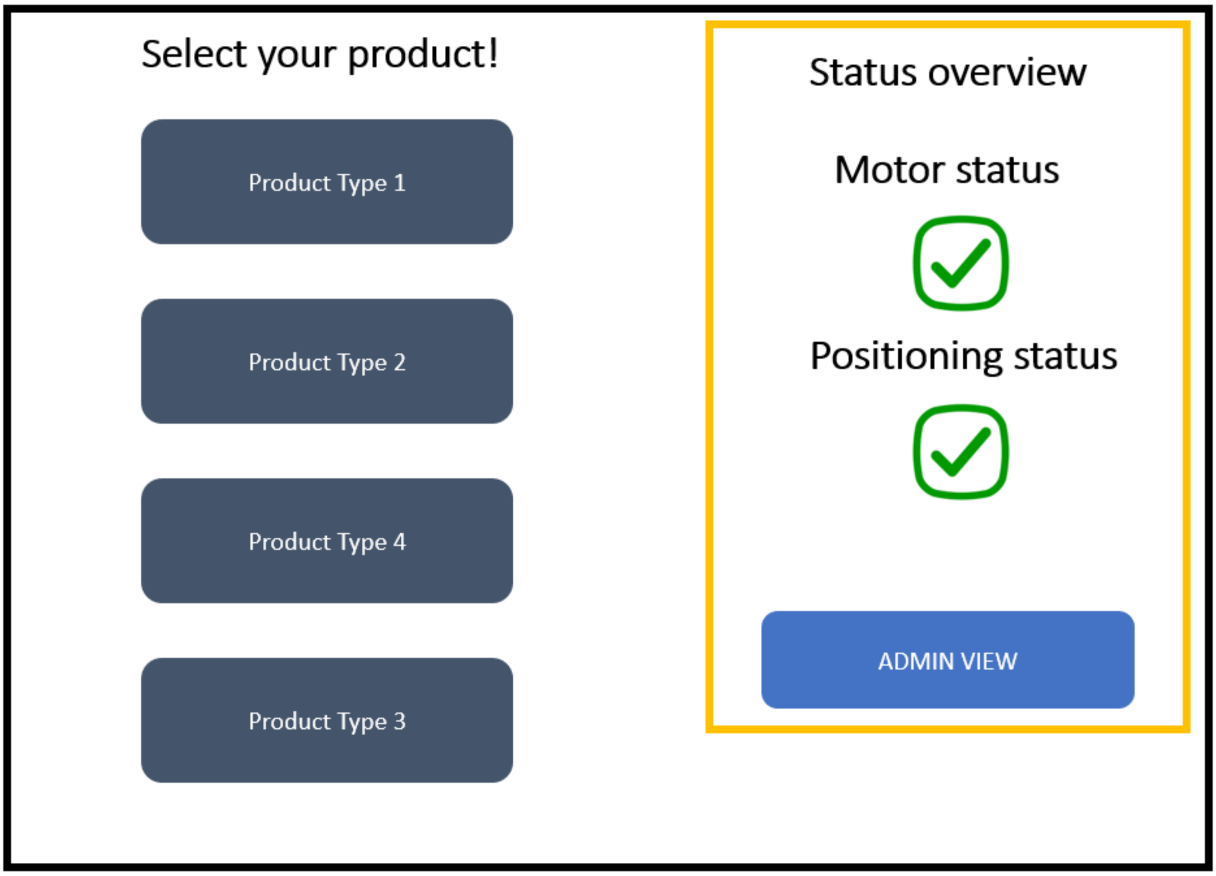

Figure 4.2 HMI home screen view

4.1.6 Network switch

A separate network switch it required for connecting the electromotor drive, PLC and HMI into one network. Additionally, one port has to be reserved for programming, therefore the switch has to have at least four RJ45 ports. The network switch can work on 24 VDC or 48 VDC as both voltages are needed. The type of the switch can be the most basic – unmanaged as there are no special requirements for configuration and additional features [41].

The selected Ethernet switch is PHOENIX CONTACT FL SWITCH SFNT 5TX-C – 2891043 as it meets all requirements. It is an unmanaged industrial Ethernet switch which has total of five RJ45 Ethernet ports, transmission speed 10/100 Mbps and the supply voltage range between 9 – 32 VDC. The network switch can be mounted to the DIN rail [42].

