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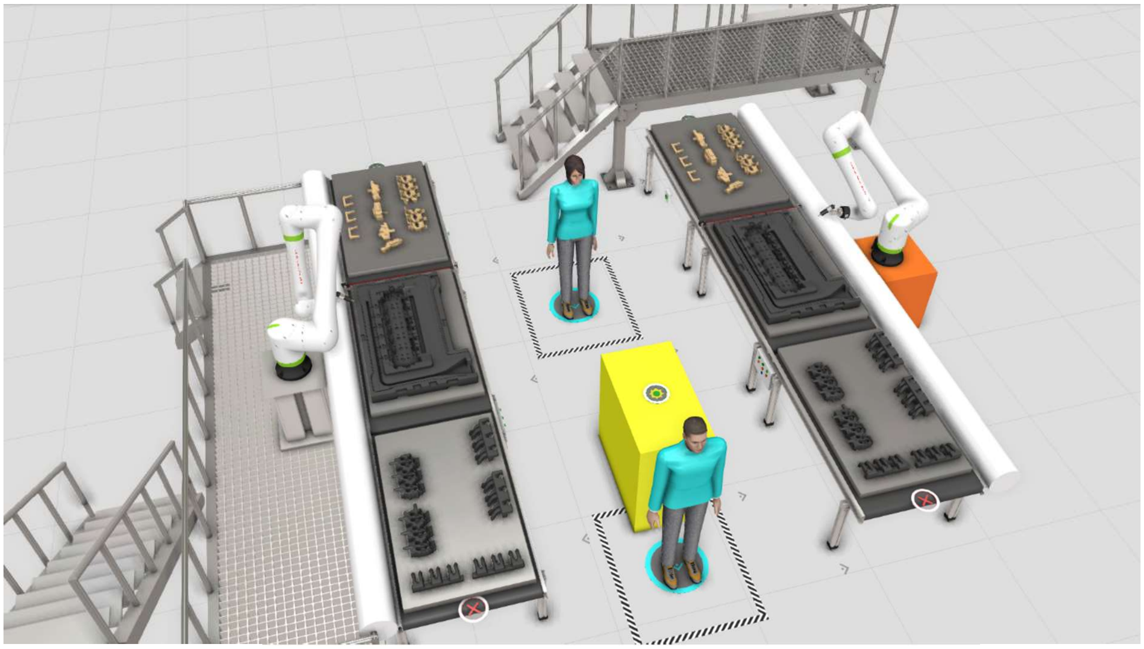

A profitable implementation of collaborative robots

A safe and affordable way of increasing production rate and quality

Bachelor's thesis in mechanical engineering

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Abstract

At Volvo Powertrain in Skövde combustion engine cylinder heads are casted at foundry 2. Most of the manufacturing of their products is fully automated, but the assembly of the sand cores prior to casting for the D6 and D4 cylinder heads is manual, since they are produced in smaller quantities. At the current workstation the manual assembly creates a bottleneck, due to problems with the production and error rates. Volvo Powertrain therefore wants a study performed about the possibility of using collaborative robots for the gluing of the sand cores.

To find a suitable concept for a new workstation a requirement specification was created. With idea generation methods, concepts were created and later evaluated using decisions matrices until a final concept remained. In unison with the decision matrices. A simplified risk assessment was performed and data from recordings of the current production was acquired. The data acquired was then statistically evaluated with the three-point method. This was then used in the visualisation. After the visualisation a simplified ergonomic and economic evaluation was performed.

The final concept consisted of two collaborative robots of the model FANUC CRX-25iA, one with a moving pedestal and one with a permanently placed pedestal. The movable pedestal opens for the use of the FANUC robot at other parts of the factory. The end effector of the FANUC robot has a glue gun attached to it that will disperse glue. A camera mounted on a beam in the workstation is used to scan the position of where the glue should be applied. The current workstation uses a telfer with a manual glue gun attached, by keeping this the flexibility is kept. In addition, preventative measures used in the risk assessment is added to the workstation.

The authors recommend the implementation of collaborative robots for the manufacturing of the D6 and D4 cylinder heads. The findings in this thesis indicates a potential increase of production rate with 44%, with less errors and high degree of safety. Also, the ergonomic evaluation points towards that the operators will experiencing less strain compared to the current workstation. The risk assessment reveals that this solution can be implemented with acceptable levels of risks to the operators and the property of Volvo Powertrain. The implementation of collaborative robots is assessed to be economically justifiable due to the payback time being 0,6 years. The authors assess that the positive effects that apply to the D6 cylinder head will also apply to the D4 cylinder head. An implementation of the solution that the authors present would increase the knowledge at Volvo Powertrain and enable new exciting projects with collaborative robots in the future.

Acknowledgements

This page is dedicated to all those that have helped us and made this thesis possible.

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We would also like to thank Peter Hammersberg our examiner at Chalmers for giving us guidance with this report and how to approach the thesis and our supervisor Endre Erös for providing us with guidance throughout this thesis.

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Table of contents

Executive summary

At Volvo Powertrain in Skövde the combustion engine cylinder heads are cast in foundry 2. The production of cylinder heads is fully automated except for the Volvo Penta D6 and D4 cylinder head, in which prior to casting, the sand cores are assembled manually. Since the sand cores are difficult for a robot to assemble and because they are produced in a lower quantity compared to other cylinder heads. At the current workstation the manual assembly creates a bottleneck in the production of the D6 and D4. This is due to a lower production rate and a high error rate when compared to the rest of the cylinder heads produced at foundry 2. Most of the production errors are gluing errors. This is a problem because it lowers the production rate at foundry 2 and because the high error rates result in a high quantity of discarded moulds.
Another problem is the ergonomics of the workstation, which can lead to fatigue and physical damage to the operators. The goal is to decrease the strain on the operators.

With the problems and their consequences as stated above, Volvo Powertrain wants to investigate if there is a possibility of implementing collaborative robots for the gluing of the sand cores in the assembly of the D6 cylinder head.

The use of both industrial and collaborative robots is well known in the world today. At Volvo Powertrain in Skövde the manufacturing in dominated by industrial robots, industrial robots are used in both foundry 1 and 2. Whereas the company's knowledge of industrial robots is substantial, the company's knowledge of collaborative robots is limited. This includes the different standards that are used, the risk assessment and general information for collaborative robots.

Several methods were used to broaden the knowledge of the uses of collaborative robots. A requirement specification was created where desirables and requirements were established. With the use of idea generation methods as well as decision matrices a suitable concept was established. A simplified risk assessment was performed along with data acquisition of the time it takes for the operators to perform their tasks at the current workstation. The data was then statistically evaluated with the three-point method. With this information the visualisation of the new workstation could be performed. Lastly an ergonomic and economic analysis of the new workstation was conducted.

In the requirement specification 2 main measurement values where defined. The production rate and the error rate. They are especially important because they tell if the implementation of the collaborative robots at foundry 2 is possible and if it is economically justifiable. The workflow of the thesis is closely related to these 2 measurement values.

In the thesis relevant information that is needed to implement collaborative robots is presented. Summarised information of different standards, rules and regulations that can be applied to collaborative robots can be found. A python script for calculating the collaborative robots speed according to ISO 15066´s force and power limiting can be found in attachment 2. The risk assessment presented in the thesis is simplified but can be used as a background or a starting point for a full risk assessment of the new workstation.

The value provided by this thesis is that it shows that collaborative robots are suitable for application at the D6 working station. This thesis also provides value in that it expands the edge of knowledge meaning that Volvo can use this knowledge in their production at other places than the D6 working station. The implementation of collaborative robots at the D6 working station will have a payback time of 0,6 years and will increase production rate with 44%, as well as lowering the gluing related error rate. This thesis will be of interest for engineers and supervisors seeking to implement collaborative robots in a production flow.

This thesis has shown what is possible to achieve with collaborative robots within the scope of the D6 working station. To implement this a full risk assessment must be made, a new economic analysis must be made, the equipment must be purchased, and a detailed construction of the station must be made. After the working station has been implemented the production rate and error rate calculated in this thesis can be validated by measuring the error and production rate after the collaborative robots has been implemented. The error rate will be lowered, and the production rate will be increased as shown in this thesis.

1 Introduction and background

Here the purpose, problem description, deliverables, limitations and company introduction is presented.

1.1 Purpose

The purpose of this thesis is to conduct a pilot study of the implementation of collaborative robots at the D6 working station at Volvo Powertrain in Skövde. The cause of why the pilot study was performed is stated in segment 1.2. Where, except from the deliverables, the aim is to increase productivity, reduce error rates and ergonomic strain while still maintaining a high safety between operators and collaborative robots.

1.2 Problem description

The cylinder heads for the Volvo Penta D6 & D4 are casted in Skövde at foundry 2. Today this process is mostly automated except for the assembly of the sand cores. The cylinder heads 11, 13 and 16 are also casted at foundry 2 and are fully automated. The D6 & D4 cylinder heads are produced in smaller quantities than the other cylinder heads. Today the D6 cylinder head production is a bottleneck in the production due to problems with high error rates and a lower production rate compared the rest of the production line. The foundry could produce more D6 cylinder heads if it had capacity but due to the problems stated above this is not possible in the current workstation.

Another problem is the ergonomics of the workstation, where the aim is to reduce the strain on the operators. Volvo Powertrain wants to investigate the possibility of using collaborative robots in the assembly of the D6 cylinder head moulds, specifically for the gluing of the sand cores.

1.3 The edge of knowledge

The knowledge of industrial robots at Volvo Powertrain is substantial, as industrial robots is used in both foundry 1 and 2. However, the company's knowledge about collaborative robots is limited in Skövde. This includes the risk assessment, standards, and general information for collaborative robots. Therefore, Volvo Powertrain wants a study performed as stated in segment 1.2 to increase the edge of knowledge.

1.4 Expanding the edge of knowledge

With the knowledge edge defined in segment 1.3, the methods of further broadening the knowledge edge for the company can be established. The methods used are described in segment 3. The two main measurement values where defined, the production rate and the error rate. The workflow of the thesis is closely related to these values as they are the main indicators for if it is possible and economically justifiable to implement collaborative robots to produce D6 cylinder heads.
In the thesis relevant information needed to implement collaborative robots is also presented. In the thesis summarised information regarding rules, regulations and standards is presented, that are applicable for the implementation of collaborative robots. As well as a python script to calculate the speed of the collaborative robot according to power and force limiting described in ISO 15066. The risk assessment presented is simplified but can be used as a starting point and background for when a full risk assessment of the workstation is conducted.

The value of presenting this is that the edge of knowledge regarding collaborative robots and the use of them in production broadens. The value of this thesis is that Volvo can use the information provided in the thesis in projects at foundry 2 and in other parts of Volvo Powertrain in Skövde to implement collaborative robots.

1.5 Deliverables

In the thesis the following shall be delivered.

- The thesis should lead to a solution which is implemented virtually.
- An assessment of the risk between collaborative robot, human, and equipment.
- Advantages and disadvantages with the application of collaborative robots within the scope of the D6 cylinder head sand core mounting.

1.6 Limitations

Before beginning the thesis, limitations were set due to time restrictions and to confine the scope of the thesis. The following bullet points are the limitations set for the thesis.

- The thesis will only consider solutions with collaborative robots.
- The thesis shall only consider the Volvo Penta D6 cylinder head.
- The thesis limits itself to only visualise the solutions in Visual Components.
- The solution will not be used directly in production.
- No physical tests will be performed to verify requirements or goals.
- Verifications of goals and requirements will if possible be performed by reason, visualisation, or calculations.
- The thesis will only discuss advantages and disadvantages with the solution.
- In the thesis a fundamental evaluation of the risks of the presented solution is performed with respect to humans and other production equipment.
- The thesis limits itself to make an economical evaluation of the solution using a fictional price for the cylinder head.
- The thesis will not collect any own data regarding fault rates.
- The thesis will use data provided by Volvo regarding fault rates.
- The position and measurements of the floor and conveyor belts are not to be changed.
- The white cores and black cores geometry are not to be changed.
- The lower and upper part of the mould are not to be changed.

1.7 Company introduction

Volvo Powertrain AB is a Swedish subsidiary to AB-Volvo group that was founded in 1897. Volvo Powertrain AB develops and manufactures drivelines for all companies within AB Volvo e.g., Volvo Trucks (Wikipedia, 2023). A supervisor at Volvo Skövde stated that currently about 9500 persons are employed by Volvo Powertrain AB. Whereas 3800 are employed at Skövde. The development work is performed in Gothenburg and Lyon while the manufacturing is in Skövde and Köping. The manufacturing plant in Skövde produces the diesel engines for Volvo Trucks and Volvo Penta. These are casted in various sizes (Wikipedia, 2023).

2 Pre-studies and theoretical foundation

In the pre-study the data given by Volvo, standards that apply to collaborative robots and programming methods are presented.

2.1 Data from Volvo

Here the data that was given by Volvo is presented.

2.1.1 Error rate

The error data (Volvo Powertrain, 2022-b) showed that the glue errors was the most prominent driver of the error rates. Where 30 % of the errors are gluing errors. The error data from the D6 cylinder head is presented in figure 1. The error data (Volvo Powertrain, 2022-a) from cylinder head 11 is presented in figure 2.

There are 4 causes of the gluing errors:

- Too little glue is applied. This results in the mould falling apart when the protective coating is applied as it is turned upside down.
- The glue dries before the sand cores are applied, this results in the mould falling apart.
- Too much glue is applied. This results in the glue pouring out into the mould which results in a distorted geometry of the cylinder head.
- The glue is applied to the wrong location. This can result in both the mould falling apart and a distorted geometry of the casted part.

These four causes in turn are caused by operator error, glue gun coking and glue gun losing its calibration or an error with the glue itself.

When comparing the data from the D6 cylinder head and cylinder head 11 in figure 1 and 2, it shows that the gluing errors for cylinder head 11 is 0,57% compared to 30% for the D6 cylinder head. The mould for cylinder head 11 is glued and assembled by robots and the D6 cylinder head is glued and assembled by operators.

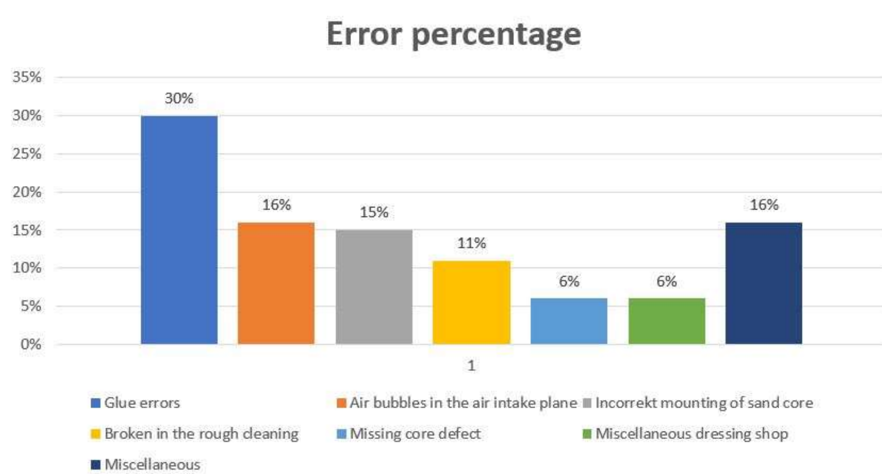

Figure 1: Error rates for the Volvo Penta D6 cylinder head (Volvo Powertrain, 2022-b).

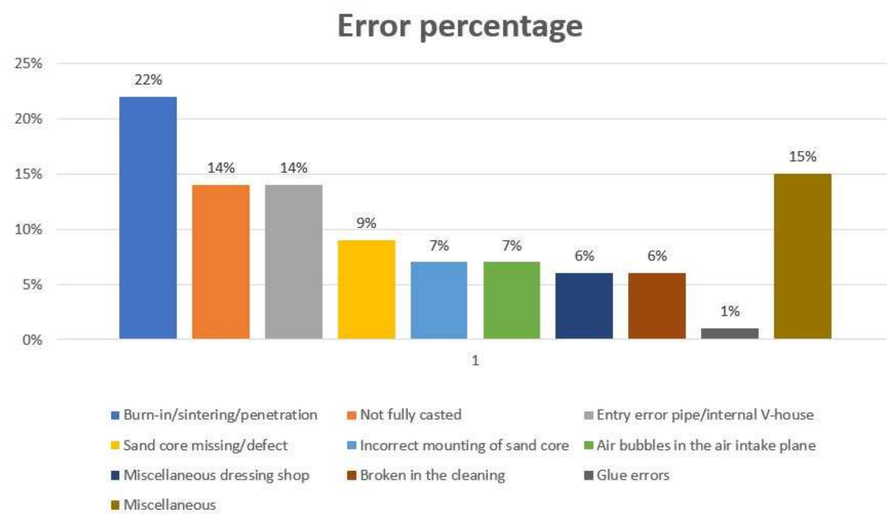

Figure 2: Error rates for cylinder head 11 (Volvo Powertrain, 2022-a).

2.1.2 Current ergonomic evaluation of the workstation

Data about the ergonomics of the workstation was collected from an interview with 2 operators and an evaluation of the ergonomics of the workstation (Volvo Powertrain, 2021).

The interview can be read under segment 2.2. The ergonomic evaluation can be summarised by the following bullet points:

- Half of the lifting are performed in the yellow zone and the other half is performed in the green zone.
- The weight of each component is estimated to be under 2kg.
- The gluing occurs in the yellow zone in 3 sets and are performed in static.
- The largest contributor to ergonomic strain according to the ergonomic evaluation is the gluing of the sand cores.
- If the operators rotate tasks within the station the gluing of the mould becomes green.
- Operators that are short are more exposed to ergonomic strain in the yellow zone.
- It is highly recommended that the operators rotate working tasks with each other.
- If the operators rotate within the station, the workstation becomes green according to Volvos ergonomic guidelines.

Following the bullet points an explanation of what the zone is affected by and what they mean:

- Green zone: Normal zone
- Yellow zone: Intervention zone
- Red zone: Danger zone

The different zones are governed by certain parameters. In the ergonomic evaluation these parameters are the frequency of the tasks per hour and for the entire day. The parameters also consist of the weight of the component the operators are working on/lifting, the working position, and the angles of the operators' body. These values were then calculated, and several tables were used to find what type of zone a working task is in, this can be seen in figure 3 and 4.

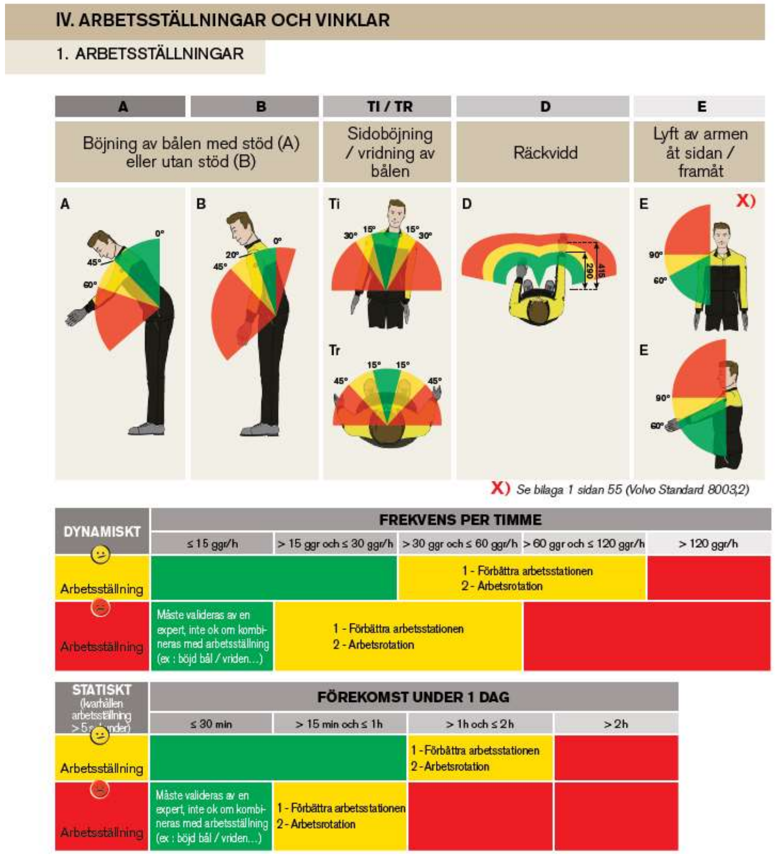

Figure 3: The table of how different working angles and frequency per hour and day affect the ergonomic evaluation. (Volvo Powertrain ,2021) Printed with permission.

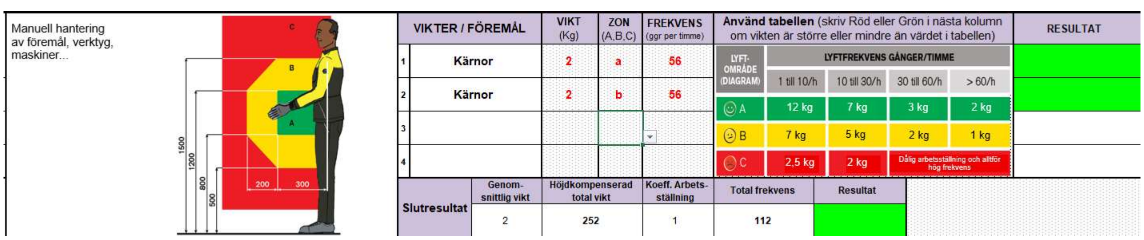

Figure 4: The table of how different working angles and frequency per hour and day affect the ergonomic evaluation. (Volvo Powertrain 2021) Printed with permission.

2.1.3 Process flow

To get a better understanding of the workstation several videos were recorded of the workstation during production and an interview with 2 workers were conducted. With this information and the data received (Volvo Powertrain, n.d.), a process analysis was made including the process flow, the current layout for the workstation and for the whole production line of the Volvo Penta D6 cylinder head.

