INCREASING PRODUCTIVITY OF A SHEET METAL FABRICATION COMPANY BY PERFORMANCE BASED BENDING MACHINE SELECTION AND WASTE REDUCTION

Lappeenranta–Lahti University of Technology LUT

Master's Programme in Sustainable Production in Mechanical Engineering, Master's thesis

2022

Matias Soini

Examiners: Professor Juha Varis, D.Sc. (Tech.)

Mikael Ollikainen, D.Sc. (Tech.)

ABSTRACT

Lappeenranta–Lahti University of Technology LUT

LUT School of Energy Systems

Mechanical Engineering

Matias Soini

Increasing productivity of a sheet metal fabrication company by performance based bending machine selection and waste reduction

Master’s thesis

2022

67 pages, 8 figures and 15 tables

Examiners: Professor Juha Varis, D.Sc. (Tech.) & Mikael Ollikainen, D.Sc. (Tech.)

Keywords: Sheet metal fabrication, sheet metal bending, job shop productivity

The case company is improving productivity of the bending department as it has been the bottleneck of the production. The case company is also implementing an enterprise resource planning system which requires production capabilities of different bending machines to function correctly. The objective of the thesis was to find production capabilities of different bending machines to create guide for performance based bending machine selection and to find most significant sources of waste in bending department.

The production capabilities of the bending machines were measured by monitoring the manufacturing times of individual products and by monitoring the number of bends made during the monitoring period of one week. New opportunities to improve productivity of the bending department were studied by conducting interviews and evaluating the results.

As a result of the study, it was found out that there are significant differences in production capabilities of different machines. The most common factors that have negative effect on the productivity of bending department were also found. Actions for reducing the effects of these factors are also presented in this thesis.

In addition to the manufacturing speed experiments and interviews, a literature review was conducted. The literature review was focused on finding actions that can be made to increase the productivity of a job shop.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUT Energiajärjestelmät

Konetekniikka

Matias Soini

Ohutlevyosia valmistavan yrityksen tuottavuuden parantaminen suorituskykyyn perustuvan taivutuskoneen valinnan ja hukan vähentämisen avulla

Konetekniikan diplomityö

2022

67 sivua, 8 kuvaa ja 15 taulukkoa

Tarkastajat: Professori Juha Varis, TkT & Mikael Ollikainen, TkT

Avainsanat: Ohutlevytuotanto, ohutlevyjen taivutus, alihankintayrityksen tuottavuus

Kohdeyritys on tehostamassa taivutusosaston tuotantoa, sillä taivutusosaston on todettu olevan tuotannon pullonkaula. Kohdeyritys on ottamassa käyttöön myös toiminnanohjausjärjestelmää, joka vaatii toimiakseen tietoa eri taivutuskoneiden valmistuskapasiteetista. Työn tavoitteena oli selvittää eri taivutuskoneiden valmistuskapasiteetit suorituskykyyn perustuvan taivutuskoneen valintaoppaan luomiseksi, sekä tunnistaa merkittävimmät hukan lähteet taivutusosastolla.

Taivutuskoneiden valmistuskapasiteettia mitattiin seuraamalla yksittäisten tuotteiden valmistusaikoja, sekä tarkkailemalla koneilla viikon tarkkailujakson aikana tehtyjen taivutusten määrää. Yrityksen tuottavuuteen negatiivisesti vaikuttavia asioita tutkittiin haastattelemalla tuotannon työntekijöitä sekä arvioimalla haastatteluista saatuja tuloksia.

Tutkimuksen tuloksena havaittiin, että eri taivutuskoneiden valmistuskapasiteeteissa on merkittäviä eroavaisuuksia. Myös yleisimmät tuottavuuteen vaikuttavat asiat saatiin tutkimuksessa selville. Toimenpiteet tutkimuksessa havaittujen asioiden vaikutusten pienentämiseen on esitelty tässä työssä.

Kirjallisuuskatsaus toteutettiin taivutuskoneiden valmistuskapasiteetin tutkimisen sekä haastatteluiden lisäksi. Kirjallisuuskatsaus keskittyi löytämään toimenpiteitä, joita voidaan tehdä alihankintayrityksen tuottavuuden kasvattamiseksi.

ACKNOWLEDGEMENTS

I want to thank Stremet Oy for offering a topic for the thesis. I want to thank especially the CEO of Stremet Oy, Hans Strömberg for the cooperation and support during the thesis. From the LUT University I want to thank my examiners professor Juha Varis and Mikael Ollikainen for supporting and giving feedback during the spring.

I want to thank my fiancée, friends, and parents for supporting me during the studies.

Matias Soini

Matias Soini

In Salo, 16.5.2022

ABBREVIATIONS AND SYMBOLS

ERP	Enterprise Resource Planner
JIT	Just-In-Time
MRP	Material Requirement Planning
MTO	Make-To-Order
POLCA	Paired-Cell Overlapping Loops of Cards with Authorization
TOT	Total Operating Time
WIP	Work-In-Process

B	Minimum bending flange
L	Width
R	Inner radius
S	Material thickness
V	Opening of the bottom V-die
σb	Tensile strength

Table of contents

1. Introduction

This thesis studies different ways to measure and increase the productivity of a bending department of a sub-contracting sheet metal fabrication company. In this chapter the background of the thesis is introduced. This chapter also includes literature review of the topic as well as objective, scope, and brief introduction to research methods that are utilized in this thesis. The data that is gathered from this thesis can be utilized in the future to choose best suitable machines for each product.

1.1. Background and motivation

This thesis is made for Stremet Oy, which is a sheet metal fabrication company located in Salo, Finland. In this thesis, the factors affecting the productivity of the company are studied. Different bending machines are also studied to develop basic rules that can be utilized when new products are manufactured. By increasing productivity, it is possible for the company to utilize current resources better. Efficient utilization of resources is vital for the company because any unused resources will increase the cost of production and thus decrease competitiveness against rivals. The effect of increased production costs is multiplied when the company is sub-contracting company, as increased production price of sub-assembly effects on the price of the final product.

The production capacity of the company has been increased by purchasing new, faster bending machines, which is common practice in sub-contracting companies in Finland (Kylmälä, 2017). However, as the machinery in the company is modernized, the operation practices have stayed mainly same throughout the history of the company. This can cause problems as many of these practices were developed when the company had only few employees and machines. Old habits can also mean that new machines are not fully utilized as some products are manufactured with an old machine instead of the new possibly faster machine. This thesis focuses on finding ways to eliminate the bottleneck that is present in the bending department. The problems of bending department can be seen from data as delay in bending department is the most common cause of late delivery of products. The bottleneck has stayed in the bending department despite new bending machines that has been purchased to increase productivity.

1.2. Objective and research problem

The objective of this thesis is to find new opportunities to improve the productivity of the bending department and to gather data about the manufacturing capability of different types of bending machines found in the bending department of the case company. The measured data can be used in the future when new production controlling system is implemented in the production.

It has been previously found out in factory level, that bending processes are not working optimal way.

In this thesis, root causes of problems that influence productivity of the process are investigated. The research questions are:

1. What are the manufacturing capabilities of different bending machinery?
2. What are the factors that affect negatively to the productivity of fabrication process?

1.3. Research methods

Several research methods are used in this thesis. The main research methods are literature review and experimental research. Literature review is included to give background information about similar studies that can be utilized when considering different methods for improving productivity. Before starting the experimental research, it is important to have a good knowledge about previous studies so that there is a clear starting point for experimental research in terms of different methods. Literature review can also be used to determine right test methods that can be used to assess productivity of the company.

Experimental research is important part of the thesis because it gives concrete results that can be used to assess productivity. Experimental research is used to identify problems and root causes of those problems, which can help to develop better methods that can be tested further.

1.4. Scope

The thesis focuses only on the bending department of the company. The methods that are developed in the thesis are not tested in other companies, as there are large differences between different companies. The thesis will not consider other factors that are present in the company operations, such as efficiency of logistics or productivity of other departments. The thesis consists of literature review and experimental research. The experiments that are performed during the experimental research will be carried out by observing the production in the company.

2. Methods

The research methods that are used in the thesis are presented in this chapter. In addition to introducing used research methods, reliability and validity analysis is conducted.

2.1. Literature review

The objective of literature review is to gather information about the field of the thesis. This information can be utilized as a base for the thesis. The literature review is conducted by searching information that can be helpful in the thesis. The information is searched utilizing LUT Primo academic search engine and Google search engine. Used keywords include for example, “5S”, “job shop production”, “press brake”, “sheet metal bending”, and “panel bender”.

The results that are gained from searching are utilized to form greater picture of the field of the thesis. By utilizing multiple references, it is possible to get familiar with already existing information about the subject. When studying the existing information, it is possible to recognize gaps in research. On the other hand, by studying previous research it is possible to reduce the need of own research as some results can be utilized from previous studies.

2.2. Practical experiments

The practical experiments can be divided into two categories. The first category is methods for increasing the productivity of the bending department. The second category is measuring data that can be used to choose right bending machine for each job based on the performance of the bending machines.

It is expected that the productivity of the bending department can be increased by identifying sources of waste during the day, which can cause a decrease in productivity. The sources of waste can be identified best by conducting interviews with bending machine operators. The interviews are conducted in two phases. In the first phase, all bending department operators are interviewed. After the first round of interviews is conducted, the results are summarized, and the summarization of results are gone through with all bending department operators. After the results from both interview rounds are evaluated, it is possible to develop possible solutions for problems that were identified in interviews. Testing the effects of these methods is not possible due to limited time that is reserved for writing this thesis.

There are several factors that should be considered when the production machine for the job is selected. The main criterion when choosing should be if the product is possible to manufacture with the machine that is considered for the job. It is possible that some products are not possible to manufacture with each bending machine, depending on various reasons, such as size of the product or thickness of the material. The second criterion is machine availability, because if the machine is not available for manufacturing the delivery of the product can be late. The third criterion for is the lead time of the manufacturing process. This depends highly on batch size of the order, as with small number of products the tooling time takes significant part of the total production time, whereas with high number of products the phase time of manufacturing is more important as tooling time is smaller percentage of total production time.

It is important to choose right machine based on measured data to make sure that the decision is correct every time. The data is collected by measuring the manufacturing time of each bending machine. With this data it is possible to choose right machine for each job. The manufacturing time should be measured with different products to find out what is the influence of different geometric features to the manufacturing time in each machine. By comparing these values, it is possible to choose right machine for each product.