4.1.7 Power supply

Two DC power supplies are needed for powering the selected components: one 24 VDC (control system) and second 48 VDC (power system). The power supply unit is selected based on consumed power by the consumers. The motor is the only device which consumes 48 VDC and the required power is already calculated in chapter 4.1.2 (P=240 W). The selected power supply for 48 VDC is PHOENIX CONTACT QUINT-PS/ 1AC/48DC/10 which has a total power output 400 W [43]. This supply unit is selected to have some safety margin and additional devices can be connected if necessary. The Machinery Directive highlights the need to prevent all hazards of electrical nature [3]. Therefore, circuit breakers are added on both sides of the power supply, the datasheet recommends circuit breakers with B6 characteristic (ABB S201-B6) [43].

There are many devices which need 24 VDC but the power supply is selected based on the biggest consumers: PLC (20,4 W) and HMI (9,12 W). The power consumption of the other devices is considered to be trivial. The select power supply is MURR ELECTRONIK MCS-B POWER SUPPLY 1-PHASE which has the output of 24 VDC / 7,5 A. The power supply output is 180 W which is more than enough and has also some buffer for additional devices. The datasheet recommends adding external circuit breakers (ABB S201-B10) to the input and outside of the supply unit [44].

A residual-current device is added as additional protection device for the electrical system which is connected after the input circuit breakers and before both power supply units. The residual-current device is used for protecting people and the system against fault current to earth. It is used for meeting the Machinery Directive and the company’s criteria. The selected residual-current device is ABB’s F202 A-16/0.01 which covers residual alternating current and pulsating DC [45]. The rated voltage is 230 V alternating current and rated current 16 A [46].

4.2 Hardware design

The hardware design is divided into three bigger subassemblies: frame design, linear system design (product pressing location) and press head design. Dividing design into smaller tasks simplifies the process and reduces possible design errors. Also, using subassemblies helps to group parts which belong to a common assembly. The mechanical design considers all the electrical components which are needed for the machine.

4.2.1 Linear system design

The first step of the hardware design is designing the linear system as the size of the linear system affects the overall size of the press station. The linear system has to be two axials to enable to press the PCB together in the right location (see Figure 1.5). The area between different pressing locations needs to cover y-axis is 12 mm and x-axis 150 mm. Additionally, it is essential to have some clearance from the left and right side while the whole PCB assembly with the production jig is positioned. In the standalone press station concept phase a decision was made that the system has to be manually managed by the operator.

The guide rail and carriage are used as they are considered to be the most affordable solutions. The suitable components are selected from the igus catalogue, because the company offers reliable and maintenance free products. Igus recommends to follow 2:1 design rule to define fixed and floating bearings (see Figure 4.3). The rule states that a in a two-rail, four-bearing setup, it is crucial to designate one rail as the stationary side - this rail should be the one closest to the drive force. The other rail serves as the movable side, utilizing bearings with slight additional space. Specifically, this rail should be the one furthest from the drive force. This installation method avoids binding of the guide which can be caused by misalignment between the rails [47].

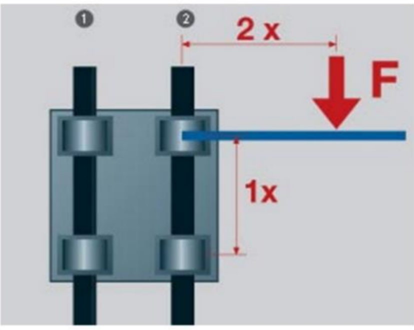

Figure 4.3 The 2:1 rule where number 1 is floating bearing and number 2 fixed bearing [47]

The development starts with designing the plate for housing the production jig during the pressing and connecting the guide carriages for positioning (see Figure 4.4). The selected carriages are from drylin T guide carriage TW-02 (TW-02-25 and TW-02-25-LLZ) series. They are used in heavy duty applications and can withstand 10000 N force in static load which is more than enough for the current application. The housing plate size is 160 x 350 mm and the distance between the carriages is 276 mm (measured from the centre of the carriage). A special sheet metal part is mounted to the housing plate which is used to move the assembly. Additionally, through this sheet metal part a lock pin is inserted which locks the assembly to the right location. The size of the given part is designed to fit igus 2:1 rule in both axes.