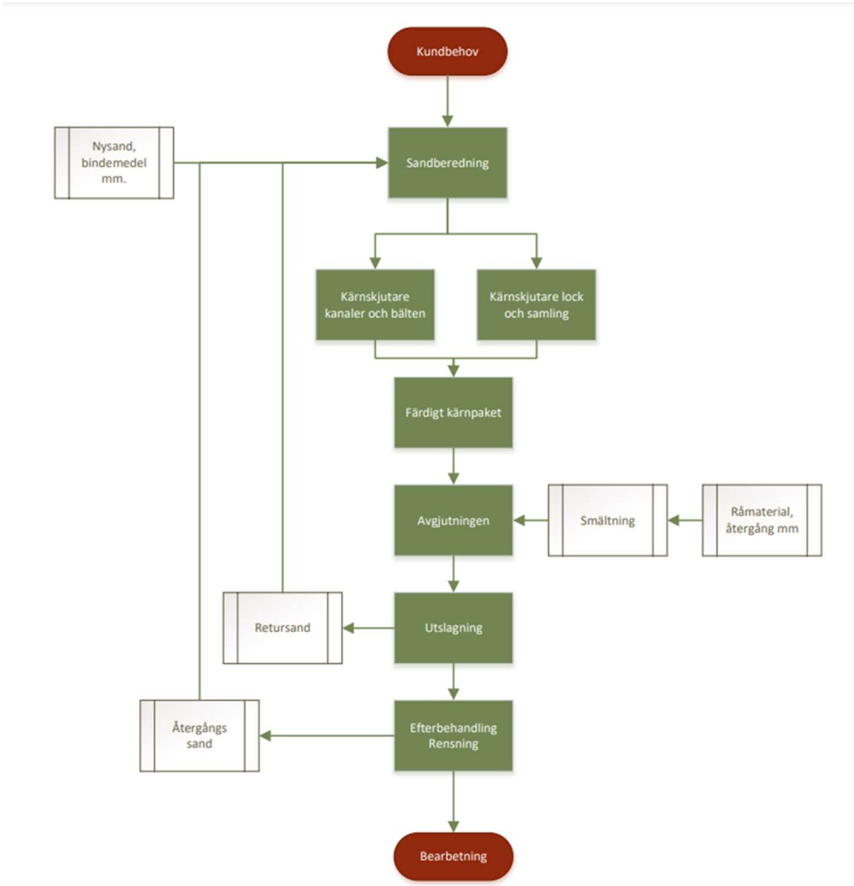

Figure 5: The process flow for the production of the cylinder heads (Volvo Powertrain, n.d.) printed with permission.

In figure 5 the process flow for the manufacturing of the cylinder heads is presented. The process begins with the preparation of new and old sand, that will be used in the manufacturing of the sand cores and the lower and upper parts of the mould. After the cores and mould halves has been made in a core shooter and have been detoxified, they are assembled by manual labour. This results in a complete mould that is ready to be used for casting. Melted iron is poured into the mould. The mould is then cooled until the metal has solidified. Thereafter the cylinder head gets separated from the mould. The sand can then be reused in a new mould. The cylinder head then goes to after-treatment and cleaning where it gets separated from the internal cores. This sand is later reused as well. The last step is additional processing.

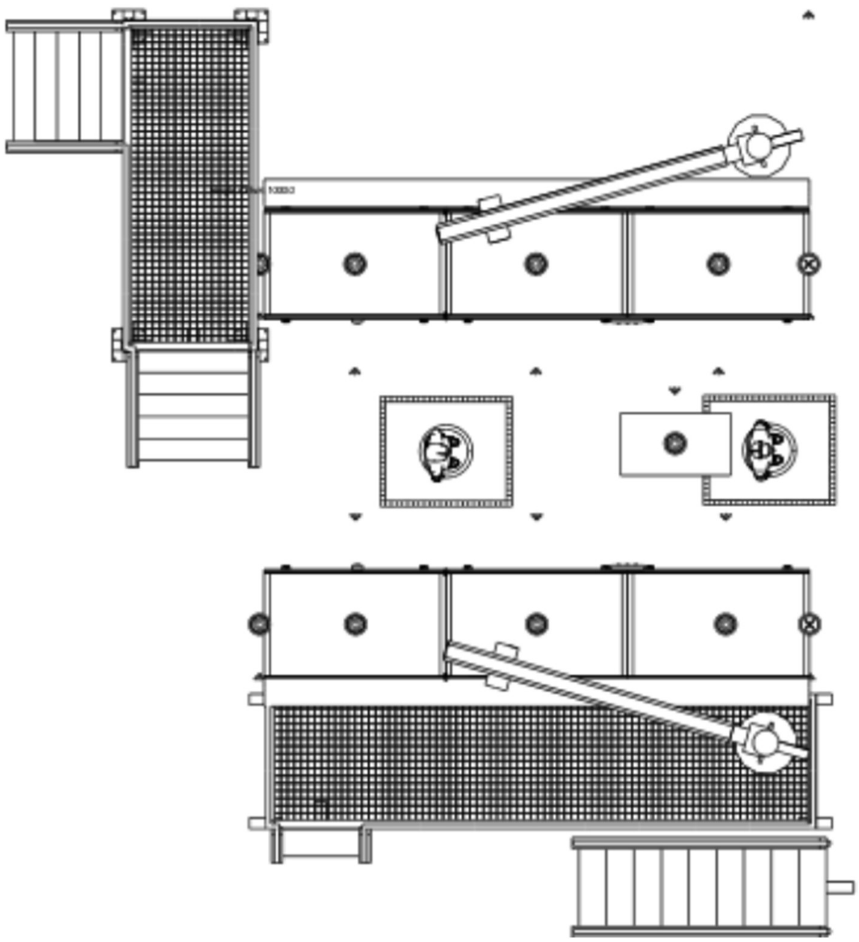

Figure 6: The current layout of the workstation.

In figure 6 the current layout of the workstation can be seen. The current layout consists of two conveyor belts on each side with 3 pallets. In the direction of the process, the first pallet contains the white sand cores, the second one contains the lower mould and the last contains the black cores. To ensure that the workers don't fall into the conveyor belt when it's operating, a light grid is placed on both conveyor belts. On the outer side of the conveyor belt there are ventilation pipes that sucks out the sulphur dioxide to reduce the level of that chemical. Above the ventilation pipe there is a mirror and lights so that the operator can clearly see the other side of the lower mould. This is used for quality control for the fully automated cylinder heads in startups or after longer breaks in production. Diagonally behind the mirror is a telfer that holds up the gluing tool and hoses. The telfer can be turned so that the operator can have full control over the gluing tool. This is the same on both sides. The floor between the conveyor belts can be adjusted in height. In the middle of the workstation, there is a special assembly tool for the black cores. After the assembly of the black cores there is a special lifting tool that aids the operator when the assembly of the black cores are to be mounted in the lower mould. This lifting tool is allowed to be moved anywhere in the workstation with the help of a traverse above the workstation.

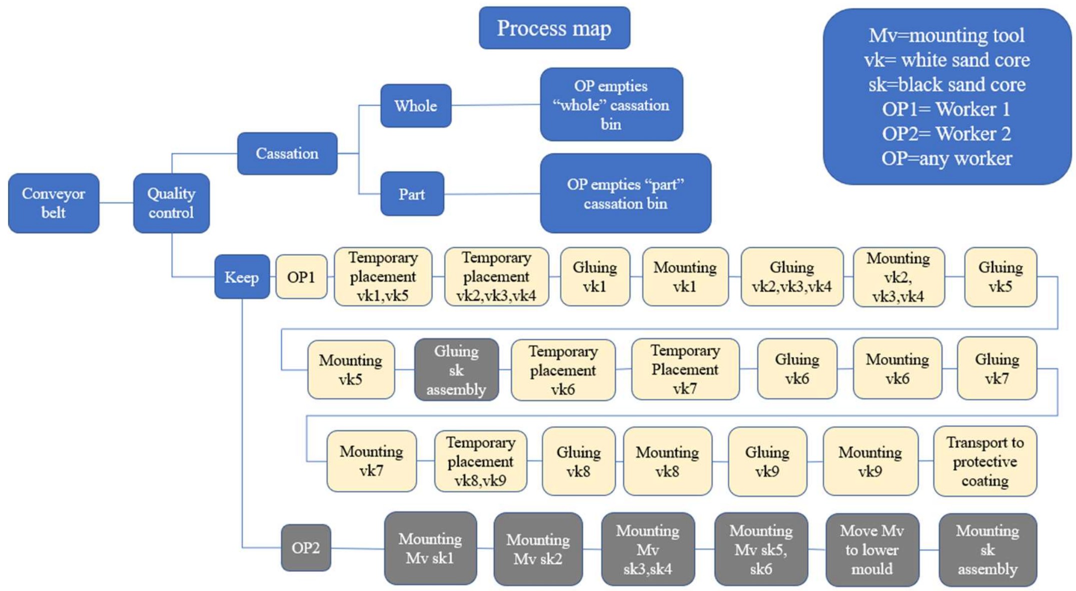

Figure 7: The process flow for the assembly of the white and black cores. In the top right corner, an explanation of the acronyms used in the process flow is present.

The current process begins with the pallets rolling into the station. The operators do a quality check for defects in the cores and mould. If a defect core is found the core is thrown into a cassation bin. If they have saved cores from earlier cassation where not every core was damaged, they will replace the damaged core with one of these.

Workflow operator 1

If the cores and mould has passed the quality control operator 1 starts by retrieving vk1-4 (white core) and puts them onto the lower mould in a temporary placement. Operator 1 then retrieves vk5 and temporary places it on the lower mould. After that operator 1 glues and assembles the white cores, starting with vk1, then vk2-4 and lastly vk5. Operator 1 then starts gluing for the mounting of the black core assembly done by operator 2. After the assembly of black cores has been mounted operator 1 retrieves and temporarily places vk6 and vk7 one at the time onto the lower mould. The operator then glues and mounts vk6 followed by vk7. Afterwards operator 1 retrieves vk8-9, temporarily places them, glues and mounts them separately. The assembly of the lower mould is then completed and is ready to be sent away to the next station. This is done by operator 1 by pressing a few buttons. The process then repeats on the other conveyor belt.

Workflow operator 2

After the cores have passed the quality control, operator 2 starts by retrieving sk1 (black core) and mounting it on the special assembly tool. Thereafter the same is done for sk2. Operator 2 then retrieves sk3-4 and mounts them in the assembly tool. After mounting sk3-4 the operator presses a button on the floor with their feet to hold sk3-4 in place. The same is repeated for sk5-6. The assembly of the black cores are then completed, and a lifting tool is brought down to pick up the assembly. The lifting tool with the assembly fixed to it is now moved from the assembly tool to the lower mould, where the black core assembly is mounted in the mould. The process then repeats on the other conveyor belt.

The assembly of the black cores is done by operator 2 and is done in parallel while operator 1 is working on assembling the white cores.

2.1.4 Glue gun data

The glue gun and glue hose are estimated to have a combined maximum weight of 5kg, but this information has a low degree of accuracy. Therefore, a safety factor of 3 was used resulting in a combined weight of 15kg for the glue gun and glue hose for the purpose of calculating the robot speed and force. The opening time for the glue gun is 0,1s per dose and 0,05 s were added for the glue gun to open and close resulting in 0,15s for a single dose and 0,25s for a double dose. The glue gun referred to is the handheld glue gun which is currently used in the manual gluing.

2.2 Interviews with the workers

According to 2 operators at foundry 2 in Skövde, the overall impression with the layout of the workstation is good. When gluing or placing the sand cores that are placed the furthest from the worker, the worker is forced to work far away from their body which results in a greater strain on the lower back and hips. Sometimes there can also be problems if the two workers have different height since the floor height is adjustable and cannot be adjusted properly for both. The operators also wanted brighter lights and they consider the light grids problematic since they slow down the work quite a lot. If the light grids are broken, the operators must go up to the control room to once again, start the conveyor belts. If the station is operating at full production rate the operators don't have time to have conversations with each other. They sometimes feel stressed by the short drying time of the glue, especially when mounting the large black core assembly. The common errors according to the operators are gluing errors, miscast cores and that the cores are easily broken in the assembly tool. The sand cores cannot be pushed too hard into the lower part of the mould since then it will break. Sometimes there can also be problems with the glue guns as they may coke if not used for some time or they may lose their calibration. Therefore, the operators must continually check the amount of glue coming out of the glue gun.

The operators want a bigger working area and they want to remove the light grids. Since the work also includes quality control, it is important to be able to work calmly since otherwise defects will appear.

2.3 Collaborative robots

Here information about the collaborative robots and operations is presented.

2.3.1 Differences between industrial robots and collaborative robots

A collaborative robot differs from an industrial robot in that they can perform collaborative operations. These robots must comply with ISO 10218-1 Svenska institutet för standarder, (2011-b). Collaborative robots are generally smaller and have rounded forms to reduce injury upon collision, they are also designed to reduce the risk of entrapment. They generally have shorter range, lower speed and can carry less load than an industrial robot.

2.3.2 Collaborative operation

Collaborative operation is described in ISO 10218-2 as an operation between robot and a person that share the same workspace. For a collaborative operation to be allowed it must be used for a predetermined task, all protective measures must be active and it must use robots with features specifically designed for collaborative operation, meaning that the robot must comply with ISO 10218-1 (Svenska institutet för standarder, 2011-b).

2.4 Rules and regulations

Here the standards that were used are introduced.

2.4.1 SIS ISO 15066: 2016

ISO 15066 describes robot operations where the robot and people share the same workspace. It shows how to implement collaborative robots and collaborative modes of operations, that are used so that the people working around the robot are safe. These are described in segment 2.5. To use ISO 15066 a thorough risk assessment must be made. The robot integration must meet ISO 10218-2 and the robot must comply with ISO 10218-1 (Svenska institutet för standarder, 2016-b).

2.4.2 SS-EN ISO 10218-1: 2011

ISO 10218-1 describes how a robot should be constructed to assure a safe design since this influences the safety of the collaborative robot implementations (Svenska institutet för standarder, 2011-a).

2.4.3 SS-EN ISO 10218-2: 2011

ISO 10218-2 describes the robot system and the robot cell. This part of ISO 10218 describes how to implement and make sure that the robot system and robot cell is safe (Svenska institutet för standarder, 2011-b).

2.4.4 SS-EN ISO 13849-1: 2016

ISO 13849-1 describes safety requirements for control systems and gives guidance in how to design them (Svenska institutet för standarder, 2016-a).

2.4.5 SS-EN ISO 13855: 2010

Describes where safeguards should be placed considering the approach speed of the human body parts and how to calculate safe separation distance for machines (Svenska institutet för standarder, 2010).

2.5 Collaborative robot operation

Different kinds of collaborative modes that can be used when implementing a collaborative robot are introduced. At least one of the collaborative modes in segment 2.5.1-2.5.4 must be used when designing a collaborative operation (Svenska institutet för standarder, 2011-b).

2.5.1 Safety-rated monitored stop

A safety-rated monitored stop is described in ISO 10218-1 as follows, if no person is inside the collaborative workspace, then the robot operates autonomously. When a person enters the collaborative workspace, the robot will stop moving. The robot can resume automatic operation when the person leaves the collaborative workspace (Svenska institutet för standarder, 2011-a).

2.5.2 Hand-guiding

The operator transfers motions to the robot via a hand-operated device, these motions are then converted to commands which the robot will perform.
The robot is guided by hand and operates with the safety rated monitored speed, which is determined by the risk assessment (Svenska institutet för standarder, 2016-b).

2.5.3 Speed and separation monitoring

The robot will maintain a safe separation distance between the operator and itself. When the safe separation distance is broken the robot will stop. The safe separation distance is a function of the robot speed so when the robots speed decreases the safe separations distance also decreases. When the operator moves away from the safe separation distance, the robot will resume motion at such speeds that the safe separation distance to the operator is maintained.

The safe separation distance is calculated using the formulas below.

$$S_P(t_0) = S_h + S_r + S_s + C + Z_d + Z_r \tag{1}$$

$S_P(t_0) = The\ protective\ seperation\ distance\ at\ time\ t_0.$

$t_0 = The\ present\ or\ current\ time.$

$S_h = The\ contribution\ to\ the\ protective\ separation\ distance\ attributable\ to\ the\ operator's\ change\ in\ location.$

$S_r = Is\ the\ contribution\ to\ the\ protective\ separation\ distance\ attributable\ to\ the\ robot\ system's\ reaction\ time.$

$S_S = Is\ the\ contribution\ to\ the\ protective\ separation\ distance\ due\ to\ the\ robot\ system's\ stopping\ distance.$

$C\ = Is\ the\ intrusion\ distance, as\ defined\ in\ ISO\ 13855;\ this\ is\ the\ distance\ that\ a\ part\ of\ the\ body\ can\ intrude$

$into\ the\ sensing\ field\ before\ it\ is\ detected.$

$Z_d = Is\ the\ position\ uncertainty\ of\ the\ operator\ in\ the\ collaborative\ workspace, as\ measured\ by\ the\ presence$

$sensing\ device\ resulting\ from\ the\ sensing\ system\ measurement\ tolerance.$

$Z_r = Is\ the\ position\ uncertainty\ of\ the\ robot\ system, resulting\ from\ the\ accuracy\ of\ the\ robot$

$position\ measurement\ system.$

$$S_h = \int_{t_0}^{t_0+T_r+T_s} V_h(t)dt \tag{2}$$

$T_r = Is\ the\ reaction\ time\ of\ the\ robot\ system, including\ times\ required\ for\ detection\ of\ operator\ position,$

$processing\ of\ this\ signal, activation\ of\ a\ robot\ stop, but\ excluding\ the\ time\ it\ takes\ the\ robot\ to\ come\ to\ a\ stop.$

$T_S = The\ stopping\ time\ of\ the\ robot, from\ the\ activation\ of\ the\ stop\ command\ until\ the\ robot\ has\ halted.$

$T_S\ is\ not\ a\ constant, but\ rather\ a\ function\ of\ robot\ configuration, planned\ motion, speed, end\ effector\ and\ load.$

$V_h = The\ directed\ speed\ of\ an\ operator\ in\ the\ collaborative\ workspace\ in\ the\ direction\ of\ the\ moving$

$part\ of\ the\ robot\ and\ can\ be\ positive\ or\ negative\ depending\ on\ whether\ the\ separation\ distance\ is\ increasing$

$or\ decreasing.$

$t = Is\ the\ integration\ variable\ in\ Formulae\ (2), (4)\ and\ (6).$

$$S_h = 1{,}6(T_r + T_s) \tag{3}$$

$$S_r = \int_{t_0}^{t_0+T_r} V_r\,(t)dt \tag{4}$$

$$S_s = \int_{t_0+T_r}^{t_0+T_r+T_s} V_s(t)\,dt \tag{5}$$

(Svenska institutet för standarder, 2016-b).

To judge if speed and separation monitoring is a suitable collaborative robot operation for the working station, a rough and ideal calculation of the minimum safety distance was calculated. The main formula is taken from ISO 15066 and is presented above in equation 1. Equation 1 is the formula that is supposed to be used when calculating the protective separation distance. Due to assuming an ideal scenario the formula can be reduced to the formula in ISO 13855, which is presented below in equation 6. This is possible when neglecting the penalty factors Z_d, Z_r and C. It is assumed that there are no uncertainties regarding the position of the operator (Z_d) and the robot (Z_r). It is also assumed that the intrusion distance (C) is 0 m. This can be achieved by placing the scanner in such a way that the height of the upper edge of the detection zone is 2,6 m. This can be seen in table 1, page 18 in ISO 13855. In essences the scanner will have a detection zone so that an intruding body part won't be possible thus C is 0.

$$S = K(T_M + T_S) \tag{6}$$

Where:

$S = Minumum\ safety\ distance$

$K = Approach\ speed$

$T_M = Stopping\ time\ for\ the\ machine\ or\ system$

$T_S = Response\ time\ of\ the\ safety\ laser\ scanner$

(Svenska institutet för standarder, 2010).

When calculating T_S a SICK s3000 scanner was used. It has as best a response time of 60ms when neglecting penalty factors (SICK, 2022). The approach speed K of the operator is 1,6 m/s Svenska institutet för standarder, (2016-b). Assuming that the robot is running at the TCP speed of 250 mm/s then the stopping time T_S is 840 ms for joint 2 (FANUC CORPORATION, 2020).

Inserting the values gives us:

$$S = \frac{1{,}6(60 + 840)}{1000} = 1{,}44\ m$$

This means that the robot will stop performing its operation if an operator enters closer than 1,44m of the robots end effector. Due to not knowing where position of the robot is, this means that the operators cannot be in the marked zones when the robot is operating as seen in figure 8.

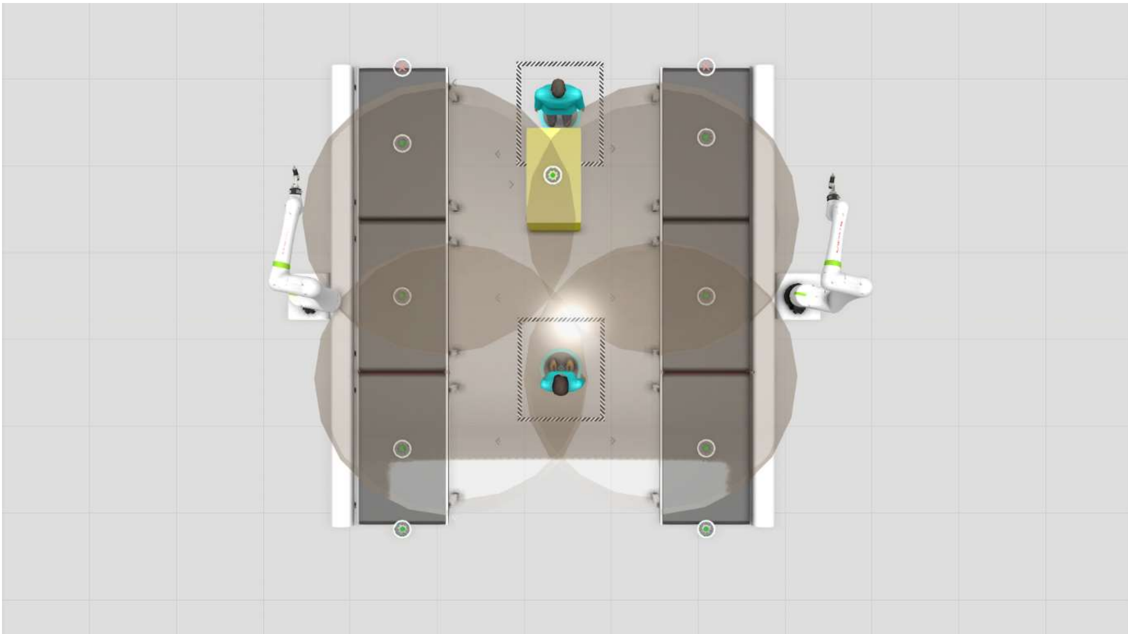

Figure 8: Workstation with speed and separation monitoring, the grey circles are where the operator are not allowed to stand during robot operations.