The data for comparison can be attained from tests. The tests should have several products that can be manufactured with more than one of the tested machines to create comparable data. The number of tested products in this thesis is four. Different products are marked as Product 1, Product 2, Product 3, and Product 4. The products are designed by the customers of the case company, which is why it is not possible to present accurate information about the geometries of the products. Product 1 has 8 bends, Product 2 has 4 bends, Product 3 has 8 bends, and Product 4 has 4 bends. The bending machines that are used in the test are marked similarly as Machine 1, Machine 2, Machine 3, and Machine 4. Machine 1 is Prima Power BCe Smart 2220 panel bender, Machine 2 is Prima Power eP-1030 press brake, Machine 3 is CoastOne CONE 900, press brake, and Machine 4 is LVD PPBL 40kN20 press brake. The test is conducted by measuring the time needed for manufacturing of 10 to 20 products of each type depending on the complexity of the product. The tooling and bending are performed by the same operator in each case to reduce the influence of the operator to the results.

All tested products have different geometry and different number of bends so that the differences between the machines can be assessed better. Because of the different geometries between the products, all products cannot be manufactured with every machine. There are several reasons, which cause restrictions regarding the machines that can be used for each product. For example, the size of the product can be too large for every machine to handle. The accuracy of some machines is also not good enough for every product, which means that the product cannot be manufactured with that machine.

The tested products and machines are presented in Table 1. The machines that are tested are presented in the left, while the products are presented at the top of the table. The ‘X’ marks are used to present which products are manufactured with which machine.

Table 1. Table of tested products and machines.

	Product 1	Product 2	Product 3	Product 4
Machine 1	X	X	X	
Machine 2	X	X	X	X
Machine 3				X
Machine 4		X		X

As seen from the Table 1, it was not possible to manufacture any of the products with every machine. Every product that is tested is however manufactured with at least two different machines, to make it possible to compare the performance of the machines.

After the initial experiments were performed, it became clear that the results gained from these experiments were not reliable indicators of real-world performance of all machines as the operates tend to work faster when they are timed. This gave an unfair advantage to operators since the panel bender did not increase the production speed when timed and thus the productivity gap between press brakes and panel bender became small. However, the results that were gained from the tests, were not useless, as the results can be used to compare the differences in manufacturing speed of tested press brakes.

To test the real-world productivity of the bending department, a new data collection method was developed. Instead of measuring manufacturing time of single product, the focus was transferred to comparing the performance of a group of bending machines during longer period. The new test focuses on measuring the number of bends made by each machine group. The measurements were gathered by utilizing the total bend counters that can be found from each machine. The total number of bends was written down from each machine after the workweek has ended. After a week, the total number of bends was written down again so that it was possible to calculate the number of bends made by every machine. To make the measurement more accurate, groups of machines were used instead of individual machines, to reduce the effect of few time-consuming jobs. As some machines are not used daily, these machines were not considered in this experiment. The machines were divided into two different machine groups: Machine group 1 and Machine group 2. Machine group 1 included two Prima Power eP-1030 press brakes and two Prima Power eP-1336 press brakes. The Machine group 2 included one CoastOne 900 press brake and one CoastOne 500 press brake.

2.3. Reliability and validity analysis

The reliability of measuring the manufacturing time of each machine is increased by measuring the manufacturing time of several different products rather than measuring the manufacturing time of only one product. The number of manufactured products is also higher to reduce the influence of mistakes with one product. All tests can be repeated if there are some factors present during the test that influences to the results of the test. These factors could be for example breaking down of the machine or some problem with the blanks. Because there is only one operator performing the manufacturing speed tests, some machines might have advantage if the operator is more familiar with one machine than the others. However, this method will reflect the differences of machines better than having multiple operators perform the tests as the differences between operators might be significant in terms of manufacturing speed.

The test methods were chosen to offer the data that is needed to achieve the objective of this thesis. The measured objects were chosen with the help of industry experts. To choose the right machine for each job it is important to know the manufacturing time of the product in each machine. The manufacturing time is important metric when choosing the machine for the product, which is why it is important to measure.

The reliability of the new productivity test is increased by selecting a longer period rather than using only a day for a measurement period. While week is a significantly longer period than day or an hour, there are still some reliability issues as the number of orders varies depending on the time of the year. The working hours cannot be measured accurately as the bending machine operators might have some other tasks to perform during the week. This can cause small error to result. Because the error caused by that is small, it can be neglected when interpreting the results.

3. Previous research on the subject

Many of the products that are manufactured in job shop environment can be manufactured with more than one machine. There are however differences in speed between bending machines, which is why it is important to production machine for each product. When the machine for the job is chosen there are several things that should be considered, such as tooling time, ability to manufacture the needed geometry, availability of the machine, and manufacturing speed.

3.1. Bending of metal sheets

Tooling time between different products is an important factor when considering the productivity of a job shop. As the number of different products increases the importance of short tooling time increases. The tooling of the machine is different depending on the type of the machine that is used. Two types of bending machines are studied in this thesis. The bending machine types are press brake and panel bender.

Usually, the bending of metal sheets is performed with press brakes. Basic design of a press brake is quite simple and the level of automation in the machine is low, which makes this kind of machinery affordable even for small companies. When the metal sheet is bent with press brake, the metal sheet is pressed between a punch and a die to create a bend (Figure 1). There are three commonly used bending methods: Air bending, bottoming, and coining. Each of these methods have their unique features. Air bending allows wide range of different bending angles with one tool. Required bending force is also smaller in air bending than in bottoming and coining. There are also downsides in air bending, with the accuracy of the bending angle being lower than in bottoming or coining as in air bending the accuracy depends on the accuracy of the bending machine. In air bending the material has also more spring back compared to bottoming or coining, which makes the setup process slower and more difficult. Bottoming is more accurate bending method, but the risk of tool failure is increased compared to air bending. Coining has very high accuracy but requires a lot of bending force. Because of the high bending force needed, only tools with high pressure resistance can be used. (Benson, 2017; Machine MFG, 2019.)

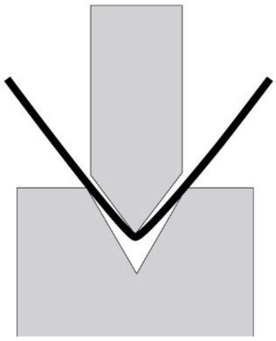

Figure 1. Sheet metal bending process on press brake. (Benson, 2017.)

There are eight basic types of punches used in sheet metal bending. The most common punches are straight punch, gooseneck punch, and acute punch. The correct type of punch is selected based on the geometry of the product that is manufactured. The parameters that affect to the selection of a punch include the bending angle, thickness of the material, and collision risk of the product and the die. Spring back phenomenon is always present when metal sheets are bent. This means that the bending angle during the bending process must be smaller than the final bending angle. For example, to bend a 90° angle, the die must have angle of 88° or smaller. (Machine MFG, 2019.)

Tooling time of press brake is relatively short if the machine is not robotized. The tooling time of press brake consists of changing the right die and punch for the job and selecting the correct parameters for the bending. Setting the bending parameters can take a long time as the right parameters depends not only on the material used, but also on the material batch. If the press brake is robotized, the robot needs to be programmed before manufacturing the product. (Panthi et al., 2010.) It is possible to attach several different punches and dies into the press brake simultaneously (Figure 2). When more than one set of punches and dies are attached to the press brake simultaneously, it is possible to make bends with different lengths without performing another setup. The multi-tool setup can be used for example to make boxes that have sides of more than one length.

Figure 2. Multi-tool setup on press brake.

Another common method for bending metal sheets is utilizing a panel bender. Panel bender is fully or semi-automated bending machine that bends the metal sheet by moving the punch and die independently (Figure 3). There are no tool changes in panel bender, which makes it easy and fast to change between different products. While there are no tooling changes between different products, the programming of panel bender still takes time when new products are manufactured. Because of the higher price of the machine, compared to press brake, and the need for programming, the panel bender might not be the best machine for small batches. (Machine MFG, 2022b.)

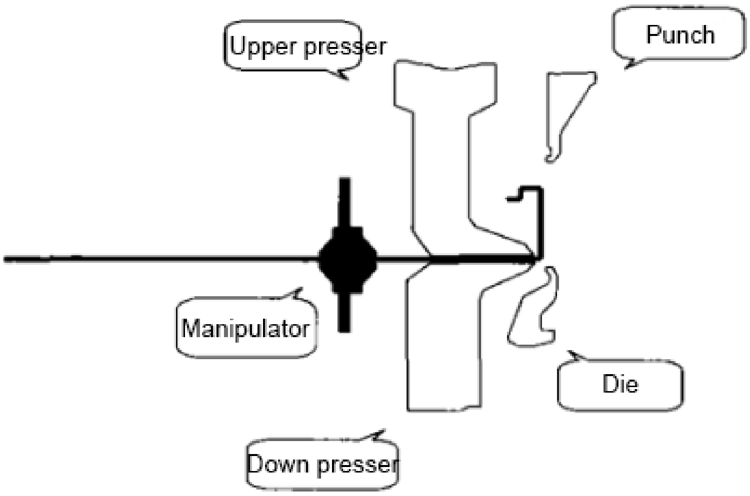

Figure 3. Working principle of a panel bender. (Machine MFG, 2022b.)

There are also other advantages in addition to faster tooling time between products. Probably the biggest advantage of panel bender over the press brake is the ease of use. While with press brake, the bending is performed by operator, the panel bender performs the bending automatically, leaving only the loading and packaging of products to the operator. Panel bender has high accuracy and because of automated bending, there are no mistakes, such as bending in the wrong direction, performed during the bending process. (Machine MFG, 2022b.)

While the bending operation is automated with panel bender, there are still the same problems present regarding the spring back, as there are with press brake. Currently there are no accurate solution for automatically fine tuning the bending parameters after the product is changed. However, the field is constantly studied, and new models are being developed for predicting the spring back phenomenon more accurately. (Chen et al., 2021.)

There are also other methods for bending metal sheets, such as stamping and roll bending. While these methods are also common in sheet metal workshops, these are not considered in this thesis and thus not covered in literature review.

