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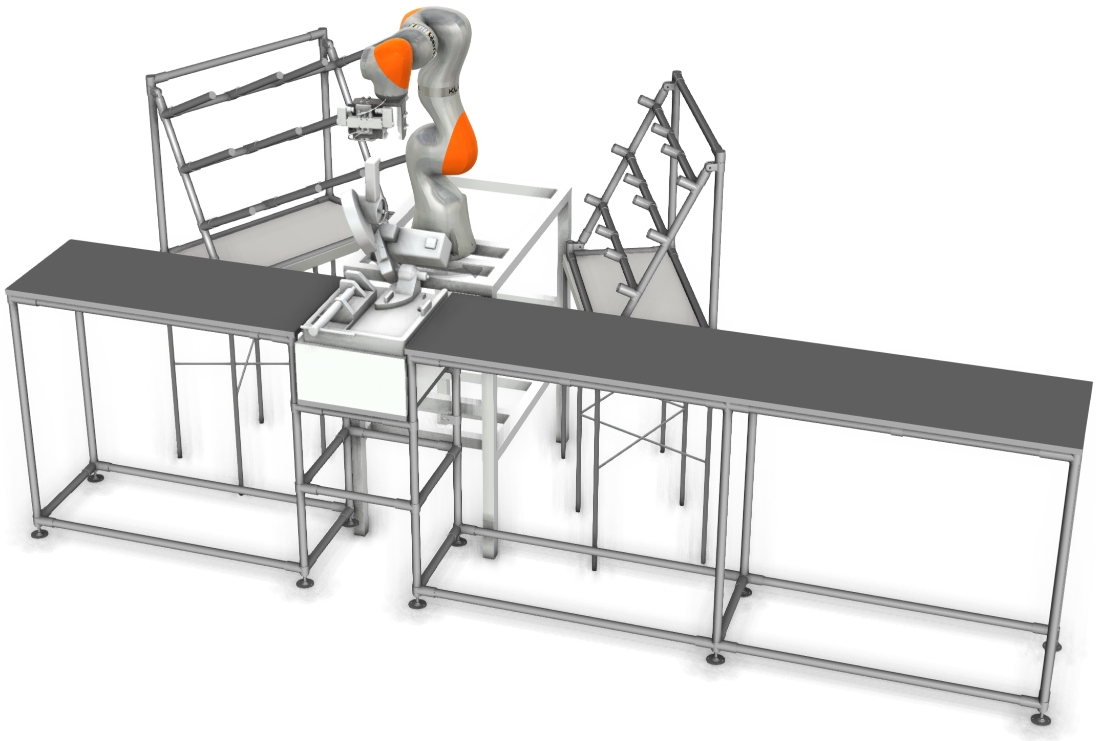

Design and development of a workstation for cutting and kitting pipes

The implementation of a collaborative robot in a process of cutting and kitting pipes at Virtual Manufacturing Sweden AB

Master's thesis in Production Engineering

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Cover: A conceptual layout for how a workstation for cutting and kitting pipes could look like when implementing a collaborative robot.

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Abstract

This thesis aims to answer how a collaborative robot can be implemented into a process of cutting and kitting pipes. Moreover, it will investigate how the robot shall receive instructions on what to cut. The thesis will also answer what benefits there are of using a robot instead of a human.

To answer these questions, a literature study was carried out to see what has been done in the area before. A current state analysis was performed to understand how the process works today and after this, the future state was developed. The proposed workstation by the future state development was also assessed with three experiments, this to determine the accuracy and repeatability of the workstation as well as the process time.

The results of the thesis was a way in which a robot workstation can be designed. This by redesigning the layout and moving all of the station contents closer to the robot, since the robot cannot move around the station as a human can. A gripping tool was also developed for the robot. The experiments carried out on the new workstation showed that the process time and accuracy was better than that of the current workstation.

This thesis shows that for simple, repetitive, and, for humans, non-developing workstations, there are many benefits of implementing a robot instead of using a human operator. The benefits are both in process time and accuracy. The robot can also work for longer hours without breaks, which enables production during more hours, without employing more personnel.

Keywords: automation, workstation, collaborative robot, cutting process, kitting, KUKA iiwa.

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Nomenclature

Abbreviations

iiwa	intelligent industrial work assistant
LBR	Lightweight Robot
TCP	Tool Center Point

Explanation of words

AviX	A software developed by SOLME AB that is used to support engineering work by using video recordings
SalesPoint	A CAD software based on IronCad that Virtual Manufacturing uses to create their products

1
Introduction

In this chapter, an introduction to the thesis is presented. First, a background is given, followed by purpose and aim, research questions, and scope and delimitations.

1.1 Background

The manufacturing industry is striving to be more efficient while at the same time protecting the personnel from injuries and unergonomic work postures. Unlike a human, a robot can work long hours, at a constant speed and in postures and environments no human being should stay in for a too long time [1].

Automation in manufacturing has been used to increase speed and efficiency for a while, but traditional industrial robots cannot solve it all since many tasks are still too complicated to automate. This creates a gap in manufacturing, which collaborative robots can fill out [2]. Collaborative robots are designed to be able to work alongside and collaborate with humans [3]. Due to advanced safety technology, the robot will stop immediately if physical contact with a human being occurs [2]. A collaborative robot is also easier to reprogram than a standard industrial robot and does not require to be installed inside a safety cage [4], which is why they have become so popular in the industry [1], even where they do not have to collaborate with a human being. Collaborative robots are also good for tight spaces, where a caged robot would not fit [1]. Another argument for using collaborative robots instead of traditional industrial robots is that they often are less expensive [5].

Virtual Manufacturing is a supplier of lean-based production development services. The company also manufacture shelves meant to be used in production areas. These shelves are built with pipes and connectors. Figure 1.1 presents an example such a construction. The pipes are today cut by an operator using a cutting machine. The operator manually reads the information from a printed list in order to know what to cut, into what length, and how many. Virtual Manufacturing wants to investigate the possibility to use a collaborative robot for this kind of task. This investigation includes how the information regarding what work to perform will reach the robot. It will include a way to ensure that the robot picks a correct pipe, since there are pipes of different types. It also includes an exploration of how the workplace layout could look in order to suit a collaborative robot, as well as what level of automation that is suitable for the workstation.

Figure 1.1: An example of a construction manufactured by Virtual Manufacturing.

1.2 Purpose and aim

The purpose of this thesis is to investigate how a collaborative robot can be implemented in a cutting station at Virtual Manufacturing's production facility. The aim is to investigate how to use a collaborative robot to cut and kit the pipes. The robot will get the information needed directly into the robot software, so that no human will be needed. Since there will be no human operator involved, the workplace layout will also be re-designed in order to fit the collaborative robot.

1.3 Research questions

Based on the background, as well as the purpose and aim, two research questions have been formulated. The goal of the thesis is to find an answer to these questions. The research questions are:

- How should a collaborative robot be implemented to cut, kit, and grip pipes in the workstation?
- What are the benefits of using a robot instead of a human operator in the workstation?

1.4 Scope and delimitations

The scope of the thesis is to design a collaborative workstation including:

- Instructions for the robot of what to cut.
- The flow of material through the station.
- Deciding how the station layout shall be designed, e.g. the placement of the robot.
- Design of the robot gripping tool.

An analysis will also be made of what operations suits the operator and the robot best. However, the new workstation should be fully automatic.

The aim is to create a proof of concept, meaning that a fully functional robot station that can be implemented in the production facility will not be created. The objective is rather to make a station that can show that the technology works and how it could be implemented. Moreover, the collaborative robot KUKA LBR iiwa 14 R820 will be used since this model is available at Virtual Manufacturing. Thus, other possible models that could be used for the station will not be investigated. Since the robot has limitations in torque and reachability, the pipes used in the production, with lengths of four to six meters, cannot be lifted with the robot. Therefore, the length of the pipes will be reduced in the proof of concept station that will be developed.

2

Frame of reference

In this chapter, the findings from the literature study are presented. First, an introduction of collaborative robots is presented. Thereafter, findings regarding how to design a collaborative workstation, along with some case studies of implementing human-robot collaboration are presented. Enterprise Resource Planning (ERP) systems will get an introduction since Virtual Manufacturing is using one today. Finally, some methods that can be used for studying and developing a workstation are presented.

2.1 Collaborative robots

Collaborative robots, or cobots, are designed to be able to share workspace and work in collaboration with human workers by assisting them, without any risk of harming them [3]. They are often used in manufacturing to work alongside humans on the factory floor [2]. Traditionally, robots have been expensive and used for mass production in large sized enterprises [6], but as the cost of sensors and computer power is decreasing, the cost of robots has gone down and made them available for all sizes of business [5]. In combination with the decreasing cost, collaborative robots are also easier to program, which makes them interesting for small and medium sized enterprises (SMEs) [1]. Some collaborative robots can be programmed by physically moving the robot arm to a position and saving the path, which makes it possible to have a collaborative robot up and running in minutes, whilst traditional industrial robots often require a specialist to install and can take up to hundreds of hours to program [2]. Antonelli et al. [6] compares the cycle time and programming time in three cases; fully automated, collaborative, and fully manual. In the fully automated case, the programming time was long, but the cycle time short. In the fully manual case, there was no programming time, but the cycle time was more than double of the fully automated case. In the collaborative case, the programming time was short and the cycle time was in between the cases mentioned before. This because only the tasks that were easy to program were programmed, and the complicated parts were left to the human worker to do. The study is presented more detailed in section 2.3.1.