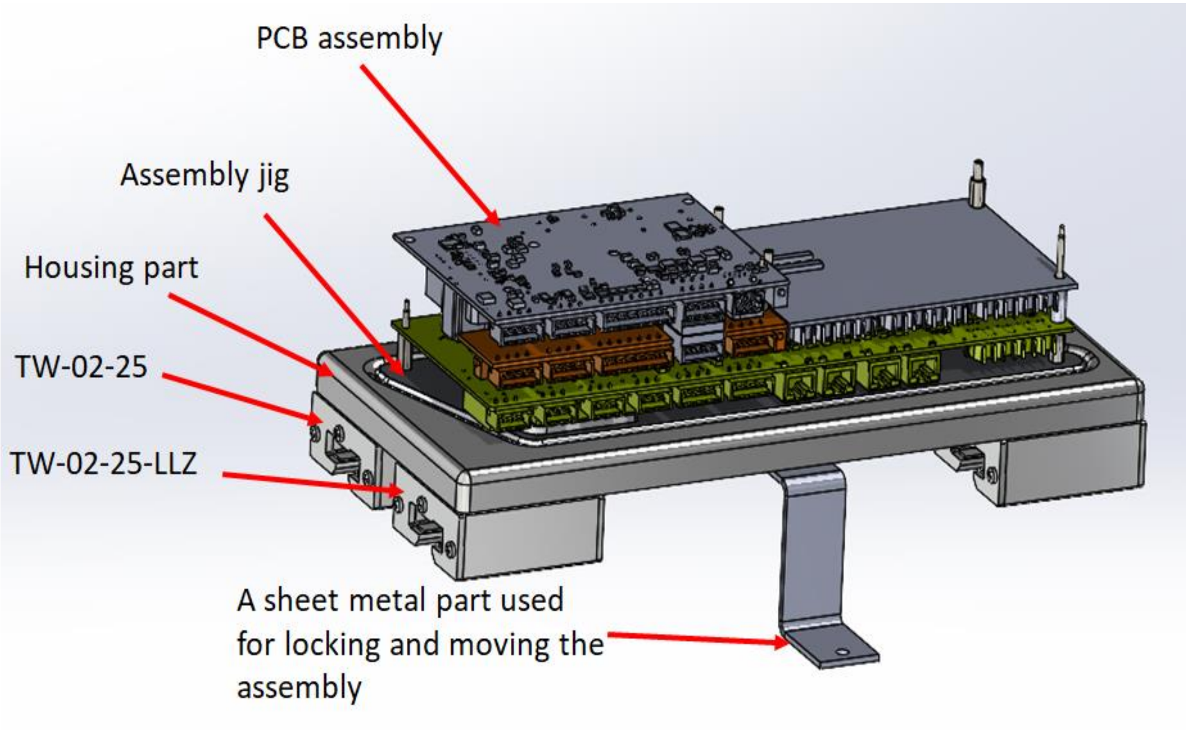

Figure 4.4 The housing plate with all components

The selected guide carriage defines the type of the guide rail which can be used in this project. TS-01-25-500 (500 mm shows the length of the rail) guide rails are used for moving the assembly in x-axis. The length of the rail (x-axis) is determined in the CAD simulation to cover all pressing locations. The guide rails are bolted on top of a 4 mm S355 sheet metal plate which is secured on top of y-axis guide carriages. The same guide carriage types are used as with the housing plate. DIN 1587 M6 nuts are used at both ends of the rail to prevent de-railing the guide carriages in both axes. The y-axis slider length simulation shows that the lengths of rails are 400 mm. In that case there is enough space to move the assembly out of the pressing area and remove the PCB assembly with the jig. The y-axis rails are secured on top of the aluminium plate (see

Figure 4.5). The pressing location holes (where the lock pin would be inserted) are made into the plate and the inductive sensors are located below the holes.