3.2. Bending limitations

There are several limiting factors that dictate what machine can be used for each product. The physical size of the product can be too large for some machines, which means that different machine must be used for manufacturing. Maximum bend width of the machine is easy to find from the technical specification of each machine. Bending clearance is important to consider when choosing the machine for manufacturing of the product. Important factors influencing the bending clearance in press brakes are stroke, shape of punch, and depth of throat. (Machine MFG, 2019.) With press brake, the bends are made by pressing the metal with the punch from inside the product. If the product has multiple bends which create an enclosure type of geometry, it is possible that the bends cannot be made with press brake. Panel bender has advantage with this type of products as the bending is performed from outside of the product. (Machine MFG, 2022b.) Because the bending process with panel bender is different, the limiting factors are also different. In panel bender the tools are not changed, which means that the limiting factors are throat depth and maximum opening of the upper tool. Panel bender can also perform negative bends on one side of the product as the product cannot be removed and rotated if the bottom of the product is not flat. With panel bender there is also a minimum size for the product as the manipulator of the panel bender must be able to stick to the manufactured product during the manufacturing process. (Crandall, 2015.)

When the right bending machine for the product is chosen, it is important to consider the required bending force. Typically, smaller machines that are designed for bending physically smaller parts have less bending force than the bending machines that are designed for bending larger products. The maximum bending force of the machine can be found from the machine specifications. There are different formulas that can be used to calculate the approximate bending force needed for the bend. There are also bending charts made by the manufacturers of the bending machines, that can be used to approximate the bending force needed for the bend. An example of a bending chart is presented in Figure 4. (Zhang, 2021.)

V		4	6	8	10	12	14	16	18	20	24	28	32	36	40	45	50	55	60	65	70	80	90	100	120
B		2.8	4	5.5	7	8.5	10	11	12.5	14	17	20	22	25	28	31	35	38	42	46	49	56	63	70	85
R		0.7	1	1.3	1.6	2	2.3	2.6	3	3.3	3.8	4.5	5	6	6.5	7	8	9	10	10.5	11	13	14	16	19
S	0.5	40	30																						
	0.6	60	40	30	30																				
	0.8		70	50	40	30																			
	1		110	80	70	60																			
	1.2			120	100	80	70	60																	
	1.5				150	120	110	90	80																
	2					220	190	170	150	130	110														
	2.5							250	220	200	170	150	130												
	3								330	290	250	210	180	160											
	3.5									400	330	290	250	220	200										
	4										440	370	330	290	260	230	210								
	4.5											470	410	370	330	300	270	250							
	5												510	450	400	360	330	300	270	250					
	6															520	470	430	390	360	340	300			
	8																		700	640	600	520	460	420	
	10																					810	720	650	
	12																							950	780
	14																							1300	1100

Figure 4. Press brake bending chart. (Zhang, 2021.)

The chart is made for a material that has width of L = 1 m and has tensile strength of σb = 450 N/mm^2. If the material is changed or the length of the bend is different, the chart cannot be used. The unit of bending force presented in the chart is kN. Symbols used in the chart are following:

S = Material thickness (mm)

V = Opening of the bottom V-die (mm)

B = Minimum bending flange (mm)

R = Inner radius (mm)

(Zhang, 2021.)

To calculate needed bending force using bending force formula material thickness, material width, opening of the bottom V-die, and tensile strength are needed. The bending force formula is following:

$$P = 1.42 * \sigma b * S^2 * \frac{L}{V} \quad (1)$$

(Zhang, 2021.)

Bending force formula can be used to calculate needed force for any V-bend. As seen from the formula, the needed bending force can be reduced by selecting V-die with wider opening. Generally, the width of V-die is around 8 times the thickness of the material. (Zhang, 2021.)

With press brake, the bending force is limiting factor with larger bends. The bending force can be limiting factor with panel bender as well, but due to different bending method, there is an upper limit for the material thickness that cannot be exceeded even if the bending force would be high enough. For example, the maximum thickness of stainless steel is 2.2 mm in Amada EP-2500 panel bender. The maximum thickness does not increase even if the bending width is decreased unlike with press brake. (Amada, 2022.)

3.3. Lean manufacturing system

Lean manufacturing is a commonly used system to increase productivity of a facility. Lean manufacturing system was developed to improve productivity of Toyota car factory. The Lean manufacturing system focuses on reducing waste such as excess inventory and unnecessary logistics inside the production facility to improve productivity. (Bozzone, 2001 pp. 3-4.) The Lean methods that are used are concrete methods that will change the way things are done during the manufacturing process.

One of the key methods in Lean manufacturing is pull system. In pull system the manufacturing is started when there is customer demand for the product. By doing that it is ensured that the inventories are minimized. Job shops work with pull system naturally, as products cannot be manufactured before an order is placed. While job shops use pull system on a larger scale, the pull system might not work inside the production facility which causes need for storing work-in-progress inside the facility. (Bozzone, 2001 pp. 5-7.)

Another important key method in Lean manufacturing is flow. Flow is important part of Lean manufacturing, as it creates pull system inside the manufacturing process. In flow manufacturing the products are manufactured in small lot sizes, possibly in dedicated manufacturing cells using KANBAN system. (Bozzone, 2001 pp. 8–9.) In KANBAN system, the production is controlled by trigger signal (usually KANBAN card) to produce right products in right amount and in right time. KANBAN system is in many cases used with Just-In-Time (JIT) scheduling. Because the system was developed to be used by Toyota it is designed to work well with mass-production, which causes some restrictions for situations where KANBAN system can be used. The restrictions reported in literature include for example, situations where demand is unstable, setup time is long, operations are non-standardised, and variety of products is great. (Lage Junior & Godinho Filho, 2010.)

In a JIT production system only necessary products are made and delivered only when needed. The basic principle behind JIT is to remove all non-value adding operations during the manufacturing process and starting the manufacturing as late as possible. The objective of JIT is to increase productivity by removing waste. Other objectives include improving production quality and reducing production costs. (Pinto et al., 2018 pp. 2.)

While the Lean manufacturing system is developed for mass-production operations, the basic principle of Lean is still applicable in job shop production. The difference between mass-production and job shop production in terms of Lean manufacturing is essentially the waste that is reduced in the process. While Lean manufacturing system in mass-production aims for reducing inventories, the Lean manufacturing system in job shop production should aim for decreasing lead times of products. (Bozzone, 2001 pp. 10.)

5S is common method that is used to increase the tidiness of workplaces in many different fields. The 5S method derives its name from Japanese terms that begin with the letter “S”. There are also rough English translations for these terms. The 5S terms and meanings are:

- Seiri (Sort) = It is the action of separating important tools, instructions, parts, and other necessary objects from unnecessary material.

- Seiton (Set in order) = It is the action of arranging and identifying parts, instructions, and tools to make them easier to find and use.
- Seiso (Shine) = It is the action of cleaning up the workplace.
- Seketsu (Standardise) = It is the action of conducting first three actions in frequent intervals to maintain the good condition of the workplace.
- Shitsuke (Sustain) = It is the action of forming a habit for following the first four activities. (Kubiak & Benbow, 2017 pp. 559.)

In some cases, Safety is added as 6^{th} S to make 5S to 6S. Adding Safety as one of the terms, emphasizes the importance of safety in working environment. (Jiménez et al., 2019.)

If the workplace is cluttered it might influence negatively on the productivity of the company. It is important that the operators have easy access to any tools and equipment necessary for the work. According to Kubiak & Benbow (2017) the cleanliness, lighting, and general housekeeping status are critical for work areas where any measurements are conducted. When 5S is implemented in the workplace it is important that the 5S is thought as continuous activity rather than thinking it as a one-time event. (Kubiak & Benbow, 2017.) To sustain the achieved level of cleanliness it is important to perform audits frequently. By performing 5S audits frequently enough, it is possible to monitor the development of cleanliness in the factory. (Gupta & Chandna, 2020.) Example of 5S audit checklist is presented in Figure 5.

Area:	Week:	1	2	3	4
Unnecessary items removed from the area					
Tools are returened in designated places					
Floor is clean and free of debris					
Workstation are cleaned and in order					
Necessary items in designated places					
Scale: Yes/No					

Figure 5. Example of weekly 5S audit checklist.

Finding root causes for the problems is important when the actions to correct problems is decided. 5 whys is a method for finding a root cause for noticed problems. In 5 whys method the root cause for a problem is found by asking why it occurred. After the first answer the "why" question is asked again until it has been asked five times. During a 5 whys method, some countermeasures can be considered to make sure that the problem will not happen again. The 5 whys is a powerful method as finding several causes for a problem means that more preventive measures can be implemented compared to singular preventive measure that might not remove all root causes. (Davies, 2019.)

3.4. POLCA

As stated earlier, the job shop environment should focus on achieving flow manufacturing. In Lean manufacturing, one key part of flow manufacturing is utilization of KANBAN system. In KANBAN the manufacturing is controlled by transferring products from one workstation to next based on KANBAN cards (Figure 6). The manufacturing stages of each product are marked to the KANBAN cards. The idea behind this system is that Work-In-Process (WIP) storage is minimized by starting the manufacturing of the product only when there is capacity to continue the production of the product on the next workstation. This creates a pull system inside the production facility. The KANBAN system works great with mass-production where the number of different products is limited, and the production machines are used only for few different products. (Sendil Kumar & Panneerselvam, 2007.)

Part description				Part Number	
Qty		Lead time		Order date	
Supplier				Due date	
Planner			Card 1 of 3		
			Location		

Figure 6. Example of KANBAN card.

The opposite of the pull system in push system. Push system is the conventional manufacturing system, where the manufacturing is started after the previous production stages are completed (Sendil Kumar & Panneerselvam, 2007). This generates more WIP as products need to wait somewhere before going to the next production stage. The advantages of push system compared to pull system are lack of KANBAN cards which can be time consuming to make for every new product.

Because there are pros and cons in both, pull and push systems in job shop production, there have been studies to combine these two systems. One method for combining these systems is POLCA. POLCA is a method that was developed by Rajan Suri in 1998, and it was introduced in his book *"Quick response manufacturing: a companywide approach to reducing lead times"*. The POLCA method is based on KANBAN and CONWIP systems (Spearman et al. 1989). While POLCA is based on these systems, it is improved and targeted to Make-To-Order (MTO) manufacturers instead on mass-manufacturing. (Riezebos, 2010.)