Industrial robots can handle large payloads and finish parts fast, as they are programmed to perform one single task in high volume [2]. Therefore, industrial robots are common in mass production. As the tasks get more advanced and varied, it gets more difficult to use an industrial robot. This is where a collaborative robot can be of use. With collaborative robots, the benefits of the industrial robots, such as strength, endurance, and consistent quality, are combined with the benefits of the human workers, which is decision making [7]. Traditionally, robots are used for repetitive tasks that might be dangerous, or not even possible, for a human to perform [1, 3]. Table 2.1 lists some differences between traditional industrial robots and collaborative robots.

Table 2.1: Collaborative robots and traditional industrial robots in comparison recreated from Djuric et al. [3].

Collaborative robots	**Traditional industrial robots**
Flexibility relocated	Fixed installation
Frequent task changes; task infrequently repeated	Periodic, repeatable tasks; infrequently changes
Online instructed and supported by offline methods	Online and offline programming
Easy to teach	Not easy to teach
Frequent interaction with the worker, even force/precision assistance	Rarely interaction with the worker, only if being programmed
Workspace sharing with worker	Worker and robot separated trough fence
Interact with people safely	Cannot interact with people safely
Profitable even at small lot size	Profitable only with medium to large lot size
Small and slow	Small or big and fast
Reduce cost and footprint to justify new applications	Cannot reduce cost and footprint to justify new applications
Requested risk assessment	Not requested risk assessment
Usually 6 or 7 axis with many offsets	Usually 6 axis with last three intersecting in wrist

Industrial robots are traditionally placed in a cage to keep humans safe [1]. This due to the potential hazards that may occur as the robots, unaware of their surroundings, are handling large weights with high forces and dynamics [2]. Light barriers and floor mats with built in force sensitivity can be used to ensure that no human being will get to close to the robot when working [8]. When a human enters the area surrounded by these systems, the robot will stop what it is doing. Compared to traditional industrial robots, integrated sensors, rounded surfaces, and force-limited joints are making the collaborative robots safe [5]. If the robot collides with a human, the sensors will react and the robot will stop immediately. The rounded surfaces minimize the impact if contact with a human occurs and the closed areas around joints make it less likely to get pinched between the joints. Since 2016, there is an ISO standard (ISO/TS 15066) regarding collaborative robotic systems and how to ensure the safety of the human worker within the system [9].

Integrated sensors and force-limited joints are not just for safety. Advanced collaborative robots can use the sensors to “feel” its way if the workspace has been adjusted, which makes them easier to move between different production lines [2].

In order to perform a task with a robot, collaborative or industrial, an end-effector is needed. The end-effector is placed at the end of the arm of the robot [8] and decides what kind of task the robot is able to perform. Depending on what task the robot should perform, different end-effectors can be of use. In material handling, grippers are often used, but there are different kinds of grippers [10]. Mechanical, vacuum, or magnetic grippers are examples of grippers. Depending on the material and shape of the part to handle, different grippers are to prefer [8]. One thing to keep in mind when using a collaborative robot is that the gripper must not be able to harm a human being. This by making sure that there are no sharp edges or possibilities for a human to get stuck with a body part in the gripper, e.g. a finger.

2.2 Collaborative workstation design

Designing a workstation with a collaborative robot is different from designing one with a traditional robot. One big difference is that a traditional robot has to be fenced off whilst a collaborative robot is meant to be used alongside human workers [1]. The suitable work tasks differ between collaborative robots and traditional robots as well, where traditional robots are used for highly repetitive and monotonous work [4], such as painting, welding, and material handling [3]. The reason for why the traditional robots are used for these tasks is that they take a lot of time to program and are therefore not as flexible as a human [6], there is also no robot that can fully replace the human capabilities but the two can be combined to take advantage of the advantages of both [11]. Collaborative robots, on the other hand, are safe enough for the worker and robot to work within the same work area [1]. Thus, collaborative robots are designed as a complementary tool to human workers and by combining the advantages of a robot, whom can work with high precision in repetitive tasks, with the flexibility and decision-making of the human, the quality, efficiency, ergonomics, costs, and ability to adapt to changes are increased [7]. Collaborative robots are most often used in stations for assembly, packaging, inspection and counting as well as pick and place [5]. This flexibility is very attractive for the smaller companies who produce in smaller batches and smaller volumes [3] as compared to larger enterprises where traditional robots make more sense.

To achieve the best results on productivity, it is important to consider the layout of the workplace as well as the task allocation of the robot and the human [12]. The tasks more suited for a human should be allocated to the human and the tasks more suitable for a robot to the robot, based on their individual characteristics [9]. As mentioned above, tasks within the workstation that are repeatable are preferably assigned to the robot, while flexible tasks and tasks that require creativity can be assigned to the human [3]. By doing so, the strengths of both units can be used in order to attain the full potential of the station [9].

In *A decision making framework for human robot collaborative workplace generation*, Tsarouchi et al. [13] propose a framework for designing the layout of a station. The framework begins with that the different components of the station are divided into two categories, passive and active resources. The active resources are the robots and humans as well as the end-effectors. The passive resources are the stationary parts of the station, for example, tables, fixtures, racks, and also the product being produced in the station. When designing the layout, it is the placement of these resources that is the main objective. The layout designing process can be divided into three steps, where the first step is the placement of the passive resources. After this, a task allocation between the active resources is made and lastly, the active resources are placed in the station. The process should give an output of multiple possible layout solutions. The different possibilities can then be evaluated based on, for example, available space, the reachability of the robot to the parts it needs to interact with, the ergonomics of the worker as well as the investment cost of the layout.

Besides what has been mentioned above, there are technical specifications that act as a guideline when designing a work cell including a collaborative robot, e.g. ISO/TS 15066: Robots and robotic devices - Collaborative robots [3].

Another decision point is the level of automation in the station. If the unit cost is high and production volume is small, a manual assembly is the best suited [3]. As the volume increases and the cost decreases, it will be more suitable to use robotic and fixed automation. In the space between what volume and cost that is suited for human and robot assembly, the human-robot-collaboration assembly is best suited [3]. This is visualized in figure 2.1 below.

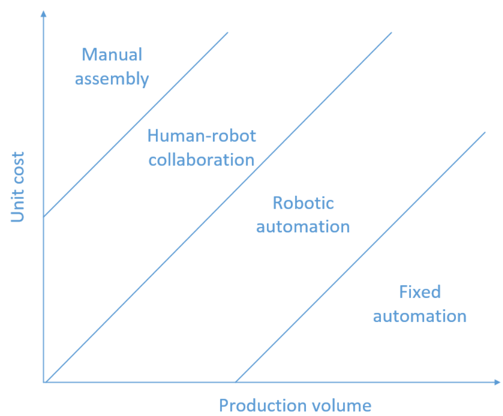

Figure 2.1: Level of automation with respect to unit cost and production volume.

2.3 Case studies on human-robot collaboration

In this section, case studies on human-robot collaboration found in the literature are presented. The section aims to give the reader an idea of what has been done and thus can see where this thesis will fit into the research area.

2.3.1 Welding cell

In a case study made by Antonelli et al. [6], a collaborative robot cell was tested against a fully automated cell and a fully manual cell. The reason for the study was to analyze the programming phase and see at which point (measured in batch size) the collaborative approach was the most effective. The station had two welding tasks, one weld in the shape of a square and one weld in the shape of an Archimedean spiral, both welds having the same length of 643 mm. The square weld require much fewer points (5 points) that the programmer has to define for the robot than the spiral (70 points).

Since the square is easier to program, this weld was chosen for the robot in the collaborative cell, whilst the operator made the spiral weld. In the fully manual cell, no programming was needed and the operator did both welds. In the fully automated cell, the robot did both welds and thus, both the easy and hard one needed to be programmed into the robot. The result of the test can be seen in table 2.2.

Table 2.2: Resulting times from the case study on a welding cell.

Times	Fully automated	Fully manual	Collaborative
Programming time	1250 s	0 s	330 s
Cycle time	320 s	1100 s	710 s

Using equation 2.1 proposed by Antonelli et al. [6], the total time (T_{total}) can be calculated.

$$T_{total} = K \cdot T_{prog} + N \cdot T_{cycle} \tag{2.1}$$

Where T_{prog} is the programming time, T_{cycle} is the cycle time, and N is the batch size. K is the number of debugging runs that have to be made.

The equation was used to calculate for which batch size the three variants were the most suiting. The result was that for batches of 1-8, a fully manual station is the most suiting, for batches from 8 to 25, the collaborative approach was the most suiting. For batches of 26 or more, the fully automated solution was the best.

2.3.2 Testing system in the automotive industry

In the case study performed by Scholer et al. [9], a collaborative solution was tested for the first time on a constantly moving assembly line. To make this possible, the robot was fastened to a track alongside the line. The robot's task in the station was to do a water leak test. The reason for why a robot would be suitable here is the high reliability of robots as compared to humans which can lead to fewer errors and thus a higher quality and less rework needed. Another benefit of having the robot in the station is that it can perform the tasks in the station that are unergonomic for a human, for example reaching into the car. To decide which tasks would be done by a human and a robot, the tasks were analyzed and tasks that were repetitive, simple, standardized, and simple to make decisions from were given to the robot. The tasks that required more cognitive skill and were more complex were given to the human.

2.3.3 KUKA iiwa rod cutting station

In the 2016 KUKA innovation award, one of the finalist teams, Team DIANA - RWTH Aachen University, presented a station utilizing a KUKA iiwa collaborative robot for cutting wooden rods. The robot picked rods from a rack, analyzed where it was holding the rod using force sensitivity, and then cut them in a table saw. After the cutting, the robot placed the wooden rods in holes using force sensitivity to locate the holes. This made it possible for the station to adapt to small changes in its environment.

2.4 ERP-systems

ERP-systems (Enterprise Resource Planning systems) are more about enterprise than any other of its names as its intent is to integrate all parts of a company within one software [14]. By gathering information from different parts of a company, ERP-systems are developed to increase the performance of the company that uses them [15].