2.5.4 Power and force limiting by design or control

Power and force limiting is a mode of operation where the robots speed and force is limited so that the operator will not be hurt if collision would occur between operator and robot. In this mode of operation, the operator and the robot can work in collaboration. To be allowed to operate in this mode the robot must comply with ISO 10218-1.

To determine maximum speed and force of the robot a risk assessment is made to determine which body parts that the robot may collide with. Calculations are then done to determine maximum speed and force that the robot may use. These calculations do not need to consider the body parts where the risk is assessed as acceptable in the risk assessment.

Table 1 below shows the maximum pressure and forces that may be applied to different body parts, for both quasi static contact and transient contact.

Table 1: Table A2 from ISO 15066 (Svenska institutet för standarder, 2016-b).

Table A2			Quasi-static contact		Transient contact	
Body region	Specific body area		Maximum possible pressure Ps N/cm^2	Maximum permissible force N	Maximum Permissible pressure multiplyer Pt	Maximum Permissible force multiplyer Ft
Skull and forehead	1	Middel of forehead	130	130	Not applicable	Not applicable
	2	Temple	110		Not applicable	
Face	3	Masticatory muscle	110	65	Not applicable	Not applicable
Neck	4	Neck muscle	140	150	2	2
	5	Seventh neck vertebra	210		2	
Back and shoulders	6	Shoulder joint	160	210	2	2
	7	Fifth lumbar vertebra	210		2	2
Chest	8	Sternum	120	140	2	2
	9	Pectoral muscle	170		2	
Abdomen	10	Abdominal muscle	140	110	2	2
Pelvis	11	Pelvic Bone	210	180	2	2
Upper arms and elbow joints	12	Deltoid muscle	190	150	2	2
	13	Humerus	220		2	
Lowe arms and wrist joints	14	Radial bone	190	160	2	2
	15	Forearm muscle	180		2	
	16	Arm nerve	180		2	
Hands and fingers	17	Forefinger pad D	300	140	2	2
	18	Forefinger pad ND	270		2	
	19	Forefinger end joint D	280		2	
	20	Forefinger end joint ND	220		2	
	21	Thenar emininence	200		2	
	22	Palm D	260		2	
	23	Palm ND	260		2	
	24	Back of the hand D	200		2	
	25	Back of the hand ND	190		2	
Thighs and knees	26	Thigh muscle	250	220	2	2
	27	Kneecap	220		2	
Lower legs	28	Middle of shin	220	130	2	2
	29	Calf muscle	210		2	

Table 2: Table A3 from ISO 15066 (Svenska institutet för standarder, 2016-b).

Table A3		
Body region	Effective Spring constant K N/mm	Effective Mass Mh Kg
Skull and forehead	150	4,4
Face	75	4,4
Neck	50	1,2
Back and shoulders	35	40
Chest	25	40
Abdomen	10	40
Pelvis	25	40
Upper arms and elbow joints	30	3
Lower arms an wrist joints	40	2
Hands and fingers	75	0,6
Thighs and knees	50	75
Lower legs	60	75

Using values from table 1 and 2. The maximum amount of energy that can be transferred to each body part can be calculated.

$E = Tranfer\ energy.$

$F_{max} = Maximum\ contact\ force\ for\ specific\ body\ region.$

$P_{max} = Maximum\ contact\ pressure\ for\ specific\ body\ area.$

$K = Effective\ spring\ constant\ for\ specific\ body\ region.$

$A = Area\ of\ contact\ between\ robot\ and\ body\ region.$

$$E = \frac{F_{max}^2}{2K} = \frac{A^2 P_{max}^2}{2K} \tag{7}$$

Then the maximum relative speed and force can be calculated using the formulas below.

$m_H = The\ effective\ mass\ of\ the\ human\ body\ region.$

$M = The\ total\ mass\ of\ the\ moving\ parts\ of\ the\ robot.$

$m_L = \ Effective\ payload\ of\ the\ robot\ system.$

$\mu = \text{the reduced mass of the two} - \text{body system, which is expressed by Formula 9}$

$$m_R = \frac{M}{2} + m_L \tag{8}$$

$$\mu = \left(\frac{1}{m_h} + \frac{1}{m_R}\right)^{-1} \tag{9}$$

$$E = \frac{F^2}{2K} = \frac{1}{2}\mu v_{rel}^2 \tag{10}$$

$F = \ The\ maximum\ force\ that\ the\ robot\ may\ use.$

$v_{rel} = Is\ the\ relative\ speed\ between\ the\ robot\ and\ the\ human\ body\ region.$

(Svenska institutet för standarder, 2016-b).

2.6 Programming of robots

Robot programming can be done in two main ways, offline programming and online programming.

Offline programming is when a robot program is created without using the robot, using computer software to create programs. This is often done using virtual simulation software.

Online programming is when the robot is used to create the robot program. Online programming can be done using both lead through programming and teach pendants.

Lead through programming is used to manually guide the robot arm by hand and then using these motions to create the robot program.

Teach pendants are commonly used to program robots. They are handheld devices which are included with the robots control systems. They usually have a keypad or a touch screen which is used to enter instructions to the robot (Robots Done Right, 2023).

3. Method

Here the methods used in the project is presented, varying from establishing the final concept to determining the production rate.

3.1 Choosing a robot solution

During the thesis several different methods has been used to choose a suitable robot for the application. First a pre-study was conducted to broaden and increase the understanding of the problem and desirables with the workstation. This can be read in segment 1 and 2. From this information the workstations functions, requirements and desirables were established. Part solutions for each part function was established and summarised in a functional diagram. Requirements and desirables were summarised in a requirement table. To generate concepts a program called Morpheus was used, which systematically combines the part solutions from the functional diagram with each other to generate concepts.

When the concepts had been created, they were ranked by 3 different matrices. This was done to eliminate concepts until a final concept was acquired. First an elimination matrix was used to eliminate all solutions that doesn't meet the requirements from the requirement table. Afterwards a Pugh-matrix was used to evaluate the concepts with respect to the desirables and their ranking from the requirement table. Thereafter a Kesselring matrix was used where certain criteria was given further evaluation of their own ranking as well as being compared to each other. From these 3 matrices a final concept was acquired. The matrices are described in segment 4.

3.2 Assembly times

To get a better understanding for the process flow of the workstation, each operation that the workers did was broken down into groups. These groups were then broken down further to find each single task of the workstation. These tasks were then timed. The timing of each task was done by recording 13 videos of the workstation when it was in use. Then looking at the recordings and writing down the time for each task in Excel. This was done for all 13 videos and the results were compiled and the average time was taken. Then the three-point estimation method was used to find the expected time for each task. The three-point estimation method has the following formula:

$$e = \frac{a + 4m + b}{6} \tag{11}$$

Where e is the expected value of each task, a is the optimistic value that has an occurrence of $\frac{1}{1000}$, b is the pessimistic value that has an occurrence of $\frac{1}{1000}$ and m which is the most likely value which in this case is the average time per task. The three-point estimation method uses a beta distribution. The advantage of using this is that it accounts for the variation and not only the most likely value. Usually, the most likely case is closer to the optimistic case than the pessimistic. The three-point estimation method accounts for this and gives a more realistic value which is the expected value. To note here is that the values used for a and b were the fastest and slowest times recorded. The time for each task was measured in seconds.

From the three-point estimation method the standard deviation s, is calculated by the formula:

$$s = \frac{b - a}{6} \tag{12}$$

Then the variance is calculated by the formula:

$$v = s^2 \quad (13)$$

The variance is then summed up from all tasks v_{sum}. To find the total standard deviation s_{sum} it is calculated by taking the square root of the total variance. To then find the high range and low range of the expected time the following formula is used.

$$High\ range = e + 3 * s \quad (14)$$

$$Low\ range = e - 3 * s \quad (15)$$

(Hammersberg, n.d).

3.3 Visualisation

Visual Components was used to visualise the assembly of the moulds. This program was used since there was a lot of available material making it easy to learn. The visualisation uses 12 different nodes. There are 2 feeder nodes which create parts, 7 work nodes where the workers pick up or assembles parts, 2 sink nodes are used to remove finished moulds from the simulation and one node is used to decide which side the operators should work on. The simulations also use 11 lamps which toggle between true and false, these are used as global variables for the simulation. The nodes use a set of predefined statements from Visual Components to create and delete parts. These 12 nodes also control when the workers work on different tasks and when the robots will start each gluing sequence. The gluing sequence have been programmed using jogging in Visual Components. The visualisation uses 6 conveyor belts, 3 on each side to transport the parts between the different nodes.

The tasks that the operators perform in the visualisation comes from the three-point estimate. The operators use a walking and turn speed that is based on how fast the operators turn and walk in reality. The velocity of the operators was calculated with the measured distance and the data from the three-point estimate.

To optimize the visualisation an effort was made to minimize the waiting times by redistributing some tasks so that they could be performed during the previous waiting time.

3.3.1 Programming of robot

The robot was programmed using jogging in Visual Components. By moving the robot in the visualisation and then saving its position this generates a script which the robot will run from.

3.4 Error rate indicators

It will not be possible for this thesis to show an actual reduction of error rates since that would require implementing the solution. It will however be possible to use indicators to show a likely quality outcome. To do this the D6 cylinder head error rates will be compared to the error rates of cylinder head 11 whose production is fully automated.

3.5 Risk assessment

A full risk assessment will not be done since that would be out of scope for this thesis. Important to note is that the risk assessment in this thesis is simplified and cannot be used in an implementation of the solution proposed in this thesis. The results achieved may differ greatly from a full risk assessment and as such can only be used as an indication of the results a full risk assessment may yield.

The first step in doing the risk assessment was to layout the prerequisites for the risk assessment, meaning laying out the layout, components, and work steps. Then brainstorming was used to determine the risks. The risk where the robot may hit or entrap the operators were divided into different body parts according to ISO 15066. The risks were then evaluated and received a rating between 1 and 5 for probability and consequence, were 1 is a low probability/low consequence and 5 is a high probability/ high consequence. These were then multiplied to receive a risk value. Preventive measures were then identified, which was done before the second risk evaluation to reduce the amount of safety measures. In the second risk evaluation the goal was to rate all the risks as green. To get a green rating the risk value must be 3 or less or have risk value of 4 where both the probability and consequence rating is a 2. If the risk value was 4-9 then the risk was marked yellow unless both probability and consequence were marked as 2. A red rating was received if the risk value exceeded 9. A green rating means that the risk is assessed as acceptable and shall be reduced if opportunity presents itself. A yellow rating means the risk requires action and a red rating means that the risk requires direct action. The preventive measures were applied to all that that had a risk value of more than the goal value. New values for probability and consequence were then devised. When determining probability and consequence the reasoning for the different values were written down so that one could go back and see how a value was chosen. When doing the risk assessment, reduced speed and force is to be avoided as a safety measure since the robot will be limited in speed and force by using this preventative measure. After the risk assessment is done the robots speed and force will be calculated. Using power and force limiting; all the risks where body impact will occur that are not limiting with respect to the robot speed and force will receive reduced speed and force countermeasures, further lowering the risk value since the robot will be moving at a lower speed and force.

3.6 Determining robot speed and force

To make it possible for the robot to use collaborative operation while gluing the sand cores, the power and force limiting mode was chosen. It was chosen because speed and separation monitoring would require a separation distance which is too large for the station as can be seen in figure 8. Hand guiding could not be used since it cannot work with a human in the collaborative workspace. This mode is only for teaching the robot movements and cannot be used in production. Safety rated monitored stop could not be used because the separation distance would be too large for the station.

To determine the robot speed and force a python script was written to calculate the speed and force using equations and table values from segment 2.5.4. The python script can be seen in attachment 2.

In the formulas used to calculate the maximum speed that the robot is allowed to run, it is not actually the robot speed that is calculated. Instead, it is the relative speed of the robot that is calculated. An assumption was made that the operators speed was set to 0 and thus the relative speed became the robot speed.

3.7 Economic analysis

A simplified economic analysis will be performed using percentages since production rate cannot be published in this thesis and the production costs are unknown. As such a formula will be delivered which is used to calculate the payback as accurately as possible with the known data and assumptions.

3.8 Determining advantages and disadvantages with collaborative robots

The advantages and disadvantages with collaborative robots are determined with the knowledge acquired in doing this thesis.

3.9 Determining production rate

The production rate was determined from the visualisation. This was done by measuring the time between sending away the first mould to sending away the second mould. This was done by adding the 18 first completed moulds on the left and right side excluding the first mould. The first mould was discarded since it can be treated as an anomaly. After adding the time for the 18 first moulds, the time were divided by 18 to acquire the mean production rate. The reason that the first mould can be treated as an anomaly is that the workers start working on the same side at the same time, this makes it so that the mould takes longer to assemble. For the following moulds operator 2 will start working before operator 1 meaning that the assembly time will be faster.

3.10 Verification of production rate

To verify the production rate in the visualisation it was compared to a production rate calculated in Excel. This was done by adding the expected values from the three-point estimate and then adding the times from the new tasks. The times for the new tasks were taken from the visualisation. The visualised production rate and calculated production rate were then compared to each other. The reason why the verification was performed was to see if the production rates coincided with each other, to check that the visualisation was programmed correctly.

3.11 Ergonomic analysis

To evaluate the ergonomics at the new workstation, the ergonomic analysis was divided into four parts. The strain on each operator and the number of bends of operator 1s back on the left and right side of the workstation. The strain on each operator is defined as the number of tasks the operators perform. These criteria are then used in the decision matrices.

4. Result part 1- Concept choice

From the information gathered in the pre-study, which can be in segment 2, the workstations functions, requirements and goals could be established. These were summarised in a functional tree-diagram, morphological table, and a requirement table. With the morphological table, concepts could be generated. These were later evaluated to find the most suitable concept for the workstation. Several methods were utilized, some of them are the morphological-matrix, elimination-matrix, Pugh-matrices and a Kesselring-matrix. How the methods work together are discussed in segment 3.1.

4.1 Requirement specification

In the requirement table the requirements and desirables of the workstation are presented which can be seen in table 3. They are formulated in such a way that they are measurable which can be seen in the columns to the right. Some criteria are requirements and other are desirables, the reasoning behind this is that the requirements are criteria's that are so important that they must be fulfilled. Desirables on the other hand must not be fulfilled. The desirables are graded on a scale from 1-4 with 1 being the least desirable and 4 being the most desirable.

Document type:		Requirment specification							
Project:		Gluing of sandcores							
Issuer:		John Bredvad-Jensen och Jakob Johansson					Created	2023-01-31	
Criterias		Ranking *1- 4: Desirable R: Requirment*					Target value	Unit	Method of verfication
		1	2	3	4	R			
1	Production								
1.1	Production rate				4		144	%	Indication from visualisation
1.2	Error rate				4		Lower	% of total units	Indication based of error data
2	Collaborative robot								
2.1	Repeatability					R	0,1	mm	Robot datasheet
2.2	Reach					R	1575	mm	Robot datasheet
2.3	Cost			3			<200000	I	Robot datasheet
2.4	Payload					R	15kg	kg	Robot datasheet
2.5	TCP Speed (tool center pint)					R	870	mm/s	Robot datasheet
2.6	Precision TCP					R	1	mm	Datasheet
2.7	Precision TCP			3			0,1	mm	Datasheet
2.8	Degrees of freedom					R	X-,Y- and Z direction	Degrees of freedom	Robot datasheet
2.9	Mounting vertically	1					Yes	Yes/No	Robot datasheet
2.10	Mounting horisontaly					R	Yes	Yes/No	Robot datasheet
2.11	EN ISO 13849-1					R	Yes	Yes/No	Robot datasheet
2.12	EN ISO 10218-1					R	Yes	Yes/No	Robot datasheet
2.13	Producer ABB			3			Yes	Yes/No	Robot datasheet
3	Ergonomics								
3.1	Less bending of back right side OP1			3			<17	Bends per batch	Indication from visualisation
3.2	Less bending of back left side OP1			3			<11	Bends per batch	Indication from visualisation
3.3	Decrease strain on OP1		2				<19	Number of tasks made by OP1	Indication from visualisation
3.4	Decrease strain on OP2		2				<10	Number of tasks made by OP2	Indication from visualisation
4	Workstation								
4.1	Mirrors for CH15					R	Yes	Yes/No	Indication from visualisation
4.2	Emergency stop button for robot					R	Yes	Yes/No	Indication from visualisation
4.3	Geometric constraint x-direction					R	<1220	mm	Measurements
4.4	Geometric constraint y-direction					R	<4160	mm	Measurements
4.5	Geometric constraint z-direction					R	<3700	mm	Measurements
4.6	Movable Robot		2				Yes	Yes/No	Indication from visualisation
4.7	Allow manual gluing			3			Yes	Yes/No	Indication from visualisation

Table 3: Requirement specification.

4.2 Concept Generation

Here the concept generation is presented and how it was performed.

4.2.1 Functional tree-diagram

In the functional tree-diagram the workstation within the scope of the thesis was split into subfunctions and each subfunction is then broken down into sub-solutions. The main function within the scope of the thesis is gluing of sand cores, which splits into the subfunctions: ability to apply glue, to reach, to be placed, to move and position tool and lastly identifying the position of the lower mould. The functional tree-diagram can be seen in figure 9.

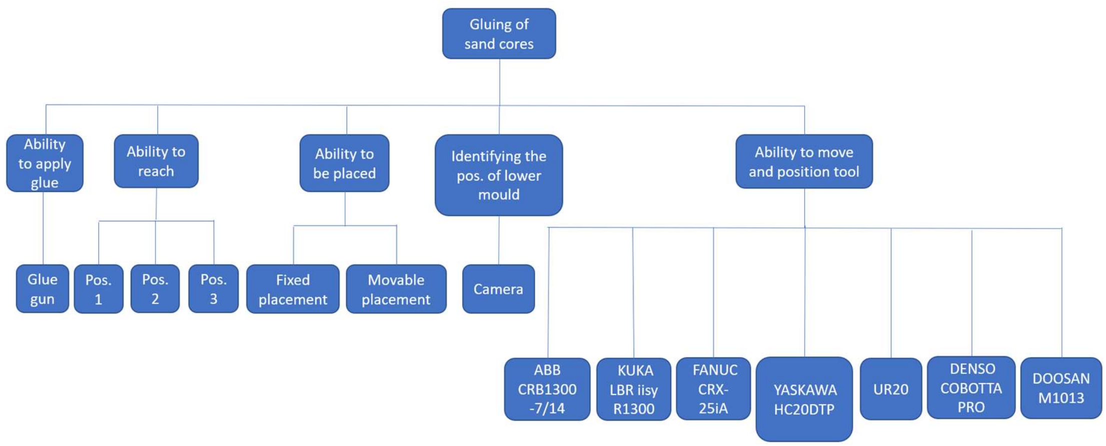

Figure 9: Functional tree-diagram for the workstation.

4.2.2 Morphological table

The morphological table derives from the functional tree-diagram. The table consists of subfunctions and sub-solutions. One sub-solution from each subfunction was systematically combined to create concepts. This was done with a program called Morpheus. A total of 42 concepts was created which can be seen in attachment 5. The table can be seen in table 4. One of the 42 concepts are also presented below in table 5. More information regarding Morphological tables can be found in Johannesson et al. (2013).

Table 4: Morphological table. Position 1,2 and 3 refers to the robot's position behind each table, position 1 is behind the white core table, position 2 is behind the mould table and position 3 is behind the black core table.

Concept Generation							
Part Functions	**Part Solutions**						
Ability to apply glue	Glue gun						
Ability to reach	Position 1	Position 2	Position 3				
Identifying the position of the lower mould	Camera						
Ability to move and position tool	FANUC CRX-25iA	UR20	ABB CRB1300-7/14	DENSO COBOTTA PRO	YASKAWA HC20DTP	KUKA LBR iisy R1300	DOOSAN M1013
Ability to be placed	Movable placement	Fixed placement					

Table 5: Concept 34.

Concept 34
Glue gun
Position 1
Camera
YASKAWA HC20DTP
Fixed placement

4.3 Concept evaluation

Here the concept evaluation process in presented. This includes elimination-, Pugh-matrices and also the reasoning behind the evaluation.

4.3.1 Elimination matrix

The elimination matrix evaluates the concepts with regards to the requirement specification. The concepts that did not fulfil the requirements were eliminated. The concepts that were eliminated, were eliminated because they had to low reachability. This resulted in 36 concepts being eliminated. The elimination matrix can be seen in table 6. More information regarding elimination matrixes can be found in Johannesson et al. (2013).

Table 6: Elimination matrix for the concepts.

	Created: 2023-03-10													
	Modified: 2023-03-10													
Concepts	Repeatability TCP	Reach	Payload	TCP Speed	Degrees of Freedom	Mounting horisontaly	EN ISO 13849-1	EN ISO 10218-1	Mirrors for CH15	Emergency stop button for robot	Geometric constraint x direction	Geometric constraint y direction	Geometric constraint z direction	**Keep**
1	Yes	No												No
2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
3	Yes	No												No
4	Yes	No												No
5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
6	Yes	No												No
7	Yes	No												No
8	Yes	No												No
9	Yes	No												No
10	Yes	No												No
11	Yes	No												No
12	Yes	No												No
13	Yes	No												No
14	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
15	Yes	No												No
16	Yes	No												No
17	Yes	No												No
18	Yes	No												No
19	Yes	No												No
20	Yes	No												No
21	Yes	No												No
22	Yes	No												No
23	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
24	Yes	No												No
25	Yes	No												No
26	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
27	Yes	No												No
28	Yes	No												No
29	Yes	No												No
30	Yes	No												No
31	Yes	No												No
32	Yes	No												No
33	Yes	No												No
34	Yes	No												No
35	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
36	Yes	No												No
37	Yes	No												No
38	Yes	No												No
39	Yes	No												No
40	Yes	No												No
41	Yes	No												No
42	Yes	No												No

4.3.2 Pugh-matrix

After the elimination matrix there were 6 concepts remaining. The remaining concepts were then evaluated using two Pugh-matrices. The Pugh-matrices evaluates the concepts comparing them with a reference concept and the desirables from the requirement table, where + means the concept is better than the reference, - if it's worse and 0 if they are equal. The Pugh-matrix 1 and 2 can be seen in tables 7 respectively 8. More information regarding Pugh-matrixes can be found in Johannesson et al. (2013).

