Pan Oston®

HEART OF STEEL / SENSE OF DESIGN

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September 21, 2022

A RESEARCH ON WHICH PANEL BENDER PAN OSTON SHOULD IMPLEMENT IN THE PRODUCTION PROCESS

BSc Industrial Engineering & Management

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Preface

Dear reader,

Hereby I provide you my research on which panel bender Pan Oston should implement in the production process. The research is conducted at Pan Oston in Raalte. This is done between May 2022 and July 2022 to finish my Bachelor of Science in Industrial Engineering and Management at the University of Twente.

First of all, I want to thank Pan Oston for the opportunity they gave me to work on this exciting assignment. It was not always easy, but the nice and helpful colleagues always wanted to help me with questions and uncertainties. This helped me a lot during the research, for which thank you.

Second, I want to thank the account managers of the manufacturers for showing interest in my assignment and helping me by collecting information. Regardless of the fact that it sometimes took a long time to receive information, I am convinced that they always wanted to help me no matter what.

Last, I want to thank my University supervisors. Especially Leo, with which I had the most contact during this research. In addition, Leo always provided very professional feedback during the meetings that helped me to improve the quality of my research.

Enjoy reading!

Daan Veuger
September, 2022

Management Summary

How efficient would it be to produce your products up to 5 times faster than that happens now. Of course, this is not reserved for every business. Pan Oston has the ability to invest in a panel bender, a machine that is able to bend metal products automatically. This seems a great opportunity, but which panel bender should Pan Oston choose?

Problem identification

Let us first start with the business of Pan Oston. It is a production company located in Raalte, the Netherlands. It is specialized in designing, engineering, and producing checkout systems for the retail sector. Examples of well-known customers are Albert Heijn, Action, Etos, and Kruidvat. The production facility in Raalte is responsible for 30% of total demand, while its production partner in Slovakia is responsible for 70% of total demand.

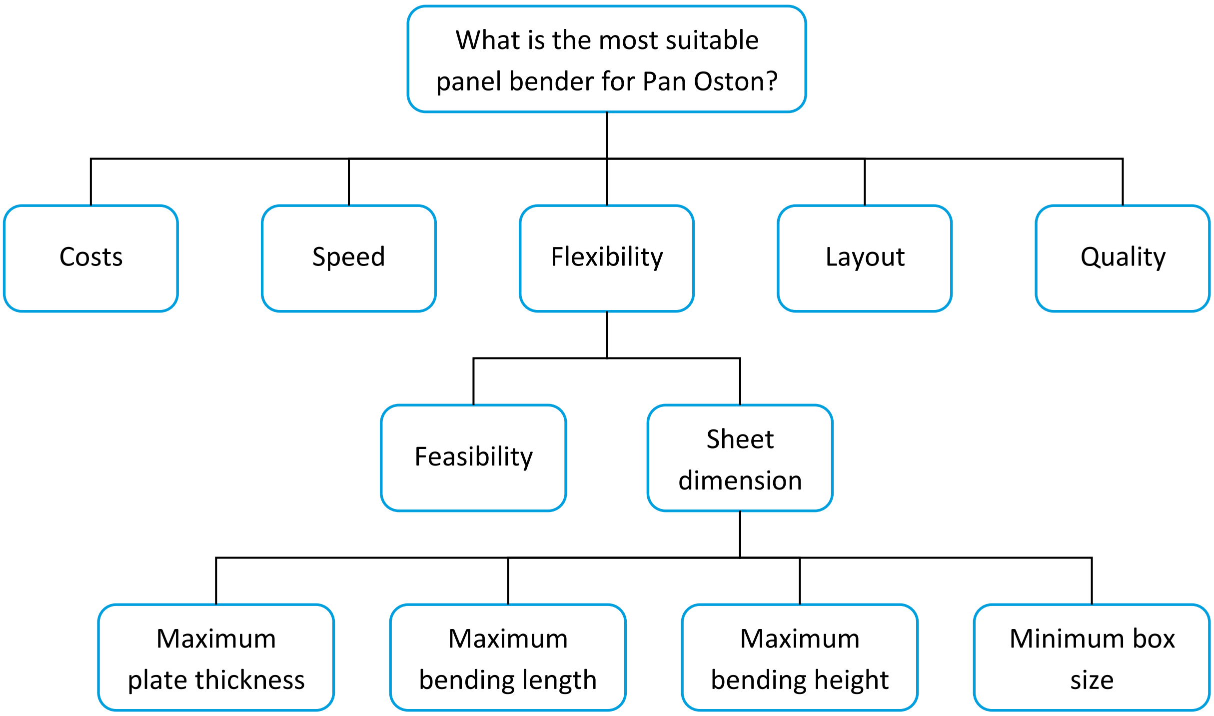
The research is conducted within the metal department of the facility in Raalte. Currently, the metal department is equipped with four traditional bending machines. The problem of Pan Oston is that it needs on average 44% of the production time to change the tools and set up the traditional bending machines. A (semi)automatic panel bender must be the solution to this problem, but which panel bender should Pan Oston choose? There are namely many different manufacturers on the market, each producing different variants. These variants range from semi-automatic to fully automatic. In this research, the following research question is answered: *"Which panel bender should Pan Oston buy in order to decrease the tool changing times at the metal department?".*

Research approach

This research is roughly divided into 7 phases. The first phase consists of identifying the problem and setting up the research questions. After that, we searched for different Multiple Criteria Decision Analyses (MCDA) types, to subsequently perform a Systematic Literature Review to know the main steps of the chosen MCDA type. Thereafter in phase three, the manufacturers were chosen and account managers were interviewed. In phase 4, we find out which production data is relevant to analyze and which not. Phase 5 provides an overview of the raw scores in combination with the machines that drop off. Eventually in phase 6, we use the Analytic Hierarchy Process (AHP) approach to work towards an answer and perform a sensitivity analysis to increase the confidence in the most preferred alternative. Last, we draw conclusions and provide recommendations for the company managers.

Criteria and sub-criteria

In this research, we used the AHP approach to determine the weights for the criteria and sub-criteria. There are 5 main criteria, and 6 sub-criteria divided over two levels. The following figure gives a clear overview of how that looks.



Results

In order to be able to come up with the results, the AHP approach was used in combination with the direct rating technique from SMART. In the first place, the AHP approach was used to determine the weights for the criteria, by means of pairwise comparisons. These pairwise comparisons are done by 4 decision makers individually, namely the Process Specialist, the Manager Operations, the Metal Department Manager, and the Chief Operational Officer. Thereafter, the direct rating technique from SMART is used to determine the values of the performances of the alternatives on each criterion. The weights for each decision maker are different, while the performances of the alternatives are all the same for each decision maker. The weights are multiplied by the values of the performances to come up with a final score of the alternatives. The final ranking of the alternatives per decision maker is presented in the table below, where 1 means that the alternative has the highest ranking, and 6 means that the alternative has the lowest ranking.

Manufacturer	**Prima Power**		**Salvagnini**		**Trumpf**	
Machine type	FBe2220	EBe2220	P4L-2120	P4L-2225	P2L-2225	7020
Process Specialist	1	3	4	6	5	2
Manager Operations	2	4	3	6	5	1
Department Manager	1	3	5	6	4	2
COO	1	3	4	6	5	2

Besides finding out what the most preferred option is, we have also calculated the Return on Investment of several machines. These results are shown in the table below. The FBe2220 is a semi-automatic variant from Prima Power, the 7020 is an automatic variant with manual loading and unloading, and the P4L-2120 is an automatic variant as well, but now with automatic loading and unloading. The savings per year are based on the amount of employee savings per year. If a panel bender is for example 3 hours per day faster than the current process, we would save 3 employee hours. In this case, we assume that the rest of the day the panel bender is turned off. In reality, this is not the case, which means that the ROI is even higher.

Machine	**Costs**	**Savings (minutes per year)**	**Savings (€ per year)**	**ROI**
FBe2220	€600,563.00	52,139.36	€56,484.31	9.41%
7020	€739,475.00	49,678.69	€53,818.58	7.28%
P4L-2120	€978,510.00	54,297.11	€58,821.87	6.01%

Conclusion & recommendations

As we have discussed the results, it is now time to draw a conclusion. Based on the results from the ranking table above, we can clearly see that the semi-automatic variant from Prima Power is the most preferred option. Only the Manager Operations has a different most preferred option. As we then look at the weights of the Manager Operations, it stands out that this decision maker has a much higher weight for flexibility than compared to the other decision makers. We performed a sensitivity analysis on this flexibility weight of the Manager Operations, and concluded that if the flexibility decreases by 0.0521 (from 0.5238 to 0.4717), the Prima Power FBe2220 becomes the most preferred option as well. This FBe2220 is a semi-automatic panel bender that requires more human interaction than compared to the automatic variants. Working with the semi-automatic variant, the operator has to load, unload, move, and turn the metal sheets in the desired position. If we look at the ROI of this FBe2220, it is 9.41%.

Based on the results and the conclusions, we come up with the following recommendations. First, we initially selected 35 products, but Trumpf only tested 20 of them. In order to increase the accuracy of the performances of the panel benders on speed and feasibility, we recommend to test the additional 15 products. This not only leads to a more accurate speed and feasibility, the accuracy of the ROI increases as well. Second, the semi-automatic variant from Prima Power has very good results. Trumpf has such a semi-automatic variant as well, namely the Trumpf TruBend 5030. Since Pan Oston already possesses several other Trumpf machines, we recommend to further investigate this option as well. Third, we recommend to provide proper training to several employees from the metal department and all the employees from the engineering department. The employees at the metal department need to be able to use the panel bender in a proper way, and the employees from the engineering department need to know which products can be made and which not. If this is not the case, the efficiency of the panel bender decreases.

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Glossary

Abbreviation	Meaning	First introduced on page
AHP	Analytic Hierarchy Process	15
CI	Consistency Index	19
COO	Chief Operational Officer	7
CR	Consistency Ratio	19
ERP	Enterprise Resource Planning	29
FTR	First Time Right	32
MCDA	Multiple Criteria Decision Analysis	9
RI	Random Index	52
ROI	Return On Investment	10
SLR	Systematic Literature Review	11

1 Introduction

The first chapter of this research is meant as an introduction chapter in which among others, the company is introduced. This company introduction is discussed in 1.1. The problem statement, norm and reality, and core problem follow in Section 1.2. Section 1.3 gives a theoretical perspective about the method that is used in this research, while in Section 1.4 the problem solving approach is discussed. Thereafter in Section 1.5, the deliverables are discussed, that are followed by the limitations in Section 1.6.

1.1 Company introduction

Pan Oston B.V. is located in Raalte, the Netherlands. The company was founded in 1969 and it is specialized in designing, engineering and producing checkout systems for the retail sector. Pan Oston produces checkout systems for many different well-known customers, for example Albert Heijn, Action, Etos and Kruidvat. Pan Oston produces 30% of its total demand in Raalte, while 70% of its demand is produced in Slovakia, at its production partner.

The focus of the research lies at the facility located in Raalte. The designing, and the engineering of the products are entirely done by Pan Oston itself, but the production of some parts is outsourced. Examples of these parts are the displays and the conveyor belt. The assembly department combines the parts into a nearly final product, only lacking customer-specific software. The installation of the software is done by the customers themselves. This means that Pan Oston sells the entire checkout, without the software. The customer only has to place the checkout system and program the desired software.

1.2 Problem statement

In this section, the problem of Pan Oston is identified. In Section 1.2.1, the nature of the problem is discussed. Thereafter, in Section 1.2.2 the gap between the norm and the reality is described. Section 1.2.3 contains the problem cluster, which gives a clear overview of all the relevant problems within the company. Last, the core problem is discussed in Section 1.2.4.

1.2.1 The problem

For this research, the aim lies within the metal department of the facility in Raalte. In this department, the metal plates are bent in the desired shape. One of the main materials that is used in the end product is metal. The start of the process begins with the supply of the metal plates, whereafter the plates are stored in inventory. Between 40 and 50 percent of the metal plates needs internal laser cutting. Pan Oston currently possesses only a single laser cutter, which is not sufficient to supply 4 bending machines. Because of this, between 50 and 60 percent of the laser cutting is outsourced. After the laser cutter, the metal plates are bent at one of the four workstations. Each workstation has a traditional bending machine operated by an employee. The characteristics of the four bending machines are the same. The only difference is that one machine is smaller than the other three. Working at the smaller machine is also less physically intense. After the bending process, the semi-finished products go to inventory or the welding process.

The products that are bent at the bending process have many different bending characteristics. For example, one product might be longer or shorter than the other, while at the same time the thickness differs as well. The bending machines that Pan Oston uses right now cannot handle all these different characteristics at the same time. Because of that, the machine tools need to be changed often. The company has performed preliminary research to determine these changing times. Their findings were that approximately 50% of the production time is spent on changing the tools. Observations and calculations of the production data from March 2021 until March 2022 have shown that this is indeed the case. How this problem will be approached is discussed in Section 1.4.

1.2.2 Norm and reality

According to Heerkens & Van Winden (2017), an action problem is a discrepancy between the norm and the reality, as perceived by the problem owner. In other words, anything or any situation that is currently not as you want it to be (Heerkens & Van Winden, 2017). During this research, the focus will lie on the action problem that is colored yellow in **Figure 1**. As said before, the metal department at Pan Oston is dealing with a tool changing time of approximately 50% of the production time. One of the results of this is that the machines are not optimally used, which in turn result in a higher throughput time of the products. The management of the company wants a decrease of this throughput time. This gap between norm and reality is expressed in numbers as follows:

The reality is that the annual tool changing times at Pan Oston B.V. amounts 2900 hours, and this should be decreased by 40% to 1740 hours.

1.2.3 Problem cluster

If all the problems are known, we must find out which problems are related. The tool that is used for this is called the problem cluster. The problem cluster gives a clear overview on which problems are causes, and which problems are results (Heerkens & Van Winden, 2017). **Figure 1** shows the problem cluster of Pan Oston in which the action problem is colored yellow and the core problem is colored green. On the left hand side of the cluster, there are only two boxes with only arrows going out, which means that these boxes are causes. Boxes that have arrows going in and going out are causes and results at the same time, while boxes with only arrows going in are results.

In order to come up with the problems provided in the problem cluster, I have spoken to several people at the company. During the first introduction meeting, I spoke to the Chief Operational Officer (COO) and he told me that the company faces high changing times for their machines. Thereafter, we spoke to the metal department manager and asked what he thinks of the current situation. The metal department employees that use the machines on a daily basis, explained a lot about their current activities. They gave me a lot of insight and understandability in the current situation. Lastly, I spoke to the Manager Operations and process specialist to justify the relations between the problems.

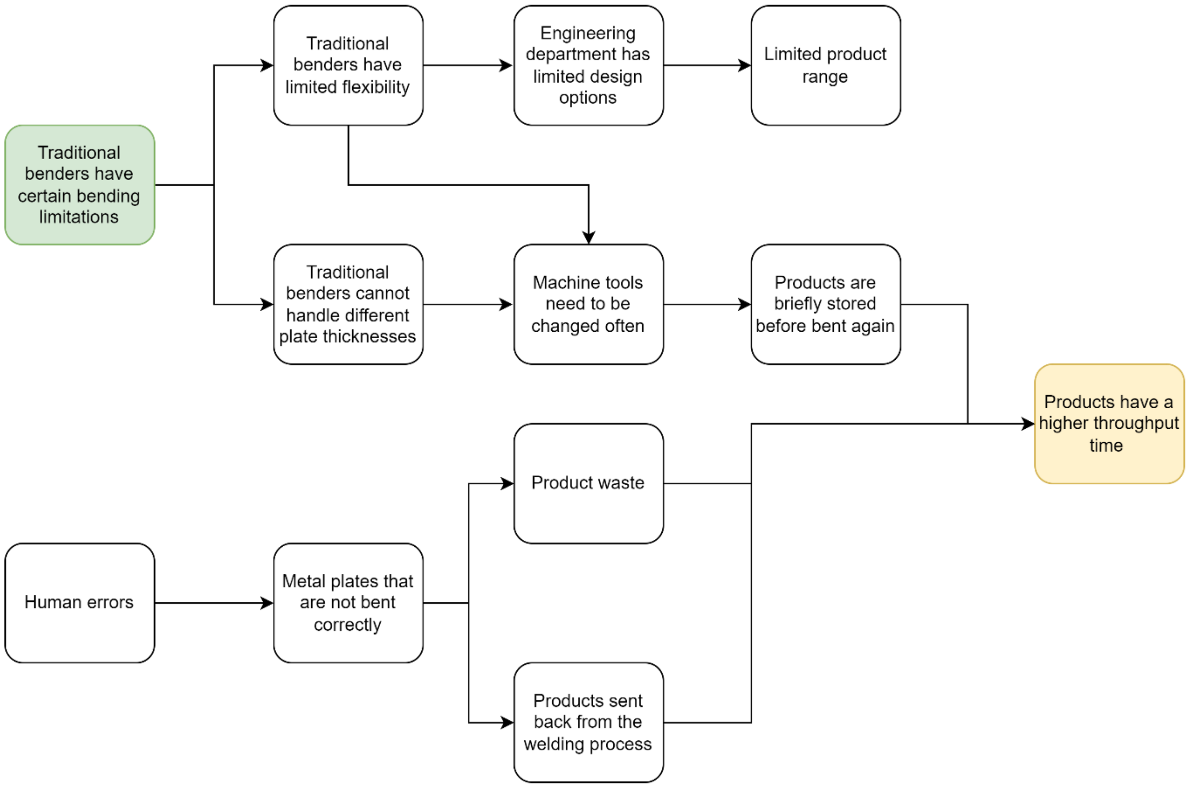

Figure 1. *The problem cluster of Pan Oston*

As said before, the metal plates are bent at the workstations that are operated by employees. During this process, it is possible that employees make mistakes. A result of these mistakes is that the metal plates are not bent in the correct way or in the desired shape. This in turn, results in product waste and items that are sent back from the subsequent welding process. This leads to a higher throughput time of the products. The higher throughput time of the products is also the action problem.

Second, Pan Oston possesses four traditional bending machines. As said, there are three big machines and only one smaller machine. The smaller machine is used for smaller products, but the main characteristics of this smaller machine are the same as of the three bigger machines. The traditional benders have certain limitations when it comes to bending. Chapter 4 elaborates on these limitations. In addition, the traditional benders also cannot handle different plate thicknesses at the same time. Therefore, the machine tools must be changed often. Before the employees can change the machine tools, they have to briefly store the products that they were working on in a rack before they can continue. This leads to a higher throughput time of the products as well. Due to the limited flexibility of the traditional benders, the engineering department has to take the limitations into account when designing a (new) product. This leads to a limited product range of the company. By solving the core problem, human errors will be reduced to some extent as well. In addition, the company enlarges their product range, due to the higher flexibility of the new machine.

1.2.4 Core problem

In practice, companies face many problems at the same time. However, there is often not enough money, time, and effort available to tackle all the problems at the same time. Therefore, it is important to choose a core problem. This is the problem that will have the greatest impact at the lowest amount of costs (Heerkens & Van Winden, 2017). In addition, a core problem has several characteristics. In the first place, it must be a situation that you can influence. Bad weather, for example, is something you cannot influence, thus this automatically cannot be a core problem. Second, a core problem should not have a cause in itself. This means that the core problem is not the result of some other problem within the company. Last, if there is more than one problem that meets these characteristics, the most important problem is chosen as the core problem (Heerkens & Van Winden, 2017).

Considering these characteristics of core problems, we can conclude from **Figure 1** that there are only 2 possible core problems. First, human errors cannot be considered as the core problem. This is due to the low percentage of occurrence. Observations and calculations of the production data have shown that during March 2022, only 291 products were bent wrongly, while 51,126 products were bent rightly. This means that the metal department has a margin of error of only 0.57%. Solving this problem would not gain the most benefits with the least amount of costs. Second, the traditional benders have certain bending limitations. Because of these limitations, the employees must change the tools of the machines quite often. As said before, the company concluded that approximately 50% of the production time is spent on changing the tools. The analysis of the production data shows that the total production time in 2021 is equal to 395,521.5 minutes. 221,842.5 minutes of the total production time was actually spent on production, while 173,679 minutes were spent on changing the tools. This means that approximately 56% of the total production time was spent on production, while 44% of the production time was spent on changing the tools. Solving this problem will have the highest beneficial impact compared to the other problems. Therefore, the core problem is:

"Traditional benders have certain bending limitations"

The purpose of this research is to provide a solution for the inefficiency at Pan Oston, specifically within the metal department. The company executed a preliminary research about possible solutions. Several fairs were visited in which different automatization possibilities were exposed. Also, a representative of the manufacturer where the current bending machines come from told the company that a lot of space is needed to automate the current bending machines. Since Pan Oston does not have enough space to accomplish this, the only suitable solution remains the panel bender. However, they also concluded that a panel bender cannot make every product, which means that at least one of the four traditional machines will be kept at the company. A panel bender is a machine that bends the metal plates automatically, with minimal human interference. However, the company does not know yet which panel bender to buy. In this research, a Multiple Criteria Decision Analysis (MCDA) is executed to come up with a solution for this situation.

1.3 Theoretical perspective

Theoretical perspectives are sets of assumptions about the reality. It guides the approach to asking questions and reaching conclusions. It is relevant to mention because it gives a clear view about the way of thinking (Crossman, 2020). During this research, an MCDA will be executed to guide us towards making a decision. Since this is one of the main parts of the research, it is important to give a definition of what we exactly mean by the term.

If we consider the expression Multiple Criteria Decision Analysis, criteria is one of the parts. Criteria is the plural form of criterion, which is a standard or means by which you judge or decide (Cambridge, 2022). When considering the decision-making context, a criterion implies a standard to judge whether one particular choice is more preferred than another. If a decision maker has multiple criteria on which multiple alternatives must be judged, this becomes a Multiple Criteria Decision Analysis (MCDA) (Belton & Stewart, 2002). For example, when buying a house or apartment, relevant criteria could be costs, accessibility to public services, and personal safety. In the case of this research, relevant criteria to assess the performance of the machines are of course not accessibility to public services, but rather flexibility, costs, and speed. An MCDA helps to structure complex problems and leads to better considered, justifiable and explainable decisions. The MCDA seems like a decision-making method in itself, but it is actually an umbrella term to describe a collection of methods that take multiple criteria into account (Belton & Stewart, 2002). In Chapter 2, we elaborate further on the different MCDA types.