ERP-systems gather data from different parts of the organization, typically manufacturing, order handling, logistics, sales, inventory, and human resources [14]. By keeping data from all departments at the same place, people from different departments within the company are able to get data that is up to date when it comes to decision making [15]. As all parts of a company are integrated, ERP-systems play a big role when it comes to business strategy [16]. As the focus can be removed from building their own systems, companies can focus on the value adding operations. Companies that produce by make-to-order can save a lot of time by integrating the CAD/CAM-systems into the ERP-system [14].

2.5 Analysis methods

Below, a set of analysis methods that will be used for assessing a current state and develop a future state are presented.

2.5.1 DYNAMO

DYNAMO (Dynamic Levels of Automation) is a methodology developed in the DYNAMO project and is used for measuring the Level of Automation (LoA) within a system and to determine what level that is suitable for the system [17]. By measuring the LoA and finding the appropriate level, high effectiveness can be achieved [18].

Granell et al. [18] presents the DYNAMO methodology in 8 steps:

1. Planning of measurement off-site. Goal, purpose, and delimitations of the production system are discussed.
2. Carry out a pre-study on-site. Document where the production flow starts and ends. The purpose of the flow, as well as the purpose of the machines and humans involved, are identified and documented. Also, different products and variants produced are documented.
3. Document and visualize the flow. Walk the process and define sections of the production flow. Document how many of each product and variant that passes through each section or buffer. What cognitive and physical tasks that are allocated to the human or what are allocated to the robot is documented. Also, if the human is responsible for more than one section or buffer.
4. Identify the main task in each section based on step 2 and 3.
5. Identify sub-tasks within each task.
6. Define LoA. LoA is defined based on two seven graded scales, one for cognitive and one for physical levels of automation. The scale goes from totally manual to totally automatic in both cases, as seen in table 2.3.
7. Set relevant maximum and minimum LoA together with the operator or/and production technician on-site. Good results can be assessed by involving people with knowledge regarding the task that is analyzed. The date for this is documented.
8. Analyze the data collected on-site in step 6 with the relevant maximum and minimum set in step 7. The observed LoA is marked with a dot and the maximum and minimum create an area around it. From this, the potential of the task to be automated is visualized.

Table 2.3: Levels of automation in the DYNAMO methodology, recreated from Fasth and Stahre [19].

LoA	Physical	Cognitive
1	Totally manual	Totally manual
2	Static hand tool	Decision giving
3	Flexible hand tool	Teaching
4	Automated hand tool	Questioning
5	Static machine/workstation	Supervision
6	Flexible machine/workstation	Intervene
7	Totally automatic	Totally automatic

2.5.2 FMEA

The Failure Modes and Effects Analysis (FMEA) is a tool to find problems in the analysis called failure modes, in systems or processes as well as their causes and effects [20]. The different failure modes are then prioritized based on a Risk Priority Number (RPN), and RPN is achieved by multiplying the factors for how frequent the problem is believed to Occur (O), how Severe (S) the problem is and how easy it is to Detect (D) [21]. The factors are often assessed as a value between 1 and 5 or 1 and 10, but there is no standardization of the scale used, the usage of the 1 to 10 scale is common and most recommended since it has a good accuracy while still being easy to understand [22]. The rating of the different factors can be done either by using historical or statistical data from the process if it already exists or if similar processes are available, if the system does not yet exist or if there is no historical data the team has to do the rating based on their own subjective judgment [22].

FMEA is an important tool to use and is, by many, considered to be the most important tool for improving reliability [23].

Process FMEA
There are many different kinds of FMEA, process FMEA, which is used to assess a production system before the first product is made, is one of them [24]. There are no standardized FMEA forms for the process FMEA and companies have their own variant that includes what is important for that particular company but the columns in the example FMEA shown in figure 2.2 cannot be removed, only moved, changed, or more can be added [24].

Here information regarding process name, who is responsible and other information that might be interesting can be included. This part can be changed and is not standardized. Companies use information that is important to their process.

												Action results				
Process function	Potential failure mode	Potential effects of failure	Critical characteristics	SEV	Potential causes of failure	OCC	Detection method	DET	RPN	Recommended action	Individual/ area responsible and completion date	Actions taken	SEV	OCC	DET	RPN

Figure 2.2: Example Process FMEA sheet based on the one provided by Stamatis [24].

2.6 Summary of the frame of reference

From this chapter, it is understood that collaborative robots are used to some extent in the manufacturing industry today. Interesting case studies and implementations have been presented. The rod cutting station, described in section 2.3.3 presents a simple and good way of determining at what distance the robot is gripping the pipes. From the welding cell implementation, described in section 2.3.1, as well as from the theory presented in section 2.2, it is understood that more advanced tasks are not suited to be automated, especially not in small batch production, due to the fact that it takes much more time to program these tasks rather than simple tasks. From the water leak test implementation, described in section 2.3.2, it is derived that the higher accuracy, as well as the possibility to store the data from the process, motivates the use of industrial robots in processes.

From the findings of what an ERP-system is and what it can be used for, together with the facts that Virtual Manufacturing already uses an ERP-system, it was decided to look into the possibilities to connect the ERP-system and the robot. This to make the robot know what to do without human interaction.

3
Methodology

In this chapter, the methodology of the thesis is presented. The thesis was divided into five parts, a literature study, a current state analysis, a future state analysis, experiments, and finally the results from the previous steps. A diagram showing the five steps of the thesis is presented in figure 3.1. By following this methodology, the research questions were able to be answered.

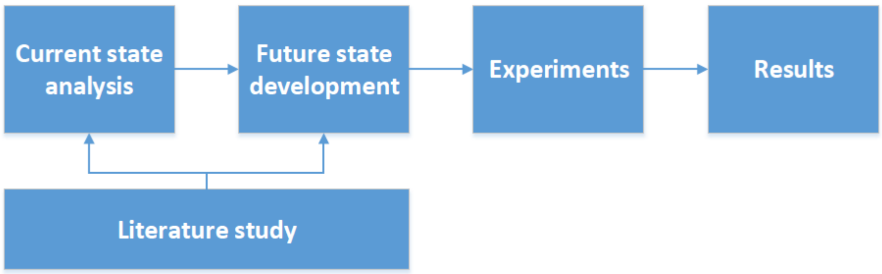

Figure 3.1: A visualization of the methodology of the thesis work.

3.1 Literature study

First of all, a literature study was carried out to discover what had previously been done within the area. This to get an idea of how to attack the thesis. The literature study was continued during the entire thesis, all the way to the results, in order to gain more information about what to do and how it could be done. Articles for the literature study was searched for in databases such as Scopus and Web of Science. Topics that were of interest were, for example, collaborative robots, collaborative workstation design, and different methods that could be of use when implementing a collaborative robot in a workstation. The literature study also provided input on how the robot can receive instructions from other sources than the ERP-system. The result of the literature study was the base of the Frame of Reference in Chapter 2.

3.2 Current state analysis

Thereafter, it was of importance to understand the current state by analyzing the process. This was made by visiting the production facility and see how the process works as for now. Video recordings were made to be able to analyze the work process and divide it into sub-tasks in AviX to see how much time the operator spent on each sub-task. An interview was carried out with the operator to get an understanding of what problems there might be in the process today and how the information about what to do reaches the operator. What systems that were available for use was also investigated. This including what robot that was available and what ERP-system that was currently used. It was also decided what the level of automation was in the current state, and what level that could be suitable for the station in the future. A tool for this is DYNAMO [19], which was used in this thesis.

3.3 Future state development

With the findings from the literature study as a base, together with the current state analysis, a future state was developed. The first step in this was to decide how the process would be. A gripper that would be used for moving the pipes was also designed and manufactured, as well as a layout for the workstation suitable to the robot. The programming of the robot was also a part of the future state development.

3.4 Experimental design

Experiments were used to assess the proof of concept from a time and accuracy point of view. This to benchmark the station as well as finding improvement potentials. The different experiments that were carried out are presented below.

3.4.1 Repeatability of the robot in the measurement position

The tolerance of the current station is set to ± 1 mm. Therefore, it is of importance to prove that the future state has a repeatability that is within this tolerance. To test this, an experiment was conducted to determine the repeatability of the robot in the measurement position. The experiment had the robot hold a pipe at a set distance, then it measured the pipe by running it into an angled steel bracket, called the wall in the figure 3.2. The point where the pipe hit the wall has before the experiment been defined. When the torque sensors detected that the pipe had hit the wall the robot stopped. The point on the wall was compared to the TCP position of the robot and the robot could thus determine where it was gripping the pipe. This experiment was repeated for 5 different lengths of pipe with 20 runs per length. A visualization of the experiment is shown in figure 3.2. The result of the experiment will help in determining the spread of the measurements and by that tell the repeatability.

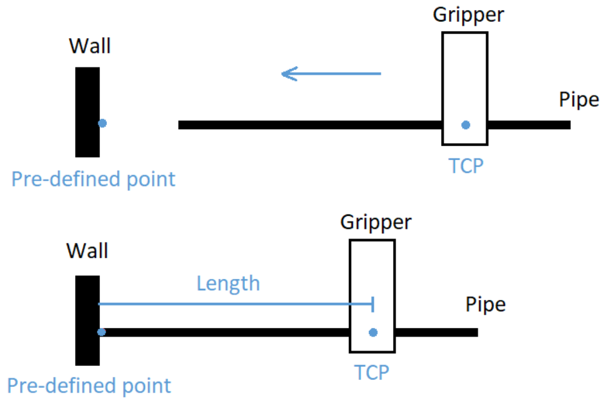

Figure 3.2: A visualization of the measuring process in the experiment.