The goal of POLCA method is to reduce lead times of products. In POLCA the products are manufactured in manufacturing cells. The manufacturing cells create loops that are used to move products from one production stage to next. Each product (or batch of products) has a POLCA card attached to it. The POLCA card provides information about in which production cell the product is going next, and from which cell it is from. The number of POLCA cards is limited to ensure that no excess WIP inventory is formed. The manufacturing of the product can be started only if there is POLCA cards available for the next cell. After the operations in the cell have been completed, the POLCA card that came with the product should be returned to the previous cell. (Riezebos, 2010.)

Conventionally these POLCA cards are physical cards (Figure 7) that are transferred with products. This however causes need of labour for returning these cards to previous cell. With modern technology this can be handled digitally to reduce need of labour for transportation of the cards. For example, Vandaele et al. (2008) have used digital POLCA cards successfully to implement POLCA system to a job shop environment. Another advantage of using digital POLCA cards is that the number of cards is easier to calculate accurately, as there is no delay in transfer of information (Riezebos, 2010). There are some digital POLCA solutions available for companies to use, such as Digital POLCA by PROPOS Software (PROPOS Software, 2022).

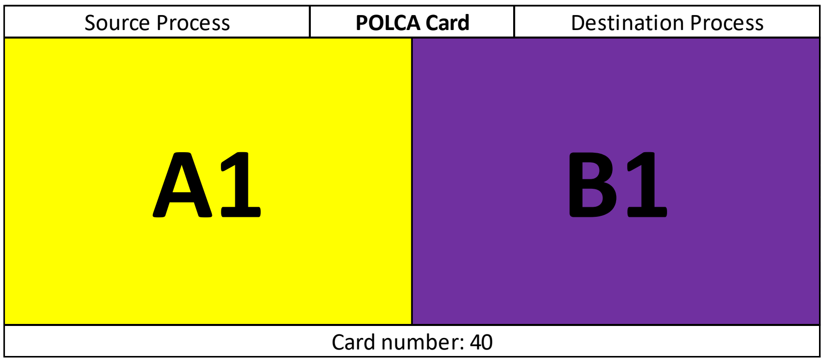

Figure 7. Example of POLCA card.

The POLCA card system can be further improved by utilizing colour coding to make it easier for production workers to know where the product is going next by taking a brief glance at the POLCA card. When using colour coding on the POLCA cards, every production cell should have its own colour (Riezebos, 2010). The POLCA card colour coding cannot however rely solely on colours, as colour blindness is somewhat common in general population as around 4.5 % of population has colour-blindness (Colour Blind Awareness, 2022). A good practice is to use for example numbers in addition to colours in the POLCA cards to make them distinguishable for everyone.

4. Case Stremet Oy

Stremet Oy was founded in 1995 in Salo, Finland and has been growing from small sub-contracting sheet metal fabricator to larger sub-contracting firm that is well-known locally. In 2021 the sales of Stremet Oy were 10.9 MEUR with profit of 673 000 EUR. Due to recent growth in sales, Stremet Oy has become one of the largest metal industry companies in the Salo area. (Finder, 2022a; Finder, 2022b.)

Stremet Oy employs a total of 63 employees, of which 45 are operators, 7 are office workers, 6 are designers, 3 supervisors and 2 executives. Stremet Oy has experienced strong growth in sales during past years, which has caused interest in increasing the productivity. The goal of the company is to continue growth in the future and to become one of the largest companies in the industry.

It is important to acknowledge the idiosyncrasies of the production before implementing any methods that influence the production. Production type at Stremet Oy is job shop production, which means that it has high product variety and low to mid production volume. Because the production is job shop production, the machinery can be used to produce wide variety of different products.

4.1. Current state of production

There are three types of machinery used in the company to cut metal sheets. There are seven punch presses for cutting and forming sheet metal. In addition to these there is also one combined punch press and shearing machine that can be used for producing rectangular products. There are also two fibre lasers that can be utilized to cut more advanced geometries or thicker materials. (Stremet Oy, 2022.)

The production layout follows mostly the process layout, with similar machines near each other. The advantage of this is that it is easier to exchange tools between different machines, which reduces the tool changing time significantly. The production facility is divided into five main departments (Figure 8). The material flow is mainly in one direction, with punch press department located in opposite end of the facility than assembly and dispatching. Only point where the material flow is not in one direction is from material warehousing to punch press and laser departments.

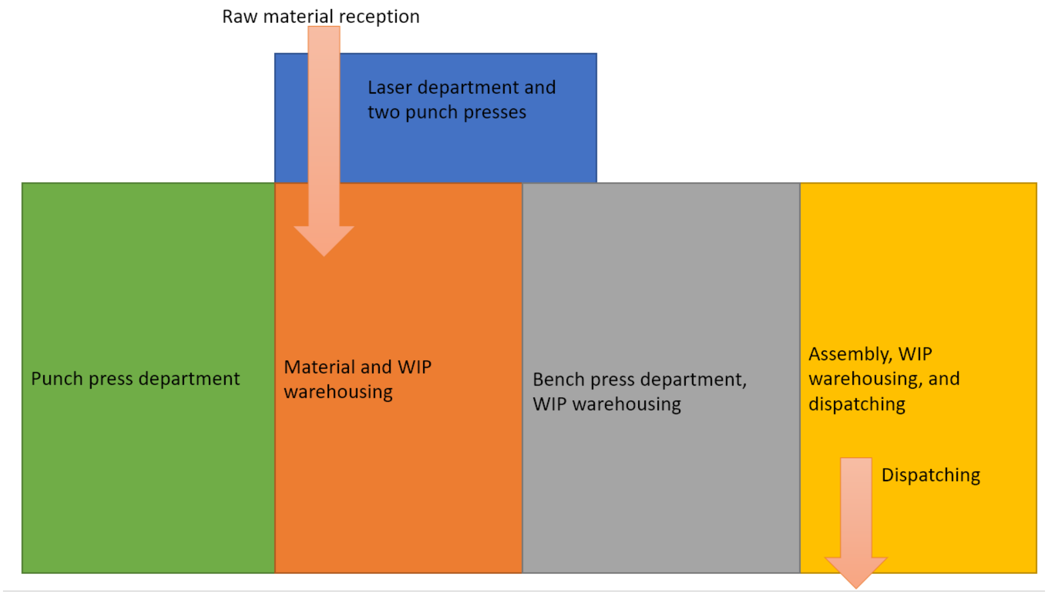

Figure 8. Process layout used in the company.

Currently the orders are manufactured within a week from placing the order. Bending department is acting as a bottleneck, which means that it is not possible to reduce lead time without applying any changes to the bending department. Previously the security of supply has also dropped when the number of orders increase above certain threshold.

4.2. Production controlling

Production is currently controlled manually without any softwares. When new order arrives it goes to nesting, billing, and dispatching departments. The orders are manufactured usually in the order of delivery dates. After the blanks are cut, the blanks are transported to the WIP warehouse (orange department in Figure 8). Production supervisors take the blanks from the WIP warehouse and transport them to the next workstation, for example to a press brake. Currently there is no slot system used for storing the blanks in WIP warehouse, which means that there is a lot of searching involved when the blanks are transported from WIP warehouse to next processes.

Production controlling is facing a change at Stremet Oy, as a new Enterprise Resource Planning (ERP) system is going to be implemented during this year. With the new production controlling software, it is expected that the production becomes more predictable and easier to control. New production controlling system also allows tracking of products inside the manufacturing facility, which should reduce the time used in searching of the products significantly. ERP system should also increase quality, because with ERP system it is possible to transfer more information about manufacturing of the products to the operators. One example of this new information is 3D model of the final product that can be used in bending department to check if the product is like the 3D model.

Current production controlling system does not consider what bending machine has highest manufacturing speed for each product. The machine is chosen based on the ability to produce the product in question and the availability of the machine. Because of this, currently some products are manufactured with bending machines that are not best suitable for the product. The results of this thesis can be utilized to develop a better production controlling system, that considers the differences in manufacturing speed between bending machines.

4.3. Current methods used for increasing productivity

There are number of different methods that have been implemented to increase productivity at Stremet Oy. Latest methods include new layout, which brought similar machines closer together. The new layout also improved the material flow inside the facility by reducing two-way transportation between different processes. Other methods include training operators to use multiple machines, increasing automation in the factory, and investing in new, better machinery.

Automated production machines and new, faster manual machines have made largest impact on productivity of the company. With new machines it has been possible to reduce the cost of labour while increasing the billed hourly rate simultaneously. Currently the bending department is the bottleneck of the production. This has been noted and new machinery has been ordered. However, because also new cutting machinery has been ordered it is possible that the bending department will remain as the bottleneck of the production if no other changes are made to increase the productivity of the bending department.

4.4. Production in the future

Stremet Oy has purchased several new production machines that are arriving during the summer of 2022. The new machinery should increase the production volume in metal cutting department and bending department. The importance of knowing the capabilities of each machine is emphasized as higher number of machines create more possibilities for choosing production machines for each job.

While the new ERP system should make it easier to follow the status of the production, it also creates opportunity to increase the productivity by optimizing the production routes of different products. The data gathered from this thesis can be utilized to choose best suitable machines for each product. The advantage of choosing production machines in advance is that when the production machines are known it is possible to design the production schedule in a way that the needed machines are available at the right time.

5. Results

The results gained from the experiments are presented in this chapter. Analysis and discussion of the results are not considered in this chapter.

5.1. Results from interviews

The results that were gathered from interviews are presented here. There were six questions that were asked from every operator working in bending department. The questions were the following:

- What are the 3 biggest problem areas in your own job?
- Do you have any development proposals related to your job?
- Are there any issues that slows or distracts your working during the day?
- Does the cleanliness of your workstation affect your work performance?
- Do you think that you are learning new things about your work?
- Do you believe that your work can be improved?

After these questions were asked from everyone, a summary of the results was made, and the summary was went through with every operator. After the summary was went through with each operator, they were given the chance to answer again to all questions stated above.

5.1.1. First round of interviews

The answers to first question are presented in Table 2. Many of the answers were given only by one operator, but there are also several answers that were given by multiple operators. Total number of operators interviewed on first round of interviews was 19.

Table 2. Answers to first question on first round of interviews.