Table 7: Pugh-matrix 1.

	Document type	Pugh-matrix					
	Created by	Jakob J & John B-J					
	Created	20-04-2022					
	Version	1.1					
Criteria	Importance 1-Least 4-Most	Reference	Concept				
		Concept 35	Concept 2	Concept 5	Concept 14	Concept 23	Concept 26
Production rate	4		SC	SC	SC	SC	SC
Error rate	4		SC	SC	SC	SC	SC
Cost	3		+	0	-	+	+
Mounting vertically	1		+	+	0	+	+
Producer ABB	3		0	0	0	0	0
Less bending of back right side OP1	3		0	0	0	0	0
Less bending of back left side OP1	3		0	0	0	0	0
Decrease strain on OP1	3		0	0	0	0	0
Decrease strain on OP2	2		0	0	0	0	0
Movable robot	2		+	+	+	0	0
Allow manual gluing	3		0	0	0	0	0
Total +			3	2	1	2	2
Total -			0	0	1	0	0
Totalsum			3	2	0	2	2
Weighted total +			6	3	2	4	4
Weighted total -			0	0	-3	0	0
Weighted totalsum			6	3	-1	4	4
Further development? Yes/No		Yes	Yes	Yes	Yes	Yes	Yes

Table 8: Pugh-matrix 2.

	Document type	Pugh-matrix					
	Created by	Jakob J & John B-J					
	Created	20-04-2022					
	Version	1.1					
Criteria	Importance 1-Least 4-Most	Reference	Concept				
		Concept 2	Concept 5	Concept 14	Concept 23	Concept 26	Concept 35
Production rate	4		SC	SC	SC	SC	SC
Error rate	4		SC	SC	SC	SC	SC
Cost	3		-	-	+	-	-
Mounting vertically	1		0	-	0	0	-
Producer ABB	3		0	0	0	0	0
Less bending of back right side OP1	3		0	0	0	0	0
Less bending of back left side OP1	3		0	0	0	0	0
Decrease strain on OP1	3		0	0	0	0	0
Decrease strain on OP2	2		0	0	0	0	0
Movable robot	2		0	0	-	-	-
Allow manual gluing	3		0	0	0	0	0
Total +			0	0	1	0	0
Total -			1	2	1	2	3
Totalsum			-1	-2	0	-2	-3
Weighted total +			0	0	3	0	0
Weighted total -			-3	-4	1	-5	-6
Weighted totalsum			-3	-4	1	-5	-6
Further development? Yes/No		Yes	Yes	No	Yes	No	No

4.3.2.1 Reasoning in Pugh-matrix

In the Pugh-matrices the criteria's production rate and error rate were set as secondary criteria or SC due to them not being able to get evaluated until later in the Kesselring matrix, after the power and velocity calculations from the risk assessment was completed. Most of the criteria for each concept had the same score due to the concepts being equal. The criteria of being able to be mounted vertically was evaluated with data that was collected from the different manufacturers. Where the Yaskawa performed worse because it lost operating range for an axis if the robot was tilted more than 30 degrees (Yaskawa, n.d). In the movable robot criteria, a concept performed better if it was possible to move the robot in comparison to only having a fixed base. To move the robot is beneficial because the foundry doesn't manufacture the D6/D4 all the time, so when the D6/D4 isn't produced the robot can be used elsewhere. The cost of having a movable pedestal were estimated by the calculations made in table 9. The total cost was estimated at 20000 SEK (about 2000 €). This cost was then used in unison with the robot prices acquired by the manufacturers to evaluate the cost criteria. In the first Pugh-matrix the concepts that performed the worst can be eliminated, but due to having so few concepts the choice of keeping them to the second Pugh-matrix was made.

Table 9: Cost calculations for the moveable base.

Movable pedestal	Cost [SEK]	Dimension [mm]
Pipe body	3850	150x100x5
Bottom slots (for forklift)	2033	8x30x3
Top and bottom plate	2058	350x350x20
One phase installation	2000	
Design	1500	
Welding (800SEK/hour)	6400	
Miscellaneous	2000	
Total	19841	

4.4 Final evaluation of the concepts

In this chapter a pairwise comparison, further ranking of the criteria, the Kesselring matrix, and a description of the final concept will be presented.

4.4.1 Pairwise comparison

In the pairwise comparison the criteria are evaluated with respect to each other. The objective is to find which criteria that are more important than others. The ranking scale is 1 if the criteria is better, 0,5 if it's equal and 0 if it's worse. Each criteria row was summed up creating a sum-column. That column was then summed up as well to a total sum-value (45). To find the relative sum (W) each criteria's summed row was divided by the sum-value. The greater the value, the more important the criteria are. The table can be seen in table 10.

Table 10: The pairwise comparison for the criteria.

	Production rate	Error rate	Cost	Mounting vertically	Less bending of back right side OP1	Less bending of back left side OP1	Decrease strain on OP1	Decrease strain on OP2	Movable robot	Allow manual gluing	Sum	W
Production rate	-	0	1	1	1	1	1	1	1	1	8	0,178
Error rate	1	-	1	1	1	1	1	1	1	1	9	0,2
Cost	0	0	-	1	0	0	0,5	0,5	1	0,5	3,5	0,078
Mounting vertically	0	0	0	-	0	0	0	0	0	0	0	0
Less bending of back right side OP1	0	0	1	1	-	0,5	1	1	1	0,5	6	0,133
Less bending of back left side OP1	0	0	1	1	0,5	-	1	1	1	0,5	6	0,133
Decrease strain on OP1	0	0	0,5	1	0	0	-	0,5	1	0	3	0,067
Decrease strain on OP2	0	0	0,5	1	0	0	0,5	-	1	0	3	0,067
Movable robot	0	0	0	1	0	0	0	0	-	0	1	0,022
Allow manual gluing	0	0	0,5	1	0,5	0,5	1	1	1	-	5,5	0,122

4.4.2 Further ranking of the criteria

In the further ranking of the criteria, each criterion is divided into values that are given a certain ranking value. The ranking value are from 1 to 6, where 1 is least desirable and 6 is most desirable. The value 1 is based on the current workstation's performance. Some criteria were only divided into 1 or 6 because either they can achieve the criterion or not. The objective of this is to further quantify what is more desirable within each criterion and in comparison to other criteria. The secondary criteria production rate and error rate could now be quantified due to the risk assessment and visualisation being completed. By completing the risk assessment, the maximum velocity and force that the collaborative robot could use was acquired. These parameters in unison with the visualisation of the new workstation yielded in that the secondary criteria could be quantified. Later in the Kesselring matrix this was used to find the final concept. The table of the further ranking of the criteria can be seen in table 11.

Table 11: Table of the further ranking of the criteria.

	1	2	3	4	5	6
Production rate	<=100%	100 to 110%	111 to 121%	122 to 132%	133 to 144%	>144%
Error rate	Same	-	-	-	-	Lower
Cost (K€)	>120	120 to 100	99 to 80	79 to 60	59 to 40	<40
Mounting vertically	No	-	-	-	-	Yes
Less bending of back right side OP1	>=13	12 to 11	10 to 9	8 to 7	6 to 5	<4
Less bending of back left side OP1	>=23	22 to 20	19 to 17	16 to 14	13 to 11	<11
Decrease strain on OP1	>=21	20 to 18	17 to 15	14 to 12	11 to 9	<9
Decrease strain on OP2	>=10	9	8	7	6	<6
Movable robot	No	-	-	-	-	Yes
Allow manual gluing	No	-	-	-	-	Yes

4.4.3 Kesselring matrix

With the use of the pairwise comparison and the further ranking of the criteria the Kesselring matrix can be established. The concepts were weighted with the help of table 10 and 11. An ideal concept was created so that the concepts could be compared to it. The Kesselring matrix can be seen in table 12. More information regarding Kesselring matrixes can be found in Johannesson et al. (2013).

Table 12: Kesselring matrix.

		Document type	Kesselring matrix					
		Creator	Jakob J and John B-J					
		Date	12-03-2023					
		Version	1.0					
		Ideal	Concept 2		Concept 5		Concept 23	
	w	t	v	t	v	t	v	t
Production rate	0,178	1,068	6	1,068	6	1,068	6	1,068
Error rate	0,2	1,2	6	1,2	6	1,2	6	1,2
Cost	0,078	0,468	3	0,234	2	0,156	4	0,312
Mounting vertically	0	0	6	0	6	0	6	0
Less bending of back right side OP1	0,133	0,798	2	0,266	2	0,266	2	0,266
Less bending of back left side OP1	0,133	0,798	2	0,266	2	0,266	2	0,266
Decrease strain on OP1	0,067	0,402	3	0,201	3	0,201	3	0,201
Decrease strain on OP2	0,067	0,402	1	0,067	1	0,067	1	0,067
Movable robot	0,022	0,132	6	0,132	6	0,132	1	0,022
Allow manual gluing	0,122	0,732	6	0,732	6	0,732	6	0,732
T		6		4,166		4,088		4,134
T/Tideal		1	0,694333333		0,681333333		0,689	
Ranking			1		3		2	

In table 12 all criteria except cost and movable robot have the same ranked value. This is because the concepts behaved similarly to each other, the concepts had similar prerequisites to reach the criteria. The sum of the values T for each concept are similar, this is due to all the other concepts that are worse have already been eliminated, resulting in the remaining concept solutions being similar to each other. The main difference is if the robot will be having a movable pedestal or not and if the robot type will be a FANUC CRX-25iA or an UR20. The final concept is concept 2 which is implemented in the visualisation of the working station. However, the movable pedestal will only be used on the left side of the working station where the robot can easily be moved. On the right side of the working station a forklift cannot move the collaborative robot because its boxed in between other working stations and thus the robot is not easily moved and will use a fixed pedestal.

4.4.4 Description of the final concept

The concept contains a FANUC CRX-25iA with a glue gun mounted as the end effector. The position of the FANUC CRX-25iA is on the outside and placed in the middle, closest to the lower mould pallet. This allows the current telfer with the manual glue gun attached to be used when running tests or if the collaborative robot fails. The concept also involves a camera that is mounted on a beam above that will scan the position of the lower mould as well as the collaborative robot. There are several reasons for this. One is that the camera will have a broad view so that the robot applies glue to the right positions. Another reason is that when the camera is not mounted on the robot the scan time reduces significantly due to the robot's speed limitation. In figure 10 the fixed and movable pedestal can be seen, where the movable pedestal is represented by the orange box.

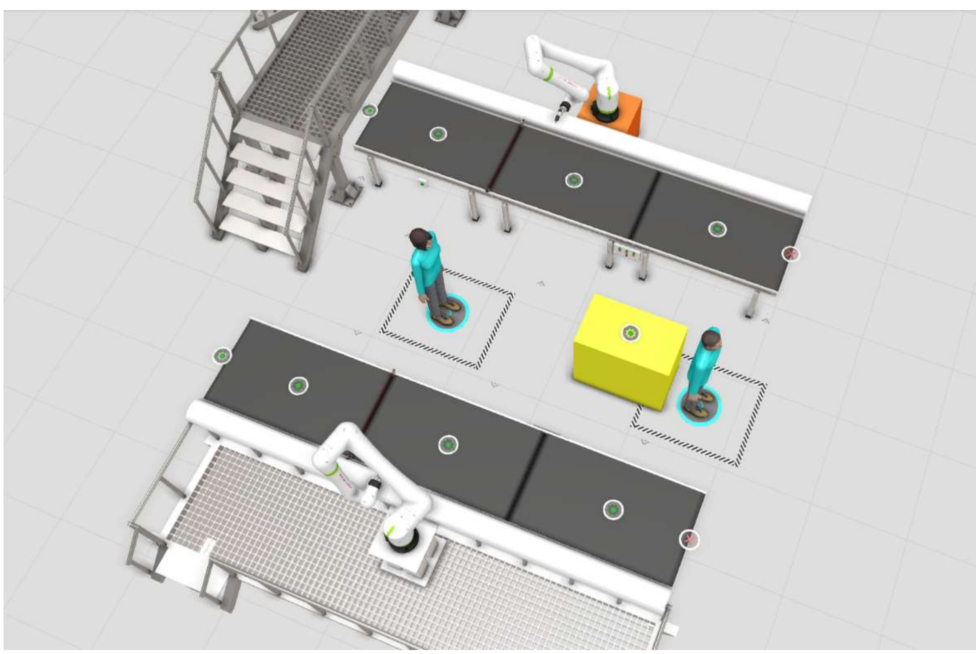

Figure 10: A screenshot of the new layout of the working station.

4.4.5 Further development

To further develop the final concept, preventative measures that was implemented in the risk assessment is added to the workstation. This is presented in the bullet points below.

- Protective elliptical housing around the glue gun.
- Protective fences around the collaborative robots.
- Guide rails for the collaborative robot's movable pedestal.
- Control panel for the activation for the gluing sequence.
- Control panel for the collaborative robots.
- Switch for the telfer with manual glue gun.
- Emergency stop connected to a line running across the inside of the conveyor belt.
- Mirrors that can slide away when the collaborative robot is in use.
- Change in the geometry of the ventilation pipes.
- New fixture for the lights.

The risk assessment is presented in attachment 6-9.

5. Result part 2 – Performance of final concept

Here the result of the thesis is presented including visualisation, production rate, ergonomic evaluation, and economic evaluation.

5.1 Visualisation of new workstation

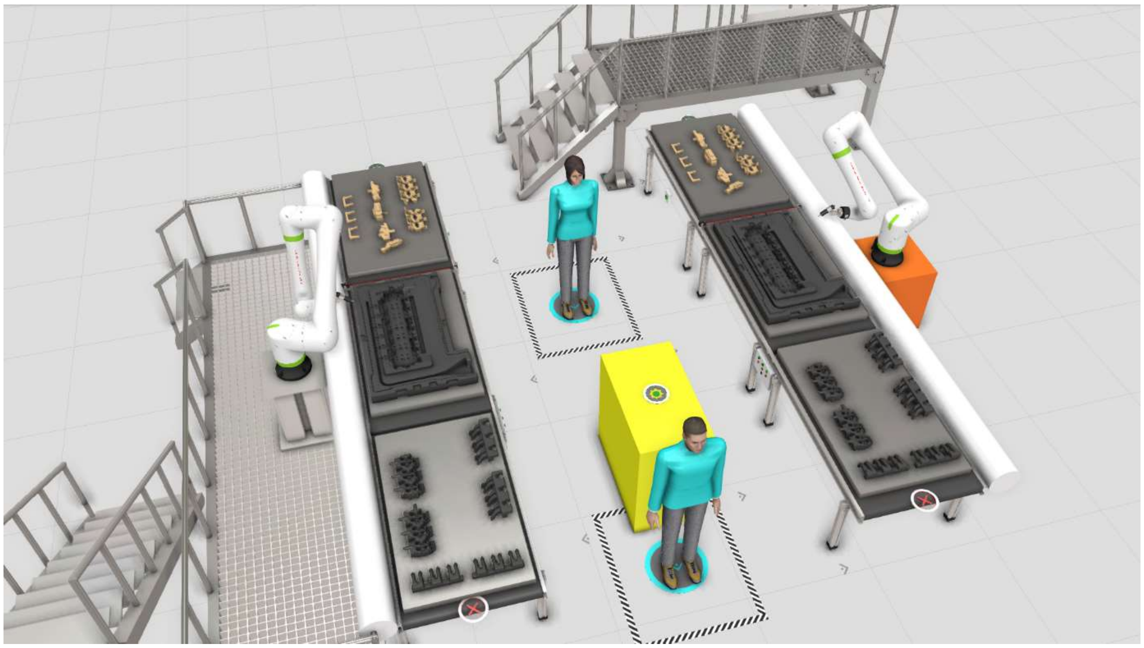

Figure 11: New workstation.

The new workstation layout was visualised in Visual Components. The visualisation consists of three conveyor belts placed on each side for a total of 6 conveyor belts. The lifting tool is represented by the yellow box in the middle. The moveable pedestal is represented by the orange pedestal and 2 collaborative robots were added. 2 humans were also added to represent the operators working in the station. The humans are set to a speed so that the walking times are the same as in reality. The simulation uses 12 nodes. 2 feed nodes, 6 work nodes, 2 sink nodes, a node for the lifting tool and one controlling when the workers should start working on the other side. The new process flow can be seen in figure 12.

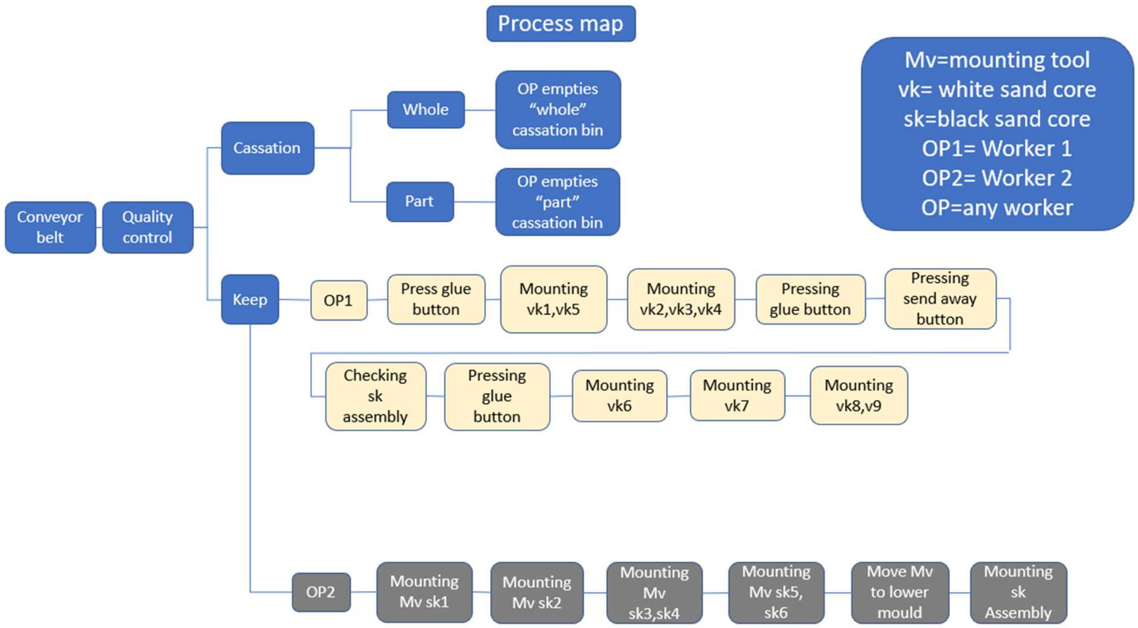

Figure 12: New process flow.

5.2 Production rate

The visualised total production rate for the new workstation could be increased by 51,2% but due to the rest of the foundry having a production rate of 144% the production rate of the new working station is set to 144% instead of 151,2%.

The right and left side of the workstation differ slightly in time to complete the production cycle. The production rate for the left side is 49,8% and the right side is 54,7% in the visualisation. This is due to the lower mould's orientation being the same. Resulting in the robot having further to travel on the left side of the workstation.

The production rates are summarized table 13:

Table 13: The increase in production rate for the new workstation with respect to the measured production rate of the current workstation.

Production rate	[%]
Total	52,1
Left side	49,8
Right side	54,7
Usable	44

5.3 Verification of production rate

To verify the visualisation's production rate, the production rate for operator 1 and operator 2 was calculated. This can be seen in table 14. The verification was made on the left side, but the same reason could be used for the right side. In table 14 it can be seen that the simulated production rate on the left side is increased by 49,8% while the calculated is 51,7% and 50,3% for operator 1 respectively operator 2.

Taking a closer look at table 14 the production rate range calculated from the three-point estimation method for operator 2 is at best 74,2% and at worst 32,5 % For operator 1 it is at best 81,5% and at worst 30,9%. To note here is that the visualised production rate is when operators 1 and 2 are working in unison, while the calculated production rate for operator 1 and operator 2 is individual.

Table 14: The verification of the left´s side visualised production rate and the calculated production rate for operator 1 and operator 2.

Verification left side	Production rate [%]	Low range [%]	High range [%]
Visualised	49,8	-	-
Calculated operator 1	51,7	81,5	30,9
Calculated operator 2	50,3	74,2	32,5

5.4 Waiting times

In table 15 the percentage of waiting time in comparison to the total time for each operator to complete one production cycle is presented. The waiting time has increased 16 percentage points for operator 1 and for operator 2 it has decreased 8,4 percentage points.

Table 15: Percentage of waiting time for each individual operator in the current and new workstation.

Waiting times	Percentage of wait [%]
New station operator 1	30,4
New station operator 2	7,2
Current station operator 1	14,4
Current station operator 2	15,6

5.5 Gluing times

The gluing times for each sequence that the collaborative robot executes are presented in table 16. The difference in time for the right and left side is due to that the collaborative robot must move a further distance due to the lower mould´s placement.

Table 16: Gluing times for each glue sequence. Where glue sequence 1 is for the white cores, 2 for the black core assembly and 3 for the remaining white cores.

First glue dot applied to sequence end	Left side [s]	Right side [s]
Sequence 1	24,768	25,052
Sequence 2	23,182	22,909
Sequence 3	32,09	32,253

5.6 Error rate result

The relative error rate for the gluing for cylinder head 11 which is fully automated is 0,57% which can be compared to 30% for the D6 cylinder head where the glue is currently applied by hand. This is an indication that the error rate will be lowered if the solution presented in this thesis is implemented since the gluing process will be automated. The difference in the error rate can be seen in figure 1 and 2 in segment 2.

5.7 Risk assessment result

The risk assessment resulted in 113 risks being evaluated. 20 preventive measures were used to reduce the probability and consequence of the risks. After the preventive measures was used, 7 risks received a yellow rating and the remaining 106 received a green rating. A green rating means that the risk is assessed as acceptable and shall be reduced if opportunity presents itself. A yellow rating means the risk requires action and a red rating means that the risk requires direct action. The risk assessment was used to determine the robot speed and force. The robot speed was calculated to 150mm/s and the robot force was calculated to 110N. The robot speed was limited by the sternum in entrapment and the force was limited by the abdominal muscle in entrapment. The risk assessment including reasoning and preventative measures can be found under attachment 6-9 and the maximum permissible speeds and forces can be seen under attachments 3 and 4.