1.4 Problem solving approach

Now it is clear what the core problem is, and what an MCDA includes, it is useful to think of a way to come up with a possible solution. To solve the core problem, the following research question is formulated.

> *"Which panel bender should Pan Oston buy in order to decrease the tool changing times at the metal department?"*

In order to be able to answer this research question, several sub-questions are formulated. These sub-questions will function as a guidance through this research. This research will go through several phases, that are schematically shown in **Figure 2**. Thereafter, the sub-questions are formulated along with a brief explanation about how this question will be solved, how the data is gathered, and how the question contributes to answering the main research question.

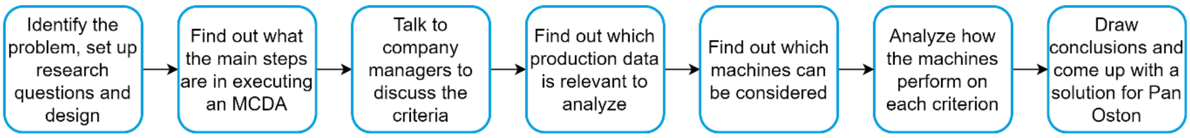

Figure 2. *Flowchart of the problem solving approach*

1.4.1 Research questions

The following sub-questions are formulated in order to be able to answer the main research question.

1a. What types of Multiple Criteria Decision Analyses can be considered?
1b. Which Multiple Criteria Decision Analysis is chosen?
1c. What are the main steps of this chosen analysis type?

As discussed in Section 1.3, an MCDA is an umbrella term to describe a collection of different methods. All of these methods have their advantages and disadvantages. Question 1a is a descriptive question and its purpose is to collect the most relevant MCDA types and their corresponding advantages and disadvantages. This helps to select the most appropriate type in question 1b.

Eventually in question 1c, the main steps of the chosen MCDA type are discussed. A Systematic Literature Review (SLR) is used to answer question 1a. The key concepts, and the inclusion and exclusion criteria are defined in the SLR as well, in order to have proper search results. Eventually, a conceptual matrix is made to summarize the findings of each article. It is important to use reliable information, thus search sources as Google Scholar, Web of Science, or the UT-library are used during this research. In addition, the Operations Research book from Winston (2003) contains examples about how to execute an MCDA. This will also help to understand the MCDA, rather than only describing the theoretical background behind it. The answer on this question can be found in Chapter 2.

2a. Which machine brands can be considered?
2b. What are the most important criteria to assess the performances of the machines?

In Chapter 3, we are going to look at the manufacturers that can be considered. During the first meetings with the decision makers, it was clear that they want premium brand machine. One of the things that is very important at Pan Oston is the quality of their products. Therefore, they want a premium brand machine that complies with high quality standards. This question can be classified as a descriptive question, because it describes the manufacturers and their machines that comply with the high quality standards of Pan Oston. Conversations with the decision makers are going to help to answer this question, in combination with searching for information on the internet.

In order to come up with a conclusion, the machines must be judged based on a set of criteria and sub-criteria. Interviews with the COO, Metal Department Manager, Manager Operations, and Process Specialist indicate which criteria are the most relevant to analyze. These criteria and sub-criteria are shortly described, in combination with how these criteria are going to measure the performance of the machines. Eventually, we discuss which criteria are left out of consideration. Since the research is bounded to a time limit, we can only select the most relevant criteria.

3. Which production data is important to analyze?

In Chapter 4, we look at the production data of Pan Oston. The production data plays an dominant role during the decision making process, since the score of some criteria depend on the production data. In addition, not every product that the company produces is equally important. A simple example illustrates this. If a machine is very good and very fast in producing a specific product, this seems to be a good option. However, if this company only produces this product once every month, then it is suddenly not such a good option. Therefore, the production data needs to be analyzed carefully. To find out which production data is important, we need to use the software of Pan Oston to get a clear visual about the production numbers, quantities, and times. Eventually, the products that take the longest amount of time out of the total dataset are picked to represent the activities at Pan Oston. Since it is not possible to analyze all the production data, the selected products need to say something about the reality. How these products represent the reality is discussed after the product selection.

4a. Which machine types are selected?
4b. What are the raw scores of these machine types?

Eventually in Chapter 5, we first discuss the boundary conditions where the machine types should comply with. This is important, since the more machines are analyzed, the more work needs to be done. In combination with the fact that the research is bounded to a time limit, we only select the most relevant machines for Pan Oston on beforehand. Thereafter, the raw scores of the relevant machines are discussed. This gives an overview on how each machine performs on each criterion. This question is a descriptive question as well. This question describes why certain machines drop off and why not. Interviews with account managers from each manufacturer are going to help to answer these questions.

5a. How does each panel bender perform on the chosen criteria?
5b. Which panel bender is the most preferred?

Before we can determine which panel bender is the most preferred, we first need to know how the panel benders perform on the chosen criteria. Because not every criterion is equal in importance, we have to give each criterion a weight. The higher this weight is, the higher the importance of the criterion. The decision makers can indicate how important they think a single criterion is, by performing pairwise comparisons. In Chapter 2, we elaborate further on these pairwise comparisons. After the weights are known, we consider the machine types from question 4 and analyze the data of these machines. This data is then used to create values for each criterion and sub-criterion. These values reflect the performances of the machines on the criterion or sub-criterion. For example, the better the machine is on a specific criterion, the higher the value for this criterion will be. After all the data of the machines on the criteria and sub-criteria are collected, and the values are determined, we use the weights in combination with the values to determine the ranking of the machines. The machines that perform better receive a higher ranking, and machines that perform worse receive a lower ranking. If we consider the ranking, the higher the machine is placed on the list, the more preferred that option is. From there on, conclusions can be drawn and recommendations can be given. These points can be found in Chapter 6 of this report.

1.5 Deliverables

This section will briefly discuss the intended deliverables of this research. In the first place, an advisory report will include all the important findings and conclusions. This report must be accurate but concise in order to maintain the understandability. One of the ways to do that is to give a schematic overview of each of the investigated machines and how they score on each of the weighted criteria. Second, the MCDA is shared to support the decisions and conclusions given in the advisory report. Calculations that form the return on investment might be difficult to understand in Word. Therefore, I will deliver an Excel file with corresponding explanation to clarify the calculations. Third, a list is shared with the production data that was used during the research to assess the performance of each of the investigated machines. This eventually sketches a view on how the answers in the research are obtained.

1.6 Limitations

In this section, the limitations of the research are discussed. There are a few limitations while conducting this research. In the first place, the company produces too much products to investigate all of them, especially within a time period of approximately 10 weeks. This means that the amount of detail is limited to some extent. Therefore, a decision must be made about which products to investigate and which not. The downside of this is that the outcomes will not be 100 percent accurate. For example, the number of products that can be made on a panel bender is in reality a bit higher or lower than the claimed number. A second limitation is that the results obtained in this research cannot be used in other organizations. The production data of Pan Oston cannot be compared to other companies. This means that the conclusions drawn for Pan Oston cannot be used across companies. Because the research must be conducted within a time period of approximately 10 weeks, it is not possible to implement and evaluate the eventual solution. Before the implementation can take place, the results must be evaluated by several company managers before a definite decision can be made. After this decision, it takes an additional number of weeks, maybe even months before the machine can be placed. Therefore, it is also not possible to evaluate the solution.

1.7 Assessment of validity and reliability

In this section the validity and the reliability of this research is discussed. Many forms of validity can be mentioned, however in this part the validities can be categorized to internal validity and external validity.

1.7.1 Internal validity

Internal validity can been seen as the validity of a research instrument to measure what it is purported to measure (Cooper & Schindler, 2014). In other words, does the instrument really measure what the researcher is claiming? Internal validity can be classified under 3 forms: content validity, criterion-related validity, and construct validity (Cooper & Schindler, 2014).

First, content validity is the extent to which the investigated research questions are adequately covered. This can be determined by judgments. Initially, the designer of the research may determine this carefully. Second, an independent panel of people may assess the essentiality of the test items for an instrument (Cooper & Schindler, 2014). In this research, the goal is to find out which machine fits the best within the organization. Together with department managers, decisions will be made about which machines and what criteria to investigate, otherwise the research will be too complex. This will cover not every aspect, but will cover the most important aspects and wishes of the company.

Second, criterion-related validity considers how successful the measures are for the predictions and estimations. In addition, this type of validity is closely related to the availability of data (Cooper & Schindler, 2014). In order to obtain a clear view about the capabilities of each machine, the manufacturers must be provided with relevant production data. The outcomes will reflect the reality in a good way, however it is possible that production data changes, which results in a distorted view of the reality. Since the time it takes to produce a certain product does not change much, this can be seen as a reliable criteria. However, this must be considered carefully.

Third and last, construct validity concerns the identification of causes and effects, settings, and participants that are present in the study (Reichardt, 2005). Illustrated by an example, if the researcher wants to know the degree of aggression by using a survey, the researcher must be sure that the behavior is related to aggression and not to dominance for example. In this research, the observations of the production data show in a precise way how long the machines are operating and how long the employees are busy with changing the tools. Thanks to this, the production times per unit are very accurate. This means that this is a reliable criterion.

1.7.2 External validity

External validity concerns the ability of the data to generalize to and across settings, times, or persons (Cooper & Schindler, 2014). As said in the Limitations section, conclusions drawn for Pan Oston cannot be used for other companies. The production process together with the production data is very specific and therefore cannot be used across other companies. On the other hand, it is possible that some of the data can be used by other companies. This is due to the fact that the product numbers correspond between manufacturers. In other words, if the same product is produced by company X, this has the same product number as when this product is produced by company Y. Therefore, calculations with single products can be used by other companies.

1.7.3 Reliability

When a measurement supplies consistent results, this is considered as reliable. Although reliability is a necessary component of validity, it is not a sufficient condition for validity. (Cooper & Schindler, 2014). In other words, it is possible to have reliability without validity, but it is necessary to have reliability for validity. If this research is redone at a certain point, it is important to consider the same production data with the same machines. Different production data with the same machines could give a very different view of the machines performances. However, if in the meantime the company attracts new customers and produces different products in different quantities, this may also affect the view on the production data. In order to redo the research in a reliable way, it is necessary to use the same production data, the same machines, and the same method.

2 Literature

In this chapter, we give an answer to the first research question discussed in Section 1.4.1. In section 2.1, a short introduction is given about which questions are answered in the remaining of the chapter. Thereafter in Section 2.2, different types of Multiple Criteria Decision Analyses are discussed. Eventually, from this information, a choice is made about which MCDA type to use in Section 2.3. Subsequently, in Section 2.4, the main steps of this chosen MCDA type are described.

2.1 Introduction

In order to be able to give an answer to the main research question, we have to think of a method that enables us to do this. As discussed in the previous chapter, a Multiple Criteria Decision Analysis (MCDA) is a decision-making technique that evaluates the different alternatives based on weighted criteria (Belton & Stewart, 2002). As known, Pan Oston wants to invest in a panel bender, and such an investment is not really an everyday decision. The choices made when selecting a new panel bender affect many people within the company, impacts are longer term, and mistakes are not easily remedied. Eventually, the panel bender must pay back itself in several years. To minimize this payback period, and the undesired consequences, the different possibilities must be considered carefully. There are many different MCDA types that can be considered, each with their corresponding advantages and disadvantages. From this, an MCDA type can be selected. In this chapter, an answer is given to the following questions: "*What types of Multiple Criteria Decision Analyses can be considered?", and "Which Multiple Criteria Decision Analysis is chosen?".* In addition, a Systematic Literature Review (SLR) is performed to answer the last question of this chapter: *"What are the main steps of the chosen MCDA type?".*

2.2 What types of Multiple Criteria Decision Analyses can be considered?

To be able to make a decision about which MCDA type is the best suitable for this research, we first set up a list with potential options. There are many different MCDA types, but the most relevant types are discussed next.

Multi-Attribute Value Theory (MAVT)

The Multi-Attribute Value Theory (MAVT) is a widely used MCDA type that explicitly takes prediction uncertainty into account. Besides, it has also the ability to handle many alternatives without a big increase in additional effort, and add new alternatives if these are found during any stage of the decision process. When using MAVT, the alternatives are ranked based on the preferences of the decision makers. An example of where MAVT is used is in water management (Schuwirth, Reichert, & Lienert, 2021).

Multi-Attribute Utility Theory (MAUT)

The Multi-Attribute Utility Theory (MAUT) is one of the most widely used MCDA types. MAUT is an extension of MAVT, that is described above. MAUT incorporates risk preferences and uncertainty into decision making. An example of when MAUT is used is during the evacuation decisions that managers need to make (Velasques & Hester, 2013). On the other hand, because of the difficulties that were experienced during the use of the MAUT model in practice, the SMART model was developed. The SMART model is discussed later in this section.

Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is in popularity similar to the MAVT technique. The major characteristic of the AHP is the use of pairwise comparisons, which are used both to compare all the alternatives against the criteria and sub-criteria, and to create an estimation of the weights for the criteria and sub-criteria. The AHP approach is among others used during performance assessment. In addition, during the AHP the researcher must perform a sensitivity analysis. This analysis reduces bias in decision making by analyzing what happens with the ranking of the alternatives if the weights of the criteria change (Velasques & Hester, 2013).

Data Envelopment Analysis (DEA)

DEA is another MCDA type that uses linear programming to measure the relative efficiencies of alternatives. It is a useful technique, since it is possible to handle multiple inputs and outputs, and to analyze and quantify efficiency. However, the technique does not take imprecise data into account and it assumes that all the data is exactly known. DEA is often used in the field of economics, utilities, medical, agriculture, and retail.

ELECTRE

ELECTRE is another MCDA type, but it takes uncertainty and vagueness explicitly into account. An disadvantage is that the process itself and the outcomes received are sometimes hard to explain to decision makers. In addition, under certain criteria the lowest performance are not displayed. Often in the fields of energy, environment, and transportation problems, ELECTRE is used.

Simple Multi-Attribute Rating Technique (SMART)

The last MCDA type that is considered is the Simple Multi-Attribute Rating Technique (SMART). As said, SMART arose from the MAUT technique, and it converts importance weights into actual numbers. One of the major advantages of SMART is that it is relatively simple to use. If we compare SMART against MAUT, SMART requires much less effort by decision makers than that is required by MAUT. SMART is often used in construction, military, and in transportation and logistics (Velasques & Hester, 2013). In addition, SMART makes use of direct rating, which has as major advantage that it does not require many pairwise comparisons as is the case with the AHP approach. To illustrate the direct rating technique, we use a simple example. Consider a student who needs to pass the last exam in order to move on to the next year. The exam is marked as pass when the student receives grade 5.5 or higher. An increase from 5.0 to 6.0 has much more value than from 6.0 to 7.0. This is because in the first case the student moves to the next year for example, and in the second case it does not make a change. When considering the direct rating technique, grade 5.0 would receive value 0, while grade 7.0 would receive value 100. The student desperately wants to move to the next year, therefore, grade 6.0 would receive value 70 or even 80. Regardless of the fact that grade 6.0 lies exactly in the middle between grades 5.0 and grade 7.0, the given value does not have to be in the absolute middle of the lowest and the highest values.

2.3 Which Multiple Criteria Decision Analysis is chosen?

As described in Section 2.2, there are many different Multiple Criteria Decision Analyses. During this research, performances of machines on chosen criteria are compared and analyzed to come up with the most preferred solution. The Analytic Hierarchy Process (AHP) is used to solve large problems, for example, when dealing with problems that compare performance between alternatives (Sumaryanti et al., 2019). Besides, it does not matter whether a company wants to invest in a new machine, or is looking for a new employee, the AHP can be used in both situations. However, if the company wants to select a new machine, obviously the decision makers look at different aspects than when they are selecting a new employee. These aspects are called criteria, and are very case specific. In Chapter 3, the criteria and sub-criteria for this research are discussed.

In addition, the AHP is a method that is relatively simple to understand. Especially within a growing company, the decision makers do not have the time to learn complicated methods. Thus, this gives a plus to the AHP approach. Besides, the AHP has the ability to mix quantitative and qualitative criteria in the same decision framework (Ramanathan, 2004). Last, a cornerstone of the AHP approach is the sensitivity analysis that is performed as a last check. This is done to increase the confidence in the selected alternative.

However, a downside of the AHP is the large number of pairwise comparisons to make. This is related to the number of criteria, the number of sub-criteria, and the number of alternatives that are considered. If one of these three factors increases, the number of pairwise comparisons to make increases as well. Thus, if the number of alternatives increases, it becomes less attractive to use the AHP approach to determine the values for these alternatives. In addition, the decision makers at Pan Oston do not have all the time to make a very large number of pairwise comparisons. In combination with the fact that many pairwise comparisons becomes a tedious job after some time, a different MCDA type can be used if the number of alternatives is too high.

One of the MCDA types that is much easier to use when dealing with a large number of alternatives, is the Simple Multi-Attribute Rating Technique (SMART). When using SMART, the performances of the alternatives are directly rated, which means that the high number of pairwise comparisons is avoided. In addition, the direct rating technique can be set up by the researcher, but also by the decision makers. If the direct rating technique is set up by the researcher, it is important that the decision makers agree with the decisions.

2.4 Axioms of the Analytic Hierarchy Process

Before we start with the main steps of the AHP, it is important to first mention the main principles of the AHP. According to the literature, the AHP approach is based on a set of assumptions. Researchers often call these assumptions “axioms”. The first axiom is about the paired comparisons. During these paired comparisons, we need to take into account both members of the pair to judge the relative value. If one criterion is judged to be five times heavier than another criterion, then the other criterion is automatically 1/5 as heavy as the first criterion, because it participated in making the first judgement. “The comparison matrices that we consider are formed by making paired reciprocal comparisons. It is this simple, but powerful means of resolving multicriteria problems that is the basis of the AHP” (Saaty, 1986).

The second axiom says: “Homogeneity is essential for comparing similar things, as the mind tends to make large errors in comparing widely disparate elements. For example we cannot compare a grain of sand with an orange according to size”. In other words, if we compare two criteria against each other, the one could not be 15 times more important than the other, because we take the fundamental scale of absolute numbers, ranging from 1 to 9, into account (Saaty, 1986).

The third axiom, also known as the *synthesis axiom* states that: "judgments about the priorities of the elements in a hierarchy do not depend on lower level elements. This axiom is required for the principle of hierarchic composition to apply and apparently means that the importance of higher level objectives should not depend on the priorities or weights of any lower level factors" (Singh & Nachtnebel, 2016).

Last, axiom 4 simply says: "those thoughtful individuals who have reasons for their beliefs should make sure that their ideas are adequately represented for the outcome to match these expectations; i.e., all alternatives are represented in the hierarchy, as well as all the criteria. It neither assumes rationality of the process nor that it can only accommodate a rational outlook. People have many expectations that are irrational". In other words, if the decision maker's intuition differs from the outcome of the AHP, the process should be reviewed to look if there are missing criteria or alternatives. On the other hand, if the process is being reviewed, this can also concludes that the intuition of the decision maker is wrong (Saaty, 1986).

2.5 The main steps of the Analytic Hierarchy Process

As discussed in the previous section, the AHP method is one of the methods that is used to systematically guide us towards answering the main research question. It is therefore important to understand what the main steps are in executing the AHP method. This section first describes the main five steps when executing the AHP, whereafter we discuss how each step should be executed.

The following five steps are part of the AHP:

1. Arrange a hierarchy that contains the alternatives and criteria.
2. Perform pairwise comparisons with criteria and alternatives, and set up the pairwise comparison matrix.
3. Calculate the local weights for each criterion and use that to determine the Consistency Index and the Consistency Ratio.
4. Use the local weights for each criterion to calculate the values for the alternatives.
5. Execute the sensitivity analysis

Step 1 – Arrange a hierarchy that contains the alternatives and criteria

In the first step, we set up the hierarchy to structure the problem. This hierarchy is often called a decision tree, and contains the alternatives and the criteria for evaluating the alternatives. At the top level, the focus or the overall goal is placed. In this research, the goal is to find the best suitable panel bender. Next, the criteria and the sub-criteria are placed at the middle level. It is possible that the sub-criteria have an additional layer of sub-criteria. This additional layer is placed at the middle level as well, while the alternatives are placed at the lowest level (Barfod & Leleur, 2014). **Figure 3** gives an schematic overview of these different levels. Furthermore, the criteria and the sub-criteria should be understandable, measurable, and non-redundant. A criterion is understandable if the decision makers have a shared understanding of the concepts to be used in the analysis. Next to that, the criteria must be measurable, which means that it must be possible to give a score to an alternative on these criteria in a consistent manner. For example, if we consider costs and speed, which could be two types of criteria, costs are measured in Euros or Dollars, while speed is measured in products per hour. Not only the scale type differs, but also the size of the scale. This means that the criteria must be measurable in order to properly use them in the AHP approach. Last, the criteria must be non-redundant, which means that more than one criterion cannot measure the same factor (Belton & Stewart, 2002).