3.4.2 Accuracy of measurement

As the points that the measuring depends on are defined manually, the accuracy of the measurement depends on how accurate the points have been defined. This accuracy could thus in theory be as good as the robots repeatability. However, to test the accuracy a similar experiment as described in figure 3.2 was conducted. A pipe was set at 10 different lengths and the pipe was manually measured with a caliper and the robot for each length. This experiment would give input on how accurate the robot can determine where it is gripping the pipe. This in turn determines how exact it can place it in the cutter. The result from this experiment will help to answer the research question on what the benefits are with using the robot instead of the worker.

3.4.3 Time study

To provide more input on the research question regarding what the benefits are from using a robot instead of a human worker, the time between two cuts was measured as well as the time it took for the robot to pick and measure a new pipe. The time consumption was determined by making a movie recording of the process and then making an analysis of the movie in AviX. By doing this, the future state could be compared with the current state and conclusions could be drawn regarding the benefits in terms of cycle time.

3.5 Results

When all parts of the future state were tested through experiments and considered done, the final test runs were made and the result of installing a collaborative robot in the workstation could be collected. These were later compared to the results from the analysis of the current state to see what the benefits are with implementing a robot instead of a human. A FMEA was carried out as the future state was finalized. This because as risk assessment is requested when using a collaborative robot [3].

4
Results

In this chapter, the results from the different steps of the thesis are presented, starting with the current state analysis. Thereafter, the results from the future state development are presented and finally the results of the experiments to validate the future state are presented.

4.1 Current state analysis

In this section, the results from the current state analysis are presented. This includes the layout, the process flow, the information flow, available systems, and the Level of Automation (LoA) of the current state.

4.1.1 Layout

From the visit of the production facility, the layout of the current workstation was analyzed. A picture of the current workstation is presented in figure 4.1. The workstation consisted of a pile of pipes (1), a table where the pipes were fed into the cutting machine (2), a table where the pipes were fed out of the cutting machine (3), a buffer storage of pipes that could be used again (4), a kitting rack for the finished pipes (5), a cutting machine (6), and a beveling machine (7). The length of the pipes to cut was set by a ruler on the table for outgoing pipes from the cutting machine. Under the ingoing table, a recycling box was placed, in which the pipes too short for the buffer were placed (8).

4.1.2 Process

From the video recordings and interview with the operator, the process of the current state was determined. The interview with the operator is presented in Appendix A. The operator cut all pipes of the same length in a row in order to get less deviation and setup time. The work was split into main tasks and divided between operator and machine. A time study was made in AviX for these main tasks and is presented in figure 4.2. The time, 29.8 seconds, shown in the figure was the time it took between two cuts. Depending on how long the pipes were, a different amount of cuts could be done using one pipe.

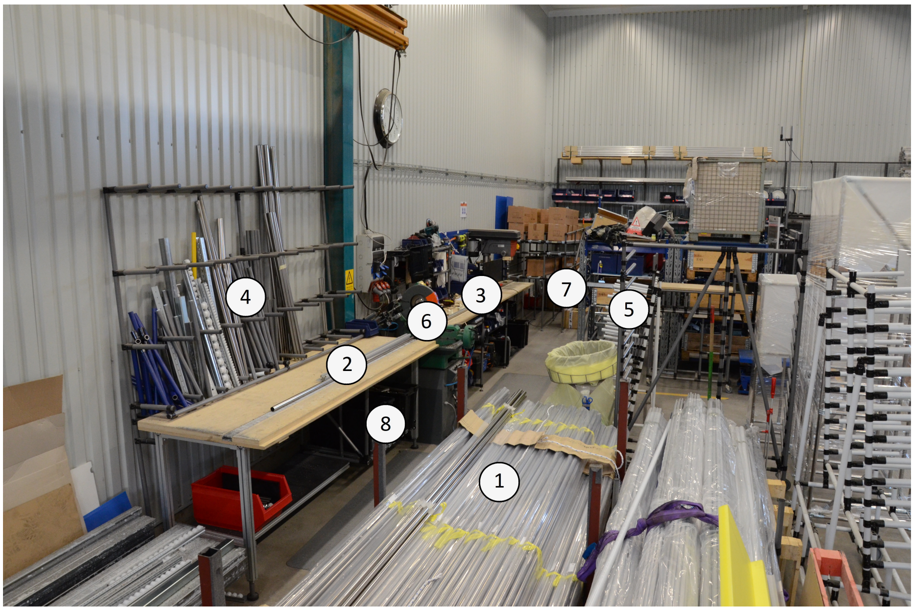

Figure 4.1: Photograph from the production facility of the workstation in the current state with numbers representing the different components within the work-station.

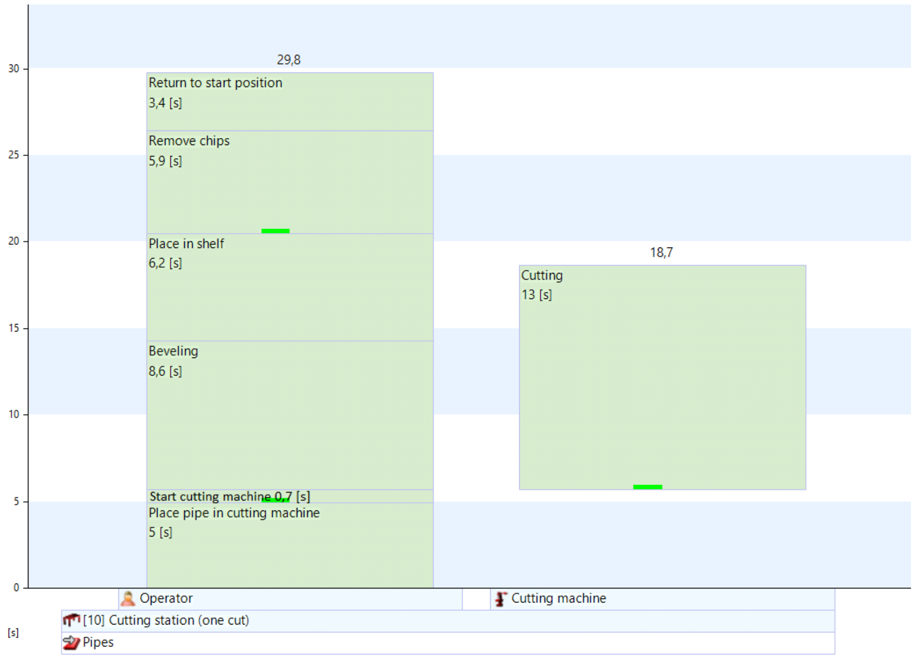

Figure 4.2: Time consumption for operator and machine in the current state in a snap-shot from AviX.

The main tasks were divided into sub-tasks in order to get a more detailed structure of the process. This to understand the different steps of the process better. The process flow with sub-tasks is presented in figure 4.3.

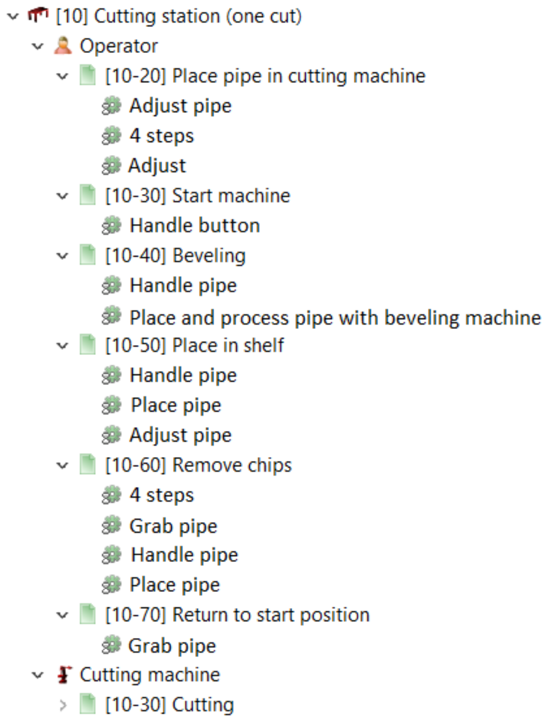

Figure 4.3: Task-breakdown of the cutting process made in AviX.

The pipes are wrapped in packages of ten when they arrive to the station in the current state. Therefore, for every tenth pipe, the operator has to unwrap new pipes. This takes 60 seconds for ten pipes, which results in 6 seconds for each new pipe. In addition, it takes 6 seconds for the operator to place one a new pipe on the ingoing table. As the operator makes all cuts of the same length in a row, the only setup time is between different lengths. This takes approximately 14 seconds. The first pipe of each length is control measured, which takes approximately 9 seconds.

4.1.3 Available systems

There are some equipment and technology available that is currently used at the cutting station and/or in other areas of Virtual Manufacturing's business. The cutting machine that is currently used at the station will be further introduced, as well as the robot that is available at Virtual Manufacturing and the ERP-system that the company currently uses.

Cutting machine
An automatic cutting machine triggered by a foot pedal is currently used at the cutting station. The material to be cut is adjusted manually to the correct length. A compressed air tool is used for removing chips from the cutting machine when needed. This cutting machine will however not be available during the future state development, due to it being in Linköping and the development of the future state will be done in Gothenburg. Thus, another much simpler manual cutting machine, that is available at the Gothenburg office, will be used as a temporary solution, however it is assumed that the cutter in the future state is the same as the one in

the current state so the manual saw will be "simulated" as automatic with the same cycle time as the one in the current state by an operator.

KUKA LBR iiwa 14 R820
The robot that will be used, due to its availability at the company, is a KUKA LBR iiwa 14 R820. The robot can detect external forces through its torque sensors in all 7 axes [5]. The pose repeatability of the robot is ± 0.15 mm [25].