Round 1 of interviews		
Question	**Answer**	**Number of answers**
Question 1 What are the 3 biggest problem areas in your own job?	Drawings are insufficient	8
	Working area is full of pallets	5
	Blanks of many different products placed on same pallet	2
	Hurry	2
	Not enough information about the functions of the company	2
	Problems with blanks	2
	The state of production is hard to monitor	1
	Job allocation between different production machines does not work	1
	Lifting equipment is took from the workstation	1
	Old and worn-out machine	1
	No instructions on how to package manufactured products	1
	There is no warehouse monitoring for manufactured products	1
	Difficult to communicate with designers	1
	Worn out tools	1
	No working peace when there is a hurry	1

When the answers to the question 1 are looked at, it seems that the biggest problems according to operators are related to the bad drawings and tidiness of the workspace. Another common problem among the bending department operators seems to be related to blanks.

The answers to question 2 are presented in Table 3. There are fewer common answers for second question than to first question. There are three answers that were answered by several operators. Two of the answers were answered by three operators and one by two operators. Common answers for second question were also related to blanks and tidiness of the workplace. Unlike in first question, there was only one answer related to improving the drawings. While the overall number of answers is same in both questions, there are fewer same answers given for the second question.

Table 3. Answers to second question on first round of interviews.

Round 1 of interviews		
Question	**Answer**	**Number of answers**
Question 2 Do you have any development proposals related to your job?	Manufactured products should be transported away from the machine	3
	Blanks should be bundled on pallets	3
	There should be greater freedom for operators to choose the manufacturing order of products	2
	Better drawings	1
	Tidiness should be improved	1
	When new products are offered, the manufacturability should be consulted from the operators	1
	Working time monitoring should be improved	1
	Packaging instructions should be improved	1

	There should be help with robots during rush hour	1
	Tools should be closer to the machine to reduce setup time	1
	Ergonomics should be improved	1
	Better education on how to operate the machines	1
	Supervision should be improved	1
	Safety should be improved	1
	Every machine should have cleaning equipment available	1

The answers to third question are presented in Table 4. There were only two answers for third question that were answered by more than one operator. Also, the total number of answers is lower than with other questions. The two most common answers were related to bad drawings and the need of searching for the pallet jacks during the day.

Table 4. Answers to third question on first round of interviews.

Round 1 of interviews		
Question	**Answer**	**Number of answers**
Question 3 Are there any issues that slows or distracts your working during the day?	Bad drawings	3
	Pallet jacks will not stay in the right places	3
	Blanks for new products are placed to random spots to wait for manufacturing	1
	Manufactured products must be transported away by the operator	1
	There are waste pieces among blanks	1
	Blanks are not bundled	1

	Manufacturing of small batches of new products during larger batches	1
	Previous manufacturing stages are incomplete	1
	Forklift must be looked for	1
	Workspace gets filled with pallets	1
	Different blanks on the same pallet	1
	There is no working peace	1

The answers for the last three questions are presented in Table 5. While there are 15 “Yes” answers and 4 “No” for each question, the answers were given by different operators. It is thus only a coincidence that the number of “Yes” and “No” answers are the same on each question.

Table 5. Answers to question 4, 5 & 6 on first round of interviews.

Round 1 of interviews		
Question	**Answer**	**Number of answers**
Question 4 Does the cleanliness of your workstation affect your work performance?	Yes	15
	No	4
Question 5	Yes	15
	No	4

Do you think that you are learning new things about your work?		
Question 6 Do you believe that your work can be improved?	Yes	15
	No	4

5.1.2. Second round of interviews

In the second round of interviews the answers that were given by other operators during the first round of interviews were presented to the operators during the second round. Operators were asked to tell which ones of the answers they thought were important to them. There was no upper limit for number of different answers, which means that the total number of answers is higher than the number of interviewed operators. Due to winter holiday season, only 17 operators were interviewed instead of 19 operators that were interviewed during for the first round of interviews. The answers for Question 1 are presented in Table 6.

Table 6. Answers to Question 1 on second round of interviews.

Round 2 of interviews		
Question	**Answer**	**Number of answers**
Question 1 What are the biggest problem areas in your own job?	Drawings are insufficient	13
	Working area is full of pallets	12
	Blanks of many different products placed on same pallet	6
	Hurry	5
	Not enough information about the functions of the company	4
	Problems with blanks	6
		2

	The state of production is hard to monitor	
	Job allocation between different production machines does not work	3
	Lifting equipment is took from the workstation	9
	Old and worn-out machine	2
	No instructions on how to package manufactured products	8
	There is no warehouse monitoring for manufactured products	1
	Difficult to communicate with designers	2
	Worn out tools	0
	No working peace when there is a rush	1

The number of answers given to the first question on second round of interviews were between 0 and 13. The answers for Question 2 are presented in Table 7.

Table 7. Answers to Question 2 on second round of interviews.

Round 2 of interviews		
Question	**Answer**	**Number of answers**
Question 2 Do you have any development proposals related to your job?	Manufactured products should be transported away from the machine	11
	Blanks should be bundled on pallets	7
	There should be greater freedom for operators to choose the manufacturing order of products	0
	Better drawings	11
	Tidiness should be improved	11
	When new products are offered, the manufacturability should be consulted from the operators	6
	Working time monitoring should be improved	4

	Packaging instructions should be improved	9
	There should be help with robots during rush hour	2
	Tools should be closer to the machine to reduce setup time	0
	Ergonomics should be improved	5
	Better education on how to operate the machines	0
	Supervision should be improved	2
	Safety should be improved	2
	Every machine should have cleaning equipment available	10

The deviation of number of answers between different answers was smaller on Question 2 than it was on Question 1 as the number of answers for Question 2 was between 0 and 11. The answers for Question 3 are presented in Table 8.

Table 8. Answers to Question 3 on second round of interviews.

Round 2 of interviews		
Question	**Answer**	**Number of answers**
Question 3 Are there any issues that slows or distracts your working during the day?	Bad drawings	10
	Pallet jacks will not stay in the right places	9
	Blanks for new products are placed to random spots to wait for manufacturing	4
	Manufactured products must be transported away by the operator	8
	There are waste pieces among blanks	6
	Blanks are not bundled	5
		3

	Manufacturing of small batches of new products during larger batches	
	Previous manufacturing stages are incomplete	4
	Forklift must be looked for	8
	Workspace gets filled with pallets	8
	Different blanks on the same pallet	5
	There is no working peace	0

The deviation of number of answers between different answers was lowest on Question 3 as the number of answers were between 0 and 10.

5.2. Results from manufacturing speed experiments

The differences in manufacturing speed of Product 1 were small between the two machines. It was expected by the production supervisors that the Machine 1 would be significantly faster than the Machine 2 for manufacturing the product. Due to the geometry of Product 1, it can only be manufactured completely with Machine 2. The product could not be manufactured completely with Machine 1, which meant that one bend for the product must be done with Machine 2. The manufacturing time that is presented in the Table 9 does not consider the time it takes to move the product from Machine 1 to Machine 2, which means that the complete production time is lower if the product is manufactured with only the Machine 2.

Table 9. Manufacturing times of Product 1.

	Machine 1	**Machine 2**
Manufacturing Time	45.1 sec/product	47.3 sec/product

The difference in manufacturing speed between the Machine 2 and Machine 4 is rather small with Product 2 (Table 10). The Machine 2 is fastest machine for this product, with Machine 1 being almost 10 seconds slower per one product. The geometry of Product 2 is easier than the geometry of Product 1, which reduces the production times of Product 2 in all machines. It is however worthwhile to notice that the difference between Machine 1 and Machine 2 is smaller with the Product 1 than with the product 2.

Table 10. Manufacturing times of Product 2.

	Machine 1	**Machine 2**	**Machine 4**
Manufacturing Time	31.4 sec/product	21.9 sec/product	24.7 sec/product

The manufacturing times of Product 3 are shown in the Table 11. The Product 3 was manufactured only with Machine 1 and Machine 2, as the geometry of the product restricted the use of other machines.

Table 11. Manufacturing times of Product 3.

	Machine 1	**Machine 2**
Manufacturing Time	45.2 sec/product	46.6 sec/product

There are significant differences in terms of productivity between different machines with the product 4. As seen from the Table 12 the Machine 3 is the fastest machine, with relatively small difference to Machine 2. While the Machine 2 and Machine 3 are roughly as fast, the Machine 4 has significantly lower productivity. The productivity of Machine 4 is 38.2 % lower than the productivity of Machine 3, which is a large difference that is especially significant when the production batch is large. The difference in productivity is caused by the slower movement of back support and the punch compared to Machine 2 or Machine 3. The movement of back support in Machine 4 is also not as accurate as the movement of back support in other Machines, which means that the tolerances of the machine are not good enough for several products.

Table 12. Manufacturing times of Product 4.

	Machine 2	Machine 3	Machine 4
Manufacturing Time	13.9 sec/product	13.1 sec/product	18.1 sec/product

The tooling times between Machines 2, 3, and 4 were similar for each product. Reliable examination of tooling times was not possible to do as there were such a high number of variables during each tooling. These variables include human errors, such as installing wrong tools, and the need of angle adjustments depending on the material of each product.

The formulas that were used to make the calculations of second manufacturing speed experiment are presented below. Total operating time (TOT) was noted before starting the experiment and after the experiment so that the total manufacturing time was possible to calculate. Machines 5 and 6 do not have a total operating time feature, which means that the total operating time for these machines was the time that the operators of these machines were present.

$$Working\ time = TOT\ at\ first - TOT\ after\ week \tag{2}$$

$$\frac{Bends}{hour} = \frac{Bends\ after\ week - Bends\ at\ first}{Working\ time} \tag{3}$$

The results from the second manufacturing experiment are presented in Table 13. As seen from the following table, there are significant differences in manufacturing speed between different machines. The differences of the results can be explained in some extend by different types of products that were manufactured in each machine. For example, with Machines 5 and 6 the products were small and thus fast to manufacture. The products that were manufactured with machines of Machine group 1, were larger in size. Also, the batch sizes were significantly smaller with machines of Machine group 1 compared to machines of Machine group 2.

Table 13. Results of the second manufacturing speed experiment. Total number of bends of each bending machine was written down on Friday after the operators had left the workplace. The gathered number was marked in this table under the "Bends at first (qty)"-column. Total number of bends was written down exactly week later again. The gathered number was marked in this table under the "Bends after a week (qty)"-column.