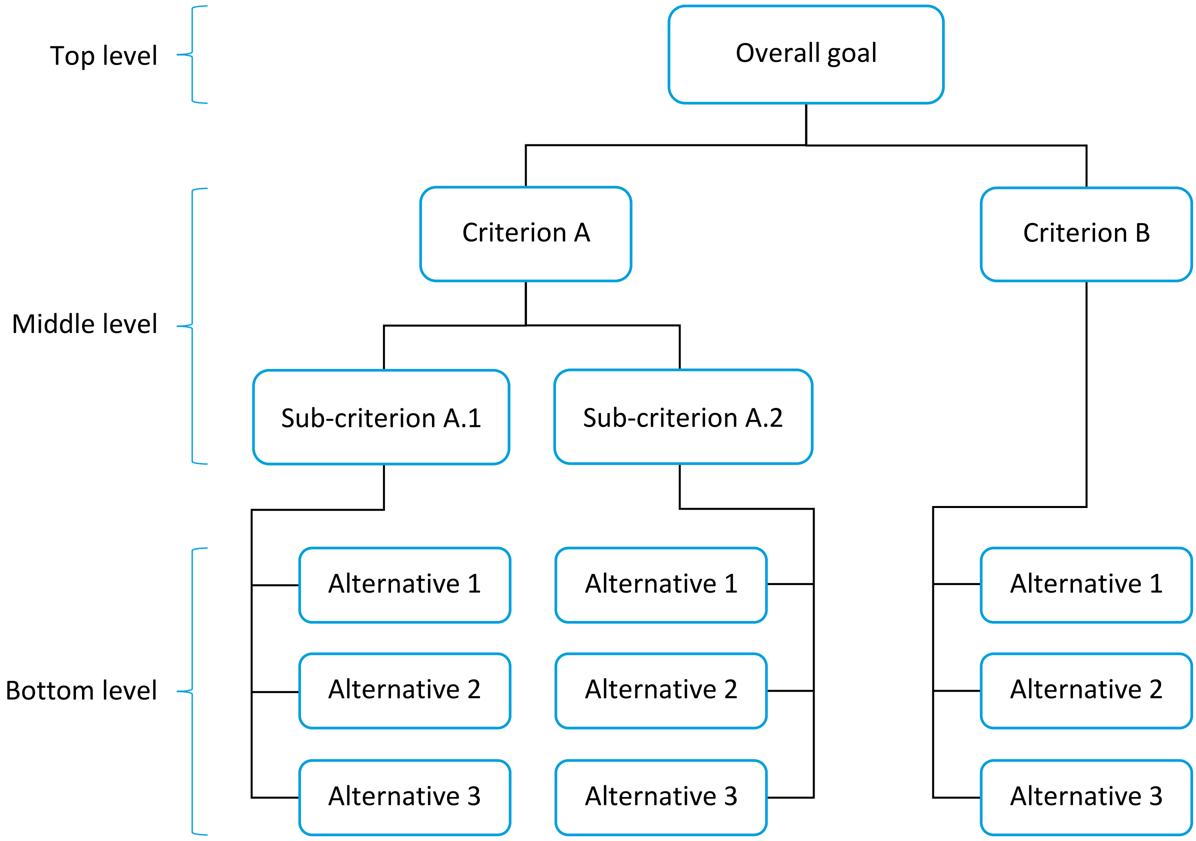

Figure 3: *A schematic overview of the decision hierarchy*

Step 2 – Perform pairwise comparisons with criteria and alternatives, and set up the pairwise comparison matrix

In the second step, we make pairwise comparisons with criteria and alternatives, and that is used to set up the pairwise comparison matrix. The pairwise comparisons are part of the AHP approach, and allows decision makers to provide verbal descriptions of their view of the importance of criteria, in terms of "moderately", "strongly" or "absolutely" more important. These are in turn converted into assumed ratios (Belton & Stewart, 2002). These verbal descriptions have a numerical value, presented in **Figure 4.** For the understandability of this method, a simple example is given. Assume that you want to buy a car, and you can choose between air-conditioning and navigation. Since you have to drive a lot to unknown customers, navigation is preferred. In this case, the decision maker indicates that navigation is strongly more important than air-conditioning. This verbal description is transformed into the corresponding numerical value from **Figure 4**. In this example, value 5 would be given.

Intensity of Importance	*Definition*	*Explanation*
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above non-zero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A reasonable assumption
1.1–1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

Figure 4: *The fundamental scale of absolute numbers (Saaty, 2008).*

Eventually, these numerical values are used to fill up the pairwise comparison matrix that is later used to determine the relative priorities of the alternatives. This pairwise comparison matrix is discussed next.

The pairwise comparison matrices are set up for every level of criteria and sub-criteria. In Chapter 6, an elaboration is given about which criteria belong to which level, and which criteria form a combined matrix. Since there are four decision makers at Pan Oston, all the pairwise comparisons are done per decision maker individually. As discussed, the AHP uses pairwise comparisons to determine the values for the alternatives as well. If the number of alternatives is high, it is also possible to use another method that is much easier in determining the values for the alternatives. However, if the AHP is used, there are also pairwise comparisons to make between all the alternatives on the criteria. Only the criteria that are an endpoint, and sub-criteria that are an endpoint are used with these comparisons. A criteria is an endpoint when there is no additional level with sub-criteria under that criterion.

The pairwise comparison matrices indicate how much more important the row criterion is compared to the column criterion. For example, if row 1 contains criterion A, and column 2 contains criterion B, and criterion A is strongly more important than B, this matrix position a_{12} receives value 5. This in turn, means that the reciprocal is automatically placed in the transpose position. In this example, this would mean that position a_{21} receives value 1/5. The pairwise comparisons are used because pairwise comparisons are much easier to make than a comparison of all the criteria simultaneously. However, the pairwise comparison method has as drawback the large number of comparisons to make. The hierarchy consists of several levels, each of which needs a comparison matrix. The decision maker should make *J* judgements for each criterion, where *J* is:

$$J = \frac{n * (n-1)}{2} \tag{1}$$

where:

n is the number of criteria

Nevertheless, using pairwise comparisons is a powerful approach when decision makers find it difficult to rate the alternatives directly (Barfod & Leleur, 2014). The pairwise comparison matrix is set up based on the components described above. **Table 1** presents an example of a pairwise comparison matrix. This example uses 4 criteria, but it is possible to use more or less criteria, with as minimum 2 criteria. Criteria that are compared against itself always receive value 1. In this example, the decision maker indicates that criterion A is strongly more important than criterion C. The matrix position a_{13} receives value 5, while position a_{31} receives value 1/5. It is also possible that the decision maker indicates that criterion C is strongly more important than criterion A. In this case, a_{13} would receive 1/5 and a_{31} would receive 5. In this way, the entire matrix is set up.

	Criterion A	Criterion B	Criterion C	Criterion D
Criterion A	1	3	5	7
Criterion B	1/3	1	3	5
Criterion C	1/5	1/3	1	3
Criterion D	1/7	1/5	1/3	1

Table 1: *An example of a pairwise comparison matrix*

Step 3 – Calculate the local weights for each criterion and use that to determine the Consistency Index and the Consistency Ratio

In the third step, the local weights for each criterion are determined to be able to calculate the Consistency Index (CI) and the Consistency Ratio (CR). It is important to reflect the wishes and needs of the different decision makers into these local weights. The comparison matrix from step 2 is used and normalized into a matrix in which the columns sum to 1. Eventually, after adding up the row values and dividing this by the number of criteria, an approximation can be made about the weight that should be given to the specific criterion. Thereafter, the CI and the CR are set up, which are used to check the consistency of the decision maker's comparisons (Winston, 2003). The pairwise comparison matrices and the local weights are used to compute λ_{max}, which is the maximum eigenvalue of the comparison matrix (Singh & Nachtnebel, 2016). Eventually, this λ_{max} is used to compute the CI, which in turn is used to compute the CR. According to Winston (2003), the CR should be smaller than .1 in order to have meaningful results from the AHP. By using the CI and the CR, we can check whether we are sufficiently consistent or not, and thereby reducing bias in decision making (Prieto-Amparán, et al., 2021). An elaboration about how to set up the CI and CR can be found in the appendix.

Step 4 – Use the local weights for each criterion to calculate the values for the alternatives

In the fourth step, the local weights for each criterion and sub-criterion are used to calculate the values for the alternatives. These local weights are determined by the decisions of the decision makers on the pairwise comparisons. As discussed, there are several levels of criteria and sub-criteria that are used to assess the performance of the alternative. Criteria and sub-criteria that are dependent on each other, have a combined weight on the alternative. For example, if criterion A has weight .3 and under criterion A there is a sub-criterion A.1 with weight .5, this sub-criterion has weight .3 times .5 equals .15. This means that the performance on sub-criterion A.1 has .15 influence on the total performance of the alternative. Thereafter, to determine the overall value of the alternatives, the additive model is used. According to Belton & Stewart (2002), the additive model is the most simplest and widely used form to obtain the values for the alternatives. The formula is shown below:

$$V(a) = \sum_{i=1}^{m} w_i v_i(a) \qquad (2)$$

Where:

$V(a)$ is the overall value of alternative *a.*

$v_i(a)$ is the normalized score that reflects the performance of alternative a on criterion i.

w_i is the local weight that reflects the importance of criterion i.

From this, every alternative receives a value and from this value the decision maker can easily conclude that the alternative that scores higher is more preferred, compared to an alternative that scores lower.

Step 5 – Execute the sensitivity analysis

In the final step, the sensitivity analysis is executed. As discussed in the previous section, the final priorities of the alternatives are based on the weights given to the criteria. It could be possible that small changes in these weights cause major changes in the final raking of the alternatives (Chang, Wu, Lin, & Chen, 2007). In general, there are a few reasons why the sensitivity analysis is performed. First, if there are multiple decision makers involved in the process, these decision makers could have different opinions about the relative importance of the criteria. It is therefore useful to gather information from the decision makers individually. In this way, the decision makers that usually have less power in the decision making process, can share their full opinion about the current situation. Second, the weights for the criteria are based on subjective judgements. If the ranking of the alternatives is highly sensitive to small changes in the weights of the criteria, these weights must be reviewed carefully by a sensitivity analysis. Third, because of the sensitivity analysis, the decision makers does not have to be perfectly consistent in the comparisons between the criteria. Especially when the number of criteria increases, it becomes harder to be perfectly consistent. Eventually, when the decision makers select the most preferred alternatives, the sensitivity analysis could address further questions on a selected set of alternatives (Erkut & Tarimcilar, 1991). Examples of these questions are:

1. “What is the smallest change in the weights that will result in a change of the selected alternative?”
2. “What is the smallest change in the weights such that a specific alternative has the highest ranking?”
3. “If there are multiple decision makers, each with different weights, how many decision makers are actually selecting the same alternative?”

According to Erkut & Tarimcilar (1991), finding answers on these questions increases the confidence in the selected alternative. A downside of the sensitivity analysis is that a lot of weights have to be changed in a systematic way before the different final rankings can be calculated. This could turn into a very tedious exercise.

2.6 Conclusion

This chapter provides a theoretical background behind the method that is used during this research. The general method is the Multiple Criteria Decision Analysis, but this is an umbrella term to describe more specific methods. A few of these methods are the MAVT, MAUT, AHP, DEA, ELECTRE, and SMART. The main type that is used in this research is the AHP approach, since this MCDA type is among others used during performance assessment. In addition, a cornerstone of the AHP is that a sensitivity analysis is performed, with as goal to reduce bias in decision making. However, a downside of the AHP approach could be the large number of pairwise comparisons to make. This is directly related to the number of criteria and sub-criteria, and the number of alternatives. If the number of alternatives is high, another MCDA type can be used to determine the values for the alternatives. For example, SMART is an MCDA type that uses the direct rating technique to determine these values for the alternatives. When using the direct rating technique, the lowest outcome receives value 0, and the highest outcome receives value 100. The outcomes that are in between the lowest outcome and the highest outcome receive a value between 0 and 100. These values are determined by the decision makers. The AHP approach is used to determine the weights of the criteria and sub-criteria. To successfully use the AHP approach, the 5 main steps are described. In short, the five main steps are (1) arranging a hierarchy for the alternatives and the criteria, (2) determining the priorities and set up the pairwise comparison matrix, (3) calculating the local weights for each criterion and use that to determine the consistency index and ratio, (4) using the weights to calculate the values for the alternatives, and eventually (5) executing the sensitivity analysis.

3 The alternatives and the relevant criteria

In this chapter, the alternatives and the relevant criteria and sub-criteria are discussed. First, in Section 3.1, the different machine manufacturers that are considered are discussed, in combination with the relevant machine types. In Section 3.2, the criteria and sub-criteria are discussed that are used to assess the performance of the different machine types. Thereafter in Section 3.3, the criteria that are left out of consideration are discussed. Last, in Section 3.4 a conclusion is given in combination with an overview about everything that is discussed in this chapter.

3.1 The manufacturers that are considered

The market consists of many different companies that produce tools that can be used during sheet metal working. If we take a look at complete machines that are able to bend metal plates, the set of companies that are able to deliver this already shrinks. If we eventually look at machines that are able to bend metal plates automatically, the list of possible manufacturers shrinks even further. Machines that are able to bend the metal plates automatically are called panel benders. A difference can be made between a fully automatic panel bender, and a semi-automatic panel bender. An automatic panel bender does not need the interference of an operator for producing a product, while a semi-automatic panel bender does need an operator to complete the product. Besides, the automatic panel bender comes roughly in two variants. The first variant is with automatic loading and unloading, and the second one is with manual loading and unloading. In this section, the machines that comply with the high quality standards set by the company are discussed. All the information about these panel benders are obtained via websites on the internet and/or interviews with account managers of the companies. All the account managers gave permission to use the information that was obtained during the interviews.

Due to the high quality standards that are set by Pan Oston, there are only a few possible machine manufacturers that can be considered. However, each of these manufacturers have different types of machines to fulfill the wishes and needs of different types of customers. In the following sections, the manufacturers are shortly discussed and the different machine types are discussed to give an overview about the characteristics. The brands that are considered by the company are:

1. Salvagnini
2. Trumpf
3. RAS
4. Prima Power

3.1.1 Salvagnini

Salvagnini is a private company that provides flexible automatic solutions for turning sheet metal for more than 50 years. The headquarters of Salvagnini is located in Sarego, Vicenza Italy. The company is specialized in punching machines, fiber laser cutting machines, panel benders, and press brakes. Salvagnini has direct customer service in approximately 35 countries, including 1750 employees. In 2021, they had approximately 400 Million Euros in revenues. Last, they have 7000 machine installations worldwide, of which 3600 panel benders. The majority of the installations of Salvagnini are panel benders, which means that they have a lot of experience with this (Salvagnini: Who we are, 2022). An account manager was invited by Pan Oston to discuss questions and characteristics about the panel benders that Salvagnini offers. The machines of Salvagnini that are the most relevant to analyze are:

1. Salvagnini P4L-3220
2. Salvagnini P4L-3125
3. Salvagnini P4L-2120
4. Salvagnini P4L-2225
5. Salvagnini P2L-2120
6. Salvagnini P2L-2225

3.1.2 Trumpf

The second manufacturer that is considered is Trumpf. Pan Oston has already good connections with Trumpf since they have installed several Trumpf machines in the past. Therefore, Trumpf is the second manufacturer that is considered. Trumpf was founded in 1923 near Stuttgart, Germany. The group is currently represented in nearly every European country, in North and South America and in Asia. Trumpf produces machines for bending, punching, laser cutting, and laser welding applications. In addition, they also deliver automation solutions and software for networked manufacturing solutions (Nickel & Mauden, 2021). Trumpf is bigger than Salvagnini if we look at the revenues in 2021. Trumpf has namely 3.5 Billion Euros of revenues. In addition, they have direct customer service in 63 countries, including 15.000 employees worldwide. Again, an account manager from Trumpf was invited by Pan Oston to discuss some questions and characteristics about the possible new panel bender. There are three different types of panel benders that Trumpf offers that all can be considered:

1. Trumpf TruBend Center 7030
2. Trumpf TruBend Center 7020
3. Trumpf TruBend Center 5030

3.1.3 RAS

The third manufacturer is RAS, also known as RAS-Systems. Founded in 1939, RAS started as a mechanical workshop. The headquarters of RAS is located in Sindelfingen, a city near Stuttgart Germany. In 1991, RAS developed the first fully automated panel bender. Pan Oston decided to consider the RAS panel bender as well, since RAS is specialized in metal cutting and forming machines. RAS has 45 Million Euros of revenues in 2021 and has 275 employees worldwide. In addition, they serve in 46 countries and have a total of 270 running panel benders. Just as the previous manufacturers, an account manager from RAS was invited by Pan Oston to discuss the questions and characteristics. The following machines can be considered:

1. RAS Multibend-Center 79.22-2 (ECO)
2. RAS Multibend-Center 79.26-2 (ECO)
3. RAS Multibend-Center 79.31-2 (ECO)

The three types of machines can be configurated as a normal version and an ECO-version. The main difference between the normal version and the ECO version is that the ECO version consists of a cheaper outside finish of the machine, while the normal version has a more premium and high quality outside finish. In addition, the ECO version cannot be connected to automatization processes, while the normal version is able to do this. The raw performances between the ECO version and the normal version is equal. For example, it does not matter if product A is produced by the normal version of the ECO version, the quality and the speed are the same.

3.1.4 Prima Power

The fourth and last manufacturer is Prima Power. Prima Power is an another Italian company that is founded in 1969 with its headquarters located in Turin. They are specialized in producing machines and systems for sheet metal working. They produce machines for laser processing, bending, punching, and automation. Prima Power has 1500 worldwide employees and has a comparable revenue with Salvagnini, namely 381 Million Euros in 2021. Besides, Prima Power delivers direct customer service in 47 countries. Again, an account manager was invited to talk about the different types and specifications. This resulted in the following machines:

1. Prima Power EBe Express Bender 2720
2. Prima Power EBe Express Bender 2220
3. Prima Power FBe Fast Bend 2220

The research must be conducted in a time period of approximately 10 weeks, which means that the number of manufacturers to consider must be kept at a limit. As discussed in Chapter 0, adding more manufacturers and thus more alternatives, results in additional pairwise comparisons to make. In combination with the fact that these 4 manufacturers produce different types of machines, we do not consider more than 4 manufacturers. After Pan Oston visited some fairs, they selected three manufacturers of which they think that these are appropriate. The last manufacturer, Prima Power, was found by searching through the internet. The headquarters of all these manufacturers are located in Europe, which was one of the requirements the manufacturers should comply with.

3.2 The criteria and the sub-criteria

Before we can determine which panel bender is the most preferred, we have to choose criteria and sub-criteria that help are used to assess the performances of the machines. To fulfill the wishes and needs of the decision makers at Pan Oston, it is important to listen to their concerns. Conversations with the COO, Process Specialist, Metal Department Manager, and the Manager Operations helped to identify the most important criteria. This section discusses these criteria, including the sub-criteria that are used to score the different panel benders.

Criterion 1 – Costs

The first criterion where we look at is costs. The manufacturers come with an advice about which configuration is the best suitable for Pan Oston. This configuration consists of the standard machine in combination with additional options. The manufacturers offer a total price for this configuration, including installation costs and transportation costs. On the other hand, employee costs are not taken into account. Several videos of panel benders have shown that there is enough time for a single operator to keep the panel bender running. This means that the operator has enough time to load and unload the machine by himself. In addition, all the account managers from the different brands have confirmed that the panel bender is indeed operatable by a single employee. Since the employee costs are the same regardless of which machine is chosen, the employee costs are left out of consideration. Costs is certainly not an unimportant criterion, because the company has many more activities that requires a sufficient liquidity. Decision makers have to take this into account, in combination with the expected growth in the upcoming years to estimate how big the investment at the highest may be. All the manufacturers are located in Europe, which means that the costs of the machines are in Euros. Thus, the criterion costs is measured on a numerical scale, where lower costs receive a higher score, and higher costs receive a lower score.

Criterion 2 – Speed

The second criterion is speed. The goal of Pan Oston is to decrease the set up time per product, and thereby increasing the efficiency at the metal department. To achieve this, the panel bender should be at least faster than the current process, otherwise the goal of Pan Oston cannot be achieved. Since every panel bender has different characteristics, the speed of the one panel bender cannot be used for the other panel bender. In order to be able to assess the speed by which the panel benders are producing their products, the manufacturers perform tests from a selected set of products of Pan Oston. In the next chapter, we further elaborate on which products are chosen and why. Eventually, after we have selected the most relevant machines, the speed of the different machine types can be compared to the current process. This gives an indication about how fast the different panel benders are. In order to create a clear view about how fast the panel benders are, we use a percentage out of the current production process to indicate the speed. For example, if the current production time of product A is 100 seconds, and the panel bender produces product A in 40 seconds, the speed is indicated by 40%. The average speed of all the products is taken to find the speed of each panel bender. This is measured on a numerical scale. On this numerical scale, a highest outcome receives value 0, while the lowest outcome receives value 100. This is due to the fact that a higher outcome indicates that the panel bender is slower than compared to a lower outcome.

Criterion 3 – Flexibility

The third criterion that is considered is flexibility. The production facility of Pan Oston in Raalte produces a lot of small series, tests, and demos. This means that they do not produce many of the same types of product, but many different and diversified types of products. In order to have a sufficient supply of products for the panel bender, the panel bender must have the ability to produce products with a wide range of different bending characteristics. Currently, Pan Oston is in a transition phase in which the traditional checkouts for supermarkets are produced less, and checkouts for kiosks are produced in higher quantities. Checkout systems for kiosks are much smaller and have more compact parts. If we then look at the future, it might be important to select a panel bender that is able to produce these smaller parts in order to have a sufficient supply of products. If the panel bender does not have this sufficient supply, the return on investment will be too high and unacceptable. Therefore, the panel bender must have a sufficient flexibility. Because flexibility is a wide term, we divide flexibility into two smaller components, called sub-criteria. These two sub-criteria are also used to measure the criterion flexibility.

Sub-criterion 3.1 – Feasibility

Sub-criterion 1 under flexibility is feasibility. What is meant by feasibility is the number of different products that can be made at the panel bender. As discussed, to determine the feasibility of each machine type, we have to send a set of products to the manufacturers. These products are not only tested on speed, but also on feasibility. The set of products that we send to the manufacturers must have a wide variety of dimensions and bending characteristics. In this way, we can estimate how many products can be made out of the total set of products. This criterion is measured on a numerical scale, on which a low value indicates that very few products can be made, while a high value indicates that a lot of product can be made on the panel bender.