Monitor G5
Monitor G5 is the ERP-system currently used by Virtual Manufacturing. Orders are entered into the system, but not the exact length of every pipe, just the total quantity of pipe needed for the product. The system is used for order tracking and economics.

4.1.4 Information flow

The information flow in the current state is presented in figure 4.4. As can be seen from the figure, first the order is received and a design engineer creates the shelf in the CAD-program SalesPoint. From the CAD-drawing, a Bill Of Material (BOM) is created which is then sent to the factory in a production documentation. At the factory, the order is planned and given a starting time and then it is released to the cutting station. The order is released in the form of the production documentation and the operator uses the BOM included in the documentation as a orderlist of what to cut. An example of a BOM is shown in figure 4.5. In the analysis it was found that the BOM for the order is not entered into the ERP-system, just the total amount of each article, for example 12 meters of pipe (not 3 pipes of 2 meters and 6 pipes of 0.5 meters).

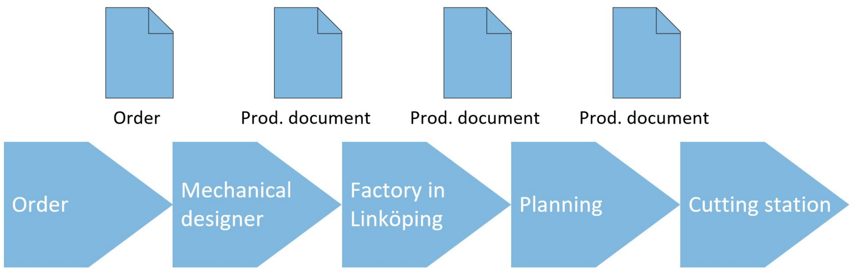

Figure 4.4: The flow of information from the order being placed until the operator in the cutting station receives the cutting instructions.

VM_320_900x1765_revE.xls:

BOM / Plocklista

Item No.	Art. Number	Part Name	Qty	Length	Product group
1	M8 Washer	M8 Washer	24		Fastener Washer
2	M6S M8x25	M6S M8x25	24		Fastener Screw
3	M6M M8 Nyloc	M6M M8 Nyloc	24		Fastener Nut
4	8201	L-PO 100G-FI	2		Castors with fixing plate
5	46565	L-PO 100G	2		Castors with fixing plate
6	311464	B-PO 100G	2		Castors with fixing plate
7	117717	GAP-4AT	2		Cover caps AT-pipes
8	117690	AT2829SA	2	1568	Alu pipe
9	117516	ARG-35B	4	1830	Lateral guide
10	117516	ARG-35B	2	1705	Lateral guide
11	117516	ARG-35B	2	1580	Lateral guide
12	115014	GAP-P	22		Name plates
13	115013	NP-P-1500	6	807	Name plates
14	115013	NP-P-1500	2	250	Name plates
15	114941	MCP-C WZ	2		Middle section
16	114334	GA-13S WZ	8		Metal Joints
17	114330	GA-7S WZ	8		metal joints
18	114326	GA-4S WZ	2		metal joints
19	114321	GA-1S WZ	47		metal joints
20	109993	MCP-B-R WZ	2		Mount corner
21	109992	MCP-B-L WZ	2		Mount corner
22	109983	LA-CA6-E	2		Name plates
23	109709	GAP-4-S-B	9		Cover caps
24	100573	S2812-PF	1	1895	SUS Pipe
25	100573	S2812-PF	4	1652	SUS Pipe
26	100573	S2812-PF	1	1568	SUS Pipe
27	100573	S2812-PF	4	1490	SUS Pipe
28	100573	S2812-PF	2	1484	SUS Pipe
29	100573	S2812-PF	2	1466	SUS Pipe
30	100573	S2812-PF	4	802,5	SUS Pipe
31	100573	S2812-PF	18	797	SUS Pipe
32	100573	S2812-PF	6	230	SUS Pipe
33	100573	S2812-PF	1	153	SUS Pipe
34	100573	S2812-PF	2	105	SUS Pipe
35	100573	S2812-PF	2	80	SUS Pipe
36	100573	S2812-PF	2	65	SUS Pipe
37	100528	GP-3533B	20	1930	Roller tracks
38	100528	GP-3533B	10	1805	Roller tracks
39	100528	GP-3533B	10	1680	Roller tracks
40	100494	GP-D35	40		Mounting brackets for roller tracks
41	100490	GP-A35	40		Mounting brackets for roller tracks
42	100460	GAP-06-G	4		plastic Holder

Figure 4.5: The order printout currently used as cutting instructions. The pipes are marked with the blue box.

At the office in Gothenburg, where the CAD-drawings are created, an optimization is made for the cutting of the pipes. This means that the different lengths are sorted in an order that will require as few pipes as possible and thus, minimize the leftovers. This requires more changeover in the cutting station and may lead to variations. This is the reason for why the operator in the current state does not utilize the optimization. The operator uses the BOM and cuts all pipes of the same length in a row and saves the leftovers that are long enough to use again. The reason is mainly to reduce changeover and to get the pipes of the same lengths with as little variation as possible due to using the same settings. According to the operator, this system does not produce a lot of waste.

The orders are registered in the system when they arrive from the ordering company. The BOM is thereafter used to register used materials in the order, in order to control in- and output of material to the production facility. This registration covers all material of a specific type, which means the total length of a specific pipe.

4.1.5 Level of Automation

By using the DYNAMO methodology, presented in section 2.5.1, the LoA for the current state was determined. The results from the analysis of layout, process, and available systems were used in the first steps of the DYNAMO methodology. Therefore, the results from the DYNAMO methodology will start from step 7.

Step 7
Relevant minimum level of automation for the cutting station was set to be level 2 in both physical and cognitive. The physical level could at minimum be of level 2 since the operator needed some kind of tool to cut the pipes, it could not be done by hand. The cognitive level was set to be 2 as a minimum since the operator needed to get some information of what to cut, it cannot be made straight from previous experiences since what to cut differed for each order. In the physical LoA, the maximum was set to be 7. This from the interview of the operator, input from the company, and due to the fact that the tasks and sub-tasks of the station was simple and easily could be automated. The maximum level of cognitive LoA was also set to be 7, get the information from the BOM directly, no instructions would be needed and the robot could perform the cutting.

Step 8
Figure 4.6 visualizes the current state analysis, where the current state level is marked with a dot. The green area is the possible levels of the system based on the minimum and maximum. The different LoA is explained in table 2.3 in Chapter 2.

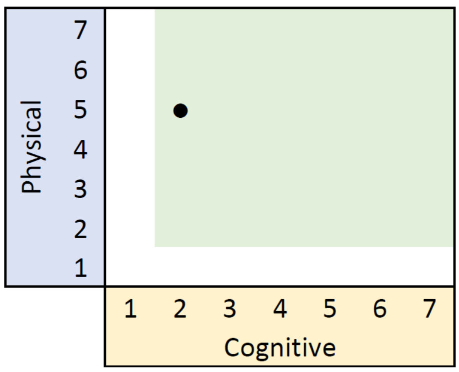

Figure 4.6: Analyzed LoA in the current state. The dot represents the current LoA and the green area marks the minimum and maximum LoA of the station.

4.2 Future state design

In this section, the results from the future state are presented. First, the developed end-effector will be presented. Thereafter, the layout, process, and information flow of the future state are presented. Finally, the result from the FMEA is presented.

4.2.1 End-effector

For the workstation, a gripper was chosen as end-effector. To make the gripper best suited for the task and at a fair price, the gripper used in the test runs was created by the authors instead of buying a complete solution. The gripper consisted of a double acting pneumatic cylinder, a pneumatic 5/2 valve and steel parts for holding the pipe. A pneumatic system was chosen for its simplicity as compared to hydraulics and low investment cost as compared to electrics. The gripper can be seen in figure 4.7.

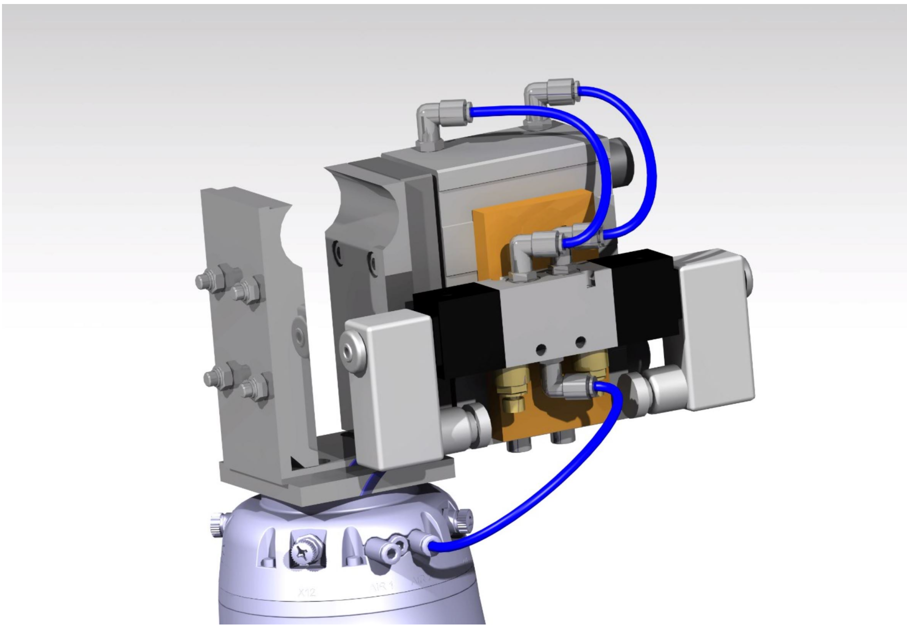

Figure 4.7: 3D-model of the gripper mounted to the robot.