	Bends at first (qty)	**Bends after a week (qty)**	**Working time/week (h)**	**Bends/hour**
Machine group 1				
Machine 1	3 757 596	3 770 407	67.75	189
Machine 2	3 309 080	3 320 281	64.75	173
Machine 3	967 492	976 065	70.75	121
Machine 4	1 354 651	1 362 064	74.5	100
Machine group 2				
Machine 5	1 142 380	1 150 229	31	253
Machine 6	6 334 910	6 344 910	39	256

The average manufacturing speed values of both Machine groups are presented in Table 14. The operator of Machine 4 had to cover for another employee in a different workstation during the week, which is why the manufacturing speed value is smaller in Machine 4. Because of that, Machine 4 is not considered in the average manufacturing speed table, but instead the average for Machine group 1 is calculated by utilizing the results from Machines 1, 2 & 3 only.

Table 14. Average manufacturing speeds of both Machine groups.

	Average manufacturing speed (Bends/hour)
Machine group 1	161
Machine group 2	255

The manufacturing speeds of machines of Machine group 2 are close to each other. However, with machines of Machine group 1 there is more dispersion. There are several reasons for that, which are analysed further in next chapter.

6. Analysis and discussion

There were many different answers that were given to the questions during the first round of interviews. Most of the answers were however given by only one operator. The considered actions in the future should relate to the answers that were most popular as these problems have the largest effect on the total performance of the bending department. According to 80-20 rule the changes should be made to the few most common problems as these have the largest effect on the productivity (Tardi, 2020).

There was a total of 15 different answers given to the first question in the first round of interviews. Six of the answers were given by more than one operator. These answers were the following:

- Drawings are insufficient
- Working area is full of pallets
- Blanks of many different products placed on same pallet
- Hurry
- Not enough information about the functions of the company
- Problems with blanks.

While most of these problems have rather clear solutions, the first problem is more difficult to solve. Most of the drawings come from the customers, which leaves little to no possibilities for the case company to solve the problem. While there are some easy methods that can be used to solve the problem such as redrawing all the drawings by company’s own designers, these methods increase the cost of products as more time is needed for the total manufacturing process.

For the second question there were the same number of different answers but only three answers that were answered by more than one operator. These answers were the following:

- Manufactured products should be transported away from the machine
- Blanks should be bundled on pallets
- There should be greater freedom for operators to choose the manufacturing order of products

For the third question there were only two answers that were answered by more than one operator. These answers were the following:

- Bad drawings
- Pallet jacks will not stay in the right places

Both answers were answered by three operators. The first problem is like the most common problem answered in the first question, while the second one was not answered by anyone in the first question.

For the last three questions, the number of “Yes” and “No” answers were the same. For each of these questions the “Yes” option was answered by 15 operators and the “No” option was answered by 4 operators. From the answers to these questions, it can be concluded that the operators feel that the cleanliness of the working environment influences the work performance. Another important conclusion that can be made based on the answers to the last two questions is that most of the operators feel that they are learning new things about their work.

The answers for the last question indicate that most of the operators feel that their work can be improved. This is important aspect as there are multiple improvements planned to be performed in the future. The feeling that the work can be improved can help when there are new technologies such as ERP system implemented into the production.

The answers of second round of interviews are interesting as the deviation number of answers were higher than in any question of first round of interviews. Due to high number of different answers, the focus should be on finding solutions to answers that were commonly answered. Only the answers that had five or more answers are considered in this thesis.

For the first question there are seven answers that were answered by five or more operators. These answers are:

- Drawings are insufficient
- Working area is full of pallets
- Blanks of many different products are placed on same pallet
- Hurry
- Problems with blanks
- Lifting equipment is took from the workstation
- No instructions on how to package manufactured products

Many of the popular answers from the first round of interviews were popular also on second round. From the second round of interviews, it seems that operators receive generally enough information about the functions of the company despite the answer ending up on among the most common answers in first round of interviews. Two new answers ended up among the most common answers in second round as “Lifting equipment took from the workstation” and “No instructions on how to package manufactured products” were answered by more than five operators.

For the second question there are eight answers given by five or more operators. These answers are:

- Manufactured products should be transported away from the machine

- Blanks should be bundled on pallets
- Better drawings
- Tidiness should be improved
- When new products are offered, the manufacturability should be consulted from the operators
- Packaging instructions should be improved
- Ergonomics should be improved
- Every machine should have cleaning equipment available

In the first round of the interviews there were only three answers that were given by more than one operator. The answers that were popular in first round of interviews were also popular on second round of interviews except the “There should be greater freedom for operators to choose the manufacturing order of products” answer which was not answered by anyone on second round of interviews.

For the third question, there are eight answers that were answered by five or more operators. These answers are:

- Bad drawings
- Pallet jacks will not stay in the right places
- Manufactured products must be transported away by the operator
- There are waste pieces among blanks
- Blanks are not bundled
- Forklift must be looked for
- Workspace gets filled with pallets
- Different blanks on the same pallet

In the first round of interviews only “Bad drawings” and “Pallet jacks will not stay in the right places” were answered by more than one operator. Both answers were still among the most popular answers in the second round.

It is important to notice from the answers of second round of interviews that there were several answers that were given in first round of interviews that received no support on second round of interviews. This shows the importance of conducting the interview with more than one round as otherwise some minor issues might end up on results as interviewees try to come up with some answer.

The manufacturing speed test time varied between different products. It can be seen from the results that the manufacturing speed depends highly on the geometry of the product. It was expected that the Machine 4 would be slowest with each product, and Machine 1 to be fastest with each product. From the data, the Machine 4 is significantly slower than Machine 2 or Machine 3. However, with Machine 1, the manufacturing speed compared to other machines is highly dependent on the geometry of the product. With Product 1 and Product 3 the Machine 1 is the fastest, but with Product 2 the Machine 1 is significantly slower than other machines. It is worthwhile to notice that the Product 1 cannot be fully manufactured with Machine 1.

While there are differences in manufacturing speed between different machines, there are also other differences that should be noted when the machine for manufacturing a product is chosen. For example, when the size of the product is small, the Machine 3 is far more ergonomic than other machines. This can affect on the physical well-being of employees, as when the products are manufactured with a machine with bad ergonomics it can be expected that the number of health-related problems would increase after some time.

The manufacturing speed results that were gathered from the first tests were found out not to represent the real-world manufacturing speeds. While the results gained from the first tests can be used to compare the manufacturing speed of different manual machines, it cannot be used to compare manual bending machines against automated bending machines. The tested manufacturing speed of Product 4 was found out to be around 2 times faster than the real-world manufacturing time that was measured during normal manufacturing process if the operator did not know about the test. It is expected that the gap between measured manufacturing times and real-world manufacturing times of each product is similar. However, this could not be verified as none of the products are manufactured with multiple different machines in regular basis.

To gather a more accurate manufacturing speed results, the total number of bends performed during a week was written down. In addition to total number of bends performed, also total operation time was monitored, so that it would be possible to calculate the average number of bends performed in an hour for each machine. This number can be utilized to assess the speed differences between each machine and thus gain data that can be utilized as a parameter when the manufacturing machine is chosen for any product.

It should be noted that a week is a short period when the total performance of a bending machine is measured. While the measurement period is short, it should still provide useful data that can be used to make further assessments. There is a total operating hours counter in each machine of Machine group 1. This means that the total number of bends can be compared to the total number of operating hours to gather a performance data of the bending machine since the machine was manufactured. This value can be compared to the value that was measured in the period of one week.

6.1. Discussion and possible solutions for the found problems

Discussion of the results and solutions for the problems that are found based on the results are discussed in this chapter.

6.1.1. Discussion of results from interviews

It can be concluded based on the interviews that the bad quality of drawings is the biggest problem according to the operators. There are some solutions that can be applied to improve the quality of drawings. The best quality can be most likely achieved if the drawings are drawn by the designers of the case company. There is however a problem with this approach as it would increase the workload of the designers. It is also possible that the expenses of utilizing case company’s designers to redraw all drawings cannot be charged from the customers. Most common issues with drawings are related to missing measurements or too small print which cannot be seen when the drawing is printed on paper. With the ERP system the drawings can be attached to the orders and the files can be opened by the operators, which should make it possible to get missing measurements from the original drawing file. The drawings can be uploaded as 2D or 3D files to the ERP system, from where the operators can open the drawings and measure possible missing measurements by themselves.

Many of the problems that are encountered by operators are related to tidiness of the workplace. The tidiness can be improved by utilizing methods such as 5S that help to keep the workplace in order. Cleaning equipment should be available in every machine to make it possible to clean the workstation often enough. Markings on the floor should also increase workplace safety as forklifts will not move around operators. By marking the spots for different equipment such as pallet jacks, the equipment will most likely be returned to their correct places more often.

When the KANBAN or POLCA system is combined with 5S the workstations should become tidier. The 5S process in bending department should not focus on placing the tools in right places as the number of different tools is low. The 5S in bending department should focus on keeping the floor around the workplaces as tidy as possible to make sure that there is no need to move several pallets to start manufacturing a new product. There should be marked spots for pallets on each workstation to make sure that the pallets are in the right places all the time. While safety was not among top concerns the utilization of 5S should also improve safety. Safety can be improved by decreasing the risk of stumbling on pallets or products that are placed incorrectly. The safety can also be improved if the areas where forklifts are driving is separated from the area where operators are walking. Markings on the floor helps also to make sure that the fire extinguishers and electrical cabinets are accessible all the time without having to move anything out of the way first. The effects of 5S are significant on several areas of operations in the shop floor, which is why it is advised that the 5S is introduced into the production environment in the future.

There are several answers that are related to blanks. One problem with blanks is that blanks of different products are placed on the same pallet, which makes it harder for bending department operator to find the right blanks for the job. It is advised that only one type of blanks should be put on one pallet. This should be monitored more closely by the work supervisors to make sure that the pallets are loaded in correctly. Many operators answered that the blanks are not bundled on the pallet. Based on the results of the interviews, it seems to increase the productivity of the bending department if the blanks are bundled. When the blanks are bundled, the bending department operator can rely on having all the blanks in the same way. Based on the interviews, it seems that the larger blanks are already usually bundled, while smaller blanks are not bundled on the pallets. While bundling blanks increases the productivity of the bending department, it might decrease the productivity of cutting department as there would be more work for the operators there.

According to the interviews there are also other problems that are blank related. Especially with smaller blanks, there are waste pieces among the blanks, which makes it harder for bending department operators to notice the right blanks. There are no easy ways to remove waste pieces among blanks especially on the blanks that are cut with automated machines. The blanks that are cut with manual cutting machines should be inspected more carefully by the cutting department operator to make sure that there are no waste pieces among the blanks. The final blank related answer is: “Problems with blanks”. This answer refers to the design flaws that are found on the blanks. Some of the blanks are designed in a way that it is not possible to bend the product according to the measurements that are marked on the drawings.