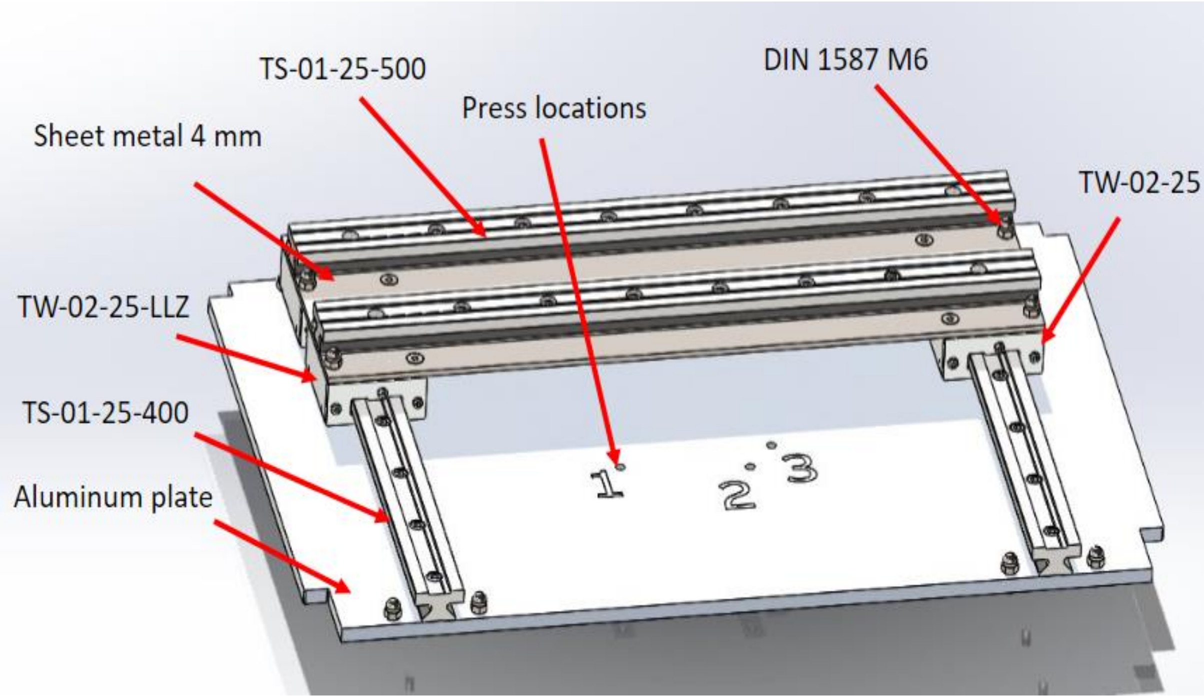

Figure 4.5 The slider system

4.2.2 Press heads design

A press head is used during the pressing phase on the top of the PCB. The actuator presses the press head which pushes the board in the designated location and supports the alignment between the PCBs and standoffs. A combined press head was considered during the concept phase which would suit all PCB types. However, this proved to be challenging as all PCBs have different pressing locations and heights. Also, the standoffs which are used for securing the assembly together are located in different places and have different heights (see Figure 4.6). Moreover, the handling module (EHMZ-EGSC-60-BS-KF-12P-200-T-S1-W-X) which is used for pressing has a flat mounting surface and it would require a special connector for holding the press head. This would increase the tool changing time and make the process more complicated. It is simpler for the operator to prepare the PCB assembly and add the appropriate press head on top of it. The handling module flat surface is directly engaging with the press head while the press operation is ongoing. The press heads is firmly positioned on top of the PCB which would make it challenging to move it during the process.