5.8 Ergonomic evaluation of new workstation

The difference between the new and the current workstation can be seen in table 17. By implementing the collaborative robots, operator 1 no longer needs to glue and temporary place the sand cores. This resulted in the strain on operator 1 being reduced from 21 operations to 17 operations. It also reduced the number of bends operator 1 needs to perform, from 13 to 12 on the right side and from 23 to 22 on the left side. The strain on operator 2 remained the same for the new workstation compared to the current workstation.

Table 17: Difference between the criteria for the new and current workstation.

Criteria	Current workstation	New workstation
Less bending of back right side OP1	13	12
Less bending of back left side OP1	23	22
Decrease strain on OP1	21	17
Decrease strain on OP2	10	10

5.9 Economic evaluation of new workstation

The payback time in years can be calculated using the formula below. The derivation of the formula can be seen in attachment 1.

$NPR = New\ Production\ Rate$

$PR = Current\ Production\ Rate$

$Part\ Cost = Production\ Cost\ of\ mould\ excluding\ salary\ for\ operator\ at\ station.$

$Implementation\ Cost = Cost\ to\ implement\ proposed\ solution$

The following relation could be made:

$Y = \frac{NPR}{PR}$

Using the following equation:

$$Time = \frac{Implementations\ Cost}{\left(Salary * (Y - 1)\right)} \tag{16}$$

Inserting the values gives us:

$$\frac{\left(38325 + (38325 + 2000)\right)}{(2 * 3 * 50000(1{,}44 - 1))} = Payback\ Time = 0{,}5958 = 0{,}6\ years$$

For this calculation the following assumptions were made:

- The new production rate is 144% due to the rest of the foundry has this as its maximum production rate.
- The current production rate that was measured was set as 100%.
- There are 2 operators at the workstation.
- The salary of the operators is the same and is set to 50000 € a year.
- The production of the Volvo Penta D6 cylinder head at the foundry is in 3-shift working all year around and all hours of the day.
- Only the cost of the collaborative robots and a movable pedestal is included in the implementation cost.

6.Discussion

In segment 6 the results from the thesis are discussed.

6.1 Visualisation of new workstation

The visualisation was performed in Visual Components. This made it easy to visualise and identify when the operators were waiting, allowing for easy optimisation. Alternatively, the workstation could be visualised on paper, this would be hard to oversee and would take a lot of time. It would also be very hard to identify errors if the visualisation was done on paper. Visual Components make it easy to find and identify these errors since everything is shown in a graphical interface. A problem that was encountered when creating the visualisation was that the workers could only use a fixed walking and turn speed. This was solved by adjusting turning and walking speed so that it matched most of the walking times. Where the walking time does not represent reality, a penalty factor was added to the following work task for the operator so that the total time would be correct. As described in segment 3 effort was made to minimize the waiting times.

6.2 Assembly times

When collecting and analysing data from the 13 video recordings taken of the operators when working, the maximum accuracy of each task was measured in seconds. This could have an influence on the result.

In most of the videos recorded there was not a continuous flow in production. With flow it is meant that the operators work on one side and directly go to the other side and start working immediately. In most of the videos there were complications with either small or larger stops or the cores where damaged which resulted in cassation of the cores. There were also instances with complications with the glue guns which halted the production. As a result of this the majority of the data collected were not collected when there was a continuous flow in production. This has most likely impacted the times for each task, most likely resulting in each task taking longer time.

Another source of error is that in 10 of the 13 videos recorded a new operator was trained. Resulting in the data collected being influenced by this. The times for each task in these 10 videos were longer compared to when 2 experienced operators performed the same task in the 3 remaining videos. This is however not a problem since it only leads to longer times making the times more conservative, which makes the production rate less sensitive to complication that might occur since the operators have more time for each task.

As stated in segment 3 the three-point estimation method was used to evaluate the assembly times. However, the values used for a and b (optimistic and pessimistic) are the fastest and slowest values collected from the video recordings. The probability of the time values occurring is most likely not $\frac{1}{1000}$. Looking at the formula 11 and 12 for the expected value respectively for the standard deviation it can be seen that the a and b value has a greater influence regarding the standard deviation and later the high and low range than the expected value. The result of the three-point estimate should be regarded with this in mind. Especially the standard deviation and later the high and low range.

Even though there are some uncertainties in the values from the three-point estimate they are still used. This is due to the values for the expected time being conservative. When calculating the production rate in Excel and in the visualisation the expected value is used. When looking at the mean value that was collected by 13 videos it is lower than the three-point estimate´s expected value which means that the expected value is more conservative than the mean value.

6.3 Production rate

As stated in the result the new stations visualised total production rate has increased by 52,1% but due to the rest of the foundry being limited to a production rate of 144% the new workstations production rate is set at 144%. This increase in production rate will enable the foundry to free up capacity to produce more products. The increased production also means that the workstation has a safety factor of $\frac{152,1}{144} = 1,056$ for its production rate. This is important due to being a buffer to error sources when gathering data and calculating assembly times.

To note is that the production rate established from this thesis will merely give an indication of what production rate that can be achieved. To verify this production rate, the solution must be implemented.

6.4 Verification of production rate

After the production rate from the visualisation was acquired, it had to be verified by the calculated production rate. The tasks that are not performed in reality, their time values are taken from the visualisation to create the calculated production rate. The tasks taken from the visualisation are presented in the bullet points below.

- Operator 1 moving from the control panel when sending away the completed pallets to the white core pallet on the other side.
- Pressing the button to start the gluing for the first, second and third sequence. This was estimated to take 1 second each.
- Operator 1 moving from the white core pallet to the control panel when sending away the completed pallets on the other side.
- Operator 2 waiting for the robot to finish its gluing sequence (2) before mounting the complete black core assembly.
- Operator 2 waiting for the robot to finish gluing sequence 3.

Since these values are taken from the visualisation, they have no standard deviation. This is due to the simulation always producing the exact same time values.

From the three-point estimation method the production rate for each operator was calculated which can be seen in table 14. This was done to verify that the production rate in the simulation is correct. By simulating the production rate on the left side and comparing it to the operator's individual production rates on the left side which were calculated in Excel. The simulated left side has an increase of 49,8% while the operators 1 and 2 has 51,7% respectively 50,3%. The production rates differ slightly but the difference is negligible. The visualised production rate is lower than the calculated production rate, which suggest that the visualised production rate should be higher, meaning that the visualised production rate is conservative.

This indicates that the visualisation on the left side is correct, which indicates that the entire visualisation is correct.

To note here is that the visualised production rate is higher than the visualised production rate on the left side. This because the robot on the right side moves a shorter distance during the gluing sequence. This can be seen in table 13.

In table 14 it can be seen that operator 1 and operator 2 have a low range and a high range of their respectively production rates but a low range and high range for the visualised production rate is missing.

The reason is that there are uncertainties how different delays for operator 1 and/or operator 2 will affect each other and lastly the production rate. When the operators are working in unison, they depend on each other which makes it very difficult to calculate high and low range since relevant data is missing. It should be entirely possible to investigate this further but due to time constraints this is not regarded in the thesis.

The high and low range for operator 1 and operator 2 is however possible to acquire, by adding the fastest respectively the slowest work times the low range respectively the high range can be acquired. When looking at one operator the production rate is not dependent on the other operator´s production rate in the same way as for the total production rate. They are still dependent on each other due to the waiting time. But the waiting time is taken from the simulation meaning it has the same m, a and b value, which means it doesn't contribute to the low and high range.

6.5 Waiting times

Looking at table 15 the waiting times for the current workstation is 14,4% for operator 1 and 15,6% for operator 2. For the new workstation the waiting times are 30,4% for operator 1 and 7,2% for operator 2. The values are presented in table 15.

The waiting time for operator 1 increased by 16 percent points while the waiting time for operators 2 decreased by 8,4 percentage points. The reason why is because operator 1 is now waiting longer for operator 2 to finish mounting the black core assembly. This is mostly the case in the current workstation that was observed in the recorded videos. The waiting time has increased due to the robot speeding up the process for operator 1 due to operator 1 losing all the gluing and the temporary placement tasks of the sand cores. For operator 2 some of the waiting time was eliminated and some was redistributed. In the current workstation operator 2 often had to wait for operator 1 to finish the gluing for the black core assembly. This is to make sure that the glue doesn't dry before the black core assembly has been mounted onto the lower mould. In the new workstation the time to wait for gluing sequence 2 is decreased. A small portion of the time is also distributed towards waiting to begin with the black core assembly, on the other side until operator 2 is finished with the current side. The latter waiting time however should not come up in reality but due to how the visualisation is programmed this occurs. This is regarded as positive due to the production time being lower resulting in a more conservative production rate.

6.6 Gluing times

In table 16 one can see the gluing times for each gluing sequence that the collaborative robot performs. In the current workstation operator 1 must glue as a separate task. However, in the new workstation the operator can work alongside the robot when it performs it´s gluing sequence. Meaning that operator 1 does not have to wait during gluing sequence 1 and 3 and can instead work. During gluing sequence 2, operator 1 must wait to start the gluing sequence so that when the gluing sequence is completed, operator 2 is ready to mount the black core assembly in the lower mould. For sequence 2 this is the same scenario for the new workstation as the current one.

The importance of the value for sequence 2 in table 16 is that it is below 30 seconds. Between 30 and 40 seconds is the time that it takes for the glue at the current workstation to have an increased risk of drying. During gluing sequence 2 there is shortage of time to mount the black cores on the lower mould. Therefore, it is recommended that a glue with a slightly longer drying time is used.

6.7 Error rate

Since the solution has not been implemented, the error rate cannot be judged properly since that would require the implementation of the new workstation. Instead, indications from other products have been used to determine the error rate for the gluing. The evaluation of the error rate does also not consider any new errors that may occur due to the suggested changes in the workstation since this would require implementation of the new workstation. The data that has been received only shows the number of errors and what kind of error that has occurred. This means that it is unknown what the total error rate is. However, it is known that cylinder head 11 is produced in larger quantities then the D6 cylinder head and that both are produced in significant enough quantities that the different shares of errors should still be correct.

6.8 Risk assessment

In segment 3 an assumption of the relative speed was assumed. The velocity of the operator was set to 0 so that the formula calculating the relative speed becomes the robot´s speed. The reasoning behind this assumption was that when the mean operator speed of 1,6 m/s from Svenska institutet för standarder (2016-b) is used, the calculations yielded that in the case of a contact between operator and robot, the robot had to be moving in the same direction as the operator. This means the entire workstation would be assessed as unsafe according to Svenska institutet för standarder (2016-b) if just the robot was completely still. With this reasoning you could say that any beam or fence that is in the current workstation that an operator could walk into would make the current workstation unsafe which isn’t the case. Therefore, the assumption was made to set the operators speed to 0.

In ISO 15066 its clearly stated that the speed or force values that each body part is allowed to be subjected to, is below the minor injury threshold. It means that the operator should not feel pain. This is the reason a consequence becomes a 1, when preventative measure 1 and 2 is used. (Svenska institutet för standarder, 2016-b).

According to ISO 15066 the risk that the operator is hit in the head by the collaborative robot must be negligible (Svenska institutet för standarder, 2016-b). If the risk is negligible then the risk is assessed safe. By using the preventative measures seen in the risk assessment in attachment 6-9, the probability of the head being hit is so small it can be considered negligible.

6.9 Ergonomic evaluation of new workstation

By implementing collaborative robots into the workstation operator 1 no longer needs to glue the sand cores as stated in segment 5.9. The number of bends of the back is only reduced by 1 bend. This is because the operator instead needs to press a button to start the gluing sequence of the robot. The control panel for this button is situated under the conveyor belt just as the control panel for sending away the pallets. This means that operator 1 must bend to press the button, if the control panel instead would be situated in a way that the operator does not need to bend the back then the number would be reduced to 9 on the right side and 19 on the left side. The strain however is not reduced by doing this and remains the same.

According to the current ergonomic evaluation of the workstation the largest contributor to the ergonomic strain is the gluing of sand cores, due to the gluing being performed in static in 3 sets in the yellow zone. In the new workstation this is eliminated which should reduce the total ergonomic strain on the operator. It is however still recommended that the operators switch between working on the white cores and black cores several times during the day.

In the new workstation operator 1 has fewer tasks and the production rate has increased in comparison to the current workstation. This means that a new ergonomic evaluation must be made due to the evaluation accounting the number of lifts performed in one batch multiplied by the production rate.

6.10 Economic evaluation of new workstation

The economic evaluation shows how long it will take before the robots' production cost per product is equal to the old cost per product. The real payback time will however be shorter since this does not consider that the robots will also be used to glue the moulds for the D4 cylinder head which will shorten the payback time since the D4 cylinder heads most likely will be produced faster lowering the salary cost per product. Note that the evaluation does not consider the installation costs for the robot and procurement of glue gun, glue hose, and vision system.

The payback time is calculated when the foundry is running at the new 100 % production rate constantly which most likely will not be the case at all times. This will result in the payback time being longer. Since the D6 is not produced at all times this will be an even longer time.

The increased production rate will free up capacity to produce more cylinder heads. This will most likely be the main driver of paying for the investments. As such the real payback time should be considerably shorter than the one calculated in segment 5.9.

To note here is that the fictional price assumption was never used since the fictional price was eliminated in the derivation of the payback time.

6.11 Advantages and disadvantages with the application of collaborative robots for the workstation

The application of collaborative robots in the D6 workstation will most likely lead to higher production rates as shown by the visualisation. The application of collaborative robots will most likely lead to a reduction of the error rates as indicated by the error rate of cylinder head 11. The implementation will most likely also result in an increased production rate and lower error rates for the D4 cylinder head. This will free up capacity to produce more products and lower the wage cost per product. As the economic evaluation shows it will take 0,6 years with the D6 cylinder head production for the investment to pay for itself. This however does not take into account that the implementation of the collaborative robots will allow for more production, nor does it take into account the most likely lowered wage cost for the D4 cylinder head, as such the real payback time will be shorter. The implementation of collaborative robots will also lead to less strain on operator 1 since all the gluing will be done by the collaborative robots. Operator 1 also does not have to perform the temporary placement tasks. It will also be possible to continue the production if the collaborative robots would fail since the manual gluing equipment will be kept. This also allows for test runs to be made using the manual equipment, retaining the flexibility of the current workstation.

The disadvantage with the implementation of collaborative robots is the implementation cost of 78650€ plus the cost for installation and robot programming. This price is calculated using the price for two FANUC CRX25-iA which cost 38325€ each according to a sales coordinator at FANUC. This was then added with the price for the movable pedestal. The implementation will also require a new risk assessment and ergonomic evaluation. This will cost both money and time. The implementation is likely to lead to new production errors which cannot be predicted in this thesis.

6.12 Method

The method used in this thesis was largely dictated by the standards or available information and therefore could not be changed. However, the concept generation, decision matrices and the verification of the production rate was not strictly necessary and could perhaps have been replaced by other methods.

To generate the final concept decision matrices and a morphological matrix was used, this made it so that the authors could choose a final concept which could then be further developed. This was perhaps unnecessary since the different concepts did not differ so much between each other. As such the other concepts would likely have yielded a similar result. Therefore, it might have been better to simply choose a concept, since it took a lot of time creating the decision matrices, however it was still a good way for the authors to start the thesis. At the start of the thesis the authors knowledge about collaborative robots was very limited. Therefore, using a familiar method made it so that the authors could focus more on learning about collaborative robots. Using the decision matrices also made sure that the final concept was chosen without bias.

The verification of the production rate confirmed that the results from the visualisation was accurate. This however took a lot of time which could perhaps have been better spent on the risk assessment making it closer to a full risk assessment.

7. Conclusion

In this segment the project is analysed and compared with the requirement specification. At the end of this segment the authors of this thesis present their recommendations.

7.1 Analysis of requirements and desirables

In table 18 and 19 the evaluation of the requirement respectively the desirables can be seen. For the requirements 13 out of 13 have been fulfilled. However, this is not surprising due to the concept not being eliminated in the elimination matrix. For the desirables 9 out of 11 have been fulfilled. The desirable producer ABB is not met due to the collaborative robot in the final concept being a FANUC CRX-25iA. For the desirable decrease strain on operator 2 the number of tasks remain the same in the new working station as in the current one. However, 9 out of 11 fulfilled desirables is something the authors are satisfied with, especially for the production rate and error rate.

In summary the evaluation of the requirement specification is seen as a success due to all requirements being fulfilled and most of the desirables being fulfilled.

Table 18: Evaluation of the requirements from the requirement specification.

Requirements	Target value	Unit	Method of verification	Requirement fulfilled: Yes/No
Repeatability	0,1	mm	Robot datasheet	Yes
Reach	1575	mm	Robot datasheet	Yes
Payload	15	kg	Robot datasheet	Yes
Speed (tool center point)	0,87	mm/s	Robot datasheet	Yes
Degree of freedom	K-,Y- and Z-directio	Degree of freedom	Robot datasheet	Yes
Mounting horisontaly	Yes	Yes/No	Robot datasheet	Yes
EN ISO 13849-1	Yes	Yes/No	Robot datasheet	Yes
EN ISO 10218-1	Yes	Yes/No	Robot datasheet	Yes
Mirrors for D11,D13 and D16	Yes	Yes/No	Indication from visualisation	Yes
Emergency stop for button for robot	Yes	Yes/No	Indication from visualisation	Yes
Geometric constraint x-direction	<1220	mm	Measurements	Yes
Geometric constraint y-direction	<4160	mm	Measurements	Yes
Geometric constraint z-direction	<3700	mm	Measurements	Yes

Table 19: Evaluation of the desirables from the requirement specification.

Desireables	Target value	Unit	Method of verification	Desireables fulfilled: Yes/No
Production rate	25,35	Units/hour	Indication from visualisation	Yes
Error rate	Lower	% of total units	Indication based on error data	Yes
Cost	<200000	I	Robot datasheet	Yes
Mounting vertically	Yes	Yes/No	Robot datasheet	Yes
Producer ABB	Yes	Yes/No	Robot datasheet	No
Less bending of back right side OP1	<17	Bends per batch	Indication from visualisation	Yes
Less bending of back left side OP1	<11	Bends per batch	Indication from visualisation	Yes
Decrease strain on OP1	<19	Number of tasks made	Indication from visualisation	Yes
Decrease strain on OP2	<10	Number of tasks made	Indication from visualisation	No
Movable robot	Yes	Yes/No	Indication from visualisation	Yes
Allow manual gluing	Yes	Yes/No	Indication from visualisation	Yes

7.2 Evaluation of the deliverables

In segment 1.5 the deliverables are presented. The deliverables were the following:

1. **The thesis should lead to a solution which is implemented virtually.**

In the first deliverable a visualisation of the new workstation was created using Visual Components. From the visualisation an estimated production rate could be acquired. However, a video of the visualisation is not presented in the thesis, but the result and discussion are presented in segment 5.1 respectively 6.1.

2. **An assessment of the risk between collaborative robot, human, and equipment.**

In the second deliverable a simplified risk assessment was created where all thinkable risks between human, robot and equipment was treated. With the risk assessment the collaborative robot speed and force could be calculated. The risk assessment´s result and discussion are presented in segment 5.7 respectively 6.4. The full risk assessment is presented in attachment 6-9.

3. **Advantages and disadvantages with the application of collaborative robots within the scope of the D6 cylinder head sand core mounting.**

The third deliverable is presented in segment 6.5. A summary was created of the advantages and disadvantages found in the thesis regarding the implementation of collaborative robots for the workstation. The advantages are more prominent than the disadvantages.

In summary all the deliverables have been delivered and are presented in the various chapters stated above.

7.3 Recommendation

An implementation of the new workstation would most likely lead to the elimination of the D6 cylinder head bottle neck which will allow an increased production rate. The quality outcome is also likely to improve when it comes to gluing errors which are a significant proportion of the error rate for the D6 cylinder head production. The simplified risk assessment shows that the changes proposed in this thesis can be implemented with acceptable risks to the operators and property of Volvo. The ergonomics of the workstation will improve resulting in a better working environment for the operators. The increased production rate is estimated to pay for the investment of the robots in a short time span. The exact time span is not known since the profit per part is not known. However, considering the production volumes involved, the authors of this thesis assess this to be the case. The collaboratives robots implemented for the D6 cylinder head production will also be used for the D4 cylinder head production. As such all the benefits that apply to the D6 cylinder head production will most likely also apply to the D4 cylinder head production even though the D4 cylinder head production is out the scope for this thesis. The implementation of collaborative robots at the D6 working station will also come with the benefit of improving the knowledge about collaborative robots at Volvo Powertrain in Skövde. This will enable easier implementation of collaborative robots elsewhere in the production plant. Since the manual gluing equipment will be kept this implementation will not limit the flexibility of the workstation.

The main drawback of implementing collaborative robots at the workstation is the implementation cost. This cost however is assessed to be repaid in a relatively quick manner. The implementation of collaborative robots is also likely to lead to new problems as with any change. With the result, discussion, advantages and disadvantages of the new workstation in mind. The recommendation of the authors is that an implementation of the new workstation should be performed.

7.4 The next step

The next step in implementing the proposed solution would be to do a full risk assessment and begin planning of a detailed construction of the new workstation. A new economic analysis must be made using all the required information. The equipment must be purchased and then the final shaping of the proposed solution must be done making sure that it complies with all applicable standards and then the solution can be implemented fully.