4.2.2 Layout and process

As the robot does not have the same reachability and ability to move as a human worker, the layout of the workstation had to be redesigned. The design process followed the framework presented in section 2.2 and the final workstation layout was chosen by the authors with input from the company supervisor. The layout is presented in figure 4.8. Due to safety aspects, the layout and process were designed so that the robot does not have to swing pipes around too much.

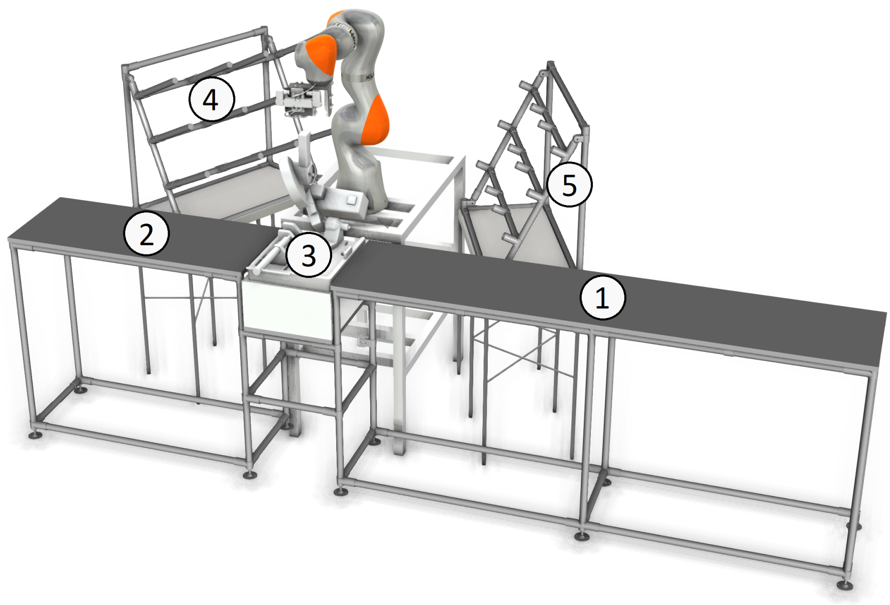

Figure 4.8: Layout including robot, mount, gripper, workbench, cutting machine, kitting rack, and buffer rack.

The layout consisted of a cutting machine, as described in section 4.1.3. There were also two tables, one for ingoing pipes (1) and one for outgoing pipes (2), these had a U-profile mounted on them acting as a guide for the pipe to make it easier for the robot to align the pipe with the cutting machine (3). There were also two racks, one kitting rack (4) in which the robot could place the cut pipes into. It was equipped with multiple stories so that pipes of different length could be separated. The other rack was a buffer (5) where the robot could place pipes that were not long enough for the next cut. When the robot needed a new pipe, it searched through the buffer (the pipe lengths are stored in an array in the robot program) to see if there was a pipe long enough in there. If it was, it picked that pipe instead of picking a new pipe. A recycling bin for pipe leftovers too short for the buffer was also placed in the station. On the ingoing table there was also an angled steel bracket used for the measuring where the robot was gripping the pipe, this solution was inspired by the case study in section 2.3.3. A more detailed description on how this was done is presented in section 3.4.1, especially in figure 3.2. The measuring was made when the robot picked a new pipe or a pipe from the buffer. The pipe was then placed perfectly in the cutter, even if there was a deviation in how the pipe was placed in the racks. An important part of the process that has been excluded from the scope of this workstation is how the pipes are fed into the station. Since there is another thesis project with the scope of feeding the pipes onto the table one by one, the station in this thesis work assumes that there always is a new pipe ready when needed.

The process flow chart can be found in Appendix B. It consists of all steps needed for the robot in order to run the workstation as it is today, except for the beveling.

4.2.3 Information flow

The information flow that will enable the robot to receive cutting instructions is based on what was discovered in the current state analysis of the current information flow. Since the instructions are currently being distributed as a pdf- and an excel-file (.xlsx) and placed on a server accessible by anyone inside the company, it was decided that the robot would fetch the cutting instructions from this server. The robot used for the workstation is programmed in java, from which it is easy to read excel-files to gather information regarding the cutting.

4.2.4 FMEA

A FMEA based on the process FMEA presented in section 2.5.2 was conducted for the future state, as a risk assessment is requested when implementing a collaborative robot station. The filled out FMEA sheet is presented in Appendix C. The FMEA was based on how the process had been working during the test runs, which means that the result might have been different if it would have been run for a longer period. The recommended actions were never taken in the actual process, just in theory. From the FMEA, the surrounding environment was found as the most severe area. In this FMEA, a scale from 1-10 was used for setting the RPN. The RPN for this was set to 150, this due to that there are objects in the surrounding environment that can interrupt the process. For instance, a forklift might run into the workstation and make all the pre-defined points incorrect. This would mean that the process either does not work at all or that all measurements and positions are wrong, which leads to major quality issues. The recommended action for this was to mount everything to the floor, keep it on a safe distance from forklift aisles, and use some kind of fence to avoid objects to interrupt the workstation. These actions would decrease the RPN to 40.

4.3 Experiments

In this section, the results of the experiments are presented. First, the results from the repeatability test is presented. Thereafter, the results from the accuracy measurement and time study are presented.

4.3.1 Repeatability of the robot in the measurement position

5 tests were run where the same distance was measured 20 times (the distance was changed between the tests). The results from test 1-5 are graphically presented in figure 4.9 below.

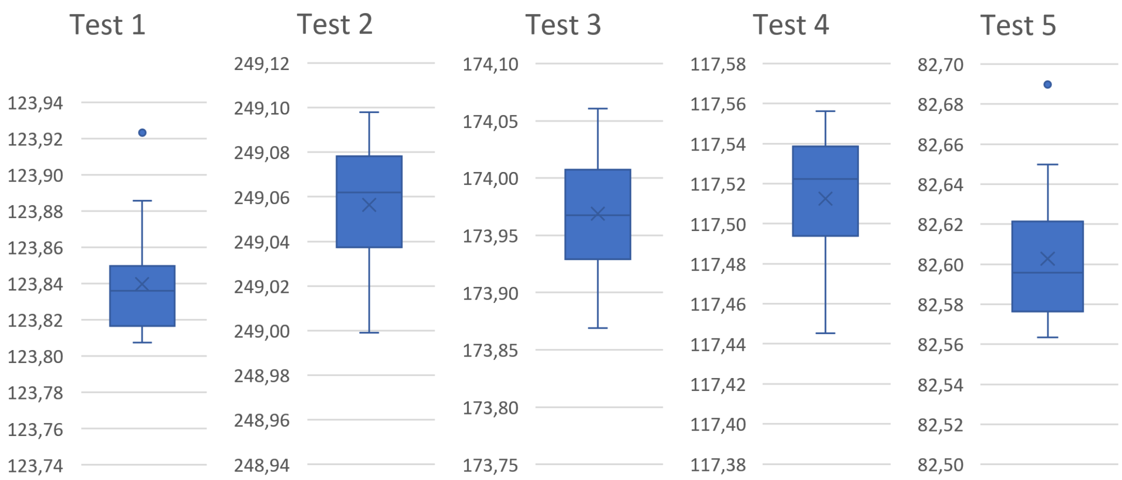

Figure 4.9: Boxplots showing the results from test 1-5.

Below, in table 4.1, the standard deviation, variance and the largest difference between the maximum and minimum value are displayed for all of the tests presented above (tests 1-5). Between the tests, the mean standard deviation is 0.02979 mm. The worst case in the experiment was in test 3, where the largest difference was 0.1919 mm. This is well within the tolerance of ± 1 mm.

Table 4.1: The standard deviation, variance, and largest difference between the maximum and minimum value (Max - Min) of the measurements from test 1-5.

	Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**
Std. deviation	0.02941	0.02795	0.04659	0.03463	0.03409
Variance	0.00086	0.00078	0.00217	0.00120	0.00116
Max - Min	0.1157	0.0988	0.1919	0.1109	0.1262

4.3.2 Accuracy of measurement

The same distance was measured once with the robot and once manually and thereafter the difference between these measurements was calculated. This was repeated for 10 distances. The results from the accuracy experiment is presented in table 4.2. The average difference between the two values was 0.16 mm. The highest difference was 0.32 mm and as the tolerance of the current workstation is ± 1 mm, this is well within the required tolerance. The accuracy achieved by the current state is ± 0.5 mm, so the new workstation is also more accurate than the current state.

Table 4.2: The results, in millimeters, from the accuracy experiment, including the value from the manual measuring, the robot measuring, and the difference between them.

Run	Manual	Robot	Difference
1	132.56	132.66	0.1
2	111.89	111.76	0.13
3	154.64	154.61	0.03
4	62.52	62.2	0.32
5	117.89	117.72	0.17
6	88.77	88.55	0.22
7	128.36	128.31	0.05
8	91.31	91.08	0.23
9	131.70	131.76	0.06
10	79.50	79.24	0.26

4.3.3 Time study

The time measured between two cuts when running the future state was 30 seconds. To grab a new pipe from the rack, measure it, and place it in the cutting machine took 8 seconds (can differ slightly depending on how the pipe is placed). To recycle one pipe took 10 seconds. The times of the new design in comparison to the current design is presented in table 4.3 below. As can be seen, the time between two cuts is similar but the changeover times, both between lengths and between packs of 10 have been eliminated in the new workstation. The recycle time is however longer, but this difference (6 seconds) is made up for since the unpacking is not needed in the new workstation. As the changeover is not needed in the new workstation, the time for changeover and control measuring is freed.