Sub-criterion 3.2 – Sheet dimensions

The second sub-criterion is related to the dimensions of the metal sheets. Every panel bender has its own minimum and maximum values that can be produced. Since Pan Oston uses metal sheets that are not bigger than 3000 millimeters long, it does not make sense to purchase a machine that is able to bend 4000 millimeters long, while it is also possible to choose a machine that is able to bend 3000 millimeters in length. On the other hand, if for example only 1% of all the products are above 2000 millimeters, it could be convenient to think of a smaller machine. Because Pan Oston is in a transition from traditional checkouts in supermarkets to much smaller checkouts in supermarkets, decision makers have to think of elements that the panel bender should have. If we compare the sub-criterion dimensions against the sub-criterion feasibility, dimensions is much more focused on the ability to produce products with design changes in the future, while feasibility is more focused on the current production set. There are many different dimensions where we can think of, but not all these dimensions have to be taken into account. The dimensions that we take into account are *maximum plate thickness, maximum bending length, maximum bending height, and minimum box size*. The specific sheet dimensions that are not taken into account are discussed later, in Section 3.3.

Sub-criterion 3.2.1 – Maximum plate thickness

The first sub-criterion under sheet dimensions is the maximum plate thickness that the panel bender can handle. Because Pan Oston uses not the same plate thickness across all the different products, it is important to consider this criterion as well. For example, if Pan Oston produces only uses a plate thickness of 3 millimeters and higher, it does not makes sense to choose a machine that is only able to bend 2 millimeters in thickness. To measure this sub-criterion, a numerical scale is used. Because machines that are able to bend a higher thickness have more abilities in bending, a higher maximum plate thickness receives a higher score, while a lower maximum plate thickness receives a lower score.

Sub-criterion 3.2.2 – Maximum bending length

The second sub-criterion under sheet dimensions has to do with the maximum length that the panel bender is able to bend. The maximum bending length is not the same as the maximum sheet length, which means that the metal sheets could be a bit longer than the maximum bending length. Also, since their products shift from big checkouts in supermarkets to more compact checkouts in kiosks, it might not be necessary to invest in a big machine that is able to bend 3000 millimeters. This criterion is measured on a numerical scale. Higher maximum bending lengths receive higher scores, while machines that have a lower maximum bending length receive a lower score.

Sub-criterion 3.2.3 – Maximum bending height

Sub-criterion three is related to the maximum bending height that can be produced by a panel bender. This is not unimportant to consider, because there are many different products with different heights. Analyzing the production data must show how many products have higher height, and how many products have a lower height. Decision makers have to decide if it is necessary to have a panel bender that has the ability to bend higher products, while only smaller products are made for checkouts at kiosks. This sub-criterion is measured on a numerical scale, where higher maximum bending heights receive higher scores, and lower maximum bending heights receive lower scores.

Sub-criterion 3.2.4 – Minimum box size

The fourth and last sub-criterion under sheet dimensions is the minimum box size. The minimum box size is related to the minimum dimensions that the product should have in bent condition. The smaller this value is, the more products that can be made by the panel bender. An example of a small product that Pan Oston produces is a box where the electronic system of the checkout is installed. The smaller the minimum box size of the panel bender, the more of these boxes and other small parts can de produced. The more parts that can be produced by the panel bender, the higher the efficiency will be. The minimum box size is measured on a numerical scale. Bigger box sizes receive lower scores, while smaller box sizes receive higher scores.

Criterion 4 – Layout

The fourth criterion is the layout of the panel bender. To create enough space to place the new panel bender, at least two traditional benders have to be removed or placed elsewhere. There are two out of four traditional bending machines placed at the left side, and the other two are placed at the right side of the metal department. This means that at least the two machines at the left side or at the right side need to make way for the new panel bender. Dependent on the layout and the size of the panel bender, the machine is placed at the left hand side or at the right hand side of the metal department. If the panel bender is relatively compact, it is possible to turn the machine a quarter to the right or a quarter to the left to remain a good flow of the products. It is not efficient for the process if an employee has to walk past the machine, load the products, and then walk back to unload the products. This results in additional operations by the employees, which reduces the efficiency. If we look at the different layouts the panel benders could have, there are 4 main possibilities. These possibilities are presented in **Table 2.**

Loading	Unloading
Right	Right
Right	Left
Left	Right
Left	Left

Table 2: *The different design possibilities for a panel bender*

The 4 possibilities can be divided into two additional categories, namely flow and no flow. The second and third possibility from **Table 2** indicate the flow, and the first and fourth possibility indicate no flow. For every possibility, the panel bender is operatable by a single employee. Thus, this does not affect the flow of the products in a negative way. The layout is measured by yes or no, where yes means that the machine is compact enough to turn to the desired position, and no means that the machine is too big to turn. If the machine can be turned, the maximum score is given, while machines that cannot be turned receive a lower score. If the machine cannot be turned, and does not have a flow of products, this receives the lowest score.

Criterion 5 – Quality

The fifth and last criterion where we look at is the quality of the delivered products. All the manufacturers have shown that the surface finish of the products are sufficient. That is why we do not look at the surface finish, but at the First Time Right (FTR) quality of the products. Since the production facility of Pan Oston in Raalte is mainly focused on demos and tests, its production series are very small. Besides, Pan Oston has different metal sheet suppliers, which means that the sheet characteristics between these manufacturers differ a bit. It is therefore that it is necessary to have a machine that produces products for the first time right. Some manufacturers have this automatic angle measurement system integrated in their machine types. If the panel bender does not have this angle measurement system, the operator at the machine must check every first product for every series of products. This additional handling by the operator affects the production time of the products in a negative way. Checking the angle by the operator is only necessary for the first product, because if the first product is right, the subsequent products will be right as well. If the first product is not right, the machine must be adjusted which takes an additional amount of time. Since Pan Oston produces small series in Raalte, this could have a negative effect on the production time. If the production series would have been big, checking only the first product would have much less influence on the production time per product. This criterion is measured with yes or no, where yes means that the machine has an automatic angle measurement system, and no means that the machine does not have an automatic angle measurement system.

3.3 Criteria that are left out of consideration

Since the research is bounded to a time limit, we need to make choices about what things to include in the research and what not. This is also important in the process of selecting relevant criteria. As discussed in Section 2.5, the number of pairwise comparisons that is needed does not only depend on the number of alternatives, but also on the number of criteria. Therefore, some criteria are left out of consideration in the AHP approach to remain the feasibility of the research. The purpose of this section is to show that there is thought of all the criteria that relate to the characteristics of a panel bender. Furthermore, a short motivation is added about why these criteria are left out of consideration.

Criterion 1' – Safety

The first criterion that is not taken into account in the AHP approach is safety. In the first place, this seems to be an important criterion to consider. Although a panel bender is a machine that is able to bend metal plates automatically, it still needs some human interference in order to be able to work properly. All the manufacturers that are considered are located in Europe, which means that they have to comply with rules and laws of the European Union. According to the Machinery Directive 2006/42/EC, the machinery sector is an important part of the engineering industry and inherently safe design and construction of the machinery can reduce the number of accidents caused by the use of this machinery (European Union, 2006). After the implementation of the Machinery Directive 2006/42/EC in 2009, machine manufacturers must completely comply with the standards mentioned in this directive in order to be able to sell machinery within the European Union. Because the manufacturers must take into account the indicated safety requirements, we can assume that all the manufacturers produce machines that are sufficiently safe. Therefore, the criterion safety is not taken into account during the AHP (European Union, 2006).

Criterion 2' – Maximum width of incoming sheet

If we look at the maximum width of the incoming sheet, this might looks like a criterion that is important to consider. However, after analyzing the characteristics of the different machines, almost all the machines had the same values for this criterion. The maximum width of the incoming metal sheet is 1500 millimeters for all the machines, except for the two Salvagnini types. The maximum width of the incoming sheet for the two Salvagnini machines is 1524 millimeters. The largest plate dimensions that Pan Oston uses has a width of 1500 millimeters. Because all the different machine types are able to handle a plate that is 1500 millimeters wide, the maximum width of incoming sheet is not taken into account.

Criterion 3' – Minimum bending height

The third criterion that is not taken into account, is the minimum bending height. Just as criterion 2', all the different machines that are considered have a minimum bending height that is equal to 5 times the plate thickness. In addition, an experienced employee that uses the traditional bending machine daily was asked about the minimum bending height of the current machines. He replied that the minimum bending height for plates with thickness 1.0 millimeters is approximately 5 millimeters, and for 2 millimeters it becomes 16 millimeters. From this we can conclude that there are no products made at Pan Oston that have a height that is smaller than 5 times the thickness.

Criterion 4' – Options

Options are not taken into account as a separate criterion, because the budgetary quotations of the manufacturers already include the options that are needed to produce as much products of Pan Oston as possible. The feasibility criterion takes the number of products that can be made already into account. Since one of the prerequisites of the AHP approach is that a two criteria cannot measure the same, this criterion is left out of consideration.

3.4 Conclusion

In this chapter, the machine manufacturers are discussed in combination with the most relevant machine types. The headquarters of the 4 machine manufacturers are all located in Europe, which was one of the requirements the manufacturers should comply with. The 4 manufacturers are Salvagnini, Trumpf, RAS, and Prima Power. Each of these manufacturers produce several machine types. An overview of the relevant machines per manufacturer is shown in **Table 3** below.

Salvagnini	Trumpf	RAS	Prima Power
P4L-3320	TruBend Center 5030	79.22-2	EBe2220
P4L-3125	TruBend Center 7020	79.22-2 ECO	EBe2720
P4L-2120	TruBend Center 7030	79.26-2	FBe2220
P4L-2225		79.26-2 ECO	
P2L-2120		79.31-2	
P2L-2225		79.31-2 ECO	

Table 3: *Overview of the machine types per manufacturer*

After discussing the manufacturers and the machine types, the criteria and sub-criteria are discussed that are going to be used to assess the performance of the machines. The five main criteria are costs, speed, flexibility, layout, and quality. Under flexibility, sheet dimensions and feasibility are the two sub-criteria. Under sheet dimensions, an additional level of sub-criteria is placed that contain the maximum plate thickness, the maximum bending length, the maximum bending height, and the minimum box size. In addition, we have thought of criteria that can left out of consideration, because it is not possible and not needed to evaluate all the criteria. The criteria that are left out are safety, maximum width of incoming sheet, minimum bending height, and options. An overview is given in **Table 4** below.

<table>
<tr><th>Criteria</th><th>Sub-criteria</th><th>Sub-criteria</th></tr>
<tr><td>Costs</td><td></td><td></td></tr>
<tr><td>Speed</td><td></td><td></td></tr>
<tr><td rowspan="5">Flexibility</td><td>Feasibility</td><td></td></tr>
<tr><td rowspan="4">Sheet dimensions</td><td>Maximum plate thickness</td></tr>
<tr><td>Maximum bending length</td></tr>
<tr><td>Maximum bending height</td></tr>
<tr><td>Minimum box size</td></tr>
<tr><td>Layout</td><td></td><td></td></tr>
<tr><td>Quality</td><td></td><td></td></tr>
</table>

Left out criteria
Safety
Maximum width of incoming sheet
Minimum bending height
Options

Table 4: *Overview of the all the criteria, sub-criteria, and criteria that are left out of consideration*

4 Production data

This chapter elaborates on the production data that is used to assess the performance of the panel benders on speed and feasibility. In Section 4.1, a motivation is given about why it is important to not randomly select production data, but do a careful analysis. Thereafter, Section 4.2 discusses how the production data is gathered. In Section 4.3, the production data is carefully analyzed to minimize the list. In this way, this list only contains the most important production data. Section 4.4 discusses how this selected production data says something about the reality. Last, in Section 4.5 we provide a conclusion about Chapter 4.

4.1 Relevance

If we want to score the panel benders based on their performances and abilities, it is not only the technical data of the machines that we need to take into account, but also the production data of Pan Oston. For example, if one of the potential new panel benders scores very good on each criterion, it has very high flexibility and low costs, this machine could be a very good option. However, if the machine is only able to produce a very small fraction of all the products that needs to be produced, this option suddenly is not such a good choice. Furthermore, Pan Oston currently uses 4 traditional bending machines. These 4 bending machines have certain limitations, of which one is that the employees spent a lot of time on changing the machine tools. According to the metal department manager, one of the main limitations of traditional benders is that they cannot produce a radius of more than 40 degrees. The bending radius is the radius measured after the metal plate is bent. In **Figure 5** below, the character *r* represents the radius of the metal plate.

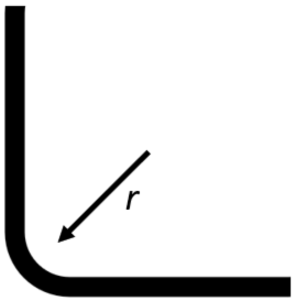

Figure 5: *An overview of bending terms in metal plates (Formfedern, 2021).*

Due to the limitations of the traditional bending machines, the engineering department of Pan Oston needs to take these limitations into account during the engineering phase of the products. If we consider the panel benders, each of them has certain bending limitations as well, however, the limitations of a panel bender are much less than compared to the traditional benders. It is therefore not only necessary to know which products are produced in the highest quantities, but it is also convenient to know why certain products are produced or not. In addition, due to the time limit, it is simply not possible to analyze all the production data. Therefore, we need to make a selection out of the total production set. In this chapter, we provide an answer on the following question: “Which production data is important to analyze?”

4.2 How is the production data gathered?

In the first place, we must carefully set up a time period in which we want to search for relevant information. Since the company produces a lot of small production series, it is useful to pick a somewhat larger interval in which we want to search. The production facility in Raalte mainly focuses on development of checkouts and kiosks, demos, and orders that have a very short delivery time. Their production partner located in Slovakia produces more production series with higher quantities. Therefore, the production data from January 2022 until May 2022 is not sufficient enough to create a representative view of the past years. Because of this, the entire year 2021 is taken into account as well. At Pan Oston, the wishes and needs of the customers are highly valuated. Not only new customers, but also existing customers want products that are designed to their taste. Theoretically, this could mean that if a product is produced 500 times in a year, it does not necessarily have to be produced in the year thereafter. To create a representative view of the reality, only the most current products are taken into account. Therefore, the years before 2021 are not taken into account.

Considering the years 2021 and 2022 until May, the search started within the Enterprise Resource Planning (ERP) software of the company. The ERP system of the company contains a lot of different data, among which the production times, production numbers, and production quantities. Before it is possible to determine the relevance of the products made, we first need to know which products are produced altogether. The ERP team leader created a list in which all the products are listed that contain at least one operation by the traditional bending machine. This is done because there are also metal plates that only go through the laser cutter, and not through the traditional bending machines. Since the products that only go through the laser cutter, will not go through the panel bender, these products are not relevant to further investigate. Eventually, this resulted in two separate lists. The one list contains all the orders from the year 2021, and the other list contains all the orders of the year 2022 until May. In order to be able to calculate the order quantities, the two lists are exported to excel. The two lists are then combined and all the duplicate values are removed. In this way, a list remains with only unique values. From these unique values, the corresponding order quantities and production quantities can be again found from the other two lists.

It is important to mention the difference between the produced quantity and the order quantity. The order quantity is the number of orders that is placed to produce a specific product. It could be the case that a single order contains 10 times product A. From this, we directly see that the order quantity is not the same as the produced quantity. The produced quantity is the total number of products that are produced. For example, if we have an order with 7 times product A and an order with 8 times product A, the order quantity equals 2 and the produced quantity equals 15. The order quantity is important to consider, because every time an order is placed, the operator of the traditional bending machine needs to setup the machine. The bigger the order size is, the lower the average setup time per product will be. This is due to the fact that separate orders are not necessarily produced consecutively, but usually in between other orders. Therefore, not only the produced quantities must be taken into account, but also the order quantities.

Eventually, the order quantities and the produced quantities per product per year are summed. Thereafter, the order quantities and the produced quantities of each year are summed to get total values of the past one and a half years. This already gives a clear overview of the products that are produced in the highest quantities and the products that are produced in the lowest quantities. However, there is a downside of this method. If we consider a single checkout, it could be possible that this checkout contains 4, 6, or even more small parts that are used for reinforcements. This shows us that the smaller parts are produced in higher quantities than the bigger parts. Since the small parts often do not have high tool changing times and the bigger parts do have high tool changing times, the machine tool changing times and the processing times are added to the list to create a better view of the spent time at the metal department. These changing times and processing times are retrieved from the ERP-system as well, and represent the times for a single order. To find out what the total time is per product, the order quantity is multiplied by the setup time and the produced quantity is multiplied by the processing time. Eventually, with the sum of these two multiplications we found the total production time per product in the past one and a half years. This total production time per product is filtered from high to low, to find the biggest values in the list.

4.3 Which production data is selected?

All the manufacturers are willing to test several products on their machines. The goal of these tests is to gain insight into the speed by which the panel benders produce the products. Besides, these tests also show how many products from the data set can be produced and how many not. Several account managers from different manufacturers are interviewed to find out the number of products that can be tested. The conclusion of this was that one manufacturer can test more products than the other. In order to have reliable results from the tests of the manufacturers, the same list must be used across all the manufacturers. Since the lowest number of products that can be tested is approximately 35, and the highest number of products that can be tested is approximately 120, the list can only contain 35 products.

Because we can only test approximately 35 products, we have to make some decisions about which products to exclude beforehand, and which not. Products that are only produced once in 2021 and 2022 are left out. This is because these products are often produced for a demo or test, and thus do not give a good representation of the reality. In addition, product names that end with "PB" indicates that this is a product with at least one compression bolt. These compression bolts are used for assembly purposes, and are not installed at the traditional bending machines, but at a separate machine. The processing times and tool changing times are automatically stored in the ERP system, and installing these compressions bolts is seen as an additional operation. The ERP system is programmed to judge the installation of a single compression bolt as the same as three normal bends. Because of this, the products that end with "PB" have very high tool changing times and processing times. This does not give a good view of the reality, and it is therefore that we leave out the products that end with "PB". Initially, there were 13658 different products found, which means that there are 13658 different products are produced in 2021 and 2022 until May. Leaving out products that are not produced, or only produced once in 2022, reduces the list from 13658 to 4997 products. Thereafter, removing the products that end with "PB", the list reduces from 4997 to 4827 relevant products.

As we knew beforehand, not all the products that Pan Oston produces can be made by a panel bender. It does not matter which panel bender is chosen, there is always a set of products that cannot be made. This is why they only replace two traditional bending machines, and not all of them. Since the panel bender manufacturers are not able to test all the products that Pan Oston produces, we have to select 35 products carefully. Eventually, the results of these manufacturers' tests indicate something about the performance of the machine.

The products that are selected are not picked randomly, but based on high production times. The total production time per product is the average setup time per produced plus the processing time per product. First, we filter the total production time from high to low. The higher the product is placed in this list, the more time is spent to produce the total number of this product in the past one and a half years. If we pick the upper 35, and send these products to the manufacturers to test, it could be possible that only 15 of these 35 products are feasible to produce on a panel bender. The more products are tested, the more accurate conclusions we can draw from the results. Therefore, we have to send as much products of which we think are feasible to produce by a panel bender. Taking the characteristics of the different panel benders in consideration, in combination with using a drawing program to find the different dimensions of the products, an estimation was made about which products are feasible to produce by a panel bender and which are not.

Not only the products should be feasible to produce by a panel bender in order to make estimations about the performances, the products should also have many different characteristics. For example, if a panel bender is 50% faster on products with a single bend, and 20% faster on products with double bends, it would give a very distorted view of the reality if we only send products with a single bend. Therefore, the list of 35 products has to contain as much different characteristics as possible, to create a representative view of the reality. This list was created in cooperation with the metal department manager. This person has a lot of experience and knowledge about the products that are made by Pan Oston. In addition, an engineering specialist was asked to check the list on differences in characteristics. In appendix C, the product numbers are added.

4.4 How do the products represent the reality?

The products are selected based on the total amount of time that was spent in the past one and a half years. The products that represent the biggest part of the total production time are listed at the top. The upper 503 products were checked to see if the dimensions are bigger than the minimum values of the panel benders. These 503 products represent exactly 50% of the total production time of the past one and a half years. Of these 503 products, there are 156 products judged as feasible to produce by a panel bender, 219 products are judged as not feasible to produce on a panel bender, and 130 products that are judged as questionable. It has to be said that there is a downside of this method, and that is that it involves human interpretation of the products. The dimensions of the products are taken into account, but to some extent it remains uncertain if the products can be made or not. If the products are a bit above or a bit under the minimum or maximum bending limits, the products are characterized as questionable. The products that are within the bending limits are marked as feasible, while the products that are not feasible to produce are marked red.

Out of the 505 products that represent 50% of the production time of the past one and a half year, there are 156 products judged as feasible to produce on a panel bender. These 156 products represent 54,692.6 production minutes, which is 15.68% of the total production time. In addition, the products that are marked as questionable represent 39,800.75 production minutes, which is 11.41% of the total production time. Last, 220 products that are judged as not feasible to produce by a panel bender, represent 80,677.29 production minutes, which is 23.13% of the total production time. Besides, out of the 505 products, 156 products are judged as feasible, which equals 30.9%. Since these 505 products represent 50% of the total production time of the past one and a half years, we can make a rough estimation that 30.9% of the total production set can be produced by a panel bender. Of course, the one panel bender can produce more products than the other, therefore, this remains a rough estimate.

One of the wishes of one of the decision makers is to receive an indication about the return on investment of the most preferred panel bender. Since the manufacturers cannot test all the products, we have to use the results of the 35 selected products to say something about all the products. Because the one product is faster to produce by a panel bender than the other, we made 9 categories to be able to distinguish different types of products. These categories are based on the average setup time per product and the processing time per product. If we then look at the 35 selected products, there is at least one product for each category. All the different categories are presented in **Table 5** below.

Category	Setup time	Processing time
1	Low	Low
2	Low	Medium
3	Low	High
4	Medium	Low
5	Medium	Medium
6	Medium	High
7	High	Low
8	High	Medium
9	High	High

Table 5: *The 9 different product categories*

The setup time per product and the processing time per product can both be divided into three different categories. This means that there are 9 different possibilities. These categories are chosen based on the setup times of the 4827 relevant products. The setup times are ordered from low to high and divided into three equal groups. This means that each group consists of 1609 products. As a result, products that have a setup time of 35 seconds or lower are categorized as low. If it is between 35 and 105 seconds, the setup time is medium and if the setup time is more than or equal to 105 seconds, the setup time is high. The same approach is used for the processing times. If the processing time is less than or equal to 70 seconds, the processing time is low. If the processing time is in between 70 and 136 seconds, the processing time is high, and if it is more than or equal to 136 seconds, the processing time is high. The categories of the selected products can be found in appendix C.