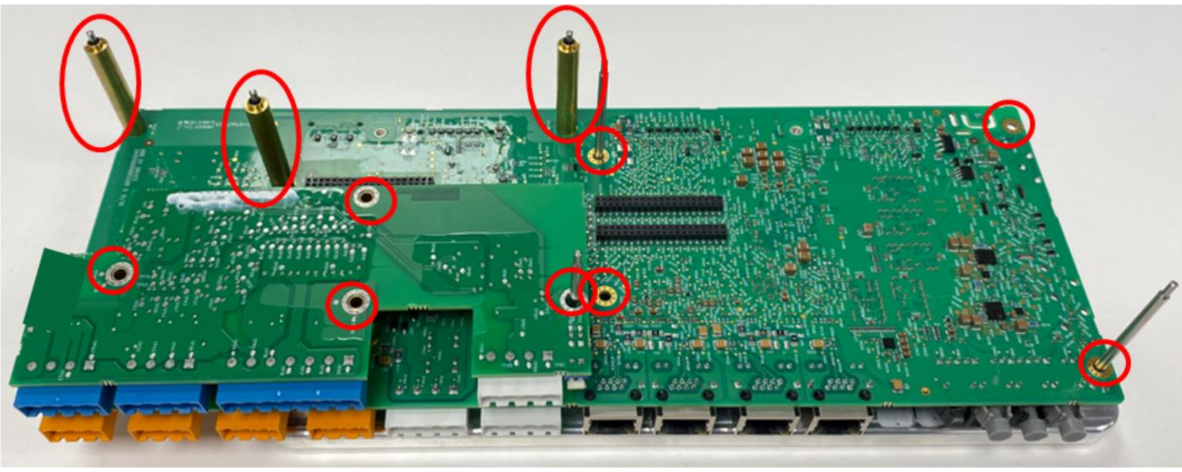

Figure 4.6 Standoffs location marked with red circle

A decision is made to have three different tailor-made press heads which are used during pressing. Additionally, the usage of separate press heads lowers the possibility of having a mistake during the pressing and it makes the process more poke-yoke. All the press heads are designed in the way that the area used for pressing is higher compared to rest of the plate and it is covered with the gasket to soften the pressing force to the board. The size of the press plates are related to the location of the guide pins and it would be comfortable to pick the press heads up from their designated slot. The guide pins which are located on the press head are inserted into the PCB standoff holes during the assembly process to support the alignment and positioning while the press heads are mounted on top of the boards. The height of the guide pins varies in every press head to avoid contact with the assembly's jig guide pins. The Charlie board press head and the Bravo board press head are shown in the Figure 4.7.

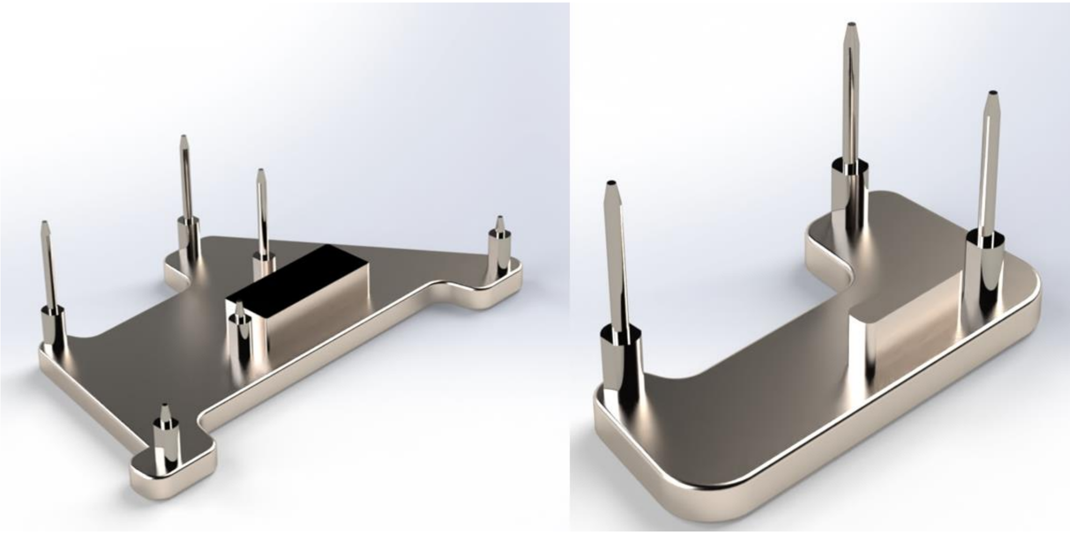

Figure 4.7 The Bravo board press head is shown on the right side and Charlie board press head is shown on the left side

4.2.3 Frame design

Minitec aluminium profiles are used for making the press station frame. MiniTec profiles offer high customization and they can be easily assembled together. Minitec has two series of the extruded aluminium profiles: the 30 series and the 45 series, the latter is used for constructing the frame. The 45 series is more rigid and stronger than 30 series which were needed for the press application, otherwise deformation in the frame could affect the pressing stability and accuracy. Minitec has a wide range of connecting elements which enable connecting two profile pieces easily. However, the power-lock fasteners 45 and M8 bolts are used in this project as they are quick to assemble and they are visually unnoticeable.

Designing the frame size starts after the linear system design is finished. This gives the input for the frame design as the plate used in the linear system determines the size of the useful work area and the overall width and length of the stations. The height of the work area is not changeable and is matches the height of the currently used production table (810 mm measured from the ground). The fixed height solution is chosen because the operator is usually sitting down while assembling the product together. The total height of the frame is determined by the mounting points of the Festo electrical press and the free working space below the electrical press. The frame has three sections as proposed in the concept generation phase: the first level for storage, the second level for electrical components and the third level for the work area. The base of the first section is made from 10 mm S355 steel plate to which the frame and the wheels are connected. The wheels are electrically conductive (ESD), two fixed wheels used in the front and two swivel castors with brakes in the back. The steel plate is used to lower the centre of gravity of the system and firmly secure the frame. The front side of the first level is open but all the other sides are closed. A 6 mm mono polycarbonate (PC) is inserted into the Minitec 45x45 UL profile and the insert seal 6 NBR is used to secure it firmly. As the PC is transparent and the natural light can access the area, there is no need to add additional lighting.