Table 4.3: The time consumption in seconds for different tasks in the new design in comparison with the current design.

	Current state	Future state
Unpack pack of 10	60 (6/pipe)	0
Get new pipe and place on table	6	8
Between two cuts	30	30
Changeover	14	0
Control measure first pipe after changeover	9	0
Recycle	4	10

5
Discussion

In this chapter, the different parts of the thesis will be discussed. The discussion has been divided into four topics, robot, process, methodology, and information flow.

5.1 Robot

In the thesis, the KUKA LBR iiwa 14 R820 is the only robot considered since it is the one that is available at Virtual Manufacturing. This robot is rather small, expensive, and might not be the robot that is best suited for the kind of task that is required in this thesis. In section 2.2 it is mentioned that simple, repetitive tasks are most suited for traditional industrial robots, whilst more flexible tasks are more suited for collaborative robots. Traditional robots are also better for material handling tasks and thus, a traditional robot might be more suited in this process. If a collaborative robot is what is wanted by the customer, there are alternatives to the KUKA used in the thesis that are cheaper and/or have a longer reachability. Having a collaborative robot also has its advantages as compared to a traditional robot. For example, the robot can be moved between stations to have it do different tasks and it can automatically calibrate itself in a workstation by using the sensors in its joints. Another benefit that this implementation benefited from is the easier programming of collaborative robots. Since the KUKA LBR iiwa is programmed in java, it was easy to have it as the single processing unit of the station. So, the robot could by itself read .xlsx files for the BOM etc. This would be harder to do with a traditional robot. Even though the new workstation was not collaborative, having the torque sensors helped with the measuring process and they could also be used to detect a crash in the station.

One of the delimitations in the thesis is that the pipes has been limited to two meters instead of the four meter lengths used in the actual process. The limitation in length is due to the large torque that would be generated in the axis of the robot if it were to lift the pipes. A way around this problem could be to have a separate feeding solution, and only slide the in-going pipe along the guide for the measuring. By doing this, the station can handle the four meter lengths.

5.2 Process

As the case study in section 2.3.1 states, fully automated stations are suitable for large batches (26 or more), in terms of programming time. The orders of the cutting process often exceeds 20 parts and the programming between two orders is very simple since it does not require any changes in the main program more than reading a new .xlsx file. As it is mentioned in section 2.4, when dealing with make-to-order production, a lot of time can be saved by making the systems talk to each other (in this case, the robot and the BOM placed on the server). Therefore, it is considered to be suitable for full automation. The result from assessing LoA for the current state in section 4.1.5 confirms that the process is suitable for automation.

The process of cutting the pipes is not a creative and flexible task and does not require any decision making from a human, which makes it suitable for a robot to perform, according to what is mentioned in section 2.2. In the case study in section 2.3.2 it is stated that robots are superior to humans when it comes to reliability and quality. This is confirmed from the experiments of accuracy and repeatability in section 4.3, which also confirms that the robot is suitable for the tasks.

Compared to the current way of working, the workstation designed in this thesis has no changeover time when changing between different lengths of pipes to cut. Therefore, it is possible to use an optimized orderlist, where as few pipes as possible are required for an order, this will reduce the leftovers, which in turn can save money in terms of material cost. As the results show in section 4.3.3, the time of the process is depending on the variety of the pipes to cut and how often a new pipe needs to be used.

The workstation designed in this thesis contains all parts from the current workstation, except for the beveling. There are some reasons for that. First of all, a requirement in terms of safety is to not swing the pipes around too much. When using one beveling machine, the pipe has to be rotated 180 degrees in order to reach the other end of the pipe, which is not considered as safe. The reachability is also an issue in this manner, as the robot grip the pipe in one end when it comes out of the cutting machine, it will be difficult if even possible to rotate a long pipe 180 degrees while holding at the end of the pipe. Installing two beveling machines would not solve the problem as the distance between the gripper and the end of the pipe that is far away from the cutter can be of any distance and it is therefore difficult to tell where the second beveling machine would be placed.

The end-effector in this thesis is not perfect but it works for the proof of concept. However, for longer pipes there was some deviation in the angle the gripper held the pipe, this can affect the measuring and thus the measuring should be done in different angles to get a better estimate on the gripping distance. Another solution to this problem could be to use some kind of guide to keep the pipes horizontal during the measurement. This was not used in the proof of concept due to lack of space on the table, due to the fact that the gripper requires a lot of space in order to move freely.

The FMEA made in this thesis is not based on the actual usage of the station, only for the test runs and how things are planned to be in theory. An analysis is therefore recommended to do for running the workstation with full orders in its actual environment (it has been run at an office and not in a traditional production facility). In this case, it was considered to be enough since the workstation is a proof of concept, but if the workstation is to be implemented in the real production facility, a new FMEA (or similar risk assessment) needs to be done.

5.2.1 Collaborative process

The workstation designed in this thesis is not a collaborative workstation. The reason for this is that there are many sharp edges, both on the pipes as well as on the gripper. The gripper also generate a very high gripping force in order to grasp the pipes securely, and if a body part would get pinched in between the gripping surface and the pipe, the human could be seriously injured. The gripper could be made collaborative by redesigning it. However, even if the gripper would be collaborative, the sharp edges of the pipes would still make it hard to classify the process as collaborative.

The speed of the robot is also a problem since the end of a long pipe would travel at a very high speed when handled and if it collides with a human, it might result in serious injuries. This means that, just as for traditional robots, this workstation has to be fenced of. This can either be done by physical fences, light barriers, or laser scanners. In the FMEA made on the designed workstation the dangers of the station are presented and the solution to some of the dangers is to fence of the station. However, the force sensitivity in the joints of the collaborative robot are used in the workstation, both for measuring at what distance the robot is gripping the pipes and also as crash detection if the robot were to crash into something in the station.

5.3 Methodology

The methodology of this thesis started with a current state analysis, this to get a good understanding of how the process works and how a new workstation could be designed. This was a fast and good way of starting the design of the new process. However, one drawback of starting with an analysis of the current state is that the observer might be locked into how the process is currently working, and thus the creativity might be impaired. Another way of doing it can be to start with a concept design phase, this might yield more creative solutions for the new workstation. These creative solutions can then be used as inspiration when creating the future state.

In the current state analysis, some of the times for the process are given as approximations, the reason for this is that when the current state was analyzed, some of the process steps were not executed by the operator. To solve this, the authors recreated the process and times were taken from these movies instead. This was repeated multiple times so that a good approximation was ensured.

5.4 Information flow

In the beginning, it was planned to use the ERP-system to receive cutting instructions for the robot. However, the actual length of each pipe in an order is not entered into the system, just the total requirement for the order. It would theoretically be possible to use the ERP-system, but all possible pipe lengths would have to be manually put in as separate products in the ERP-system, which is not practically possible due to the very high number of possible pipe lengths. This meant that the ERP-system could not be used as first intended. The way the information flow works today could instead be used, since the BOM is today saved on a server, where it is then fetched when it is released to the cutting station. This means that the new future state does not require a big change in the information flow, it just removes one step from the current way of working. This is good since it will be easy for the employees to adapt to the new work flow.

6
Future work

In this chapter, some thoughts regarding future work are presented. These ideas was not implemented in the thesis due to limitations in time and availability of material.

The gripper used in this thesis is over dimensioned and very heavy. It also has quite sharp edges and is made of steel, which makes it not classified as collaborative. The strength of the gripper might cause injuries if an operator gets to close. An alternative gripper was designed during the thesis, but never manufactured. In a future state, this alternative gripper could be manufactured through, for instance, 3D printing in carbon fibre to keep the strength but at a much lower weight. This gripper can also be rounded in the corners and modified so that no human operator can be injured.

In the result from this thesis, there are some adjustments that can be made in order to speed up the process. This by optimizing the path and removing unnecessary movements.

As the workstation developed in this thesis is a proof of concept, a next step is therefore to implement it, or a similar solution, in the actual production facility. To make this implementation successful, this could include the previously mentioned ideas for future work.

7
Conclusion

The results in this thesis propose a way in which a collaborative robot can be implemented for cutting and kitting pipes. The result covers on how the layout of the workstation can be designed, how the end-effector for the robot can be designed and how the robot can gather information on what lengths of pipe is needed for which order. The layout has been centered around the robot to make it easy for the robot to reach all positions. The end-effector is a pneumatic gripper with a high gripping force that ensures that the pipe is held securely. To know what to cut, the robot fetches the BOM directly from the server. This means that no human involvement is necessary.

The benefits of using a collaborative robot in the workstation is that it relieves the operator from the repetitive and non-developing work that is the case in the workstation today. The process time is also lowered in the new workstation and the accuracy is improved. Another big benefit of using a robot instead of a human is that the robot can work 24/7 without need for breaks (except for some stops for maintenance).

This thesis contributes to the research area with one more example of how a collaborative robot can be implemented in industry. It also shows the benefits of using a robot in a workstation as compared to a human.