As discussed, not every single product that Pan Oston produces can be tested by the manufacturers. The goal is to say something about the reality as accurate as possible, based on the selected products. It is not realistic to say that the panel bender is always a certain amount faster than the current process, because bigger products are usually faster in proportion than smaller products. Thus, in order to say something about the reality as accurately as possible, we have divided the products in 9 different categories. To eventually be able to determine the return on investment of the most preferred option, the average speed per category is calculated from the tested products and used in the total production set.

4.5 Conclusion

In this chapter, the production data is discussed that is used to get a visual about the actual performances of the machines. Not every product is equal in importance, because Pan Oston is an innovative company that changes its products. Products that are not produced in the year 2021 and

2022 can already be seen as old products, which means that only the years 2021 and 2022 are relevant. In addition, we have looked at the production quantities, order quantities, and production times to be able to select the most relevant products. In order to draw conclusions about the performances that are as accurate as possible, we have carefully selected 35 products. These products are judged to be feasible to produce on a panel bender. Thereafter, these 35 products are divided into 9 categories, that later is used to determine the return on investment of the most preferred alternative.

5 Selecting relevant machines and determining the raw scores

In this chapter, the raw scores of the machines on the criteria and sub-criteria are discussed. Before we start with the raw scores, we need to select the most relevant machines from Chapter 3. Namely, there are 18 different machine types from 4 manufacturers, which makes it very hard to analyze all of them in detail. First in Section 5.1, the boundary conditions of the panel benders are discussed, whereafter in Section 5.2, the machines that drop off are discussed. This leaves us with a selection of machines, of which we discuss the raw scores in Section 5.3. Eventually, in Section 5.4 we provide a conclusion and an overview about which machine types remain.

5.1 Boundary condition for the panel benders

In this section, the boundary condition is discussed. Boundary conditions are characteristics that the machine at least should have, otherwise it cannot be considered. As discussed in Chapter 0, the higher the number of alternatives, the more pairwise comparisons are needed. In addition, if we are able to exclude an alternative on beforehand, it reduces the amount of work to do.

Boundary condition 1 – Minimum feasibility

As discussed in Chapter 3 under the feasibility criterion, the manufacturers perform tests with selected products to indicate by which speed they are able to produce the products. Besides, this also indicates which products can be made entirely, only partially, or not even at all. Since the goal of Pan Oston is to choose a machine that can produce as much products as possible, the panel bender should be able to produce at least 75% of the selected products. Due to the fact that these products already are judged to be feasible to produce on a panel bender, this minimum percentage is determined on 75%.

5.2 Machines that drop off

As discussed in the previous chapter, we analyzed 500 products that took the most amount of time in the past one and a half years. One of the things that can be concluded from those 500 products was that the majority of the products were under 2000 millimeters in length, and almost none of them were above 2500 millimeters in length. Of the few products that were more than 2500 millimeters in length, these have very small widths as well. Panel benders have a manipulator that is used to turn the metal plates automatically, and very small products cannot be produced because of that. In other words, the majority of the products of Pan Oston that are above 2500 millimeters in length, cannot be produced by the panel benders due to the small widths. Initially, the decision makers at Pan Oston indicated that they require a machine that has the ability to bend 3000 millimeters in length. This is because Pan Oston uses a maximum plate length of 3000 millimeters. Because of this, we first started to analyze the bigger machines, and the selected products from Chapter 4 are therefore also tested on the bigger machines. After analyzing the production data, it was clear that a smaller machine satisfies as well. To ensure that reliable results are used for speed and feasibility, the account managers from Salvagnini, Prima Power, and RAS were asked if the results are comparable between the bigger machines and the smaller machines. All the manufacturers replied that the results are comparable, since they use the same type of tools across machine types. The results are not comparable between the Trumpf 7020 and the Trumpf 7030, but the products were tested on the 7020. This means that the comparability is not an issue. As a result, the following machines drop off:

- Salvagnini P4L-3320
- Salvagnini P4L-3125
- Trumpf TruBend Center 7030
- RAS Multibend-Center 79.26-2 (ECO)
- RAS Multibend-Center 79.31-2 (ECO)

In addition, the account manager of Trumpf told us that the feasibility study of the products would take at least three weeks to complete. Due to the high number of requests, this feasibility study cannot be done for all the three machine types. Because of this, we have to select a single machine on which the products are tested. The Trumpf 7030 is an automatic machine that is able to bend up to 3000 millimeters in length. As described, it is not necessary to have a machine that is able to bend up to 3000 millimeters in length. Therefore, the Trumpf 7030 drops off. In addition, the account manager of Trumpf indicated that since Pan Oston produces in small batches, a panel bender with manual loading and unloading would probably already fulfill the wishes of the decision makers. Therefore, the Trumpf 7020 is the most relevant for Pan Oston. This means that the Trumpf 5030 drops off.

Besides, the account manager of Salvagnini also indicated that for small batches a panel bender with manual loading and unloading satisfies. If we consider the machines from Salvagnini, the P4 in the product name indicates that the machine has automatic loading and unloading, while the P2 in the product name indicates that it has manual loading and unloading. If we look at the Salvagnini P4L-2225 and the P2L-2225, these machines are identical, except for the type of loading and unloading. This means that the P4 version has a higher speed. The loading and unloading of the P4 happens simultaneously with bending, while the P2 has to stop to load and unload. This takes approximately an additional 5 seconds. If we then compare the P4L-2120 against the P2L-2120, the P4 is the one with automatic loading and unloading. However, the P2 variant is only able to bend up to 165 millimeters high, compared to 203 millimeters high for the P4 version. The account manager of Salvagnini confirmed this and said that the results of the test on the bigger machines do not apply for the P2-2120.

5.3 The raw scores of the machines

In this section, the raw scores of the machine types are discussed. As described in Section 5.2, not all the machines can be considered, but only a selection. The first criterion that is considered is speed. **Table 6** presents the speed by which the panel benders can produce the products. The percentages indicate as a fraction of time that is needed by the panel benders to produce the same product. For example, if the current production time of a product is 100 seconds, and the table shows 20%, this means that the panel bender is able to produce the product in 20 seconds. The colors give an indication about the feasibility of the products. The cells that contain a percentage and that are not colored red or orange, have no limitations in production. Products that are marked red are not feasible to produce on the panel bender, and products that are marked orange are partially feasible to produce by a panel bender. If a product is only partially feasible, this means that the panel bender is not able to complete all the bends, but only a limited number of bends.

	Prima Power		RAS	Salvagnini		Trumpf
ItemID	**FBe2720**	**EBe2720**	**79.22-2 (ECO)**	**P4**	**P2**	**7020**
BE12Z504	22.66%	12.31%	12.39%	15.19%	17.19%	23.58%
BF20Z664	36.38%	35.72%	47.10%	61.59%	65.22%	46.38%
BO12Z518	59.59%	32.91%	31.51%	28.01%	31.51%	Not tested
BO20Z033	43.13%	56.25%	Not feasible	54.17%	64.58%	Not tested
BS12Z526	13.73%	7.65%	8.30%	6.18%	7.15%	Not tested
CA20Z055	20.35%	20.28%	12.72%	Not feasible	Not feasible	19.41%
EF12Z551	23.56%	17.29%	8.00%	19.11%	21.33%	Not tested
ET12Z559	52.73%	50.84%	116.35%	54.51%	59.75%	70.23%
FI12Z506	32.67%	36.00%	22.67%	32.00%	38.67%	40.00%
FI15Z537	55.34%	34.35%	26.72%	36.90%	43.26%	49.62%
FL12Z510	45.24%	91.84%	Not feasible	30.61%	47.62%	47.62%
GL12Z649	11.37%	Not feasible	Not feasible	26.47%	28.10%	Not tested
NE10L096	33.26%	23.04%	21.51%	30.72%	34.56%	33.03%
NG10L120	22.92%	14.89%	14.56%	26.43%	29.13%	Not tested
NG10L504	13.75%	10.07%	5.75%	15.71%	16.82%	Not tested
NG12Z006	38.60%	17.82%	16.57%	18.57%	21.08%	Not tested
NG12Z014	27.61%	17.44%	16.09%	20.59%	23.81%	27.67%
NG12Z242	17.36%	18.39%	Not feasible	8.63%	10.29%	Not tested
NG12Z538	46.15%	33.75%	33.33%	39.58%	44.79%	44.79%
NG20Z507	39.73%	39.60%	Not feasible	26.67%	33.33%	Not tested
NG20Z696	16.22%	12.06%	Not feasible	12.87%	14.04%	19.43%
PB12Z170SH	42.64%	29.22%	35.71%	41.13%	46.54%	54.11%
PB12Z232SH	34.63%	25.00%	37.96%	34.26%	38.89%	44.44%
PB12Z745	31.55%	21.08%	41.50%	24.37%	27.67%	32.28%
PB12Z766	31.51%	23.68%	25.58%	31.43%	35.09%	32.89%
PB12Z972	24.14%	19.40%	Not feasible	Not feasible	Not feasible	Not tested
SO10L546	50.00%	3.85%	3.47%	4.75%	5.32%	Not tested
SP12Z140	24.69%	16.10%	17.60%	19.15%	21.74%	24.84%
SP12Z238SH	50.00%	6.08%	5.03%	7.00%	8.09%	Not tested
SP12Z601	45.95%	19.77%	17.54%	21.59%	24.97%	29.01%
SP20Z037	57.27%	81.82%	48.48%	60.61%	75.76%	66.67%
SP20Z531	28.10%	19.41%	30.65%	22.35%	25.54%	23.63%
TD12Z803	40.45%	22.57%	22.52%	27.93%	30.18%	Not tested
TN12Z569	35.27%	Not feasible	Not feasible	40.56%	44.97%	41.45%
ZU12Z847	3.35%	7.43%	7.89%	Not feasible	Not feasible	Not tested

Table 6: *Overview of the speed by which the panel benders can produce the products*

As presented in **Table 6** under the machine from Trumpf, some cells are filled with not tested. This has to do with a mistake on the side of the account manager of Trumpf. Namely, this person indicated that it was possible to test approximately 35 products, but after we received the results, there were only 20 products tested instead of 35 products. The account manager indicated that due to the high number of requests, only 20 products per customer can be tested. To be able to draw reliable conclusions, we have to use the same products across the different manufacturers.

Furthermore, if we take the boundary condition into account that says that at least 75% of the selected products must be feasible, the machine from RAS already drops off. This leaves us with **Table 7** that presents the left over machines with the feasibility and speed.

	Prima Power		Salvagnini		Trumpf
ItemID	**FBe2220**	**EBe2220**	**P4**	**P2**	**7020**
BE12Z504	22.66%	12.31%	15.19%	17.19%	23.58%
BF20Z664	36.38%	35.72%	61.59%	65.22%	46.38%
CA20Z055	20.35%	20.28%	Not feasible	Not feasible	19.41%
ET12Z559	52.73%	50.84%	54.51%	59.75%	70.23%
FI12Z506	32.67%	36.00%	32.00%	38.67%	40.00%
FI15Z537	55.34%	34.35%	36.90%	43.26%	49.62%
FL12Z510	45.24%	91.84%	30.61%	47.62%	47.62%
NE10L096	33.26%	23.04%	30.72%	34.56%	33.03%
NG12Z014	27.61%	17.44%	20.59%	23.81%	27.67%
NG12Z538	46.15%	33.75%	39.58%	44.79%	44.79%
NG20Z696	16.22%	12.06%	12.87%	14.04%	19.43%
PB12Z170SH	42.64%	29.22%	41.13%	46.54%	54.11%
PB12Z232SH	34.63%	25.00%	34.26%	38.89%	44.44%
PB12Z745	31.55%	21.08%	24.37%	27.67%	32.28%
PB12Z766	31.51%	23.68%	31.43%	35.09%	32.89%
SP12Z140	24.69%	16.10%	19.15%	21.74%	24.84%
SP12Z601	45.95%	19.77%	21.59%	24.97%	29.01%
SP20Z037	57.27%	81.82%	60.61%	75.76%	66.67%
SP20Z531	28.10%	19.41%	22.35%	25.54%	23.63%
TN12Z569	35.27%	Not feasible	40.56%	44.97%	41.45%
Weighted Average	38.93%	34.13%	37.07%	42.31%	40,04%

Table 7: *The revised overview of the speed by which the panel benders can produce the products.*

The next criterion that is considered is costs. All the manufacturers were asked for a budgetary quotation for the machine types, including installation costs and transportation costs. This is presented in **Table 8** below.

	Prima Power		Trumpf	Salvagnini		
Type	FBe2220	EBe2220	7020	P4L-2120	P4L-2225	P2L-2225
Costs	€600,563	€826,295	€739,475	€978,510	€1,202,770	€1,001,910

Table 8: *Overview of the total costs per machine type*

In this next part, the different characteristics related to sheet dimensions are discussed. In the first place, the maximum plate thickness is discussed. The values presented in **Table 9** only apply to material type mild steel. The 4827 relevant products that we have selected are analyzed and 82% of these products were made of mild steel. In addition, 15.3% was made of stainless steel, and the thickness of these products did not exceed 2.0 millimeters. Since all the panel benders are able to bend at least 2.0 millimeters in thickness, this is not considered. Second and third, the maximum bending length and maximum bending height are obvious numbers, measured in millimeters. Last, the minimum box size is the minimum length and width a product needs in bend condition. For example, if the minimum box size is 150x150, the “bottom” or the flat part of the product needs to be at least 150 millimeters in length, and 150 millimeters in width. All these values in **Table 9** are applicable for mild steel, which Pan Oston uses for 82%. 3.

	Prima Power		Salvagnini			Trumpf
	FBe2220	EBe2220	P4L-2120	P4L-2225	P2L-2225	7020
Maximum plate thickness	3.0	3.0	3.2	3.2	3.2	3.5
Maximum bending length	2250	2250	2180	2200	2200	2163
Maximum bending height	204	204	203	254	254	350
Minimum box size	180x350	180x350	130x370	170x420	170x420	145x200

Table 9: *Overview of the raw scores per machine type on the lowest level of sub-criteria*

In **Table 10** below, the feasibility of the products per machine type is presented. Since there are only 20 products tested, the maximum feasibility is 20, instead of 35. Fully, partial, and not stand for fully feasible, partial feasible, and not feasible.

	Prima Power		Salvagnini			Trumpf
	FBe2220	EBe2220	P4L-2120	P4L-2225	P2L-2225	7020
Fully	20	19	19	19	19	19
Partial	0	0	0	0	0	0
Not	0	1	1	1	1	1

Table 10: *Overview of the feasibility of the products per machine type*

Last, the quality and the layout are presented in **Table 11** below. The quality is measured with yes or no, where yes indicates that the machine type has an automatic angle measurement system, and no indicates that the machine type does not have such a system. In addition, the layout relates to the side of loading and unloading, where left – right means that the operator has to load at the left side and unload at the right side. Right – left means the other way around.

	Prima Power		Salvagnini			Trumpf
	FBe2220	EBe2220	P4L-2120	P4L-2225	P2L-2225	7020
Quality	Yes	Yes	Yes	Yes	Yes	Yes
Layout	Yes, Left – Right	No, Left – Right	No, Left – Right	No, Left – Right	Yes, Left – Right	Yes, Right – Right

Table 11: *Overview of the quality and layout per machine type*

5.4 Conclusion

In this chapter, the first thing that was discussed is the boundary condition. In the previous chapter, we have selected 35 products are judged to be feasible to produce by a panel bender. Since these products are judged to be feasible to produce by a panel bender, the feasibility of these products should be at least 75%. The production data have also shown that the majority of the products is under 2000 millimeters in length. Therefore, a machine that is able to bend up to 3000 millimeters in length is unnecessary. Because of this, 5 machines are not analyzed further. This leaves us with 8 possible machines that are analyzed. When the results came in, the machine from RAS failed to meet the first boundary condition that states that at least 75% of the selected products should be feasible to produce. As a result, the machines from RAS dropped off and the following machines are analyzed:

- Prima Power FBe2220
- Prima Power EBe2220
- Salvagnini P2L-2225
- Salvagnini P4L-2120
- Salvagnini P4L-2225
- Trumpf TruBend 7020

Initially, the account manager of Trumpf indicated that it is possible to test approximately 35 products. Unfortunately, after the results came in, the account manager concluded that only 20 products can be tested per customer. This forced us to work with 20 products, instead of 35 products. Thereafter, the raw scores of the 6 machines are discussed. In the next chapter, we work towards giving values to these raw scores.

6 How does each panel bender perform on the chosen criteria?

In this chapter, the different panel benders are analyzed and compared to be able to come up with a conclusion about which type performs the best. In Section 6.1, the value tree is discussed that includes all the criteria and sub-criteria that are used during the AHP. This also gives a good overview of how the criteria and sub-criteria cohere. Thereafter, in Section 6.2, an example is given about how to set up the pairwise comparison matrix. In Section 6.3, this pairwise comparison matrix is normalized to give an estimation about the weights per criterion and sub-criterion. Then, in Section 6.4, a consistency check per decision maker is performed to check the consistency of the decisions.

Eventually, in Section 6.5, the overall values of the performances of the alternatives on the criteria are determined. Since we have 6 possible alternatives, using pairwise comparisons to determine the values for the performances becomes a tedious job. Therefore, we use the direct rating technique from SMART to determine the values. Each decision maker has different weights, but these values for the performances are the same for each decision maker. This leads to a final ranking for the alternatives for each decision maker. Thereafter, in Section 6.6 the sensitivity analysis is performed. The sensitivity analysis is used to increase the confidence in the selected alternative. In Section 6.8, we provide the Return on Investment of three alternatives, whereafter the conclusion follows in Section 6.9.

6.1 The value tree

In Chapter 2, a set of criteria and sub-criteria is discussed that reflects the wishes of the decision makers at Pan Oston. Before the weights of the criteria and sub-criteria can be determined, we have to develop a value tree. A value tree represents the overall goal of the decision making process at the top level, the criteria and the sub-criteria that include the elements of the overall goal at the middle level. The alternatives are placed at the lowest level. The value tree, and thus the criteria, are the same across all the 4 different decision makers at Pan Oston. The value tree is build based on the top-down approach, which means that we start with the overall objective. In this case, the overall objective is to find the most suitable panel bender for Pan Oston. Eventually, these initial values are expanded into more detailed and precise concepts that explains or clarifies the former. This process of dividing the overall goal into more precise concepts is continued until the emergent criteria are measurable (Belton & Stewart, 2002).

Since the value tree is used to describe the decision makers' preferences, the structure of the value tree should comply with the conditions of preferential independence. This means that the trade-offs between pairs of criteria are independent of outcomes on other criteria (Stewart, 2005). In addition, each end point in the value tree is used to assess the performances of the machines. For example, costs and speed are two end points, but flexibility is not. Under flexibility, feasibility, and the maximum plate thickness are two out of five end points. **Figure 6** presents the value tree of this research.

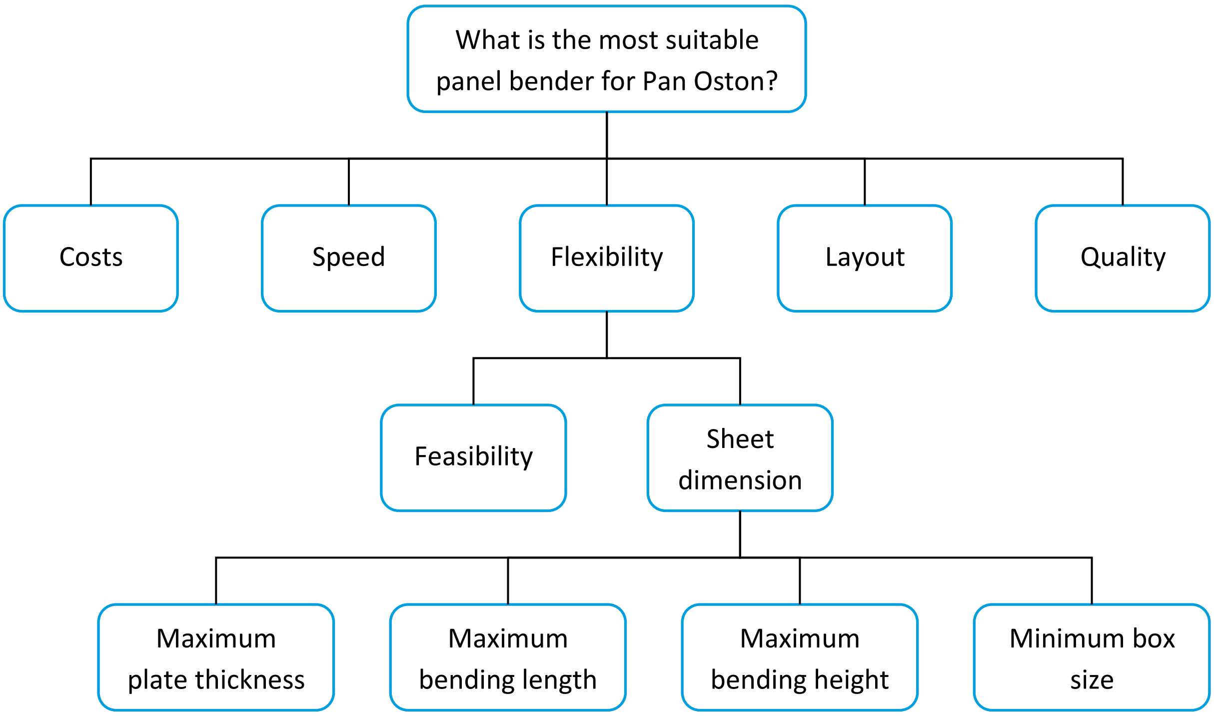

Figure 6: Value tree for finding the most suitable panel bender at Pan Oston

6.2 The pairwise comparisons of the criteria and sub-criteria

The next step is to find weights for the criteria and sub-criteria presented in the value tree. To find these weights, pairwise comparisons are made for each level in the value tree. As said in **Chapter 2** and presented in **Figure 4**, the decision makers have to indicate their preferences within the pairwise comparisons on a scale from 1 to 9, where 1 means equal importance, and 9 means extreme importance. Each 4 decision makers are asked individually about their preferences about the criteria and sub-criteria. In order to support the decision makers with giving the preferences, the findings about the production data was shared in combination with the raw scores of the machines. However, there is a downside, because there was not enough time to wait on all the raw scores of the machines. This means that the decision makers were aware of all the information, except the speed and the feasibility of the machines. For each decision maker the pairwise comparison matrix is different. All the pairwise comparisons for each decision maker can be found in appendix B. For convenience, an example of a pairwise comparison matrix is presented in **Table 12**.