The second section is housing all the required electrical components such as power supplies, terminals, circuit breakers and the PLC. All devices are mounted on the DIN rails which are directly connected to the frame to ensure ESD compliances. The second level is covered with metal plates from three sides and additionally there is an access door in the back side of the frame (see Figure 4.8). The door is locked during the normal operations and the area can be accessed only by a responsible engineer. The electrical system is maintained by authorized personnel.

The work area is located on the third level where all the control buttons and the linear slider system is located. The area can be accessed from the front and all other sides are surrounded by the 6 mm mono PC due to safeguard measures required by the ISO 16092-1:2018. In order to fulfil the safeguarding requirements described in the ISO 16092-1:2018, there are a two-hand control device and light safety curtains. The electrical press is connected to the frame but special mounting plates are required to achieve the right distance from the frame and the availability of the suitable connection points. The press is surrounded by a curved 3 mm mono PC to block access to the moving part of the actuator, only a small portion is open. The HMI has a special housing which is mounted on Minitec profile on the right side.

Figure 4.8 The image showing the first level and second level door

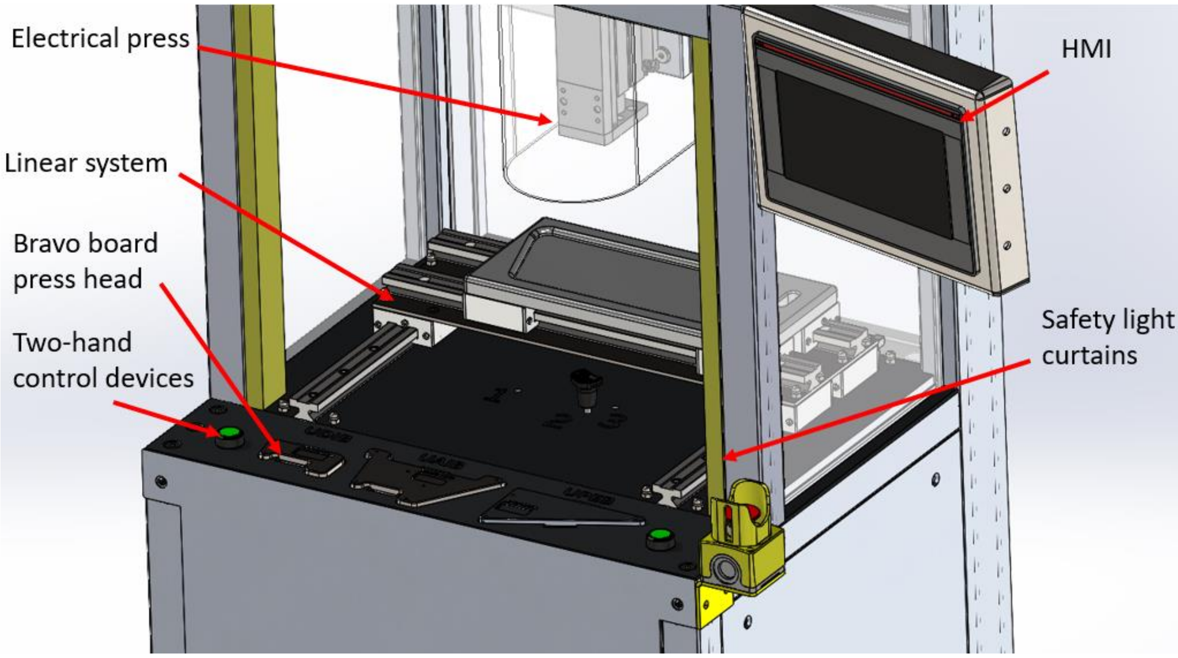

Figure 4.9 The work area of the station

All the materials of the components are defined in the Solidwork 2021 software to get realistic mass of the system and the location of the centre of gravity. The data received from the software shows that the mass is about 106 kg and the centre of the mass in the centre of the assembly, located at the height of 494 mm measured from the ground. This information is needed for calculating the force needed for tilting the system over (see Figure 4.10). The tilting force is calculated to evaluate the stability of the machine and check if there is any needs for extra weights. The tilting force is calculated based on formula 4.2 [48].

$$F = mg\frac{b}{2h} \tag{4.2}$$

where *F* – tiling force, N

m – mass, kg

g – gravity, m/s

b – wheelbase width of the machine, m

h – height above the ground where the force is applied, m

$$F = 106 * 9.81 * \frac{0{,}591}{2 * 1{,}4} \approx 219\ N$$

The calculation shows that 219 N are needed for starting the tilting over. Additionally, is should be marked that the weight of the electrical components is not included in the calculation.