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9. Attachments

Attachment 1, Derivation of payback time

Derivation

$NPR = New\ Production\ Rate$

$PR = Current\ Produiction\ Rate$

$Part\ Cost = Production\ Cost\ of\ Mould\ Excluding\ Salary\ for\ operator\ at\ station.$

$Implementation\ Cost = Cost\ To\ Implement\ Proposed\ Solution$

$$Y = \frac{NPR}{PR}$$

$$\frac{PR * Time * Part\ Cost + Salary * Time}{PR * Time} = \frac{Production\ Cost\ Current}{PR * Time}$$

$$\frac{Implementation\ Cost + NPR * Part\ Cost * Time}{NPR * Time} = \frac{New\ Production\ Cost}{NPR * Time}$$

$$\frac{Implementation\ Cost + NPR * Part\ Cost * Time + Salary * Time}{NPR * Time} - \frac{PR * Time * Part\ Cost + Salary * Time}{PR * Time} = 0$$

$$\frac{Implementation\ Cost + NPR * Part\ Cost * Time + Salary * Time}{NPR} = \frac{PR * Time * Part\ Cost + Salary * Time}{PR}$$

$$Implementation\ Cost = \frac{(PR * Time * Part\ Cost + Salary * Time) * NPR}{PR} - (NPR * Part\ Cost * Time + Salary * Time)$$

$$Implementation\ Cost = \left(\frac{(PR * Part\ Cost + Salary) * NPR}{PR} - NPR * Part\ Cost + Salary\right) * Time$$

$$\frac{Implementation\ Cost}{\frac{(PR * Part\ Cost + Salary) * NPR}{PR} - NPR * Part\ Cost + Salary} = Time$$

$NPR = Y * PR$

$$\frac{Implementation\ Cost}{\frac{(PR * Part\ Cost + Salary) * Y * PR}{PR} - Y * PR * Part\ Cost + Salary} = Time$$

$$\frac{Implementation\ Cost}{(PR * Part\ Cost + Salary) * Y - Y * PR * Part\ Cost + Salary} = Time$$

$$\frac{Implementation\ Cost}{Salary * Y - Salary} = Time$$

$$\frac{Implementation\ Cost}{Salary * (Y - 1)} = Time$$

Attachment 2, Force and speed calculations

```python
import numpy as np

A=1e-4 # Area of contact
Ps=1e4*np.array([130,110,110,140,210,160,210,120,170,
                   140,210,190,220,190,180,180,300,270,
                   280,220,200,260,260,200,190,250,220,
                   220,210]) #Max Pressure quasi static
Pt=2*Ps # Max pressure transient
Fs=np.array([130,130,65,150,150,210,210,140,140,110,180,
             150,150,160,160,160,140,140,140,140,140,140,
             140,140,140,140,220,220,130]) #Max force quasi static
Ft=2*Fs # Max Force transient
K=10**3*np.array([150,150,75,50,50,35,35,25,25,
                  10,25,30,30,40,40,40,75,75,75,
                  75,75,75,75,75,75,50,50,60,60]) # Spring constant
mh=np.array([4.4,4.4,4.4,1.2,1.2,40,40,40,40,
             40,3,3,2,2,2,0.6,0.6,0.6,0.6,0.6,
             0.6,0.6,0.6,0.6,75,75,75,75]) # Body part mass
M=112
 # robot joint mass
ml=15 #Payload mass (glue gun)

EPs=A**2*Ps*Ps/(2*K) #max energy as of quasi static Pressure
EPt=A**2*Pt*Pt/(2*K) #max energy as of transient Pressure

EFs=Fs*Fs/(2*K) #max energy as of quasi static Force
EFt=Ft*Ft/(2*K) #max energy as of  transient Force
mr=M/2+ml
my=1/(1/mh+1/mr)


# max velocity

VPs=np.sqrt(2*EPs/my) # max v as of quasi-static Pressure
VPt=np.sqrt(2*EPt/my) # max v as of transient pressure
VFs=np.sqrt(2*EFs/my) # max v as of quasi static Force
VFt=np.sqrt(2*EFt/my) # max v as of transient Force

# Maximum force

FPs=np.sqrt(EPs*2*K) # max kraft as of quasi static Pressure
FPt=np.sqrt(EPt*2*K) # max kraft as of transient pressure
FFs=np.sqrt(EFs*2*K) # max kraft as of quasi static Force
FFt=np.sqrt(EFt*2*K) # max kraft as of transient Force


print(VPs)
print(VPt)
print(VFs)
print(VFt)

print(FPs)
print(FPt)
print(FFs)
print(FFt)
```

Attachment 3, Robot speed

Part of body/Velocity	Quasi static maximum permissible velocity as of pressure	Transient maximum permissible velocity as of pressure	Quasi static maximum permissible velocity as of force	Transient maximum permissible velocity as of force
Middel of forehead	0,1649	0,3298	0,1649	0,3298
Temple	0,1395	0,2791	0,1649	0,3298
Masticatory muscle	0,1973	0,3947	0,1166	0,2332
Neck muscle	0,5764	1,1527	0,6175	1,2351
Seventh neck vertebra	0,8645	1,7291	0,6175	1,2351
Shoulder joint	0,1691	0,3382	0,2219	0,4438
Fifth lumbar vertebra	0,2219	0,4438	0,2219	0,4438
Sternum	0,1500	0,3001	0,1750	0,3501
Pectoral muscle	0,2126	0,4251	0,1750	0,3501
Abdominal muscle	0,2768	0,5536	0,2175	0,4349
Pelvic Bone	0,2626	0,5251	0,2251	0,4501
Deltoid muscle	0,6466	1,2932	0,5105	1,0209
Humerus	0,7487	1,4973	0,5105	1,0209
Radial bone	0,6811	1,3623	0,5736	1,1472
Forearm muscle	0,6453	1,2906	0,5736	1,1472
Arm nerve	0,6453	1,2906	0,5736	1,1472
Forefinger pad D	1,4202	2,8404	0,6627	1,3255
Forefinger pad ND	1,2782	2,5563	0,6627	1,3255
Forefinger end joint D	1,3255	2,6510	0,6627	1,3255
Forefinger end joint ND	1,0415	2,0829	0,6627	1,3255
Thenar emininence	0,9468	1,8936	0,6627	1,3255
Palm D	1,2308	2,4616	0,6627	1,3255
Palm ND	1,2308	2,4616	0,6627	1,3255
Back of the hand D	0,9468	1,8936	0,6627	1,3255
Back of the hand ND	0,8994	1,7989	0,6627	1,3255
Thigh muscle	0,1851	0,3703	0,1037	0,2073
Kneecap	0,1629	0,3258	0,1629	0,3258
Middle of shin	0,1487	0,2974	0,1487	0,2974
Calf muscle	0,1420	0,2839	0,0879	0,1758

Attachment 4, Robot force

Part of body/Force	Quasi static maximum permissible force as of pressure	Transient maximum permissible force as of pressure	Quasi static maximum permissible force as of force	Transient maximum permissible force as of force
Middel of forehead	130	260	130	260
Temple	110	220	130	260
Masticatory muscle	110	220	65	130
Neck muscle	140	280	150	300
Seventh neck vertebra	210	420	150	300
Shoulder joint	160	320	210	420
Fifth lumbar vertebra	210	420	210	420
Sternum	120	240	140	280
Pectoral muscle	170	340	140	280
Abdominal muscle	140	280	110	220
Pelvic Bone	210	420	180	360
Deltoid muscle	190	380	150	300
Humerus	220	440	150	300
Radial bone	190	380	160	320
Forearm muscle	180	360	160	320
Arm nerve	180	360	160	320
Forefinger pad D	300	600	140	280
Forefinger pad ND	270	540	140	280
Forefinger end joint D	280	560	140	280
Forefinger end joint ND	220	440	140	280
Thenar emininence	200	400	140	280
Palm D	260	520	140	280
Palm ND	260	520	140	280
Back of the hand D	200	400	140	280
Back of the hand ND	190	380	140	280
Thigh muscle	250	500	140	280
Kneecap	220	440	220	440
Middle of shin	220	440	220	440
Calf muscle	210	420	130	260

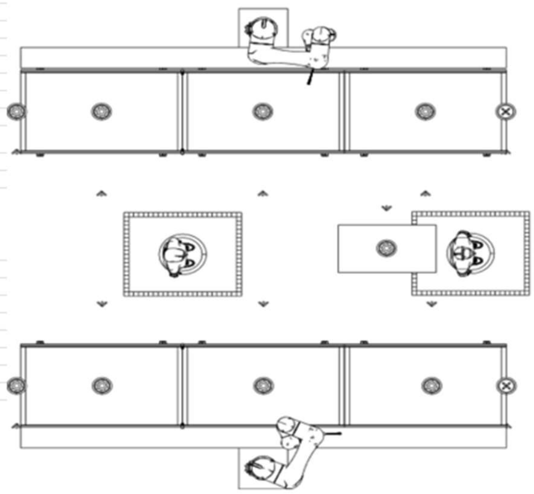
Attachment 5, Solutions

generated-solution-0001	generated-solution-0002	generated-solution-0003	generated-solution-0004	generated-solution-0005	generated-solution-0006
Glue gun	Glue gun	Glue gun	Glue gun	Glue gun	Glue gun
position 1	position 2	position 3	position 1	position 2	position 3
Camera	Camera	Camera	Camera	Camera	Camera
FANUC CRX-25iA	FANUC CRX-25iA	FANUC CRX-25iA	UR20	UR20	UR20
Movable placement	Movable placement	Movable placement	Movable placement	Movable placement	Movable placement
generated-solution-0007	generated-solution-0008	generated-solution-0009	generated-solution-0010	generated-solution-0011	generated-solution-0012
Glue gun	Glue gun	Glue gun	Glue gun	Glue gun	Glue gun
position 1	position 2	position 3	position 1	position 2	position 3
Camera	Camera	Camera	Camera	Camera	Camera
ABB CRB1300-7/14	ABB CRB1300-7/14	ABB CRB1300-7/14	DENSO COBOTTA PRO	DENSO COBOTTA PRO	DENSO COBOTTA PRO
Movable placement	Movable placement	Movable placement	Movable placement	Movable placement	Movable placement
generated-solution-0013	generated-solution-0014	generated-solution-0015	generated-solution-0016	generated-solution-0017	generated-solution-0018
Glue gun	Glue gun	Glue gun	Glue gun	Glue gun	Glue gun
position 1	position 2	position 3	position 1	position 2	position 3
Camera	Camera	Camera	Camera	Camera	Camera
YASKAWA HC20DTP	YASKAWA HC20DTP	YASKAWA HC20DTP	KUKA LBR iisy R1300	KUKA LBR iisy R1300	KUKA LBR iisy R1300
Movable placement	Movable placement	Movable placement	Movable placement	Movable placement	Movable placement
generated-solution-0019	generated-solution-0020	generated-solution-0021	generated-solution-0022	generated-solution-0023	generated-solution-0024
Glue gun	Glue gun	Glue gun	Glue gun	Glue gun	Glue gun
position 1	position 2	position 3	position 1	position 2	position 3
Camera	Camera	Camera	Camera	Camera	Camera
DOOSAN M1013	DOOSAN M1013	DOOSAN M1013	FANUC CRX-25iA	FANUC CRX-25iA	FANUC CRX-25iA
Movable placement	Movable placement	Movable placement	Fixed placement	Fixed placement	Fixed placement
generated-solution-0025	generated-solution-0026	generated-solution-0027	generated-solution-0028	generated-solution-0029	generated-solution-0030
Glue gun	Glue gun	Glue gun	Glue gun	Glue gun	Glue gun
position 1	position 2	position 3	position 1	position 2	position 3
Camera	Camera	Camera	Camera	Camera	Camera
UR20	UR20	UR20	ABB CRB1300-7/14	ABB CRB1300-7/14	ABB CRB1300-7/14
Fixed placement	Fixed placement	Fixed placement	Fixed placement	Fixed placement	Fixed placement
generated-solution-0031	generated-solution-0032	generated-solution-0033	generated-solution-0034	generated-solution-0035	generated-solution-0036
Glue gun	Glue gun	Glue gun	Glue gun	Glue gun	Glue gun
position 1	position 2	position 3	position 1	position 2	position 3
Camera	Camera	Camera	Camera	Camera	Camera
DENSO COBOTTA PRO	DENSO COBOTTA PRO	DENSO COBOTTA PRO	YASKAWA HC20DTP	YASKAWA HC20DTP	YASKAWA HC20DTP
Fixed placement	Fixed placement	Fixed placement	Fixed placement	Fixed placement	Fixed placement
generated-solution-0037	generated-solution-0038	generated-solution-0039	generated-solution-0040	generated-solution-0041	generated-solution-0042
Glue gun	Glue gun	Glue gun	Glue gun	Glue gun	Glue gun
position 1	position 2	position 3	position 1	position 2	position 3
Camera	Camera	Camera	Camera	Camera	Camera
KUKA LBR iisy R1300	KUKA LBR iisy R1300	KUKA LBR iisy R1300	DOOSAN M1013	DOOSAN M1013	DOOSAN M1013
Fixed placement	Fixed placement	Fixed placement	Fixed placement	Fixed placement	Fixed placement

Attachment 6, Risk assessment prerequisites

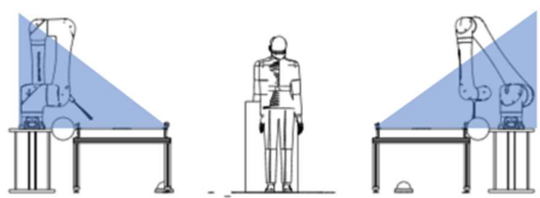
	Fall 1
What does the workstation layout look like? (picture)	See pictures in this Excel-sheet
What objects are there? (how many, dimensions, weight, fixed/movable)	Robot Fanuc Crx25iA, Rotating mass 112 kg, Weight 135 kg. (Fanuc, 2020) Robotbase Conveyor belts Lower mould pallet Black cores pallet White cores pallet Special lifting tool for black cores.
Machines at the station (objects that move with other than human power, require CE marking)	Fanuc 135iA Conveyor belt
People nearby workstation (how many,	* Operators (2) * Pedestrians, passing outside the surface. * Forklift driver, passing outside the surface.
What areas are there? (divide into coordinates or parts of the surface)	Z1. Robot-zone Z2. Operator-zone Z3. Forklift drive-zone Z4. Pedestrian zone
Characteristics of the product being handled (material, weight, sharp edges)	* Sand

Layout

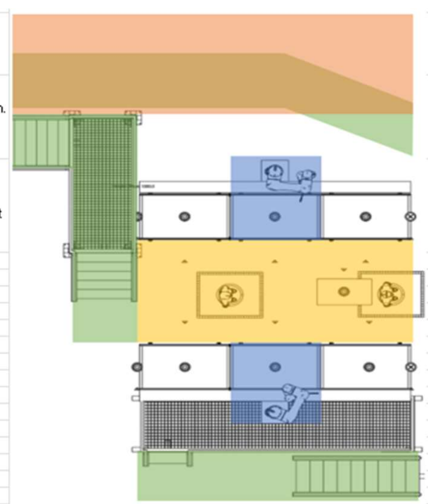


Description of the basic work step (list sequences, in correct order, with connection between parts)	* Pallets comes into workstation * Lower mould gets scanned * OP2 picks & starts assemblying black cores in mounting tool * OP1 starts gluing sequence 1 * OP1 picks & assembles the bottom white cores * OP1 starts gluing sequence 2 * OP2 assembles the black core package in the lower mould with the mounting tool * OP1 checks quality of black core mounting * OP1 starts gluing sequence 3 * OP2 picks & starts assembling black cores in mounting tool on the other side * OP1 picks & assembles top part of white cores * OP1 starts gluing sequence 1 on the other side * OP1 picks & assembles the bottom white cores * OP1 sends away first batch of assembled sand cores. * The process repeats For more detailed description of the working flow see picture of process flow in thesis.

Arbetszoner



Reguirements for safety equipment	Safety shoes and gloves
Rules regarding the work station (e.g. Forklifttrafic)	* Only trained operators on the working station.
Limitations	The basic assumption is that the robot is installed, but without any safety measures, without movement restrictions and at full robot speed



Attachment 7, Risk analysis preventative measures

Number	Standard preventive measure	Description	
1/1*	Force limiting	The robot force is limited using power and force limiting according to ISO 15066.	*=The robot speed and force is not reduced by this body part. The speed and or force is instead limited by other body parts. This is done in order to avoid unnecessary limiting of the robot speed and force. Because if the probability is low enough then it can be deemed acceptable with a higher concequence.
2/2*	Reduced robot speed	The robot speed is reduced using Power and force limiting according to ISO 15066.	
3	Safe programming	Robot is programmed so that it moves with a low profile minimizing risk of impact to the head.	
4	Protective housing	Protective housing around glue gun, increasing impact area and protects glue gun, and operator from hot glue gun.	
5	Position switch	Switch that is activated when a component is in a certain position. If switch is not active then robot cannot start.	
6	Physical barrier	Fences that hinders humans from entering a restricted space	
7	Contact stop function	When the external force exceeds the active force limit, the robot will stop.	
8	Push to escape	When the robot is pushed the robot moves in the pushed direction (works for J1,J2 & J3).	
9	Retreat after contact stop	When the robot is stopped by the contact stop and a strong force is remaining, the robot will retreat slightly.	
10	Glue button	Button that the operator press when the operator wants the robot to glue.	
11	Protective equipment	Operator wears glowes, protective clothing, Safety shoes, long sleeved clothing.	
12	Designated workspace	Robot may only move in its designated workspace.	
13	Documentation/information	It is documented what is expected of the operator and how to act in foreseen non normal situations.	
14	Inspection	Routine inspection of components in the station.	
15	Reset to start	In case of loss of power, the robot will require a reset berore it can resume it's task, after the power has returned.	
16	Scanning of robot	When the scanner scans. It scans both the robot and lower mould making sure that the robot will know it's relative position to the mould.	
17	Keep manual gluing	The equipment used for manual gluing is retained.	
18	Emergency stop	Emergency stop configured as a trip wire that will activate if a person falls over the conveyor belt	
19	Guide rails	Guide rails for robot.	
20	Glue	Glue with longer drying time.	
21	Work zone	The robot cannot move outside of the work zone.	

Attachment 8, Risk assessment part 1

Number	Scenario	Risk		Probability	Reasoning Probability	Consequence	Reasoning consequence	Risk value
1	**Human is in collaborative robot movement path/working area**							
1.1	**Quasi static Contact**		**Body part number**					
1.1.1	Middel of forehead	Entrapment between collaborativ robot and lower mould/pallet.	1	2	Operator head must be entrapped between robot and lower mould to be entrapped. Operator bends over and robot presses head into lower mould.	5	Consequence 5 because entrapment of forehead may crack skull.	10
1.1.2	Temple	Entrapment between Collaborative robot and lower mould/pallet.	2	2	See 1.1.1	5	Consequence 5 because entrapment of tempel may crack skull.	10
1.1.3	Masticatory muscle	Entrapment between collaborative robot and lower mould/pallet.	3	2	See 1.1.1	5	Consequense 5 because may crack jaw and injure head.	10
1.1.4	Neck muscle	Entrapment between Collaborative robot and lower mould/pallet.	4	2	See 1.1.1	5	Consequence 5 because of risk of suffocation.	10
1.1.5	Seventh neck vertebra	Entrapment between collaborative robot and lower mould/pallet.	5	2	See 1.1.1	5	Consequence 5 beacause may cause paralysation.	10
1.1.6	Shoulder joint	Entrapment between collaborative robot and lower mould/pallet.	6	2	Operator must bend over and robot must start simultaniusly, operator can easily escape.	4	Consequence 4, may result in permanent nerve muscle or tendon damage.	8
1.1.7	Fifth lumbar vertebra	Entrapment between collaborative robot and lower mould/pallet.	7	1	Operator must lay on the conveyer belt.	5	Consequense 5, because may cause paralysation.	5
1.1.8	Sternum	Entrapment between collaborative robot and lower mould/pallet.	8	1	Operator must be entrapped and pressed by the robot on the chest, this is only possible if the operator lays on the lower mould with his back. Since when calculating maximum preassure an area of 1cm^2 is used which is the glue gun the area of the lower mould is much bigger and as such the load is spread and operator will not be hurt	4	Consequense 4 because unlikely to cause permanent damage because of ribcage.	4
1.1.9	Pectoral muscle	Entrapment between collaborative robot and lower mould/pallet.	9	1	see 1.1.8	4	Consequense 4 because ribcage will likely prevent permanent injury.	4
1.1.10	Abdominal muscle	Entrapment between collaborative robot and lower mould/pallet.	10	1	see 1.1.8	4	Consequense 4 because may cause sick leave for about a week.	4
1.1.11	Pelvic Bone	Entrapment between collaborative robot and lower mould/pallet.	11	1	see 1.1.7	3	Consequense 3, pelvic bone will not break, will only cause lighter damage such as soft tissue damage.	3
1.1.12	Deltoid muscle	Entrapment between collaborative robot and lower mould/pallet.	12	2	see 1.1.6	3	Consequence 3, likely that operator will be back in about a week.	6
1.1.13	Humerus	Entrapment between collaborative robot and lower mould/pallet.	13	3	Operator reaches out and robot traps humerus, more likely since arm often is above the lower mould.	3	Consequense 3, entrapment will likely cause lighter damage to muscle and or tissue.	9
1.1.14	Radial bone	Entrapment between collaborative robot and lower mould/pallet.	14	4	Operator works in the lower mould while the robot is gluing. This makes it likely that that operators radial bone will be entrapped.	3	Risk of soft tissue damage unliky to cause damage to bone.	12

1.1.15	Forearm muscle	Entrapment between collaborativ robot and lower mould/pallet.	15	3	Forearm muscle is often near the lower mould while the robot is gluing, it is however a distance away from the robot tcp.	3	Risk of tissue damage unlikely to cause damage to bone.	9
1.1.16	Arm nerve	Entrapment between cobot and lower mould/pallet.	16	3	see 1.1.15	3	Risk of tissue damage unlikely to cause damage to bone.	9
1.1.17	Forefinger pad D	Entrapment between collaborativ robot and lower mould/pallet.	17	4	Biggest risk when operator is trying to correct somthing that will be glued.	4	Risk of bone fracture.	16
1.1.18	Forefinger pad ND	Entrapment between collaborativ robot and lower mould/pallet.	18	4	see 1.1.17	4	Risk of bone fracture.	16
1.1.19	Forefinger end joint D	Entrapment between collaborativ robot and lower mould/pallet.	19	4	see 1.1.17	4	Risk of bone fracture.	16
1.1.20	Forefinger end joint ND	Entrapment between collaborativ robot and lower mould/pallet.	20	4	see 1.1.17	4	Risk of bone fracture.	16
1.1.21	Thenar emininence	Entrapment between collaborativ robot and lower mould/pallet.	21	4	see 1.1.17	4	Risk of bone fracture.	16
1.1.22	Palm D	Entrapment between collaborative robot and lower mould/pallet.	22	4	see 1.1.17	3	Risk of tissue damage unlikely to cause damage to bone.	12
1.1.23	Palm ND	Entrapment between collaborative robot and lower mould/pallet.	23	4	see 1.1.17	3	Risk of tissue damage unlikely to cause damage to bone.	12
1.1.24	Back of the hand D	Entrapment between collaborative robot and lower mould/pallet.	24	4	see 1.1.17	3	Risk of tissue damage unlikely to cause damage to bone.	12