	Quality	Costs	Speed	Layout	Flexibility
Quality	1	5	3	7	1
Costs	1/5	1	1/3	5	1/3
Speed	1/3	3	1	4	1/3
Layout	1/7	1/5	1/4	1	1/7
Flexibility	1	3	3	7	1

Table 12: *An example of a pairwise comparison matrix for the 5 criteria*

6.3 Determine weights out of the pairwise comparisons

Now the pairwise comparisons are done, and the comparison matrices can be set up, we use this to give an indication about the weight per criterion and sub-criterion. First, we consider the pairwise comparisons that are used to fill the comparison matrices. This comparison matrix is needed to create the next matrix, the so-called normalized matrix. As the name suggests, the comparison matrix is normalized to create the new matrix. To give a clear view of how the normalized matrix is created, we provide an example in the next part. This example is related to the pairwise comparison matrix presented in **Table 12**, discussed in the previous section.

If we look at **Table 12**, we can immediately see that this is a 5 by 5 matrix. This automatically means that the normalized matrix is going to be a 5 by 5 matrix as well. To create this normalized matrix, we look at the comparison matrix and divide each entry in column i by the sum of entries in column i (Winston, 2003). In other words, if we look at the first column of **Table 12**, the sum of the "Quality" column is equal to 2.676. If we then look at the first entry of the first column, the normalized value for this is equal to 1 divided by 2.676 which is equal to 0.37367. This is done for every column, and if each entry of every column is divided by the sum, the normalized matrix of **Table 12** is presented in **Table 13** below.

	Quality	Costs	Speed	Layout	Flexibility
Quality	0.37367	0.40984	0.31304	0.29167	0.35593
Costs	0.07473	0.08197	0.03478	0.20833	0.11864
Speed	0.12456	0.24590	0.10435	0.16667	0.11864
Layout	0.05338	0.01639	0.02609	0.04167	0.05085
Flexibility	0.37367	0.24590	0.52174	0.29167	0.35593

Table 13: *The normalized matrix of the pairwise comparison matrix*

Eventually, the average of every row is taken to come up with an indication of the weights for each criterion and sub-criterion. For this example, we use a single decision maker and only 5 criteria. In this research, there are 4 decision makers each with weights for 5 criteria and 6 sub-criteria. To determine the weights for **Table 13**, the average of each row is taken. For example if we look at "Quality", the weight is determined by $\frac{0.37367+0.40984+0.31304+0.29167+0.35593}{5}$ which is equal to 0.36534. This is done for every row, and the results are presented in **Table 14**.

Criterion	**Weight**
Quality	0.36534
Costs	0.10553
Speed	0.15753
Layout	0.03905
Flexibility	0.33255

Table 14: *An estimation of the weights for the 5 criteria*

6.4 The consistency check of the decisions

In Section 6.3, we have discussed how the weights are determined by transforming the comparison matrix into a normalized matrix. Thereafter, an estimation can be made about the weights per criterion and sub-criterion. Now, it is important to consider the inconsistencies of each decision maker. If we look at the value tree, there are three different levels. The first level contains 5 criteria, the second level contains 2 sub-criteria, and the third level contains the last 4 sub-criteria. For each level and each decision maker, the inconsistencies are determined. This results in 4 times 3 equals 12 inconsistency ratios. By checking the inconsistencies, we can check whether the decision makers are sufficiently consistent or not, and thereby reducing bias in decision making (Prieto-Amparán, et al., 2021). The second level with the two sub-criteria feasibility and sheet dimensions requires only one pairwise comparison. This single value is filled in the comparison matrix, and since its reciprocal is automatically placed in the transpose position, this matrix is always consistent. In **Table 15:**, this is recognizable by the value 0.00. Besides, the other inconsistencies are presented in this table as well. Recall from Chapter 2 that the inconsistencies should be smaller than .1 in order to have meaningful results in the AHP. The values that exceed this limit are colored red, and the values that do not exceed this limit are colored green.

<table>
<tr><th></th><th>Process Specialist</th><th>Manager Operations</th><th>Department Manager</th><th>COO</th></tr>
<tr><td>Quality</td><td rowspan="5">0.08483</td><td rowspan="5">0.26982</td><td rowspan="5">0.89218</td><td rowspan="5">0.08117</td></tr>
<tr><td>Costs</td></tr>
<tr><td>Speed</td></tr>
<tr><td>Layout</td></tr>
<tr><td>Flexibility</td></tr>
<tr><td>Feasibility</td><td rowspan="2">0.00</td><td rowspan="2">0.00</td><td rowspan="2">0.00</td><td rowspan="2">0.00</td></tr>
<tr><td>Sheet dimensions</td></tr>
<tr><td>Maximum PT</td><td rowspan="4">0.04388</td><td rowspan="4">0.28944</td><td rowspan="4">0.09674</td><td rowspan="4">0.09912</td></tr>
<tr><td>Maximum BL</td></tr>
<tr><td>Maximum BH</td></tr>
<tr><td>Minimum BS</td></tr>
</table>

***Table 15:** The inconsistency ratios per decision maker*

Since there are three parts that are not consistent enough, we have to revise these values. The operational manager and the metal department manager were asked to revise their decisions. We put extra emphasis in explaining the principles of the AHP approach and the importance of consistency. In appendix B, an overview is given about what changes are done to decrease the inconsistency ratios. In the tables of the pairwise comparison matrices, the yellow marks are the initial choices, and the green marks are the revised choices. In addition, the results were discussed with the process specialist as well and he changed one decision from strongly more important to moderately more important. This resulted in a decrease of an inconsistency ratio as well. Now, the inconsistencies per decision maker are calculated again and presented in **Table 16**. There is still one inconsistency, but this inconsistency is not far above the limit.

	Process Specialist	Manager Operations	Department Manager	COO
Quality Costs Speed Layout Flexibility	0.06074	0.09872	0.159	0.08117
Feasibility Sheet dimensions	0.00	0.00	0.00	0.00
Maximum PT Maximum BL Maximum BH Minimum BS	0.04388	0.08694	0.09674	0.09912

***Table 16:** The revised inconsistency ratios per decision maker*

Since the inconsistencies are determined per decision maker, this means that each decision maker has its own weights for each criterion and sub-criterion as well. **Table 17** gives an overview of all the weights per decision maker.

	Process Specialist	Manager Operations	Department Manager	COO
Quality	0.36534	0.24392	0.24785	0.07213
Costs	0.10553	0.07862	0.17833	0.29752
Speed	0.15753	0.11936	0.09252	0.29752
Layout	0.03905	0.03435	0.04377	0.0353
Flexibility	0.33255	0.52376	0.43752	0.29752
Feasibility	0.75	0.8	0.83333	0.875
Sheet dimensions	0.25	0.2	0.16667	0.125
Maximum PT	0.05689	0.05565	0.06188	0.04462
Maximum BL	0.12187	0.11013	0.15632	0.19299
Maximum BH	0.26335	0.29495	0.3909	0.21287
Minimum BS	0.55789	0.53927	0.3909	0.54953

***Table 17:** The revised weights per decision maker*

6.5 Value of the performances of the alternatives on the criteria

In this section, we create values for the relevant machine types. These values represent the performance of each machine type on every criterion that is an endpoint and every sub-criterion that is an endpoint. It is possible to use the AHP approach to create values for the alternatives. As we used the AHP approach to determine the weights for the criteria, we use the direct rating technique from SMART to determine the values for the performances of the alternatives on the criteria. It is important to use a normalized value for the performances, which means that every performance receives a score between 0 and 100.

In this research, we combine two separate Multi Criteria Decision Analyses to solve one particular problem. The AHP approach was used to determine the weights for the criteria, and SMART is going to be used to determine the values of the performances. Normally, only a single MCDA type is used to determine the weights and the values of the performances. For the AHP, this would mean that the pairwise comparisons are used to determine the values of the performances, and for SMART this would mean that swing weights are used to determine the weights of the criteria.

If we look at the direct rating technique from SMART, the worst performance for a certain criterion receives value 0, and the best performance would receive value 100. If we now look at the raw scores of the alternatives, we see for example that 5 out of 6 alternatives have feasibility 19 out of 20. Normally, the weights are determined after the raw scores are known. In this situation, the 5 alternatives that score 19 out of 20 would receive 0 and the alternative that scores 20 out of 20 would receive 100. Since these performances are very close together, the decision makers would probably indicate by swing weights that the weight for feasibility is not that high. It therefore does not matter if an alternative receives value 0 even if that performance is not that bad. As discussed, one of the manufacturers needed almost 5 weeks to deliver all the necessary information. This forced us to determine the weights before all the information was known. Because the weights are determined before all the information was available, we have decided to determine the values ourselves. In consultation with the decision makers at Pan Oston, we determined the worst and best thinkable performance for each criterion. This means that not every criterion has a 0 value and a 100 value.

We first start with the easy and more obvious decisions. If we look at the quality, every machine that is considered has an automatic angle measurement system. Initially, the machine from RAS was considered as well and this machine does not have such a measurement system. Therefore, this criterion was included. If the machine from RAS would have such a system, all the relevant machines score the same on this point. In that case, it was not needed to include this criterion. Eventually, the machine from RAS dropped off because it failed to meet the first boundary condition. Since we did not know this on beforehand, the quality criterion remained part of the AHP. Because all the machines have such an automatic angle measurement system, all the machines receive value 100 for quality. **Table 18** gives an overview of the scores on all the criteria and sub-criteria per machine type.

The second criterion where we look at is costs. The costs for all the machines are presented in **Table 8**. The relative differences between costs are bigger than compared to quality and feasibility. Therefore, the values for each machine have bigger differences as well. The best value is equal to the cheapest machine, which in this case is the Prima Power FBe2220. Thus, the Prima Power FBe2220 receives value 100. The most expensive machine is the Salvagnini P4L-2225, which receives value 0. As discussed, with the direct rating technique the decision makers are asked to value the improvement on a scale from 0 to 100. According to the decision makers at Pan Oston, the improvement from €800,000.00 to €700,000.00 has equal importance as the increase from €1,000,000.00 to €900,000.00. Therefore, the values are determined based on a linear scale, where €600,563.00 receives value 100 and €1,202,770.00 receives value 0. All the raw scores of the costs are presented in **Table 8** and are converted into the following values:

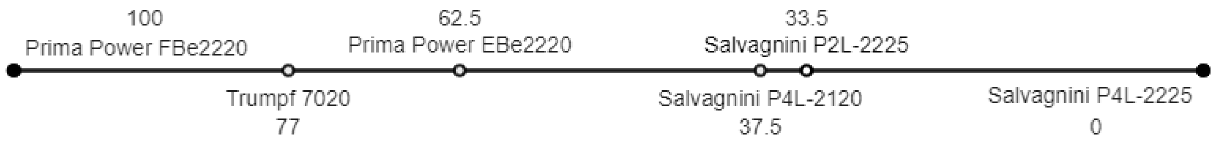

***Figure 7:** Overview of the values for costs for each alternative*

The next value that we are going to determine is the speed. Every panel bender has tested at least 20 products, from which the feasibility and speed are determined per machine type. This resulted in 20 percentages per machine type. The average is taken of these 20 products and this represents the time that the panel bender needs compared to the current process. For example, one of the values is 41.50%, which results in a value of 100 minus 41.5 equals 58.5. The other values are determined in this way as well. All the values for the different machines are presented in **Table 18**.

Eventually, the decision makers were asked about the layout of the machines. If the machine is compact enough to turn, this machine receives the maximum score. The machines that are compact enough to turn are the Prima Power FBe2220, the Salvagnini P2L-2225 and the Trumpf 7020. If we look at these three machines, they do not have an automatic loading and unloading device. This makes them relatively compact. The two P4 versions of Salvagnini and the EBe2220 of Prima Power have an automatic loading and unloading device, which means that they have an oblong structure. Because of this, these machines cannot be turned into the desired position. The current structure of the metal department has to change if a machine with automatic loading and unloading is placed. In addition, these machines do have a flow of products, which resulted in a value of 50 for these machines.

The next component that is discussed is the feasibility of the products. **Table 10** presents the feasibility per machine type. The worst conceivable outcome is that none of the 20 products can be made. Of course, we would give this performance value 0. On the other hand, the best conceivable outcome is that all the products are feasible. This would receive value 100. It is also possible to use another scale, for example that the best performing machine receives score 100 and the worst performing machine receives score 0. In this case, it is not realistic to say that the worst performing alternative receives score 0, since 19 out of 20 is actually a good performance. Since 19 out of 20 is 95%, the Prima Power EBe2220, both Salvagnini types, and the Trumpf 7020 receive value 95. The Prima Power FBe2220 receives value 100, since it is able to produce all the products.

The maximum plate thickness is the first sub-criterion under the sheet dimensions sub-criterion. After we have selected the 35 most relevant products, we added the plate material and plate thickness to the entire list. The result of this was that 29 out of 4827 products are made of thickness 5.0 millimeters. Since none of the panel benders is able to bend 5.0 millimeters, this does not have influence on the decision. In addition, 162 products are made of thickness 3.0 millimeters, which only the machine of RAS is not able to produce. In the first place, we considered the machine from RAS as well because of this, but since the machine from RAS failed to meet the first boundary condition, this machine dropped off. Because the left over selection of machines are all able to bend at least 3.0 millimeters in thickness, all the machines receive the maximum value for this sub-criterion.

The second sub-criterion under sheet dimensions is the maximum bending length. Initially, the machines that are able to bend up to 3000 millimeters in length were considered. After analyzing the production data, we can conclude that this is not necessary, since the majority of the products is under 2000 millimeters in length. The lowest outcome of the machines is the bending length of Trumpf, which is 2163 millimeters. Since the majority of the products is under 2000 millimeters in length, it does not makes sense to give the maximum bending length of Trumpf value 0. The lowest value is determined on 2000 millimeters, and the highest value is determined on 2250 millimeters. Again, the decision makers indicated that the improvement from 2000 to 2100 millimeters is equal to the improvement from 2100 to 2200 millimeters. This is due to the fact that the majority of the products is under 2000 millimeters in length. This results in a linear scale for this sub-criterion as well.

For the maximum bending height, we do not use a linear scale. In contrast to the maximum bending length, there are many different products in this range. If we consider the lowest outcomes for this sub-criterion presented in **Table 9**, this is 203 millimeters. Since none of the tested products is not feasible because of height limits, this lowest value is not bad. Therefore, value 0 is determined on a height of 150 millimeters, instead of 203 millimeters. The decision makers were asked, and indicated that the improvement from 203 to 254 millimeters in height is perceived as 2 and a half times as preferable as the improvement from 150 to 203 millimeters in height. Therefore, the machines that are able to bend 254 millimeters in height receive value 70, while the machines that are able to bend only 203 millimeters in height receive value 20. The Trumpf machine has the highest bending maximum bending height, which means that this machine receives value 100.

Last, the values for the minimum box size are determined. If we look at the raw scores, there are different possibilities in box size. Pan Oston produces a lot of different products, ranging from very small to very large. We cannot say that if a box size is under a specific dimension, it is possible to produce every single product. The decision makers indicated that the smaller the box size is, the better. Furthermore, there are not specific preferences in improvement, which means that the values are based on a linear scale. Since the box size consists of a length and a width, we first determine values for these separately and then take the average of it. The smallest width is 130 and the biggest width is 180. If we consider the Salvagnini P2, this has a width of 170. The difference between 180 and 130 equals 50 millimeters, and the difference between 180 and 170 equals 10. If we then divide 10 by 50, this equals .2. Thereafter, we do the same for the length, where 200 is the smallest value, and 420 is the biggest value. For this example, the Salvagnini P2 has outcome 420, which results in value 0. If we average 0 and 20, the value for the Salvagnini P2 on minimum box size is 10. This is done for the other machine types as well. All the results are presented in **Table 18**.

	Prima Power		Salvagnini			Trumpf
	FBe2220	EBe2220	P4L-2120	P4L-2225	P2L-2225	7020
Quality	100	100	100	100	100	100
Feasibility	100	95	95	95	95	95
Costs	100	62.5	37.5	0	33.5	77
Layout	100	50	50	50	100	100
Speed	63.99	64.81	63.5	63.5	58.5	61.45
Maximum plate thickness	100	100	100	100	100	100
Maximum bending length	100	100	72	80	80	65
Maximum bending height	20	20	20	70	70	100
Minimum box size	38.5	38.5	84	10	10	85

Table 18: *Overview of the values for all the criteria and sub-criteria per machine type*

6.6 Which panel bender is the most preferred?

Now the values are determined, we can use this in combination with the weights to determine the ranking of the alternatives. Since each decision maker has other weights, each decision maker has its own ranking of alternatives. To determine the final scores of the different machine types, each criteria weight and sub-criteria weight are multiplied by the weight of the criteria and sub-criteria that are on a higher level. To illustrate this, the full calculations of the process specialist are presented next. **Figure 8** shows the weights for each criterion. If we sum each endpoint in this value tree, this equals 1. The calculations for all the decision makers are presented in appendix E.

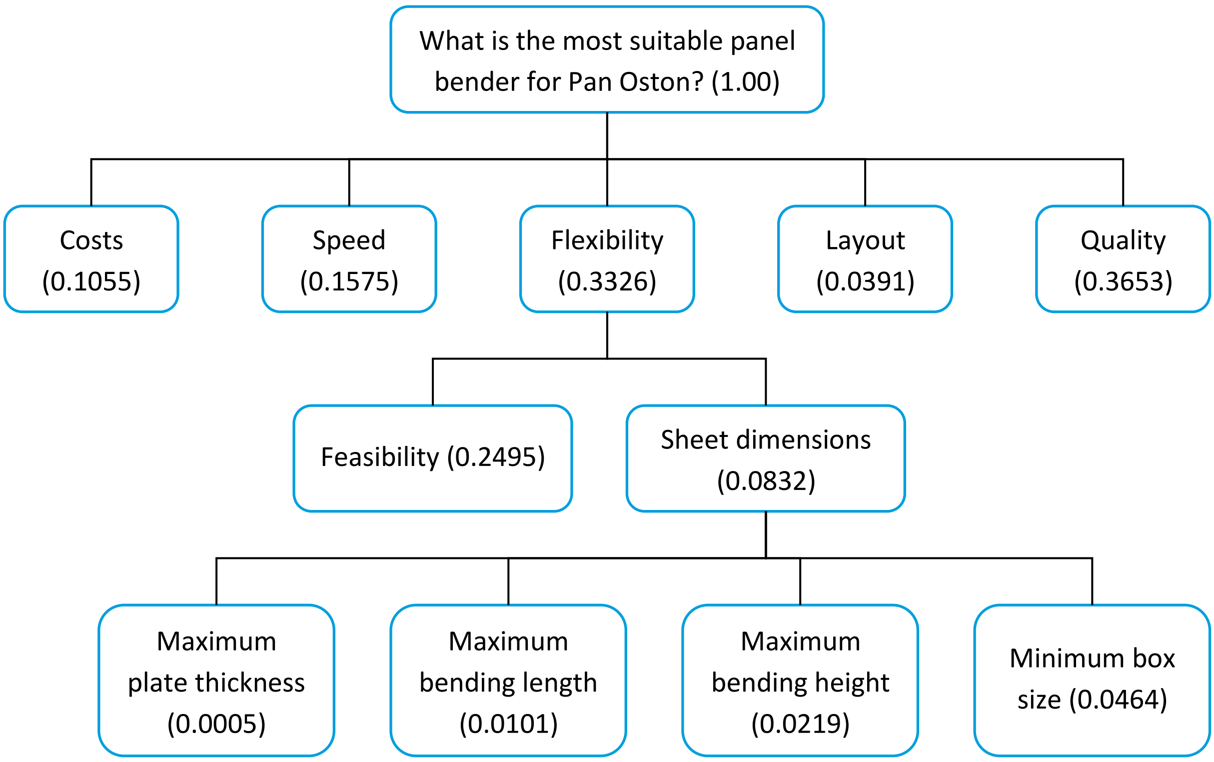

Figure 8: *The value tree with weights of one of the decision makers*

Considering **Figure 8** with the weights of one decision maker, and **Table 18** with the values for the alternatives, the following calculations are set up:

Prima Power FBe2220 = (0.1055 x 100) + (0.1575 x 63.99) + (0.0391 x 100) + (0.3653 x 100) + (0.3326 x 0.75 x 100) + (0.3326 x 0.25 x 0.0569 x 100) + (0.3326 x 0.25 x 0.1219 x 100) + (0.3326 x 0.25 x 0.2633 x 20) + (0.3326 x 0.25 x 0.5579 x 38.5) = 89.7234

Prima Power EBe2220 = (0.1055 x 62.5) + (0.1575 x 64.81) + (0.0391 x 50) + (0.3653 x 100) + (0.3326 x 0.75 x 95) + (0.3326 x 0.25 x 0.0569 x 100) + (0.3326 x 0.25 x 0.1219 x 100) + (0.3326 x 0.25 x 0.2633 x 20) + (0.3326 x 0.25 x 0.5579 x 38.5) = 82.6957

Salvagnini P4L-2120 = (0.1055 x 37.5) + (0.1575 x 63.5) + (0.0391 x 50) + (0.3653 x 100) + (0.3326 x 0.75 x 95) + (0.3326 x 0.25 x 0.0569 x 100) + (0.3326 x 0.25 x 0.1219 x 72) + (0.3326 x 0.25 x 0.2633 x 20) + (0.3326 x 0.25 x 0.5579 x 84) = 81.6777

Salvagnini P4L-2225 = (0.1055 x 0) + (0.1575 x 63.5) + (0.0391 x 50) + (0.3653 x 100) + (0.3326 x 0.75 x 95) + (0.3326 x 0.25 x 0.0569 x 100) + (0.3326 x 0.25 x 0.1219 x 80) + (0.3326 x 0.25 x 0.2633 x 70) + (0.3326 x 0.25 x 0.5579 x 10) = 75.4641

Salvagnini P2L-2225 = (0.1055 x 33.5) + (0.1575 x 58.5) + (0.0391 x 100) + (0.3653 x 100) + (0.3326 x 0.75 x 95) + (0.3326 x 0.25 x 0.0569 x 100) + (0.3326 x 0.25 x 0.1219 x 80) + (0.3326 x 0.25 x 0.2633 x 70) + (0.3326 x 0.25 x 0.5579 x 10) = 80.1641

Trumpf 7020 = (0.1055 x 100) + (0.1575 x 61.45) + (0.0391 x 100) + (0.3653 x 100) + (0.3326 x 0.75 x 95) + (0.3326 x 0.25 x 0.0569 x 100) + (0.3326 x 0.25 x 0.1219 x 65) + (0.3326 x 0.25 x 0.2633 x 100) + (0.3326 x 0.25 x 0.5579 x 85) = 89.2028

As said, these calculations are done for all the decision makers. The following table presents the ranking per decision maker:

	Prima Power		**Salvagnini**			**Trumpf**
	FBe2220	EBe2220	P4L-2120	P4L-2225	P2L-2225	7020
Process Specialist	1	3	4	6	5	2
Manager Operations	2	4	3	6	5	1
Department Manager	1	3	5	6	4	2
COO	1	3	4	6	5	2

Table 19: *Overview of the ranking of the machines per decision maker*

As visible in the results, the Prima Power FBe2220 scores very well, in combination with the Trumpf 7020 that is a very good runner-up. If we look at the calculations in appendix E, we can see that for the Process Specialist, the Manager Operations, and the Department Manager, the scores between the FBe2220 and the 7020 are very close. If we look at the Manager Operations, this is the only decision maker that has a different ranking in the top three. The difference in score between alternative 1 and alternative 2 is only 0.5 on a scale from 0 to 100. Besides, the difference in score between alternative 3 and 4 is very small as well. This difference is only 0.1. For the COO, the scores between the FBe2220 and the 7020 have a bigger difference. One of the reasons for this bigger difference is that the COO has the highest weight for costs, together with speed and flexibility. Because the Trumpf 7020 scores a bit below the FBe2220 on costs, this difference is somewhat bigger.