As stated earlier, most of the drawings come from the customers, which means that there is no easy way to make them better.

Another common problem seems to be that pallets fill the floor area near the workstation. There are already plans made for moving the dispatching department in different location. The new location has more room, which should reduce the need of storing manufactured products near the bending machines. KANBAN or POLCA can also be utilized to reduce the WIP in workstations. If the previous manufacturing stages of products are only made when there is free capacity later in the manufacturing chain, the number of products waiting for manufacturing next to bending machines should decrease. Utilization of production controlling system such as KANBAN or POLCA should also reduce the occasions where previous manufacturing stages are incomplete as all the manufacturing stages are marked in the KANBAN card. Several operators answered “Hurry” as one of the biggest problems in the production. It seems that the hurry is result of fabricating previous manufacturing stages too late or forgetting to do them. Due to this, the manufacturing time for bending department is reduced. Utilization of JIT system could reduce hurry in the bending department as the products should always arrive with enough time to perform rest of the manufacturing stages before shipping.

KANBAN or POLCA systems can be utilized with the ERP system to make sure that the production controlling is based on the real production speed of the bending department instead of calculated production speed. Electronic production controlling system should make it easier to monitor when the orders are ready for shipping. Electronic production controlling should also decrease the number of pallets at workstations as the manufactured products could be transported away from the workstation as soon as they are marked as manufactured.

One of the encountered problems was that there are no packaging instructions for products. As there are already plans on implementing the ERP system to the case company, it should be considered if the packaging instructions for the products could be included to the system.

Having packaging instructions available for every product should decrease the number of incorrectly packaged pallets and increase the productivity as less time would be consumed on finding the packaging instructions for the products.

Operators feel that before offering new products to customers, the manufacturability should be consulted from the operators first. This is a good practice that is followed by several salesmen at the case company already. By consulting the manufacturability from the operators, the salesman can be sure that the product is possible to manufacture. It should also make it easier to calculate the price of the work when the difficulty of manufacturing is known. Another recommendation by the operators was that ergonomics should be improved. By improving the ergonomics, the number of sick leaves should decrease. The ergonomic improvements should be consulted from the operators and possibly also from ergonomic specialists.

It is important to notice that the problems noticed by the operators might be different than the problems noticed by the management. Also, some problems that are noticed might occur only occasionally and not have large impact on the productivity of the department. The influence of noticed problems to the productivity of the bending department should be measured to find out what problems have largest influence on the productivity before performing the actions presented in this thesis.

6.1.2. Discussion of results from manufacturing speed experiments

The results that were gathered from the manufacturing speed experiments were surprising. It was expected that Machine 1 would be significantly faster than other machines with every product. The manufacturing speed that was measured for Machine 1 was between 637 and 657 bends/hour, while the manufacturing speed that was measured for Machine 2 was between 609 and 658 bends/hour. The manufacturing speed of Machine 2 dropped when the manufacturing speed test was conducted during a weeklong period. The manufacturing speeds of machines like Machine 2 were between 121 and 189 bends/hour (Machine 4 of

Machine group 1 excluded), which are significantly slower manufacturing speeds that were measured at the first time.

The first test shows that the Machine 4 is the slowest machine with both tested products. The manufacturing quality of Machine 4 is also inferior when comparing it to other tested machines. It was possible to measure the manufacturing speed of Machine 3 only on one product due to the Machine’s limitations. For that one product, Machine 3 was the fastest machine. The ergonomics of Machine 3 are also better for smaller products than the ergonomics of other machines.

The second manufacturing speed test gave more reliable data on the real-world manufacturing speed of machines of Machine group 1 and machines of Machine group 2. It was not possible to perform this manufacturing speed test to Machine 1 or Machine 4 as these machines does not have the necessary meters for that. There were some differences in products that were manufactured with these machines. There was high variety of different products that were manufactured with machines of Machine group 1, while there were smaller number of different products manufactured with machines of Machine group 2. Due to higher number of different products, there was higher number of setups performed during the week with machines of Machine group 1. This reduces the productivity of these machines compared to machines of Machine group 2.

While it was not possible to compare the manufacturing speed of Machine 1 to other machines, some predictions can still be made based on the data gathered from the first tests. During the first tests the average manufacturing speed of Machine 1 was 644 bends/hour. Because Machine 1 is automatic machine, it can be expected to work with that speed if the operator of the machine is present. The operator is present at the machine seven hours a shift at the most. In real-world, that number is however smaller due to bathroom breaks and transportation of products. Setup time must be included as non-productive time, which means that in the real-world the machine is operating probably between four to six hours per shift. With these numbers, the real-world manufacturing speed of Machine 1 should be between 322 and 483 bends/hour. While the average real-world manufacturing speed of machines of Machine group 1 is 161 bends/hour, the Machine 1 should be at least two times faster on average.

It is important to notice that the values that were calculated previously are indicative and were not possible to verify with proper testing. These values however seem to be close to the values that were estimated by the management of the company. The management's estimation regarding the manufacturing speed of different machines was that the Machine 1 would be 2.5 faster than the Machine 2. As the value calculated based on the first manufacturing speed test supports the estimated manufacturing speed it is expected that the real-world manufacturing speed is close to the initial estimate.

A table for choosing correct machine for each order was made based on the values presented in Table 15 and the values that were measured in this thesis. Limitations of most used bending machines are presented in the following table. Machine 4 was not included in the table as it is not in regular use. Due to limitations caused by old age, the products that are manufactured with machine 4 have same limitations that Cone 900 has. The limitations of bending machines presented in Table 15 include:

- Minimum and maximum length of bend
- Maximum bending force
- Minimum and maximum bending thickness
- Maximum bending flange length

The limitations presented in Table 15 are gathered from the technical data sheets of the machines. Minimum bending flange depends on the tools that are used in the bending process, which is why it is not included into the table. There are also several other limitations that must be considered with more complex products such as size of throat of a press brake. These limitations are not considered in the table as these basic limitations were found to be sufficient when choosing bending machine for most products.

Table 15. The limitations of bending machines.

Features of bending machines	**BCe Smart**	**Cone 500**	**Cone 900 / C9**	**CoastOne C15X**	**Amada HFT 80-25 800 kN**	**Amada HFE 1303 1300 kN**	**Prima Power eP-1030**	**Prima Power eP-1336**	**Amada EG6013AR robot**	**HFE M2 1303 1300 kN robot**
Length of a bend	Min 215 mm									
Under 200 mm		X	X	X	X	X	X	X	X	
200 - 850 mm	X		X	X	X	X	X	X		X
850 - 1 450 mm	X			X	X	X	X	X		X
1 500 - 1 800 mm	X				X	X	X	X		X
1 800 - 2 000 mm					X	X	X	X		X
2 000 - 3 000 mm						X	X	X		X
3 000 - 3 660 mm								X		
Maximum bending force [ton]	32	18	22	44	80	130	105	135	60	130
Material thickness	Min 0.5 mm								Min. 0.6 mm	
Aluminium	3.5								2.3	
Stainless Steel	1.8								2.3	
Mild Steel	2.5								2.3	
Maximum bending flange length [mm]	200	200	200	300	1 000	1 000	1 000	1 000	200	1 000

When the results gained from manufacturing speed experiments are combined with values of Table 15, it is possible to make instructions that can be used by the designers to choose right bending machine in the upcoming ERP system. While the instructions do not cover all possible bending limitations for special parts, such as boxes, it should make it possible to choose right machine for a product if the product is simple enough. Due to confidentiality purposes the instructions are not presented as a part of this thesis. The machine limitations table must be updated as new bending machines are taken into the production. While the limitations table is updated, also the instructions should be updated as new bending machines might have advantages over the old machines which makes the new machines more productive for the same products.

6.2. Reliability and validity

There are some reliability issues that can affect the results gained from this thesis. The main reliability issues are related to the short time period in manufacturing speed experiment. Another reliability issue is the current state of production, as there are typically less orders during winter than during summer, which means that the results gained from the experiment do not necessarily represent the maximum output of the studied machines. Some smaller reliability issues are present in the interview part as it is possible that some operators had given answers that they thought were sought after rather than giving answers they truly think of. While the likelihood of that happening is small, it is still important to notice. Overall, the reliability of the experiments was found to be sufficient.

There were some validity issues with the manufacturing speed experiments that were planned to be performed initially. After the experiment was redesigned the validity of the results increased as the test methods represented more closely the real-life scenario. The validity of interviews was found to be sufficient as the questions that were presented in the interview were chosen to give information that was important to this thesis.

7. Conclusions

Conclusions of the thesis are presented in this chapter. In addition to presenting key findings, also topics for future research and future actions are presented in this chapter.

7.1. Key findings

Several key findings were found from the interviews. Most common issue in the bending department seems to be that the drawings are not good enough. Bad drawings increase the likelihood of manufacturing errors as it is always not clear for the operators, how the products should be bent. Missing measurements cause waste of time as the operators have to meet designers to get all the necessary measurements to bend the product correctly. Bad quality of drawings causes waste of time also by increasing the time needed to interpret the drawings correctly.

Many of the issues in bending department were related to tidiness of workplace. The lack of tidiness in workplace causes wasted time as equipment and products must be looked for during the day. Another common issue in the bending department seems to be that the working area is full of pallets. Pallets of blanks are brought to the working area to wait for the manufacturing to start. Also, pallets filled with already manufactured products are kept waiting around the production machines for dispatching.

During the interviews it was found out that lack of packaging instructions causes problem as the operators might not know how the products should be packaged. Many operators in the bending department have problems with blanks not being bundled or blanks of several different products being on the same pallet.

The bad quality of drawings can be partly solved by uploading the original drawing files of the products to the new ERP system, where the files are accessible for the operators to measure. Productivity of the bending department can likely be improved by implementing 5S to the production. By having clearly marked spots for each product the likelihood of misplaced pallets causing more work for operators is reduced. The number of pallets filled with manufactured products is reduced due to implementation of the ERP system as the information about completed manufacturing stage is transferred instantaneously to the person who can transfer the manufactured products to the dispatching department. The ERP system can be utilized to support the visual production controlling system that is currently used to improve the predictability of the production.