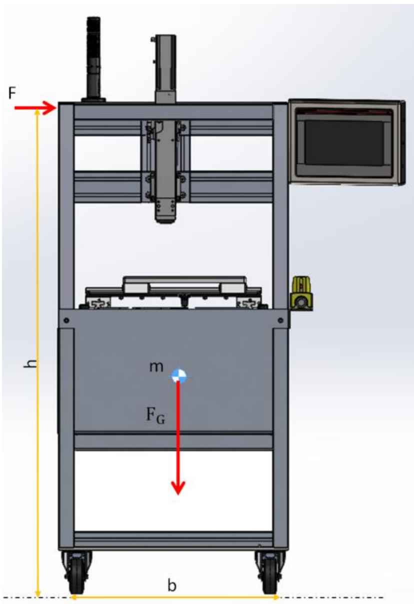

Figure 4.10 Acting forces on the pressing station

5. COST CALCULATIONS

The cost of the system is calculated to check if the cost of the project is within the budget. The Table 5.1 shows the real cost of the project including the cost of the development, assembly and components. The table follows the company's project proposal for cost estimation and the general table of costs does not reveal any confidential information. The cost of the electrical components is combined into one category and rounded to the closest hundred. Similarly to the electrical components, the cost of the hardware parts is added up and rounded to the closest hundred. The cost of the development includes the mechanical and electrical engineering cost which is calculated based on the average monthly salary of the mechanical and electrical engineers and divided by 160 to get an hourly rate (see formula 5.1). The 160 h is estimated to be average working hours in one month. According to Statistic Estonia, the average salary of a mechanical engineer in Harjumaa is 2755 € (IV quarter 2023) and the average salary of the electrical engineering is 2712 € (IV quarter 2023) [49]. The cost of the assembly is calculated based on the average salary of the electrical equipment assembler, which is 1295 € (IV quarter 2023) in Harjumaa [49]. The calculated hourly wage is then multiplied with hours which are spent on developing the system.

$$cost\ of\ an\ hour = \frac{\text{monthly salary}}{160} \tag{5.1}$$

where *cost of an hour* – cost of an hour, €/h

monthly salary – one month's salary, €

160 – average working hours in one month, h

The cost of a mechanical engineer's one working hour can be calculated as follows:

$$hourly\ wage = \frac{2755}{160} \approx 17\ \text{€/h}$$

The cost of the electrical components is around 3500 € in total and the cost of the hardware parts is around 3100 €. It is estimated that the development of the hardware parts takes around 120 hours and the design of the electrical system 100 hours which also includes the time needed for programming the PLC. The full assembly of the system should take maximum one week including the frame assembly and preparing all the electrical components. One of the most time-consuming aspects of the electrical system assembly is wiring. The total cost of the project is around 11160 €.

Table 5.1 The project cost

Description	**Hours, h**	**Cost, €**
Electrical components		3500
Hardware components		3600
Development		
Mechanical engineering	100	1700
Electrical engineering	120	2040
Assembly	40	320
Total		**11 160**

SUMMARY

The purpose of the current master thesis was to develop and design best possible pressing solution for assembling printed circuit board together. The developed solution was proposed for an Estonian manufacturing company which had increasing problems with their product quality and assembly process. During the current manufacturing process the boards might receive too much force while they are pressed together which could result in damaging the product. Additionally, there was a possible hazard for the production worker of developing occupational disease caused by using excessive force with hands long term. The product had already been introduced to the market due to which it would have been challenging to be redesigned. Therefore, a safe alternative solution was needed to improve the quality of the current production process.