If we look at the outcomes for each alternative on every criterion and sub-criterion, we see that the FBe2220 scores very well on quality, costs, layout, feasibility, and maximum bending length. The hypothesis was that this machine scores the best, which is also the case for 3 decision makers. However, it is somewhat surprising that the Trumpf 7020 is that close behind. The Prima Power FBe2220 is a semi-automatic panel bender that needs an operator for turning the metal plates. The Trumpf 7020 is an automatic panel bender, but has manual loading and unloading. Thus, we can conclude that the Prima Power FBe2220 is the most preferred option. In the next section, the sensitivity analysis is performed, to see what happens with the rankings if the weights change.

6.7 Sensitivity analysis

Since the ranking of the alternatives is dependent on the weights for the criteria and sub-criteria, and these weights are based on subjective judgements, it is important to perform a sensitivity analysis. The purpose of performing a sensitivity analysis is to increase the confidence by the decision makers in the selected alternative. Questions that are answered by a sensitivity analysis are: “what is the smallest change in the weights that will result in a change of the selected alternative?” or “if there are multiple decision makers, each with different weights, how many decision makers are actually selecting the same alternative?”. Thus, for some of the criteria the weights are changed to see what happens. It is important to mention that the sum of the weights has to remain one. This means that if a weight increases, automatically the other weights have to decrease to remain one as sum.

An example of a question that is answered in a sensitivity analysis is: “what is the smallest change in the weights such that a specific alternative has the highest ranking?”. If we look at the results, the Manager Operations is the only decision maker that has a different top three ranking. If we look at the weights of the Manager Operations, the weight for flexibility stands out. If the weight for flexibility decreases from 0.5238 to 0.4717, the Prima Power FBe2220 has the highest ranking, and the Trumpf 7020 changes to place two. This is clearly visible in **Figure 9**.

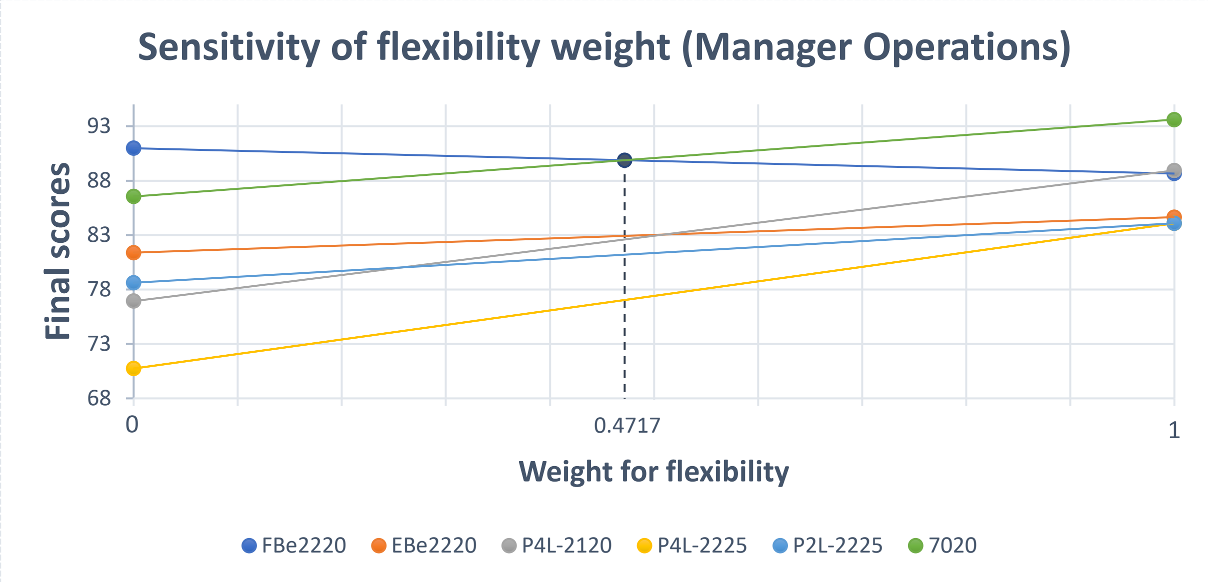

Figure 9: *Sensitivity for the flexibility criteria of the Manager Operations*

The next decision maker that we consider is the Chief Operational Officer (COO). The COO has some remarkable differences in the weights compared to the other decision makers. For example, if we look at the flexibility criterion, First, the differences are less drastic than for the Manager Operations, but some orders change. The current weight for flexibility is 0.2975 and an increase to 0.9905 leads to a different most preferred alternative. As presented in **Figure 10**, the Trumpf 7020 would then be number one instead of the Prima Power FBe2220. In addition, Salvagnini P4L-2120 would receive the third preference if the weight increases from 0.2975 to 0.8198. If the weight becomes smaller than 0.2975, the order of the machines does not changes. We can conclude that the weight for the flexibility criterion for the COO does not have as much influence on the outcome compared to the Manager Operations.

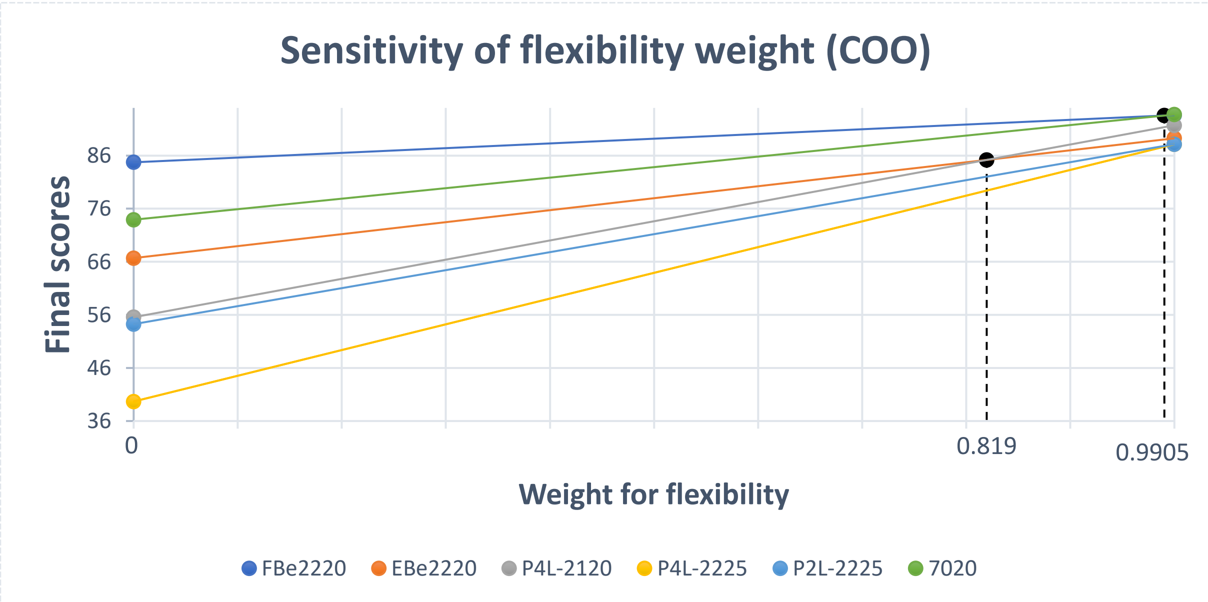

Figure 10: *Sensitivity for the flexibility of the COO*

6.8 What is the Return on Investment (ROI) of the panel bender?

One of the wishes of the decision makers at Pan Oston was an indication about the Return on Investment of the panel bender. In this section we elaborate further on the Return on Investment of different alternatives. As presented in appendix D, each product can be classified to one of four categories. These categories are based on the setup time of the products, and the processing times of the products. This is also discussed in Chapter 4, but those categories were based on 35 products. After Trumpf replied and only tested 20 products, we cannot use 9 categories anymore. Now, we do not use the category medium, but only low and high. This is less accurate than before, but it is not possible to create 9 categories out of only 20 products. Therefore, the following 4 categories remain:

Setup time	Processing time
High	High
High	Low
Low	High
Low	Low

Table 20: *The revised 4 product categories*

If the setup time is higher than 60 seconds, the setup time is categorized as high. Obviously, if the setup time is 60 seconds or lower, the setup time is low. The processing time is high if it is more than 66 seconds, otherwise it is categorized as low.

To give a clear view about the ROI of the panel benders, we calculate the ROI of three different machine types. The first one is the Prima Power FBe2220. This is a semi-automatic panel bender. Second, the Trumpf 7020 is an automatic panel bender with manual loading and unloading. Third, the Salvagnini P4L-2120 is an automatic panel bender with automatic loading and unloading. The average speed per product category is calculated and presented in **Table 21**. Again, these percentages must be interpreted as the time out of the original time. In other words, if a product takes 100 seconds, and the speed is 20%, then it only takes 20 seconds by the machine to produce that product. If we look at the Salvagnini P4L-2120 from **Table 21**, this machine produces on average products with a high setup time and high processing time in 15.74% of the total time.

		Prima Power	Trumpf	Salvagnini
Setup Time	**Processing Time**	FBe2220	7020	P4L-2120
High	High	21.19%	22.62%	15.74%
High	Low	31.51%	32.89%	31.43%
Low	High	37.94%	39.30%	41.16%
Low	Low	42.45%	49.68%	39.37%

Table 21: *Average speed of the selected products per category*

The product category is applied to the total production data set as well. The total production minutes equals 348,783.68 minutes, but as discussed in Chapter 4 not every product is suitable to produce on a panel bender. We checked 503 products and 30.9% of these products were judged as feasible to produce on a panel bender. We therefore multiply the total production minutes by 0.309 to have a more realistic estimation, which equals 107,774.16 minutes. Of these 107,774.16 minutes, 40,500.54 minutes were in the high – high category, 26,778.87 were in the high – low category, 6,652.97 were placed in the low – high category, and 33,841.78 were placed in the low – low category. If we multiply these values to the outcomes from **Table 21**, this results in the outcomes presented in **Table 22**. These outcomes are presented in minutes.

		Prima Power	Trumpf	Salvagnini
Setup Time	**Processing Time**	FBe2220	7020	P4L-2120
High	High	8,582.06	9,161.22	6,374.78
High	Low	8,438.02	8,807.57	8,416.60
Low	High	2,524.14	2,614.62	2,738.36
Low	Low	14,365.84	16,812.60	13,323.51
	Sum	33,910.06	37,396.01	30,853.25

Table 22: *Indication of the time that is needed for the products per machine type*

It is surprising that the semi-automatic variant from Prima Power is faster than the automatic variant from Trumpf with manual loading and unloading. This indicates that the manual loading and unloading takes a lot of time. If we compare the fully automatic variant from Salvagnini, this one is significantly faster than the other two. If we look at **Table 22**, we can conclude that the Prima Power saves 107,774.16 minus 33,910.06 equals 73,864.1 minutes in 17 months. Converted into a single year this equals 52,139.36 minutes. For the Trumpf 7020 this equals 49,678.69 minutes per year and for the Salvagnini P4L-2120 this equals 54,297.11 minutes. According to the COO and process specialist, an employee working at the metal department costs the company €65.00 per hour. We now can calculate how much this saves per year per machine. This is presented in **Table 23**.

Machine	Costs	Savings (minutes per year)	Savings (€ per year)	ROI
FBe2220	€600,563.00	52,139.36	€56,484.31	9.41%
7020	€739,475.00	49,678.69	€53,818.58	7.28%
P4L-2120	€978,510.00	54,297.11	€58,821.87	6.01%

Table 23: *Costs, savings, and ROI per machine type*

As presented in **Table 23** above, each Return on Investment is not very high. One of the reasons of this is that only the employee savings are taken into account. There are also other factors that could influence the ROI in a positive way. For example, it is possible to apply a small redesign to a product, causing that the panel bender can produce this product. This results in an increase of the efficiency of the panel bender, and thus an increase in the ROI as well.

Second, the production partner of Pan Oston in Slovakia is planning to invest in a panel bender as well. The production series in Slovakia are much bigger than compared to the facility in Raalte. Having bigger series means that there is less time spend on programming and setting up the machine. Eventually, this would lead to a higher ROI as well. On the other hand, the labor costs in Slovakia are much lower than in the Netherlands, which will cause a decrease of the ROI. Besides that, according to the company managers it is possible to receive an European subsidy if the production partner in Slovakia invests in a panel bender. This will again increase the ROI. The company managers of Pan Oston have to take this combination of factors into account before investing in a panel bender.

6.9 Conclusion

In this chapter we have applied the AHP approach and SMART to find the most preferred panel bender. We first determined the weights by means of pairwise comparisons. Each decision maker has done these pairwise comparisons and have received individual weights for each criterion. To ensure that the decision makers are consistent enough, we calculated the inconsistency ratios for each decision maker. Eventually, for the Manager Operations and the Metal Department Manager, some pairwise comparisons are reassessed to improve the inconsistency ratios. Thereafter, the values for the performances of the alternatives on the criteria are determined by using the direct rating technique from SMART. These values are the same for each decision maker and are multiplied by the individual weights of each decision maker. This resulted in the following rankings:

	Prima Power		**Salvagnini**			**Trumpf**
	FBe2220	EBe2220	P4L-2120	P4L-2225	P2L-2225	7020
Process Specialist	1	3	4	6	5	2
Manager Operations	2	4	3	6	5	1
Department Manager	1	3	5	6	4	2
COO	1	3	4	6	5	2

The Process Specialist, the Department Manager and the COO have the same top three, while the Manager Operations has a different top three. One of the cornerstones of the AHP approach is the sensitivity analysis, and it is used to increase the confidence by the decision makers on the selected alternative. In Section 6.7, we performed this sensitivity analysis to see what will happen with the raking if we change the weights. To change the Prima Power FBe2220 to the most preferred alternative for the Manager Operations, the weight for flexibility should decrease from 0.5238 to 0.4717. Therefore, the Prima Power FBe2220 is the most preferred option based on these 6 alternatives. One of the wishes of the decision makers was an indication about the ROI of the most preferred option. The ROI of the most preferred option, the Prima Power FBe2220, is 9.41%.

7 Conclusion and recommendations

In this last chapter we provide a conclusion and a recommendation for the decision makers at Pan Oston. The purpose of this conclusion is to give an answer to the main research question discussed in Chapter 1. We start with the conclusion in Section 7.1. The conclusion is followed by the recommendations in Section 7.2, whereafter we have the discussion in Section 7.3. Eventually in Section 7.4 we discuss the future research possibilities.

7.1 Conclusion

As said, the purpose of the conclusion is to give an answer to the main research question. In this research, the main research question is:

> *"Which panel bender should Pan Oston buy in order to decrease the tool changing times at the metal department?"*

One of the ways to answer this question is by performing a Multiple Criteria Decision Analysis (MCDA). A MCDA is an umbrella term to describe a collection of methods that take multiple criteria into account. One of these methods is the Analytic Hierarchy Process (AHP), which is used in this research. In combination with the direct rating technique from SMART, these methods were used to answer the main research question. Before the research started, Pan Oston already had contact with several potential suppliers about a panel bender. These manufactures are Salvagnini, Trumpf, and RAS. Eventually, by looking through the Internet an additional potential manufacturer was found. This last manufacturer is Prima Power and is just as Salvagnini an Italian company. Each manufacturer has different machines in different configurations. In general, three types of panel benders can be considered. First, a semi-automatic panel bender which requires manual turning, and loading and unloading. Second, an automatic panel bender with manual loading and unloading, and third an automatic panel bender with automatic loading and unloading.

To be able to assess the different alternatives, we have set up criteria and sub-criteria. This is done in combination with the 4 decision makers at Pan Oston: the Process Specialist, the Metal Department Manager, and the Chief Operational Officer. The five main criteria are costs, speed, flexibility, layout, and quality. Under flexibility, there is an additional layer with sub-criteria consisting of sheet dimensions and feasibility. Last, under sheet dimensions there is a third layer with sub-criteria consisting of maximum plate thickness, maximum bending length, maximum bending height, and minimum box size.

Now, the next important thing to consider is the production data. Since not every product is equally important, we have to select the most relevant products. For example, some products are produced in higher quantities than others, but the quantities do not say a lot about the relevance of the products. Boxes that are used for the installation of electronic systems are produced in much higher quantities than side walls or bottom plates. In addition, it is generally speaking a lot easier to produce smaller products than bigger products. Thus, bigger products take more time to produce and a panel bender can handle bigger products better than smaller products. Therefore, we looked at the total production time of the past one and a half years to select the most relevant products. We selected the 35 most relevant products based on their production times. These products were checked by the metal department manager and a engineering specialist if not any bending characteristics are missing. Eventually, the manufacturers were asked to perform tests with these 35 products. These tests say something about the speed and the feasibility of the panel bender.

Thereafter, we discussed the boundary condition that says that at least 75% of the selected products must be entirely feasible to produce by the panel bender. Since we carefully selected the 35 products based on feasibility, this value is that high. The panel benders from RAS did not meet this boundary condition, which caused that this manufacturer is not considered anymore. In addition, after analyzing the production data, we came to the conclusion that it is not necessary to analyze machines that are able to bend up to 3000 millimeters in length. The majority of the products were under 2000 millimeters in length, and the products that were above 2000 millimeters in length were in general very small. Very small products cannot be made by the panel bender, which means that a machine that is able to bend up to 2000 millimeters satisfies. This leaves us with the following list of relevant machines:

- Prima Power FBe2220
- Prima Power EBe2220
- Salvagnini P4L-2120
- Salvagnini P4L-2225
- Salvagnini P2L-2225
- Trumpf TruBend 7020

We end up with 6 possible alternatives, which means that a lot of pairwise comparisons are needed to create scores for this. We therefore decided to use the direct rating technique from SMART to give values to the alternatives. Before we continue with SMART, the AHP was used to create weights for the criteria and sub-criteria. This was done by performing pairwise comparisons for each decision maker. This is done to create individual input, rather than a joint input in which a COO could have more involvement in the decisions than the other decision makers. Subsequently, the decisions of each decision maker were checked on inconsistencies and three decision makers have made some changes. This resulted in only a single inconsistency, compared to three inconsistencies in the first place. Then, an estimation can be made about the weights per criterion and sub-criterion for every decision maker. Eventually, the weights are multiplied by the values, which resulted in a final score per alternative per decision maker.

Every decision maker has the Prima Power FBe2220 as most preferred option, except for the Manager Operations who has the Trumpf 7020 as most preferred option. As the sensitivity analysis has shown, the weight for the flexibility criterion for the Manager Operations requires a decrease of .0521 to change the Prima Power FBe2220 from second preferred option to the most preferred option. As said, three out of 4 decision makers have the FBe2220 as most preferred option. The Manager Operations has the Trumpf 7020 as most preferred option, but the FBe2220 is very close behind. If we look at the weight of the flexibility criterion for the Manager Operations, this only requires a decrease of .0521 to change the FBe2220 to the most preferred option. Therefore, we choose the Prima Power FBe2220 as most preferred option. One of the wishes of the decision makers was an indication about the ROI of the panel bender. This ROI of the FBe2220 is 9.41%.

7.2 Recommendations

In this section, we give an explanation about how the decision makers at Pan Oston can continue with the provided information and what should be investigated further. In the first place, the machine manufacturers have indicated that the prices of the raw materials can fluctuate a lot. As you can imagine, the panel benders are made of many different components ranging from metal to aluminum and to plastic. Because the prices of the raw materials can fluctuate, the budgetary reports have a date after which it expires. It is important to watch these dates carefully, otherwise unexpected additional costs may arise.