1.1.24	Back of the hand D	Entrapment between collaborative robot and lower mould/pallet.	24	4	see 1.1.17	3	Risk of tissue damage unlikely to cause damage to bone.	12
1.1.25	Back of the hand ND	Entrapment between collaborative robot and lower mould/pallet.	25	4	see 1.1.17	3	Risk of tissue damage unlikely to cause damage to bone.	12
1.1.26	Thigh muscle	Entrapment between collaborative robot and lower mould/pallet.	26	1	see 1.1.7	3	Risk of tissue damage unlikely to cause damage to bone.	3
1.1.27	Kneecap	Entrapment between collaborative robot and lower mould/pallet.	27	1	Is protected by conveyor belt.	3	Risk of tissue damage, unlikely to cause damage to bone or permanent damage to tendon or displacement of kneecap.	3
1.1.28	Middle of shin	Entrapment between collaborative robot and lower mould/pallet.	27	1	Is protected by conveyor belt.	3	Risk of tisse damage unlikely to cause damage to bone.	3
1.1.29	Calf muscle	Entrapment between collaborative robot and lower mould/pallet.	29	1	Is protected by conveyor belt.	3	Risk of tisse damage unlikely to cause damage to bone.	3
1.2	**Transient contact**							
1.2.1	Middel of forehead	Collision between collaborative robot and operator.	1	3	Robot only need to touch head compare with 1.1.1.	5	Risk of cracked skull.	15
1.2.2	Temple	Collision between collaborative robot and operator.	2	3	see 1.2.1	5	Risk of cracked skull.	15
1.2.3	Masticatory muscle	Collision between collaborative robot and operator.	3	3	see 1.2.1	5	May crack jaw or damage skull.	15
1.2.4	Neck muscle	Collision between collaborative robot and operator.	4	3	see 1.2.1	5	May cause paralysation or permanent brain damage or death.	15
1.2.5	Seventh neck vertebra	Collision between collaborative robot and operator.	5	3	see 1.2.1	5	May cause paralysation.	15
1.2.6	Shoulder joint	Collision between collaborative robot and operator.	6	3	Robot only needs to touch shoulder, no operator bending required.	4	May cause bone fracture.	12
1.2.7	Fifth lumbar vertebra	Collision between collaborative robot and operator.	7	2	If operator turns around and leans on conveyor belt robot may impact.	5	May cause paralysation.	10
1.2.8	Sternum	Collision between collaborative robot and operator.	8	3	The sternum has a big area and is close to the robot path it is also hard to dodge the robot.	4	May fracture ribcage.	12
1.2.9	Pectoral muscle	Collision between collaborative robot and operator.	9	3	See. 1.2.8 but smaller area.	4	May fracture ribcage.	12

1.2.10	Abdominal muscle	Collision between collaborative robot and operator.	10	3	Big area and is close to the robot path and har to dodge.	4	May cause internal bleeding and or damage to organs.	12
1.2.11	Pelvic Bone	Collision between collaborative robot and operator.	11	2	Close to robot path but always outside of i,t robot will only hit if robot makes erratic moves or if operator sits or lays on lower mould.	4	May fracture bone.	8
1.2.12	Deltoid muscle	Collision between collaborative robot and operator.	12	3	Operator leans in to perform moments but easy to dodge.	3	May soft tissue damage.	9
1.2.13	Humerus	Collision between collaborative robot and operator.	13	3	Humerus i close to robot path.	3	May cause soft tissue damage.	9
1.2.14	Radial bone	Collision between collaborative robot and operator.	14	5	Radial bone is very close to robot path and may accidently be thrown into it.	4	May cause bone fracture.	20
1.2.15	Forearm muscle	Collision between collaborative robot and operator.	15	3	Close to robot working path.	3	May cause soft tissue damage.	9
1.2.16	Arm nerve	Collision between collaborative robot and operator.	16	3	Close to robot working path.	4	May cause damage to nerves.	12
1.2.17	Forefinger pad D	Collision between collaborative robot and operator.	17	5	See 1.2.14	4	Risk of bone fracture.	20
1.2.18	Forefinger pad ND	Collision between collaborative robot and operator.	18	5	See 1.2.14	4	Risk of bone fracture.	20
1.2.19	Forefinger end joint D	Collision between collaborative robot and operator.	19	5	See 1.2.14	4	Risk of bone fracture.	20
1.2.20	Forefinger end joint ND	Collision between collaborative robot and operator.	20	5	See 1.2.14	4	Risk of bone fracture.	20
1.2.21	Thenar emininence	Collision between collaborative robot and operator.	21	5	See 1.2.14	4	Risk of bone fracture.	20
1.2.22	Palm D	Collision between collaborative robot and operator.	22	5	See 1.2.14	4	Risk of bone fracture.	20
1.2.23	Palm ND	Collision between collaborative robot and operator.	23	5	See 1.2.14	4	Risk of bone fracture.	20

1.2.24	Back of the hand D	Collision between collaborative robot and operator.	24	5	See 1.2.14	4	Risk of bone fracture.	20
1.2.25	Back of the hand ND	Collision between collaborative robot and operator.	25	5	See 1.2.14	4	Risk of bone fracture.	20
1.2.26	Thigh muscle	Collision between collaborative robot and operator.	26	1	Is protected by conveyor belt.	4	Risk of bone fracture.	4
1.2.27	Kneecap	Collision between collaborative robot and operator.	27	1	Is protected by conveyor belt.	4	Risk of bone fracture or displacement of kneecap.	4
1.2.28	Middle of shin	Collision between collaborative robot and operator.	27	1	Is protected by conveyor belt.	4	Risk of bone fracture.	4
1.2.29	Calf muscle	Collision between collaborative robot and operator.	29	1	Is protected by conveyor belt.	4	Risk of bone fracture.	4
2	**Items in the robots movement path/working area**							
2.1	Telfer	Robot collides with telfer.		3	Operator may forget to remove telfer from operating area.	2	May cause minor damage to telfer and robot which need reparing at a later time.	6
2.2	Telfer entangles with glue hose.	Glue hose,telfer and robot takes damage.		2	Omperator must forget to remove telfer and then the robot must entangle itslef in the glue hose.	3	Hose breaks and production line will run at half speed.	6
2.3	Robot entagles with glue hose.	Production stop (to untangle glue hose, glue hose does not break).		2	Will not happen if properly programmed, unless robot makes erratic movements.	2	Production stops temporarily.	4
2.4		Glue hose takes damage.		2	Large chance to break if entangled.	3	See 2.2	6
2.5	Mounting tool is in robots movement path/working area.	Robot collides with mounting tool.		2	Operator will rarely forget mounting tool in robot path.	2	Might cause lighter repair work but unlikely to halt production.	4
2.6	Forklift is in robots movement path/working area	Robot collides with forklift behind station		1	Forklift is in a position where it should not be and robot makes erratic movements.	2	Might cause lighter repair work but unlikely to halt production.	2
2.7	Forklift drives to close to robot and/or robot stand.	Forklift collides with robot and/or robot stand.		2	Forklift drives into robot.	5	Likely to destroy robot causing mayor damage and long production stop.	10
3	**Robot makes unpredicted movements**							
3.1	Robot crashes into lower mould.	Glue gun breakes.		1	Robot unlikely to make erratic movements.	4	Will halt or reduce production untill new glue gun is delivered.	4
3.2		Mould brakes		1	Robot unlikely to make erratic movements.	1	Mould is destroyed neglible impact on production.	1

3.3	Robot pushes lower mould of the pallet.	Operator is hit by mould		1	Robot unlikely to make erratic movements.	4	Mould is very heavy risk of bone fracture unlikely to hit head.	4
3.4		Mould brakes.		1	Robot unlikely to make erratic movements.	2	Mould must be romeved from work station, which will halt production for a short amount of time.	2
3.5	Robot collides into white cores	White cores breaks.		2	Operator mounts core incorrectly and or robot makes erratic movements.	1	Minor material damage, neglible impact on production.	2
3.6	Robot collides into black cores	Black cores breaks		2	Operator mounts core incorrectly and or robot makes erratic movements.	1	Minor material damage neglible impact on production.	2
3.7	Robot collides into white cores held by operator.	Hand injury (hits white core not hand).		3	Operator mount sandcores in the robot working area while the robot is gluing.	2	May cause light damage since white core protects hand.	6
3.8		White core breakes.		3	Operator mount sandcores in the robot working area while the robot is gluing.	1	Minor material damage.	3
3.9	Robot collides into white cores held by operator.	Hand injury (hits black core not hand).		3	Operator mount sandcores in the robot working area while the robot is gluing.	2	May require bandage on hand but operator can resume work.	6
3.10		Black cores breaks.		3	Operator mount sandcores in the robot working area while the robot is gluing.	1	Minor material damage, neglible production stop.	3
3.11	Robot collides into blackcores held in the mounting tool held by the operator.	Hand injury (hits black core not hand).		1	Unlikely to hit black cores and black cores + mounting tool acts as a buffert between robot and hand.	2	May require bandage on hand but operator can resume work.	2
3.12		Black core breakes.		2	Mounting tool is held outside robot path while waiting to be assembled.	1	Minor material damage neglible impact on production.	2
3.13	Robot collides into mounting tool held by operator.	Operator gets injured.		1	Mounting tool is held outside robot path, while waiting to be assembled and acts as a buffert between hand and robot.	2	May cause light damage since mounting tool protects the operator.	2
3.14		Black core breakes.		1	Mounting tool is held outside robot path, while waiting to be assembled and acts as a buffert between black cores and robot.	1	Minor material damage neglible impact on production.	1
3.15	Robot collides with the mounting tool cables.	Cables takes damage		2	Robot may hit cables as a result of operator error.	3	May break the mounting tool resulting in a short production stop for both sides, will require immidiate repair but uses of the shelves parts and will be fast to reapir, it should not take more than a day.	6
3.16	Robot collides with traverse.	Traverse takes damage.		1	Requires robot to make erratic movements.	4	Production will stop until traverse is repaired.	4
3.17	Robot collides with human behind station.	Operator gets injured (refer to 1 and 2).		2	Human may be impacted if working behind robot.	5	May cause death.	10
3.18	Robot collides with mirror.	Mirror takes damage		2	May be hit if operator forget to slide away mirror from robot since mirror will break if hit. Operators are unlikely to forget to remove the mirror.	2	Mirror breaks but hand held mirrors can be used while waiting for a replacement mirror.	4
3.19	Robot collides with airduct.	Airduct takes damage.		1	Requires robot to make erratic movements.	3	Reduces production efficiency for up to a day only one side can be used.	3
4	Operator is in the robot workspace while robot dispense glue.							

4.1	Operator holds body part below glue gun.	Operator gets burns on glue.		4	Operator mounts cores while the robot is gluing.	2	Minor burns.	8
4.2	Operator touches glue gun.	Operator get burns from glue gun.		3	Since glue gun is always visible, operator is less likely to touch it compared to being hit by glue.	2	Minor burns	6
4.3	Robot sprays glue meaning that the spray pattern changes.	Product damage		2	Glue gun can get clogged up, if glue consistency is different resulting in a spray.	1	Minor material damage neglible production stop.	2
4.4		Body injury		2	See 4.3 and operator must hold hand close to glue gun.	2	Minor burns	4
4.5	Operator gets glue in eyes	Eye injury		1	Operator must more or less purpessfully get glue in eyes.	4	Could result in blindness.	4
5	**Operator makes unpredicted movements**							
5.1	Operator trips and falls on conveyor.	Body injury		1	Operator unlikely to fall since there is no objekts on the floor that operator may trip on.	4	.	4
5.2	Operator climbs robot	Body injury		1	Requires grave operator error.	5	Could result in death if falling from robot to concrete floor.	5
5.3	Operator stands on conveyor belt.	Body injury		1	Rrequires grave operator error.	5	Could result in falling down from the conveyor belt to the concrete floor may cause death or signinficant injuries.	5
6	**Glue gun failure**							
6.1	Glue gun breakes during collision.	Production stop and product damage.		2	Most likely to collide with core held by operator glue gun must also break.	4	Production on one side is halted untill new glue gun can be ordered.	8
6.2	Robot disperses to little glue.	Product damage.		4	Happens relatively often with the manual glue gun implying that the problem will be the same with on the robot.	2	Mould will fall appart in protective coating proces, resulting in minor production stop, also the amount of glue dispersed must be fixed.	8
6.3	Robot disperses to much glue.	Product damage		4	Happens relatiovely often with the manual glue gun, implying that the problem will be the same with on the robot.	2	Faulty castings which may need to be scraped, production stop too recalibrate glue gun.	8
6.4	Glue gun unscrews itself .	Production stop and product damage.		1	Neglible chance.	2	Glue gun may fall and destroy ,mould smaller production stop in order to remaount glue gun.	2

7	**Scan failure**							
7.1	Scan error	Robot makes unpredicted movements.		1	Scanners are reliable, based on error rates of CH11.	5	May impact operator in the head.	5
7.2		Production stop.		1	Scanners are reliable, based on error rates of CH11.	4	Production is halted on one side untill scanning error is resolved.	4
7.2	Scanner lens gets coated.	Production stop (not damaged)		2	May get coated by dust from mould and cores.	2	Minor production stop is easily fixed	4
7.3		Scanner is damaged.		1	Can be scratched when the lens is cleaned.	4	Production is halted on one side untill scanner is reapaired or replaced.	4
7.4	Mounting tool blocking scanning.	Production stop.		1	Operator must remove mounting tool before mould is finsihed. Scan is done first before anything else is done to the mould.	2	Smaller production stop.	2
7.5	Traverse blocking scan.	Production stop		1	see 7.4	2	Smaller production stop.	2
8	**Miscellaneous**							
8.1	Robot arm outside of workspace.	Material damage and body injury.		1	Robot does erratic moves.	5	May impact human in the head.	5
8.2	Robot sequence is interupted.	Robot can't complete sequence.		4	If robot touches human worker sequence will not complete.	2	Minor production stop.	8
8.3	Power outage	Robot makes unpredicted movements.		2	When power returns, robot may resume current operation resulting in unpredicted movement.	5	May impact operator in the head.	10
8.4		Production stop		2		4	Production will be halted untill power returns.	8
8.5	No glue flow.	Glue gun cokes.		3	Might occur during a production stop.	3	Reduces production efficency.	9

8.6	Reset after emergency stop.	Robot makes unpredicted movements.		3	The other operator might not be ready when robot is restarted.	5	May impact operator in the head.	15
8.7	Robot base missplaced.	Robot makes unpredicted movements.		3	Robot may be misplaced due to operator error.	5	May impact operator in the head.	15
8.8	Damaged wiring.	Operator gets electric shock.		2	Cables will rarely get damaged.	5	May cause death.	10
8.9	Robots loses calibration.	Production stop and product damage.		1	Robots loses calibraton very rarely.	4	May cause damage to robot and tooling requires calibration of robot resulting in production stop.	4
8.10	Robot vibrates	Robot unscrevs itself.		1	Robot unlikely to vibrate.	4	Causes damage to robot if it falls of will also halt production untill robot is repaired and remounted.	4
8.11	Operator presses glue buttom at wrong time.	Robot makes unpredicted movements.		2	Misscomunication between robot and operator.	5	May impact head.	10
8.12	Sand cores are not mounted in time.	Glue cures before sand core is placed.		4	Gluing of black cores take a long time.	1	Minor material damage and or neglible productionstop.	4

Attachments 9, Risk assessment part 2

Number	Scenario	Risk		Preventive measures	New Probability	New Consequence	New Risk Value	New probability reasoning	New consequence reasoning	Comment
1	Human is in collaborative robots movement path/working area									
1.1	**Quasi static Contact**		**Body part number**							
1.1.1	Middel of forehead	Entrapment between collaborative robot and lower mould/pallet.	1	Pm.1,2,3,4,7,8,9 ,12,13,20	1	1	1	In order to entrapp the operators head, the operator must attempt to get his head entrapped therefore the probability is rated 1.	The speed and force is limited according to power and force limiting so that the operator will not be hurt.	
1.1.2	Temple	Entrapment between collaborative robot and lower mould/pallet.	2	Pm.1*,2*,3,4,7,8,9,12 ,13,20	1	2	2	See 1.1.1	The speed and force is reduced and the glue gun has a protective housing reducing the concequence. The robot may still injure the operator, but since the speed and force is reduced by another body part it will only be a light injury.	
1.1.3	Masticatory muscle	Entrapment between collaborative robot and lower mould/pallet.	3	Pm.1*,2*,3,4,7,8,9,12, 13,20	1	2	2	See 1.1.1	The speed and force is reduced and the glue gun has a protective housing reducing the concequence. The robot may still injure the operator, but since the speed and force is reduced by another body part it will only be a light injury.	
1.1.4	Neck muscle	Entrapment between collaborative robot and lower mould/pallet.	4	Pm.1,2,3,4,7,8,9,12, 13,20	1	1	1	See 1.1.1	The speed and force is limited according to power and force limiting so that the operator will not be hurt.	
1.1.5	Seventh neck vertebra	Entrapment between collaborative robot and lower mould/pallet.	5	Pm.1,2,3,4,7,8,9,12,13 ,20	1	1	1	See 1.1.1	The speed and force is limited according to power and force limiting so that the operator will not be hurt.	
1.1.6	Shoulder joint	Entrapment between collaborative robot and lower mould/pallet.	6	Pm.1,2,3,4,7,8 and 9	1	1	1	Highly unlikely to entrapp operators shoulder.	Concequence is 1 because Speed and force limiting is used.	
1.1.7	Fifth lumbar vertebra	Entrapment between collaborative robot and lower mould/pallet.	7	Pm.1,2,4,7,8,9	1	1	1		Consequence is 1 beacuse Speed and force limiting is used.	
1.1.8	Sternum	Entrapment between collaborative robot and lower mould/pallet.	8	Pm 1,2,3,4,7,8,9	1	1	1		Consequence is reduced by power and force limiting and by using a protective housing around the glue gun.	
1.1.9	Pectoral muscle	Entrapment between collaborative robot and lower mould/pallet.	9	Pm 1,2,3,4,7,8,9	1	1	1		See 1.1.8	
1.1.10	Abdominal muscle	Entrapment between collaborative robot and lower mould/pallet.	10	Pm 1,2,3,4,7,8,9	1	1	1		See 1.1.8	

1.1.11	Pelvic Bone	Entrapment between collaborative robot and lower mould/pallet.	11	No preventative measure needed	1	3	3			
1.1.12	Deltoid muscle	Entrapment between collaborative robot and lower mould/pallet.	12	Pm.3,7,8 and 9	1	3	3	Operator is higly unlikely to trapped since the robot moves low above the Mould.	With P.m. 7,8 and 9 the robot will stop as it hits the operator, if the operator would be stuck between robot and lower mould, the robot will retreat a certain distance and can be pushed away.	
1.1.13	Humerus	Entrapment between collaborative robot and lower mould/pallet.	13	Pm.,1,2,3,7,8,9	2	1	2	Since robot moves slowly and there is a low risk for entrappment is the probability is 2.	Force and speed is limited so that operator will not be hurt if entrapped by the robot. Also the robot will initiate contact stop if touching the operator and if entrappment occurs it will move away.	
1.1.14	Radial bone	Entrapment between collaborative robot and lower mould/pallet.	14	Pm.1,2,7,8,9	3	1	3	Probability is reduced due to lower robot speed.	Force and speed is limited so that operator will not be hurt if entrapped by the robot. Also the robot will initiate contact stop if touching the operator and if entrappment occurs it will move away.	
1.1.15	Forearm muscle	Entrapment between collaborative robot and lower mould/pallet.	15	Pm.1,2,3,7,8,9	2	1	2	Probability is reduced due to lower robot speed and beacause the robot moves just above the mold . Forearmmuscle is not to likely to get entrapped between robot and mould.	Force and speed is limited so that operator will not be hurt if entrapped by the robot. Also the robot will initiate contact stop if touching the operator and if entrappment occurs it will move away.	
1.1.16	Arm nerve	Entrapment between collaborative robot and lower mould/pallet.	16	Pm.1,2,3,7,8,9	2	1	2	Probability is reduced due to lower robot speed and beacause the robot moves just above the mold. Arm nerve is not to likely to get entrapped between robot and mould.	Force and speed is limited so that operator will not be hurt if entrapped by the robot. Also the robot will initiate contact stop if touching the operator and if entrappment occurs it will move away.	
1.1.17	Forefinger pad D	Entrapment between collaborative robot and lower mould/pallet.	17	Pm.1,2,7,8,9,11	3	1	3	Robot moves slowly and operater works behind robot movement path, fingers are however always in close vicinity to the robot TCP.	Force and speed is limited so that operator will not be hurt if entrapped by the robot. Also the robot will initiate contact stop if touching the operator and if entrappment occurs it will move away. The consequence is further reduced by wearing glowes.	
1.1.18	Forefinger pad ND	Entrapment between collaborative robot and lower mould/pallet.	18	Pm.1,2,7,8,9,11	3	1	3	Robot moves slowly and operater work behind robot movement path fingers are however always in close vicinity to the robot TCP.	Force and speed is limited so that operator will not be hurt if entrapped by the robot. Also the robot will initiate contact stop if touching the operator and if entrappment occurs it will move away. The consequence is further reduced by wearing glowes.	
1.1.19	Forefinger end joint D	Entrapment between collaborative robot and lower mould/pallet.	19	Pm.1,2,7,8,9,11	3	1	3	Robot moves slowly and operater works behind robot movement path, fingers are however always in close vicinity to the robot TCP.	Force and speed is limited so that operator will not be hurt if entrapped by the robot. Also the robot will initiate contact stop if touching the operator and if entrappment occurs it will move away. The consequence is further reduced by wearing glowes.	
1.1.20	Forefinger end joint ND	Entrapment between collaborative robot and lower mould/pallet.	20	Pm.1,2,7,8,9,11	3	1	3	Robot moves slowly and operater works behind robot movement path, fingers are however always in close vicinity to the robot TCP.	Force and speed is limited so that operator will not be hurt if entrapped by the robot. Also the robot will initiate contact stop if touching the operator and if entrappment occurs it will move away. The consequence is further reduced by wearing glowes.	