Lack of packaging instructions was found to be a problem in the bending department. The packaging instructions should be made and uploaded to the ERP system, where the packaging instructions are available for any operator to use. The blanks not being bundled on the pallets is a problem with blanks with smaller size that are manufactured with automated punching machines. The company should look for possible automated solutions that could be used to bundle the products onto the pallets automatically. This would reduce the needed manhours as no time would be wasted on bundling the products manually.

Based on the manufacturing speed experiment, there is a significant speed difference between different bending machines which means that selecting right bending machine for each product is important. It can be assumed that the Machine 1 is fastest bending machine in real-world conditions and thus it should be primarily used if the product can be manufactured with it and the batch is large enough. Measurements showed also that other machines can closely match the manufacturing speed of Machine 1 for a short period of time. The measured manufacturing speeds were between 100 and 256 bends per hour for the press brakes. Panel bender was found to be roughly 2.5 times faster than the press brakes that were studied, which suggests that the panel bender should be used for large orders if possible.

The manufacturing speeds that were measured in the second manufacturing speed test represent closely the manufacturing speed estimates gave by operators. It is thus expected that the values gathered from measurements closely represent the real-world productivity of the bending department.

The measured manufacturing speeds are used to create instructions on choosing the right bending machine for each product. Measured manufacturing speed results can also be used to improve calculation of manufacturing cost for the products. In addition, measured manufacturing speeds can be used in the ERP system to calculate available capacity of the bending department.

7.2. Topics for future research and actions

Some actions should take place in the future to improve the productivity of the bending department. As the bad quality of drawings is the biggest problem currently in the bending department, some actions should be considered to make interpreting the drawings easier for the operators. Digital tools such as pdf-documents and 3D models of the products should be utilized in the production to make sure that the operators can manufacture the products correctly. If the customer is not capable of making drawings that are good enough drawings, the drawings should be made by the designers of the case company.

To further improve the productivity of the bending department, some Lean methods should be implemented into the production. The Lean-methods that should be considered include 5S, KANBAN/POLCA, and JIT. Tidiness of the workplace can be improved by implementing 5S methods in the production. 5S method should also make it easier to keep lifting equipment in the right places. Weekly 5S audits should also make sure that the workplace stays clean.

Creating packaging instructions for every product would increase productivity as by having packaging instructions, the operators would know for sure how the products should be packaged. The packaging instructions should be digitally available on every workstation to make it possible to manufacture the products with different machines. Productivity of the bending department could be increased by bundling the blanks after cutting. Larger blanks are generally bundled, while the blanks with smaller size are not bundled. The bundling of smaller blanks is not possible as there is not enough time in cutting department to manually bundle the blanks. Possible ways of automating the bundling process for smaller blanks should be studied to make it possible to also bundle the smaller blanks.

Future research topics include more research on the performance of the bending department. Another future research could be targeted on studying the productivity of other departments in addition to studying the bending department further. Future research could also focus on studying the effects of actions that were presented in this thesis to find out what is the effect of implementing these changes to the production.

While some possible actions to correct the problems that occurred during the interviews are presented in this thesis, the actions could be confirmed by utilizing for example 5 whys method. By utilizing 5 whys method the root causes of each problem can be determined and correct actions can be planned. The effects of each action should be monitored to make sure that the actions created based on 5 whys method are correct. 5 whys method can also be utilized to find relations between different problems that might be possible to correct with same measures.

References

Amada, (2022). EP-2500. [Web page]. Accessed: 28.3.2022. Available: https://www.amada.de/bending/ep-2500/specifications.html

Benson, (2017). Press brake bending basics: Do we really need more cowbell? [Article]. Accessed: 28.3.2022. Available: https://www.thefabricator.com/thefabricator/article/bending/press-brake-bending-basics-do-we-really-need-more-cowbell-

Bozzone, V. (2001). Speed to market: lean manufacturing for job shops. 2nd ed. [Book]. ISBN: 9780814406946, pp. 3–14.

Chen, C., Gong, F., Chen, Y. & Wang, J., (2021). A prediction model for bending springback of AZM120 sheet metal and mechanical compensation of CNC automatic panel bender. In: The International Journal of Advanced Manufacturing Technology, 20.7.2021, pp. 1–13. [Article].

Colour Blind Awareness, (2022). Colour Blindness. [Web page]. Accessed: 7.1.2022. Available: https://www.colourblindawareness.org/colour-blindness/

Crandall, J., (2015). Panel Benders vs. Press Brakes. [Article]. Accessed: 28.3.2022. Available: https://www.fabricatingandmetalworking.com/2015/11/panel-benders-vs-press-brakes/

Da Silva, I. B. & Filho, M. G., (2019). Single-minute exchange of die (SMED): a state-of-the-art literature review. In: The International Journal of Advanced Manufacturing Technology, 9.3.2019, pp. 1–19. [Article].

Davies, M., (2019). The “5 whys” Method (5Ys) – how to collaboratively identify and solve the root cause of problems. [Article]. Accessed: 13.4.2022. Available: https://www.linkedin.com/pulse/5-whys-method-5ys-matt-davies-/

Finder, (2022a). Stremet Oy. [Web page]. Accessed: 2.5.2022. Available: https://www.finder.fi/Metallituotteet/Stremet+Oy/Salo/yhteystiedot/3185615

Finder, (2022b). Metalliteollisuus Salo. [Web page]. Accessed: 25.1.2022. Available: https://www.finder.fi/search?what=Metalliteollisuus%20Salo&type=company

Finnerty, J., (2013). Automating OEE for the job shop. [Article]. Accessed: 13.1.2022. Available: https://www.thefabricator.com/thefabricator/article/shopmanagement/automating-oee-for-the-job-shop

Gupta, S. & Chandna, P., (2020). A case study concerning the 5S lean technique in a scientific equipment manufacturing company. In: Grey Systems: Theory and Application, Volume 10 Issue 3, 18.6.2020, pp. 339–357. [Article].

Jeyaraj, K. L., Muralidharan, C., Mahalingam, R. & Deshmukh, S. G., (2013). Applying Value Stream Mapping Technique for Production Improvement in a Manufacturing Company: A Case Study. In: Journal of The Institution of Engineers (India): Series C, 19.3.2013, pp. 43–52. [Article].

Jiménez, M., Romero, L., Fernández, J., del Mar Espinosa, M. & Domínguez, M., (2019). Extension of the Lean 5S methodology to 6S with An Additional Layer to Ensure Occupational Safety and Health Levels. In: Safety and Security Issues in Industrial Parks, 12.7.2019, pp. 1–18. [Article]. Accessed: 14.1.2022. Available: https://www.mdpi.com/2071-1050/11/14/3827/htm

Kubiak T. M. & Benbow D. W., (2017). Certified Six Sigma Black Belt Handbook. 3rd Edition. [Book]. ISBN: 9780873899413, pp. 557–561.

Kylmälä, M. (2017). Contributing factors in productivity of sheet metal small series production. [Thesis]. Accessed: 3.1.2022. Available: https://lutpub.lut.fi/bitstream/handle/10024/147652/Kylmala_Markus-Mikko_Kandidaatintyo.pdf?sequence=1&isAllowed=y

Lage Junior, M. & Godinho Filho, M., (2010). Variations of the kanban system: Literature review and classification. In: International Journal of Production Economics: Volume 125, Issue 1, May 2010, pp. 13–21. [Article]

Machine MFG, (2019). Press Brake Dies (Toolings): The Ultimate Guide. [Article]. Accessed: 14.2.2022. Available: https://www.machinemfg.com/press-brake-dies-guide/

Machine MFG, (2022a). Press Brake Dies Practical Use (and It’s Scope). [Article]. Accessed: 14.2.2022. Available: https://www.machinemfg.com/press-brake-dies-practical-use/

Machine MFG, (2022b). The Basic Guide to Panel Bender (You Should Know). [Article]. Accessed: 14.2.2022. Available: https://www.machinemfg.com/panel-bender-guide/

Mesa, J., Heriberto, M., René, A., Lesmes, C., Jorge, B. (2017). A novel approach to include sustainability concepts in classical DFMA methodology for sheet metal enclosure devices. Research in engineering design, 21.7.2017, pp. 227–244. [Article].

Panthi, S.K., Ramakrishnan, N., Ahmed, M., Singh, S. & Goel, M.D., (2010). Finite Element Analysis of sheet metal bending process to predict the springback. In: Materials & Design: Volume 31, Issue 2, February 2010, pp. 657–662. [Article].

Pinto, J. L. Q., Matias, J. C. O., Pimentel, C., Azevedo, S. G. & Govindan, K. (2018). Just in Time Factory Implementation Through Lean Manufacturing Tools. In: Management for Professionals (MANAGPROF), 2018, pp. 5–112. [Book].

PROPOS Software, (2022). Digital POLCA. [Web page]. Accessed: 7.1.2022. Available: https://www.propos-software.com/fully-automated-planning/digital-polca/

Riezebos, J. (2010). Design of POLCA material control systems. In: International journal of production research, 2010, pp. 1455–1477. [Article].

Sendil Kumar, C. & Panneerselvam, R. (2007). Literature review of JIT-KANBAN system. In: International journal of advanced manufacturing technology, 2007, pp. 393–408. [Article].

Spearman, M., Woodruff, D. & Hopp, W. (1989). CONWIP: a pull alternative to Kanban. In: International journal of production research: Volume 28, Issue 5, 1.5.1990, pp. 879–894. [Article].

Stremet Oy, (2022). Ohutlevytyöt. [Company Website]. Accessed: 13.1.2022. Available: https://stremet.fi/pages/ohutlevytyot

Tardi, C., (2020). What Is the 80-20 Rule? [Article]. Accessed: 25.2.2022. Available: https://www.investopedia.com/terms/1/80-20-rule.asp

Vandaele, N., Van Nieuwenhuyse, I., Claerhout, D. & Cremmery, R. (2008). Load-Based POLCA: An Integrated Material Control System for Multiproduct, Multimachine Job Shops. In: Manufacturing & service operations management: Volume 10, Issue 2, 1.1.2008, pp. 181–197. [Article].

Zhang, A., (2021). How to Calculate Press Brake Machines Tonnage (By Chart, Formula & Calculator). [Article]. Accessed: 28.3.2022. Available: https://www.vistmac.com/how-to-calculate-press-brake-machines-tonnage-by-chart-formula-calculator/