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A

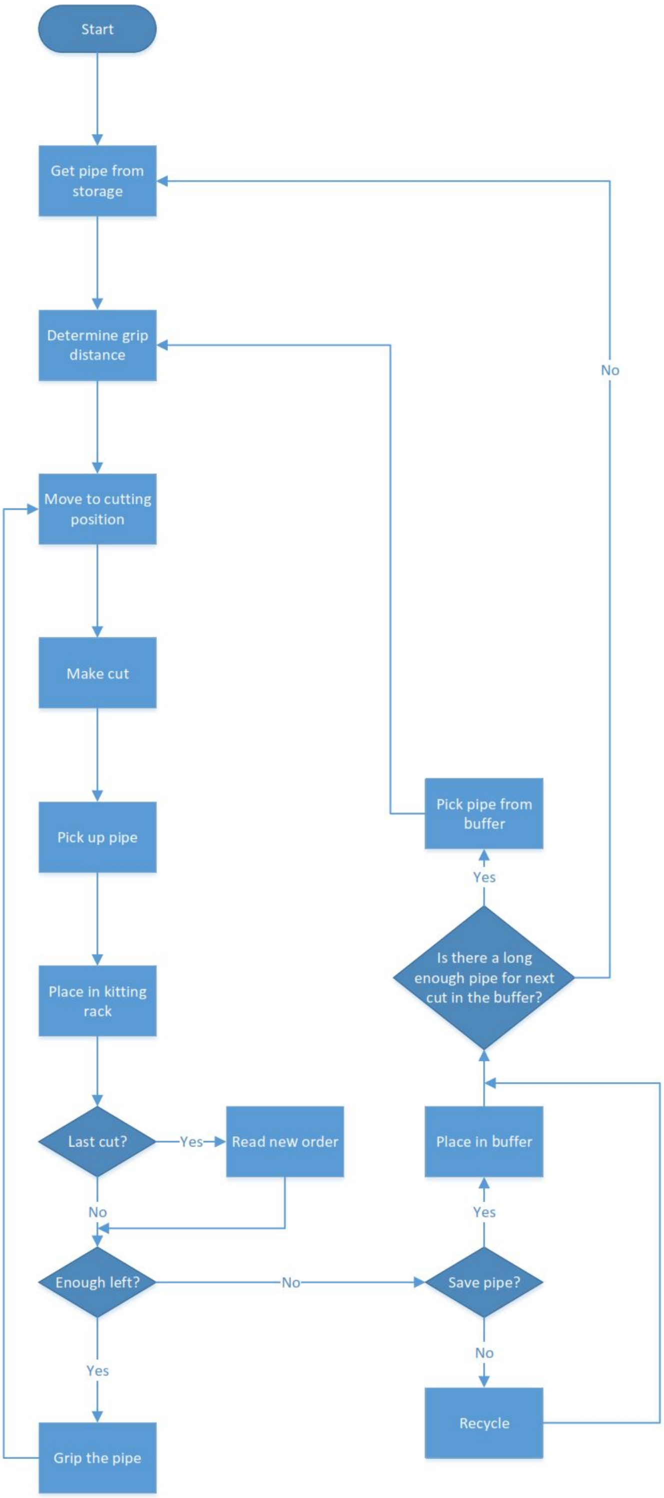
Interview with the operator

The interview was held in Swedish and has been translated into English by the authors.

- How do you think that the process is working currently?
  - It works well.
- Is there something regarding the layout of the station that you would like to change?
  - Not really, it works pretty good as it is today.
- Does the work require any unergonomic postures?
  - It can be a bit heavy when the pipes are lifted up into the cutting machine. Other operators lift a whole bunch of pipes at the same time with a traverse and put them at the table, which minimizes the lifting. Otherwise, the height of the table is pretty good. It would be nice to be able to adjust the height of the pallet where the pipes are though.
- Are there some tasks that you think are more suited to be automated?
  - Everything. Lifting the pipes and push them into the machine.
- Is there some task that you think a human operator is required for?
  - Enter dimensions.
  - Unpack the material that is in plastic bags, straps, and other packaging materials.
  - Cut rails with rollers since they might be a bit tricky since a roller might be damaged and needs to be removed. This could be difficult for a robot to handle.
  - When deburring, short pieces can be difficult to hold.
- Do you work at irregular hours? E.g. due to variation in production orders?
  - Often work from 05:00 to 13:30. Some days during some periods it can be up to 15 hours a day. It differs from period to period, but there is often work to do.
- Do you have other work tasks but cutting?
  - I sometimes work with assembly.
- How do you receive instructions for what to cut?
  - Through a list, from order documentation.
- Are there different dimensions of the pipes?
  - Different colors. Different dimensions and shapes in terms of rollers, pipes, and guides. A changeover is needed between pipes and rollers. Then cutting rollers, they are two at the time.
- How does the material enter the station?

  - *Documented through film recordings and pictures.*
- How does the material exit the station?
  - *Documented through film recordings and pictures.*
- Is there something that cannot be changed at the workstation?
  - No. Electricity and compressed air are needed.
- How many times do you cut in a day? How many can it be at the most?
  - Difficult to say, it differs from day to day. One order can be around 20-30 but it varies from order to order.
- How do you handle leftovers? Are pipes of a specific length kept?
  - Longer pipes are sorted saved above the table at the workstation, while smaller are kept in boxes underneath the table.
- How is the cutting made, is it optimized to get as much as possible out of one pipe or to get as good accuracy as possible?
  - There is an optimization software, but it requires a lot of changeovers, which leads to less accuracy. Currently, I follow the production order (BOM) which starts with the longer pipes fist.
- How do you handle a pipe that is cut in the wrong length?
  - That does not happen often with the method that is used today. This is handled differently depending on length. The first pipe after a length changeover is measured.
- How often do you use the compressed air?
  - It varies, when needed. When smaller pieces are cut I use the compressor air tool to pick up the pieces.
- Any other things that are good to know?
  - The cutting machine requires at least 5 cm to grip the pipes (on the left side, the right side is worn out and does not work). When shorter pieces are to be cut, the pipe can be turned around so that the leftover piece is on the right side. A piece of wood is used for smaller pieces. If this is not taken into consideration, the cutting machine can nab.

B
Process flow chart



C

FMEA future state

Process FMEA													Action results			
Process/ function	Potential failure mode	Potential effects of failure	Critical characteristics	SEV	Potential causes of failure	OCC	Detection method	DET	RPN	Recommended action	Area responsible and completion date	Actions taken	SEV	OCC	DET	RPN
Gripping pipes	Not gripping the pipe	The process continues without a pipe	Y	2	Pipe gets moved out of the picking spot	2	No detection method	1	4	Sensor in gripper	N/A	N/A	2	2	1	4
	A body part gets stuck	A person gets injured	Y	9	A person enters the station	6	Visual	1	54	Fence or sensor wall around the station	N/A	N/A	9	1	1	9
	Dropping the pipe	Pipe hits a person	Y	9	Loss of pressure in pneumatic system	1	No detection method	1	9	Pressure sensor with alarm	N/A	N/A	9	1	1	9
	The pipe hits cutting machine	Crash that stops the process	Y	4	Pipe placed too far to the left in the ingoing rack	2	Visual	1	8	Add something on the rack that makes it impossible for pipes to be too far to the left	N/A	N/A	4	1	1	4
Releasing pipes	The pipe does not drop as planned	Pipe get into a wrong position or falls out of place	Y	3	Rubber coating gets sticky due to wear	8	No detection method	2	48	Remove/improve coating from gripper surface	N/A	N/A	3	2	2	12
Clamping in cutter	Not clamped	Pipe is loose, might result in bad quality	Y	6	Loss of pressure in pneumatic system	1	No detection method	3	18	Pressure sensor with alarm	N/A	N/A	6	1	1	6
	Clamp stuck	Robot stops when torque sensors detect large resistance	Y	2	Robot lifts a pipe that is stuck	2	Visual	1	4	Position sensor in pneumatic cylinder	N/A	N/A	2	1	1	2
Kitting	Pipe falls out	Pipe gets lost from the order	Y	3	There are not enough supporting beams	7	Visual	2	42	Add more beams in kitting rack	N/A	N/A	3	1	2	6
	A lot of pipes of different length in the same slot	Hard to determine what pipe to use when assembling	N	1	There are too few slots in the kitting rack	6	Simulation runs	1	6	Add more slots in kitting rack	N/A	N/A	1	1	1	1
	A slot is full	Crash when the robot shall place a new pipe in the slot	Y	5	There are too few slots in the kitting rack/ too short slots	4	Simulation runs	1	20	Add more slots in kitting rack and counter in program	N/A	N/A	5	1	1	5
Buffer	Buffered pipes are forgotten by the robot	The robot places a pipe where there is already a pipe placed	Y	4	Process must be rebooted for some reason	6	No detection method	3	72	Start program with weighing all buffer locations	N/A	N/A	4	1	3	12
Recycling	Recycling bin overfilled	Overflow of pipes	N	1	Recycling bin too small or has not been emptied	7	Simulation runs	1	7	Empty recycling bin every morning in a routine and make sure that the bin is large enough	N/A	N/A	1	1	1	1
Measure	Wrong length	First pipe is not correctly cut	Y	3	Other torque input (wobbly pipe, forklift passing close)	3	Visual (During assembly)	5	45	Team torque measuring with weight measuring	N/A	N/A	3	1	5	15
Cutting	Sawblade malfunction	Cut not made or made with poor quality	Y	6	Sawblade worn	4	No detection method	3	72	Preventive maintenance with visual inspection	N/A	N/A	6	1	1	6
	Cannot pick up the cut pipe	The cut pipe will not be moved into the right position	Y	3	Ordered pipe length too short	2	Visual (During assembly)	2	12	Do not accept orders under a specific length. Give these orders to the operator to handle	N/A	N/A	3	1	1	3
Process in general	The process does not start	The pipes are not cut	Y	4	Power failure	1	No detection method	1	4	N/A	N/A	N/A	4	1	1	4
	A person gets hit by robot or pipe	Human injured	Y	9	Human inside workstation	6	Visual	1	54	Make the process stop when human enters the area	N/A	N/A	9	1	1	9
Surrounding environment	Defined points are moved out of place	The robot cannot pick or leave pipes, potential crash	Y	5	External force hits workstation (Eg forklift)	6	Visual	5	150	Mount everything securely to the floor, no close forklift aisles, good fencing around the station	N/A	N/A	5	2	4	40