The author of the current thesis conducted an overview of research publications, legislations, different manufacturer’s datasheets and patents which described different pressing solutions for manufacturing the products. Three different technologies were studied – manually operated press, pneumatic press and electrical press solution. Based on the gathered information, an evaluation matrix was made to select the most reasonable solution. The matrix showed that the electrical press solution was meeting the project specification and was the most suitable option compared to other solutions. Three different design concepts were generated for the electrical press to find the most optimal design. A three-dimensional gantry YXCR pressing station solution was considered to be the most automated solution as well as the most expensive. The second idea was a table mounted press which would have taken a lot of space from the current manufacturing table. The third generated concept was standalone pressing station which combined the two previous designs. The evaluation matrix showed that the standalone press station was the most optimal solution which was developed further. The new process flow for the standalone press station and the preliminary risk assessment was conducted to cover all safety aspects to evaluate the concept and to avoid any mistakes in the design. The assessment indicated that the new concept would increase the level of safety.

The design of the machine was divided into two sections: the electrical design and the hardware design. The electrical focused on selecting all necessary electrical components for the system including the safety elements and electromotor. The hardware design covered the mechanical aspects of the system including the frame and the linear system. The cost calculation showed that the project cost was around 11160 € which was lower than the estimated budget.

In conclusion, the main goal of the master thesis was achieved. A new pressing solution for assembling printed circuit board together was proposed and developed for the company.

KOKKUVÕTE

Käesoleva magistritöö eesmärk oli välja töötada ja projekteerida pressimislahendus trükkplaatide kokkupanekuks. Välja töötatud lahendust pakutakse ühele Eesti tootmisettevõttele, kellel on üha enam probleeme toodete kvaliteedi ja koosteprotsessiga. Olemasoleva käsitsi kokkupaneku protsessi käigus võivad trükkplaadid kokku pressimisel saada liiga suurt jõudu, mis võib põhjustada toote kahjustamist. Lisaks sellele on võimalik oht tootmistöötajal kutsehaiguse tekkimiseks, mis tuleneb liigse jõu kasutamisest käega kokku surumisel. Toode oli juba turul, mistõttu oleks olnud keeruline seda ümber projekteerida. Seetõttu oli vaja ohutut alternatiivset pressimise lahendust, et parandada praeguse tootmisprotsessi kvaliteeti.

Käesoleva lõputöö tehti ülevaade teaduspublikatsioonidest, õigusaktidest, erinevate tootjate andmelehtedest ja patentidest, milles kirjeldati erinevaid pressimislahendusi toodete valmistamiseks. Uuriti kolme erinevat tehnoloogiat - käsitsi töötav press, pneumaatiline press ja elektriline pressilahendus. Kogutud teabe põhjal koostati hindamismaatriks, et valida kõige optimaalsem lahendus. Maatriks näitas, et elektriline pressilahendus vastas projekti spetsifikatsioonile ja oli teiste lahendustega võrreldes kõige sobivam. Elektrilise pressi jaoks koostati kolm erinevat disaini kontseptsiooni, et leida kõige optimaalsem lahendus. Kolmemõõtmeline kantri YXCR-pressimisjaama lahendus peeti kõige automatiseeritumaks lahenduseks ning kõige kallimaks. Teiseks ideeks oli lauapress, mis oleks võtnud ära liiga palju ruumi praeguselt tootmislaualt. Kolmas loodud kontseptsioon oli eraldiseisev pressimisjaam, mis ühendas kaks eelnevat lahendust. Hindamismaatriks näitas, et eraldiseisev pressimisjaam oli kõige optimaalsem lahendus, mida arendati edasi. Kontseptsiooni hindamiseks ja projekteerimise vigade vältimiseks koostati uus protsessivoog ning esialgne riskianalüüs, et hõlmata kõiki ohutusaspekte ja vältida projekteerimisel tekkivaid vigu. Hindamine näitas, et uus kontseptsioon tõstab ohutustaset võrreldes olemasoleva tootmisprotsessiga.

Pressimisjaama projekteerimine oli jagatud kahte ossa: elektriline ja riistvara projekteerimine. Elektriline osa keskendus masina jaoks vajalike elektriliste komponentide, sealhulgas turvaelementide ja elektrimootori valimisele. Riistvara projekteerimine hõlmas süsteemi mehaanilisi aspekte, sealhulgas raami ja lineaarsüsteemi. Kulude arvutamine näitas, et projekti maksumus oli umbes 11160 eurot, mis oli hinnangulisest eelarvest väiksem.

Kokkuvõtteks võib öelda, et magistritöö peamine eesmärk on saavutatud. Arendati ja projekteeriti uus pressimislahendus trükkplaatide kokkupanekuks.

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GRAPHICAL MATERIAL

All technical drawings are included in the master's thesis folder.