1.1.21	Thenar emininence	Entrapment between collaborative robot and lower mould/pallet.	21	Pm.1,2,7,8,9,11	3	1	3	Robot moves slowly and operater works behind robot movement path, fingers are however always in close vicinity to the robot TCP.	Force and speed is limited so that operator will not be hurt if entrapped by the robot. Also the robot will initiate contact stop if touching the operator and if entrappment occurs it will move away. The consequence is further reduced by wearing glowes.	
1.1.22	Palm D	Entrapment between collaborative robot and lower mould/pallet.	22	Pm.1,2,7,8,9,11	3	1	3	Robot moves slowly and operater works behind robot movement path, fingers are however always in close vicinity to the robot TCP.	Force and speed is limited so that operator will not be hurt if entrapped by the robot. Also the robot will initiate contact stop if touching the operator and if entrappment occurs it will move away. The consequence is further reduced by wearing glowes.	
1.1.23	Palm ND	Entrapment between collaborative robot and lower mould/pallet.	23	Pm.1,2,7,8,9,11	3	1	3	Robot moves slowly and operater works behind robot movement path, fingers are however always in close vicinity to the robot TCP.	Force and speed is limited so that operator will not be hurt if entrapped by the robot. Also the robot will initiate contact stop if touching the operator and if entrappment occurs it will move away. The consequence is further reduced by wearing glowes.	
1.1.24	Back of the hand D	Entrapment between collaborative robot and lower mould/pallet.	24	Pm.1,2,7,8,9,11	3	1	3	Robot moves slowly and operater works behind robot movement path, fingers are however always in close vicinity to the robot TCP.	Force and speed is limited so that operator will not be hurt if entrapped by the robot. Also the robot will initiate contact stop if touching the operator and if entrappment occurs it will move away consequence is further reduced by wearing glowes.	
1.1.25	Back of the hand ND	Entrapment between collaborative robot and lower mould/pallet.	25	Pm.1,2,7,8,9,11	3	1	3	Robot moves slowly and operater work behind robot movement path fingers are however always in close vicinity to the robot TCP.	Force and speed is limited so that operator will not be hurt if entrapped by the robot. Also the robot will initiate contact stop if touching the operator and if entrappment occurs it will move away. The consequence is further reduced by wearing glowes.	
1.1.26	Thigh muscle	Entrapment between collaborative robot and lower mould/pallet.	26	No preventative measure needed.	1	3	3			
1.1.27	Kneecap	Entrapment between collaborative robot and lower mould/pallet.	27	No preventative measure needed.	1	3	3			
1.1.28	Middle of shin	Entrapment between collaborative robot and lower mould/pallet.	27	No preventative measure needed.	1	3	3			
1.1.29	Calf muscle	Entrapment between collaborative robot and lower mould/pallet.	29	No preventative measure needed.	1	3	3			
1.2	**Transient contact**									
1.2.1	Middel of forehead	Collision beetween collaborative robot and operator.	1	Pm.1,2,3,4,7,8,9,12,13,20	1	1	1	Robot moves low resulting in a probability of 1 for contact with head. Operator also knows how to act when robot does unexepected foresen moves.	The speed and force is limited according to power and force limiting so that the operator will not be hurt.	

1.2.2	Temple	Collision beetween collaborative robot and operator.	2	Pm.1,2,3,4,7,8,9,12,13,20	1	1	1	Robot moves low resulting in a probability of 1 for contact with head. Operator also knows how to act when robot does unexepected foresen moves.	The speed and force is limited according to power and force limiting so that the operator will not be hurt.	
1.2.3	Masticatory muscle	Collision beetween collaborative robot and operator.	3	Pm.1,2,3,4,7,8,9,12,13,20	1	1	1	Robot moves low resulting in a probability of 1 for contact with head. Operator also knows how to act when robot does unexepected foresen moves.	The speed and force is limited according to power and force limiting so that the operator will not be hurt.	
1.2.4	Neck muscle	Collision beetween collaborative robot and operator.	4	Pm.1,2,3,4,7,8,9,12,13,20	1	1	1	Robot moves low resulting in a probability of 1 for contact with head. Operator also knows how to act when robot does unexepected foresen moves.	The speed and force is limited according to power and force limiting so that the operator will not be hurt.	
1.2.5	Seventh neck vertebra	Collision beetween collaborative robot and operator.	5	Pm.1,2,3,4,7,8,9,12,13,20	1	1	1	Robot moves low resulting in a probability of 1 for contact with head. Operator also knows how to act when robot does unexepected foresen moves.	The speed and force is limited according to power and force limiting so that the operator will not be hurt.	
1.2.6	Shoulder joint	Collision beetween collaborative robot and operator.	6	Pm.1,2,3,4,7,8,9,13	1	1	1	Robot is very unlikely to hit shoulder joint if robot moves along a low path and the operator has recieved training in safety.	The speed and force is reduced by force, power limiting and a protective housing around the glue gun.	
1.2.7	Fifth lumbar vertebra	Collision beetween collaborative robot and operator.	7	Pm 1,2,3,7,8,9,13	1	1	1	Robot moves slowly and the operator has recieved information regarding safety during robot operations i.e. dont lean on the conveyor belt.	The robot will stop if it comes in contact with operator, it will also retreat and can be pushed away. The robot also uses power and force limiting which reduces the consequence when hit.	
1.2.8	Sternum	Collision beetween collaborative robot and operator.	8	Pm. 1,2,3,7,8,9,13	1	1	1	Robot moves low and slow and is trained not to expose sternum.	The robot will stop if in contact with the operator and it uses power and force limiting so that the operator will not be hurt.	
1.2.9	Pectoral muscle	Collision beetween collaborative robot and operator.	9	Pm. 1,2,3,7,8,9,13	1	1	1	Robot moves low and slow and is trained not to expose sternum.	The robot will stop if in contact with the operator and it uses power and force limiting so that the operator will not be hurt.	
1.2.10	Abdominal muscle	Collision beetween collaborative robot and operator.	10	Pm.1,2,7,8,9,13	1	1	1	Robot moves slowly and operator have no reason to lean over Mould while robot goes towards him.	The robot will stop if in contact with the operator and it uses power and force limiting so that the operator will not be hurt.	
1.2.11	Pelvic Bone	Collision beetween collaborative robot and operator.	11	Pm. 1,2,7,8,9,13	1	1	1	Robot moves slowly and operator is informed not to sit on conveyor.	The robot will stop if in contact with the operator and it uses power and force limiting so that the operator will not be hurt.	
1.2.12	Deltoid muscle	Collision beetween collaborative robot and operator.	12	Pm. 3,7,8,9,13	1	3	3	Robot is very unlikely to hit shoulder if robot moves along a low path and the operator has recieved training in safety.		
1.2.13	Humerus	Collision beetween collaborative robot and operator.	13	Pm. 1,2,7,8,9	2	1	2	Robot may hit humerus even though it moves slowly humerus may still be hit since it is very close to robot.	The robot will stop if in contact with the operator and it uses power and force limiting so that the operator will not be hurt.	
1.2.14	Radial bone	Collision beetween collaborative robot and operator.	14	P.m 1,2,7,8,9,13	3	1	3	Robot moves slowly however the hand i still very close to the robot tcp and may hit operator hand, operator i taught to work behind the robot.	The robot will stop if in contact with the operator and it uses power and force limiting so that the operator will not be hurt.	

1.2.15	Forearm muscle	Collision beetween collaborative robot and operator.	15	Pm. 1,2,7,8,9	2	1	2	Robot may hit forearm muscle even though it moves slowly forearm muscle may still be hit since it is very close to robot.	The robot will stop if in contact with the operator and it uses power and force limiting so that the operator will not be hurt.	
1.2.16	Arm nerve	Collision beetween collaborative robot and operator.	16	Pm. 1,2,7,8,9	2	1	2	Robot may hit arm nerve even though it moves slowly arm nerve may still be hit since it is very close to robot.	The robot will stop if in contact with the operator and it uses power and force limiting so that the operator will not be hurt.	
1.2.17	Forefinger pad D	Collision beetween collaborative robot and operator.	17	Pm. 1,2,7,8,9	3	1	3	Robot may hit hand even though it moves slowly, the hands are very close to the robot.	The robot will stop if in contact with the operators hand or finger, with force and power limiting the operator will not get hurt, the robot can also be pushed away.	
1.2.18	Forefinger pad ND	Collision beetween cobot and operator.	18	Pm. 1,2,7,8,9	3	1	3	Robot may hit hand even though it moves slowly, the hands are very close to the robot.	The robot will stop if in contact with the operators hand or finger, with force and power limiting the operator will not get hurt, the robot can also be pushed away.	
1.2.19	Forefinger end joint D	Collision beetween collaborative robot and operator.	19	Pm. 1,2,7,8,9	3	1	3	Robot may hit hand even though it moves slowly the hands are very close to the robot.	The robot will stop if in contact with the operators hand or finger, with force and power limiting the operator will not get hurt, the robot can also be pushed away.	
1.2.20	Forefinger end joint ND	Collision beetween collaborative robot and operator.	20	Pm. 1,2,7,8,9	3	1	3	Robot may hit hand even though it moves slowly the hands are very close to the robot.	The robot will stop if in contact with the operators hand or finger, with force and power limiting the operator will not get hurt, the robot can also be pushed away.	
1.2.21	Thenar emininence	Collision beetween collaborative robot and operator.	21	Pm. 1,2,7,8,9	3	1	3	Robot may hit hand even though it moves slowly, the hands are very close to the robot.	The robot will stop if in contact with the operators hand or finger, with force and power limiting the operator will not get hurt, the robot can also be pushed away.	
1.2.22	Palm D	Collision beetween collaborative robot and operator.	22	Pm. 1,2,7,8,9	3	1	3	Robot may hit hand even though it moves slowly the hands are very close to the robot.	The robot will stop if in contact with the operators hand or finger, with force and power limiting the operator will not get hurt, the robot can also be pushed away.	
1.2.23	Palm ND	Collision beetween collaborative robot and operator.	23	Pm. 1,2,7,8,9	3	1	3	Robot may hit hand even though it moves slowly the hands are very close to the robot.	The robot will stop if in contact with the operators hand or finger, with force and power limiting the operator will not get hurt, the robot can also be pushed away.	
1.2.24	Back of the hand D	Collision beetween collaborative robot and operator.	24	Pm. 1,2,7,8,9	3	1	3	Robot may hit hand even though it moves slowly the hands are very close to the robot.	The robot will stop if in contact with the operators hand or finger, with force and power limiting the operator will not get hurt, the robot can also be pushed away.	
1.2.25	Back of the hand ND	Collision beetween collaborative robot and operator.	25	Pm. 1,2,7,8,9	3	1	3	Robot may hit hand even though it moves slowly the hands are very close to the robot.	The robot will stop if in contact with the operators hand or finger, with force and power limiting the operator will not get hurt, the robot can also be pushed away.	
1.2.26	Thigh muscle	Collision beetween collaborative robot and operator.	26	Pm1*,2*,4,7,8,9	1	3	3		The speed and force is reduced and the glue gun has a protective housing reducing the concequence. The robot may still injure the operator but since the speed and force is reduced by another body part it will only be a light injury.	
1.2.27	Kneecap	Collision beetween collaborative robot and operator.	27	Pm1*,2*,4,7,8,9	1	2	2		Speed and force is limited using power and force limiting.	

1.2.28	Middle of shin	Collision beetween collaborative robot and operator.	27	Pm1*,2*,4,7,8,9	1	2	2		The speed and force is reduced and the glue gun has a protective housing reducing the concequence. The robot may still injure the operator but since the speed and force is reduced by another body part it will only be a light injury.	
1.2.29	Calf muscle	Collision beetween collaborative robot and operator.	29	Pm1*,2*,4,7,8,9	1	3	3		The speed and force is reduced and the glue gun has a protective housing reducing the concequence. The robot may still injure the operator but since the speed and force is reduced by another body part it will only be a light injury.	
2	**Items in the robots movement path/working area.**									
2.1	Telfer	Robot collides with telfer.		P.m 5,13	1	2	2	Using a sensor that is activated when the top of the telfer touches a beam, when telfer is not touching the beam the robot wont initiate a sequence.		
2.2	Telfer entangles with glue hose.	Glue hose,telfer and robot takes damage.		P.m 5,13	1	3	3	Using a sensor that is activated when the top of the telfer touches a beam, when telfer is not touching the beam the robot wont initiate a sequence.		
2.3	Robot entagles with glue hose.	Production stop (to untangle glue hose, the glue hose does not break).		No preventative measures needed.	2	2	4			
2.4		Glue hose takes damage.		P.m 5,13	1	3	3	See 2.2	No movement behind robot possible.	
2.5	Mounting tool is in robots movement path/working area.	Robot collides with mounting tool.		No preventative measures needed.	2	2	4			
2.6	Forklift is in robots movement path/working area.	Robot collides with forklift behind station.		No Preventative measures needed.	1	2	2		No movement behind robot possible.	
2.7	Forklift drives to close to robot and/or robot stand.	Forklift collides with robot and/or robot stand.		P.m 6	1	3	3	The physical barrier prevents a forklift from colliding with the robot.	By being able to use the old glue gun for production, the production can commence but at a reduced rate	
3	**Robot makes unpredicted movements.**									
3.1	Robot crashes into lower mould.	Glue gun breakes.		Pm 17	1	3	3		By being able to use the old glue gun production can commence but at a reduced rate.	
3.2		Mould brakes		No preventative measures needed.	1	1	1			
3.3	Robot pushes lower mould of the pallet.	Operator is hit by mould.		Pm 1*,2*,7,8,9	1	4	4	Because of contact stop, power and force limiting and that the mould is not in the robot path. This should be more or less impossible.		
3.4		Mould brakes		No preventative measures needed.	1	2	2			
3.5	Robot collides into white cores.	White cores breaks.		No preventative measures needed.	2	1	2			
3.6	Robot collides into black cores.	Black cores breaks.		No preventative measures needed.	2	1	2			

3.7	Robot collides into white cores held by operator.	Hand injury (hits white core not hand).		Pm 1*,2*,7,8,9,13	3	1	3			
3.8		White core breakes.		No preventative measures needed.	3	1	3			
3.9	Robot collides into white cores held by operator.	Hand injury (hits black core not hand).		P.m 1,2,7,8,9,13	3	1	3			
3.10		Black cores breaks.		No preventative measures needed.	3	1	3			
3.11	Robot collides into blackcores held in the mounting tool held by the operator.	Hand injury (hits black core not hand)		No preventative measures needed.	1	2	2			
3.12		Black core breakes.		No preventative measures needed.	2	1	2			
3.13	Robot collides into mounting tool held by operator.	Operator gets injured		No preventative measures needed.	1	2	2			
3.14		Black core breakes.		No preventative measures needed.	1	1	1			

3.15	Robot collides with the mounting tool cables.	Cables takes damage.		Pm.1*,2*,3,7,8,9,13	1	3	3	With the robot working very close to the lower mould and slowly and with operators recieving information on when and how to use the mounting tool with collaborative robots the probability is reduced. The speed of the robot is determined by the body part that is most sensitive to collision or pressure.		
3.16	Robot collides with traverse.	Traverse takes damage		Pm.1*,2*,3,7,8,9	1	4	4	The probability is further reduced by preventive measures.		There are no reasonable countermeasures for the consequence for this risk, but the probability of this occuring is so small that the risk is almost negliable.
3.17	Robot collides with human behind station.	Operator gets injured (refer to 1 and 2).		Pm.1*,2*,6,7,8,9	1	3	3	Fence will prevent the robot impacting a human unless the human climbs over the fence.	The speed and force is reduced and the glue gun has a protective housing reducing the concequence. The robot may still injure the operator but since the speed and force is reduced by another body part it will only be a light injury.	
3.18	Robot collides with mirror.	Mirror takes damage.		No preventative measures needed.	2	2	4			
3.19	Robot collides with airduct	Airduct takes damage		No preventative measures needed.	1	3	3			
4	Operator is in the robot workspace while robot dispense glue.									

4.1	Operator holds body part below glue gun.	Operator gets burns on glue.		Pm. 11,13	2	2	4	Operators work close to the robot but with information and working behind the where the robot moves th eprobability is reduced. By using protective equipment the chance of getting burned by the glue reduces By using a protective housing the risk of getting burn.		
4.2	Operator touches glue gun.	Operator get burns from glue gun.		Pm.4	1	2	2	Operators work close to the robot but with information and working behind the where the robot moves the probability is reduced. By using protective equipment the chance of getting burned by the glue reduces. By using a protective housing the risk of getting burn also gets reduced.		
4.3	Robot sprays glue meaning that the spray pattern changes.	Product damage		No preventative measures needed.	2	1	2			
4.4		Body injury		No preventative measures needed.	2	2	4			
4.5	Operator gets glue in eyes	Eye injury		No preventative measures needed.	1	4	4			The risk is the same as at the current layout of the workstation, therefore the risk is deemed acceptable.
5	Operator makes unpredicted movements.									
5.1	Operator trips and falls on conveyor.	Body injury		Pm.18	1	3	3		When the operator falls over the conveyor belt all machinery will stop.	
5.2	Operator climbs robot.	Body injury		Pm.1*,2*,3,4,7,8,9,13	1	1	1		The robot should initiate a protective stop if operator has climbed the robot.	Climbing the robot and falling of it is the same as climbing the telfer at the current station layout, the operators are given information not to do that.
5.3	Operator stands on conveyor belt.	Body injury		Pm.1*,2*,3,4,7,8,9,13	1	3	3		The speed and force is reduced and the glue gun has a protective housing reducing the concequence. The robot may still injure the operator but since the speed and force is reduced by another body part it will only be a light injury.	
6	**Glue gun failure**									
6.1	Glue gun breakes during collision.	Production stop and product damage.		Pm.1*,2*,4,7,9,17	1	3	3	Force and powerlimiting combined with a protective housing makes it highly unlikely that the glue gun will break due to a collision.	Consequence is reduced to a 3 since manual gluing can replace the aoutomatred gluing.	
6.2	Robot disperses to little glue.	Product damage.		Pm.13,14	2	2	4	By performing routine inspection and testing of the glue dispersion, the operators can quickly see if the robot disperses to much/little glue resulting in reducing the risk of failure later on in the production line.		
6.3	Robot disperses to much glue.	Product damage.		Pm.13,14	2	2	4	By performing routine inspection and testing of the glue dispersion the operators can quickly see if the robot disperses to much/little glue resulting in reducing the risk of failure later on in the production line.		

6.4	Glue gun unscrews itself.	Production stop and product damage.		No preventative measures needed.	1	2	2			Routine inspection of glue gun and its mounting.
7	**Scan failure**									
7.1	Scan error	Robot makes unpredicted movements.		Pm.1*,2*,3,4,7,8,9	1	2	2		The speed and force is reduced and the glue gun has a protective housing reducing the concequence. The robot may still injure the operator but since the speed and force is reduced by another body part it will only be a light injury.	
7.2		Production stop.		Pm.17	1	3	3		Consequence is reduced to a three since manual gluing can replace the aoutomatred gluing.	
7.2	Scanner lens gets coated.	Production stop.		No preventative measures needed.	2	2	4			
7.3		Scanner is damaged.		Pm.17	1	3	3		Consequence is reduced to a three since manual gluing can replace the aoutomatred gluing.	
7.4	Mounting tool blocking scanning.	Production stop.		No preventative measures needed.	1	2	2			
7.5	Traverse blocking scan.	Production stop.		No preventative measures needed.	1	2	2			
8	**Miscellaneous**									
8.1	Robot arm outside of workspace.	Material damage and body injury.		Pm.1*,2*,3,4,7,8,9	1	2	2		The speed and force is reduced and the glue gun has a protective housing reducing the concequence. The robot may still injure the operator but since the speed and force is reduced by another body part it will only be a light injury.	
8.2	Robot sequence is interupted.	Robot can't complete sequence.		Pm.7,10,13	2	2	4	By using power and force limiting the operator has more time to react to the robot movement so that unnecessary contact stops occur, by having a button for when the robot shall glue gives operators control and knowledge in what the robot will do next, by giving the operator training and information on how to work beside the robot the probability is reduced.		
8.3	Power outage	Robot makes unpredicted movements.		P.m 1*,2*,3,4,7,8,9,13,15	1	2	2	Since robot will not start when power return unless reset. The risk of the robot hitting the operators head when power returns is neglible.	The speed and force is reduced and the glue gun has a protective housing reducing the concequence. The robot may still injure the operator but since the speed and force is reduced by another body part it will only be a light injury.	
8.4		Production stop.			2	4	8			There are no reasonable countermeasures for the consequence and probability for this risk, but its the same as it is for the current layout of the workstation.
8.5	No glue flow.	Glue gun cokes.		Pm13,14,17	2	3	6	By performing routine inspection and testing of the glue dispersion the operators can quickly see if the robot even disperses glue or if it disperses to much/little glue resulting in reducing the risk of failure later on in the production line.	Same consequence as before but now the automated gluing is performed by manual gluing.	

8.6	Reset after emergency stop.	Robot makes unpredicted movements.		Pm. 1*,2*,4,7,8,9,13,15	2	2	4	Risk is reduced by communication between operator 1 and 2 operator must check that the other operator is ready before a reset is done.	The speed and force is reduced and the glue gun has a protective housing reducing the concequence. The robot may still injure the operator but since the speed and force is reduced by another body part it will only be a light injury.	
8.7	Robot base missplaced.	Robot makes unpredicted movements.		P.m 1*,2*,4,7,8,9,13,16,19	1	2	2	The probability is reduced with giving information and education to the operators, also having guiderails in the floor accompanied by the robot scanning the position of the robot.	The speed and force is reduced and the glue gun has a protective housing reducing the concequence. The robot may still injure the operator but since the speed and force is reduced by another body part it will only be a light injury.	
8.8	Damaged wiring.	Operator gets electric shock.		P.m 13,14	1	5	5	By giving operators information and education on what to look for and what to do when wires are damaged in unison with routine inspection the probability reduces.		There are no reasonable countermeasures for the consequence and probability for this risk, but its the same as it is for the current layout of the workstation.
8.9	Robots loses calibration.	Production stop and product damage.		Pm.17	1	3	3		Consequence is reduced to a 3 since manual gluing can replace the automatred gluing.	
8.10	Robot vibrates.	Robot unscrews itself.		No preventative measures needed	1	4	4	Routine inspection of robot mounting and base.		
8.11	Operator presses glue buttom at wrong time.	Robot makes unpredicted movements.		P.m 1*,2*,4,7,8,9,13	2	2	4	Education reduces probability but it is still a 2.	The speed and force is reduced and the glue gun has a protective housing reducing the concequence. The robot may still injure the operator but since the speed and force is reduced by another body part it will only be a light injury.	
8.12	Sand cores are not mounted in time.	Glue cures before sand core is placed.		Pm 20	2	1	2	Use glue with longer drying time.		