Second, unfortunately Trumpf could only test a single machine, rather than two or three. This forced us to make a choice in advance about which machine potentially is the best for Pan Oston. We chose the automatic variant with manual loading and unloading. However, the Prima Power FBe2220 is the semi-automatic variant which is the most preferred option after performing the AHP approach. Trumpf has also a semi-automatic variant in the form of the Trumpf TruBend 5030. Therefore, it is surely worth the effort to look at the Trumpf 5030, because the production facility of Pan Oston in Raalte already has a Trumpf laser. In addition, the production partner in Slovakia has many traditional bending machines from Trumpf. Because of this, we recommend to look at the Trumpf 5030 as well.

In addition, Trumpf only tested 20 products instead of the 35 products that were desired. We have now drawn conclusions based on these 20 products. To come up with conclusions that are more precise, Pan Oston should ask Trumpf to test the remaining 15 products. In this way, a more accurate conclusion can be made about how much faster the panel bender exactly is compared to the current process.

Then we move on to the recommendations for the implementation. Before the implementation can start, the company managers of Pan Oston should inform all the employees that a new machine is coming. Especially the employees from the metal department where the machine will be placed. In addition, the employees of the engineering department need training about which products can be made and which not. In addition, the management team has to set clear goals and express their expectations about using the panel bender.

In addition, Pan Oston possesses a single laser. This single laser cannot supply 4 traditional bending machines, which means that between 50 and 60 percent of the laser cutting is outsourced. During calculating the ROI, we have found that for the FBe2220 3.34 hours per day are saved. In other words, if it normally takes a day (8 hours) to produce a set, this now takes only 5 hours, 39 minutes, and 36 seconds. This does not only mean that the panel bender is faster, it can also produce more products per day. To keep the panel bender running as much as possible, it is important to consider the capacity of the suppliers. Thus, before the company invests in a panel bender, it must make sure that the suppliers have enough capacity to keep the panel bender running.

Thereafter, not only suppliers are important to keep the panel bender running, the employees of the metal department as well. In the past 7 months we have done research at Pan Oston ranging from 2 days per week to 5 days per week. In this period, we have experienced that a workweek for Pan Oston employees at the metal department consists of 4 days, from 7:00 AM until 17:00 PM. This means that the employees have a day off once per week. Currently, the planner takes this already into account. However, there are some days that there is only a single person working. To keep optimal efficiency, at least a single person must operate the panel bender and at least a single person must operate a traditional bending machine. To facilitate this, more than one person should be trained to operate the panel bender, in order to keep the panel bender running at all times.

7.3 Discussion

In this discussion section, we look back at the decisions that were made during the research and give an elaboration about why these decisions were taken. In the first place, to be able to assess the performance of the panel benders on speed and feasibility, we had to send the manufacturers a set with products. To create this set, 503 products were checked on dimensions and eventually judged on feasibility. One of the main results of the tests was that the semi-automatic variant scores very well, despite the fact that this variant does not use any automatic loading or unloading device. This is mainly due to the fact that the production series of Pan Oston in Raalte are very low. If we then look at the Return on Investment of the most preferred panel bender, this is a very rough estimate. First, the products are judged on feasibility based on their dimensions. This is a subjective judgement which means that the actual percentage of the feasibility of the products could be a bit higher or lower. Second, during calculating the ROI, only the employee savings are taken into account. In other words, if a panel bender is 3 hours per day faster than the current process, we would save 3 employee hours, and the rest of the day the panel bender would be shut off. This is not the case in reality, and therefore the decision makers at Pan Oston should not hold on this ROI values too much.

Second, in order to gather all the information about the panel benders, account managers were interviewed and the Internet was searched. Some account managers needed almost 5 weeks to provide all the information. As a result, we were forced to determine the weights for the criteria before all the information was available, which normally happens after the information is known. One of the results of this was that the quality criterion and the maximum plate thickness criterion were included in the AHP approach, while this was not needed. Second, we used both the AHP approach and SMART during this research. A better way to use the AHP approach was to determine the weights after all the information was known, and a better way to use the SMART technique was to use a normalized scale, for example ranging from 0 to 100.

7.4 Future research

In this section, we elaborate further on the possibilities Pan Oston has on doing further research on the panel bender. First of all, the production partner of Pan Oston in Slovakia is not taken into account. The production partner of Pan Oston must be adjusted to the production process in Raalte. This means that if the facility in Raalte decides to invest in a panel bender, the production partner in Slovakia needs a panel bender as well. This production partner of Pan Oston is producing much more production series, which could mean that a more automatic panel bender is more suitable. However, the production data of this production partner must be taken into account to be able to make an adequate decision.

Second, we have only looked at the current products of Pan Oston. All the account managers of the manufacturers indicated that a lot of tricks can be applied in order to produce even more products on a panel bender. Some of these tricks are producing multiple of the same products out of the same part. These products are connected with a so-called “micro joint”. This is a very small and sensitive connection that can be broken by hand. Future research can be to determine how many products are suitable for this, and thereby more accurately determine the Return on Investment of the panel bender. However, this might be a very hard and intensive research to do.

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Appendix

A. Systematic Literature Review

In this part of the appendix, the main steps of the systematic literature review (SLR) are described.

1. Inclusion and exclusion criteria

Table 24 shows the inclusion and **Table 25** shows the exclusion criteria that are used to answer the first sub-question.

Inclusion	Motivation
Dutch or English language	In order to be able to understand the articles completely, the language must be Dutch or English.
Academic sources	The sources must be academic to use the information.
Steps	The sources should include the explanation of the steps that need to be taken, not just an research in which an MCDA is used

Table 24: *Inclusion criteria used during the SLR*

Exclusion	Motivation
Paid source	In order to get access to the source, it should be accessible through the University of Twente. Otherwise the sources are not relevant.
Not the term MCDA, Multiple Criteria Decision Analysis, or AHP in the title	The focus of this sub-question is to find out what the main steps are in executing an MCDA. If this terms are not included in the title, I will not use that source.

Table 25: *Exclusion criteria used during the SLR*

2. Defining the databases

During the systematic literature review, several databases can be used to gather information:

- Scopus
- Web of Science
- arXiv.org

Marit van Eck and Roberto Cruz Martinez both belong to the Information Specialist Faculty BMS at the University of Twente. According to them, the databases above are most suitable for the Industrial Engineering and Management program. Scopus and Web of Science both have a lot of scientific articles, while the articles from arXiv.org are more related to mathematics, physics, statistics, and mathematical finance.

3. Search strategy

The sub-question that we want to answer is: "What are the main steps in executing a Multiple Criteria Decision Analysis (MCDA)?" In order to find relevant literature, it is useful to think of the key concepts. The key concepts of this sub-question are marked in bold:
"What are the main **steps** in **executing** a **Multiple Criteria Decision Analysis (MCDA)**?"

Table 26 shows the search matrix to answer the first sub-question.

Key concepts	Related terms	Broader terms	Narrower terms
Steps	Strategy, Method, Parts, Aspects	Way	Components, Characteristics
Multiple Criteria Decision Analysis	MCDA, Multiple Criteria Decision Making, MCDM	Analysis	SMART, AHP
Execut*	Carry out, How to use	Implement, Approach	Perform, Apply
Criteria	Criterion	Attributes	

Table 26: *Search Matrix*

Considering these terms together with the inclusion and exclusion criteria, the literature search started. In **Table 27,** the systematic search is documented.

4. Search results

As discussed, the search results are discussed in this section and can be found in **Table 27**. At the bottom, the total number of articles is visible. This number does not contain the first entry, because these articles are not used during the search. Because the MCDA is a general approach, consisting of several methods, the search term AHP is used to narrow the results. To find the duplicates, the serial identifiers from the search results are exported to Excel, in which several formulas and actions are used to find the duplicates in the list. First, the "Text to Columns" function is used to sort the data. Thereafter, the data is selected and "Conditional Formatting" is used to highlight the cells that are duplicates. Last, arXiv.org is not used, because a more theoretical background was needed rather than mathematical or financial examples.

Date	Database	Search string	Results	Relevancy
4-11-2022	Scopus	how AND to AND use AND an AND MCDA	3891	There are too many results. I need to narrow the search string. Therefore, no results are selected.
4-11-2022	Scopus	mcda AND execution	22	By scanning the titles and some abstracts, only one article was relevant to use.
4-11-2022	Scopus	(ahp OR analytic hierarchy process) AND (smart OR simple multi-attribute rating technique)	25	This search string resulted in a few good outcomes, however, there were many very old results, which is not preferred. In addition, there was one practical example that helped me by the understanding of the AHP.
4-12-2022	Scopus	steps AND (execut* OR performing OR implementing) AND ahp	79	The results obtained seemed to be useful, however there were a lot of sources that were not supported by the UT. Therefore, only one source was useful.
4-12-2022	Scopus	ahp AND smart AND comparison	90	This string resulted in good results as well. There were (only) three useful options, because the other articles were more practical examples.

4-13-2022	Web of Science	characteristics AND apply* AND MCDA	28	This resulted also in an article that compares two types of MCDA's. However, only one article was useful.

Total articles	244
Duplicates	19
Removals	237
Total relevant sources	8

Table 27: *Search results*

As described above, there were many practical examples found. The goal is to describe the main steps of an MCDA, thus these articles were not very useful. Of course, some articles that contained an practical example did also explain the steps that are taken during the analysis. These articles mainly helped me to understand the AHP, rather than answering the concerned sub-question. Because of that, some articles were excluded. The following articles are used for the integration of theory:

Winston, W. L. (2003). *Operations Research.* Belmont, CA: Cengage Learning, Inc.

Al-Harbi, K. M. A.-S. (2001, January). Application of the AHP in project management. *International Journal of Project Management*, pp. 19-27.

Sumaryanti, L., Rahayu, T. K., Prayitno, A., & Salju. (2019). *Comparison study of SMART and AHP method for paddy fertilizer recommendation in decision support system.* Merauke: IOP Publishing.

Prieto-Amparán, J. A., Pinedo-Alvarez, A., Morales-Nieto, C. R., Valles-Aragón, M. C., Álvarez-Holguín, A., & Villarreal-Guerrero, F. (2021, February 18). A Regional GIS-Assisted Multi-Criteria Evaluation of Site-Suitability for the Development of Solar Farms. *Special Issue: Land Management in Territorial Planning: Analysis, Appraisal, Strategies for Sustainability II*, pp. 1-19.

Lakicevic, M., Srdjevic, B., & Velichkov, I. (2018, September 12). Combining AHP and SMARTER in Forestry Decision Making. *Technical development in forest regeneration in Finland, 24*(1), pp. 42-49.

Kadoic, N. (2018, December). Characteristics of the Analytic Network Process, a Multi-Criteria Decision-Making Method. *Croatian Operational Research Review*, pp. 235-244.

After reading the articles, I created the conceptual matrix. This conceptual matrix is can be found in Appendix 5, in **Table 28**.

5. Conceptual matrix

Below, the conceptual matrix can be found. The conceptual matrix contains the author(s) and the year of publication, the main concepts, and the most important findings that are found in the articles.

Author(s)	Concepts	Most important findings
(Winston, W. L., 2003)	Practical examples and theory of AHP	Winston describes the main steps that need to be taken during the AHP and gives an practical example about an AHP. This source helps by understanding the theory, rather than only describing the theoretical background.
(Sumaryanti, Rahayu, Prayitno, & Salju, 2019)	Comparison between AHP and SMART	The AHP is mainly used to solve larger problems, for example when dealing with problems that compare performance between alternatives, while SMART is used for environmental issues, and transportation and logistics.
(Sumaryanti, Rahayu, Prayitno, & Salju, 2019)	Theoretical background AHP	The 5 main steps of AHP are (1) set up the criteria and the alternatives, (2) determine the weights for the criteria, (3) calculate the consistency index, (4) calculate the local weights, and (5) determine the best alternative
(Al-Harbi, K. M. A.-S., 2001)	Theory supported by an practical example	The Consistency Index is calculated with the following function: CI = (λmax - n)/(n - 1). The judgement consistency can be checked by the given table and is acceptable if it is not higher than 0.10.
(Prieto-Amparán, et al., 2021)	Theory	The AHP method reduces complex decisions to a series of side-by-side comparisons. In addition, the method allows checking the consistency of the decision, thereby reducing bias in decision making.
(Lakicevic, Srdjevic, & Velichkov, 2018)	Theory	The weights that need to be given to the criteria are based on the Saaty's scale of relative importance. The value 1 means equally important, 3 means weakly more important, 5 means strongly more important, 7 means very strongly more important, and 9 means absolutely more important. Obviously, 2, 4, 6, and 8 are intermediate values.
(Lakicevic, Srdjevic, & Velichkov, 2018)	Mathematical examples	The formula mentioned by Al-Harbi, K. M. A.-S. (2001) is used in an example. Three decision makers used the formula, resulting in two valid outcomes and only one invalid outcome.
(Kadoic, 2018)	Theory and examples	This source uses a more comprehensive example, which is more applicable for my assignment. A big matrix (supermatrix) is separated into smaller clusters to avoid misunderstanding of the comparisons.

***Table 28:** The conceptual matrix*

6. Pairwise Comparison Matrix

All of the following information is gathered from the Operations Research book by Winston (2003). As said, this book helps by the understanding of the AHP, rather than only the theoretical background behind it. As described in Section 2.5, this section will give an elaboration on how to set up the pairwise comparison matrix. **Figure 11** shows the pairwise comparison matrix.

$$A = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \vdots & \vdots & & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{bmatrix}$$

Figure 11. *The pairwise comparison matrix. (Winston, 2003, p. 791)*

In this matrix, there are n objectives and w_i = the weight given to objective *i.* For example, if $w_1 = \frac{1}{2}$ and $w_2 = \frac{1}{6}$, objective 1 is three times as important as objective 2. Thus, $a_{12} = \frac{w1}{w2} = 3$ (Winston, 2003). Using a_{12} means that the first row and the second column is considered. Eventually, from this pairwise comparison matrix, the weights for the criteria can be calculated. Thereafter, these weights are used to set up the consistency index. This consistency index is discussed next, in Section 7.

7. Consistency Index

As said before, the consistency index (CI) is the index that measures the consistency of the judgements that are made across all the pairwise comparisons. By checking for consistency, the researcher reduces the bias in decision making (Prieto-Amparán, et al., 2021). How the CI is set up, can be find below.

The following figures contain a practical example, to illustrate how the CI is set up.

$$A\mathbf{w}^T = \begin{bmatrix} 1 & 5 & 2 & 4 \\ \frac{1}{5} & 1 & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & 2 & 1 & 2 \\ \frac{1}{4} & 2 & \frac{1}{2} & 1 \end{bmatrix} \begin{bmatrix} .5115 \\ .0986 \\ .2433 \\ .1466 \end{bmatrix} = \begin{bmatrix} 2.0775 \\ 0.3959 \\ 0.9894 \\ 0.5933 \end{bmatrix}$$

Figure 12: *A practical example of the first step in setting up the CI. (Winston, 2003, p. 792)*

The 4 by 4 matrix in **Figure 12** is equal to the pairwise comparison matrix from the previous step. However, this matrix already contains numbers instead of variables. Thereafter, the 4 by 4 matrix is multiplied by a 4 by 1 matrix containing the weights for the criteria. The answer from this multiplication is used in the next step.

$$\frac{1}{n}\sum_{i=1}^{i=n}\frac{i\text{th entry in }A\mathbf{w}^T}{i\text{th entry in }\mathbf{w}^T}$$
$$=\left(\frac{1}{4}\right)\left\{\frac{2.0775}{.5115}+\frac{.3959}{.0986}+\frac{.9894}{.2433}+\frac{.5933}{.1466}\right\}$$
$$=4.05$$

Figure 13: *The second step in setting up the CI. (Winston, 2003, p. 792)*

In this second step, the outcomes from step one are divided by the corresponding weights for the criteria. These values are summed up, whereafter this sum is multiplied by 1/*n* (*n* equals the number of criteria).

$$\text{CI}=\frac{(\text{Step 2 result})-n}{n-1}=\frac{4.05-4}{3}=.017$$

Figure 14: *The third step in setting up the CI. (Winston, 2003, p. 793)*

Eventually, the consistency index is calculated with the formula given in **Figure 14**. Thereafter, the CI must be compared to the random index (RI) for the appropriate value of n. This value can be obtained from **Table 29**. The last step is to check if $\frac{CI}{RI} < .10$. If this is the case, the pairwise comparison matrix does not have any serious inconsistencies (Winston, 2003).

n	RI
2	0
3	.58
4	.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.51

Table 29: *Values of the Random Index (RI). (Winston, 2003, p. 793)*

B. Pairwise comparisons of the Analytic Hierarchy Process

As discussed in Chapter 2, the Analytic Hierarchy Process (AHP) uses pairwise comparisons to determine the relative importance of the criteria and sub-criteria. The AHP allows decision makers to provide verbal descriptions of their view of the importance of criteria, in terms of “moderately”, “strongly”, or “absolutely” more important. These verbal descriptions are converted into numerical ratios (Belton & Stewart, 2002). These numerical values can be found in Chapter 2. in **Figure 4**, Important to mention is that intermediate values are possible as well. This means that the decision maker is able to choose an 8, while this is not presented in the table. This is indicated with double marking. For example, if moderate plus importance is chosen, which is equal to numerical value 4, both cell 3 and 5 are colored. In addition, in the third matrix, a few abbreviations are used to use a bit less space. Maximum PT stands for the maximum plate thickness, maximum BL stands for the maximum bending length, maximum BH stands for the maximum bending height, and minimum BS stands for the minimum box size.

The first decision maker that was interviewed was the process specialist. His preferences about the criteria are presented in the following tables.

Quality	1/9	1/7	1/5	1/3	1	3	5	7	9	Costs
Quality	1/9	1/7	1/5	1/3	1	3	5	7	9	Speed
Quality	1/9	1/7	1/5	1/3	1	3	5	7	9	Layout
Quality	1/9	1/7	1/5	1/3	1	3	5	7	9	Flexibility
Costs	1/9	1/7	1/5	1/3	1	3	5	7	9	Speed
Costs	1/9	1/7	1/5	1/3	1	3	5	7	9	Layout
Costs	1/9	1/7	1/5	1/3	1	3	5	7	9	Flexibility
Speed	1/9	1/7	1/5	1/3	1	3	5	7	9	Layout
Speed	1/9	1/7	1/5	1/3	1	3	5	7	9	Flexibility
Layout	1/9	1/7	1/5	1/3	1	3	5	7	9	Flexibility

Sheet dimensions	1/9	1/7	1/5	1/3	1	3	5	7	9	Feasibility

Maximum PT	1/9	1/7	1/5	1/3	1	3	5	7	9	Maximum BL
Maximum PT	1/9	1/7	1/5	1/3	1	3	5	7	9	Maximum BH
Maximum PT	1/9	1/7	1/5	1/3	1	3	5	7	9	Minimum BS
Maximum BL	1/9	1/7	1/5	1/3	1	3	5	7	9	Maximum BH
Maximum BL	1/9	1/7	1/5	1/3	1	3	5	7	9	Minimum BS
Maximum BH	1/9	1/7	1/5	1/3	1	3	5	7	9	Minimum BS

The second decision maker that is interviewed was the operational manager. His preferences about the criteria and sub-criteria are presented in the tables below.

Quality	1/9	1/7	1/5	1/3	1	3	5	7	9	Costs
Quality	1/9	1/7	1/5	1/3	1	3	5	7	9	Speed
Quality	1/9	1/7	1/5	1/3	1	3	5	7	9	Layout
Quality	1/9	1/7	1/5	1/3	1	3	5	7	9	Flexibility
Costs	1/9	1/7	1/5	1/3	1	3	5	7	9	Speed
Costs	1/9	1/7	1/5	1/3	1	3	5	7	9	Layout
Costs	1/9	1/7	1/5	1/3	1	3	5	7	9	Flexibility
Speed	1/9	1/7	1/5	1/3	1	3	5	7	9	Layout
Speed	1/9	1/7	1/5	1/3	1	3	5	7	9	Flexibility
Layout	1/9	1/7	1/5	1/3	1	3	5	7	9	Flexibility

Sheet dimensions	1/9	1/7	1/5	1/3	1	3	5	7	9	Feasibility

Maximum PT	1/9	1/7	1/5	1/3	1	3	5	7	9	Maximum BL
Maximum PT	1/9	1/7	1/5	1/3	1	3	5	7	9	Maximum BH

Maximum PT	1/9	1/7	1/5	1/3	1	3	5	7	9	Minimum BS
Maximum BL	1/9	1/7	1/5	1/3	1	3	5	7	9	Maximum BH
Maximum BL	1/9	1/7	1/5	1/3	1	3	5	7	9	Minimum BS
Maximum BH	1/9	1/7	1/5	1/3	1	3	5	7	9	Minimum BS

The third decision maker that was interviewed was the metal department manager. The new panel bender will be placed within this department. Therefore, this person is a decision maker as well. His preferences are visible in the tables below.

Quality	1/9	1/7	1/5	1/3	1	3	5	7	9	Costs
Quality	1/9	1/7	1/5	1/3	1	3	5	7	9	Speed
Quality	1/9	1/7	1/5	1/3	1	3	5	7	9	Layout
Quality	1/9	1/7	1/5	1/3	1	3	5	7	9	Flexibility
Costs	1/9	1/7	1/5	1/3	1	3	5	7	9	Speed
Costs	1/9	1/7	1/5	1/3	1	3	5	7	9	Layout
Costs	1/9	1/7	1/5	1/3	1	3	5	7	9	Flexibility
Speed	1/9	1/7	1/5	1/3	1	3	5	7	9	Layout
Speed	1/9	1/7	1/5	1/3	1	3	5	7	9	Flexibility
Layout	1/9	1/7	1/5	1/3	1	3	5	7	9	Flexibility

Sheet dimensions	1/9	1/7	1/5	1/3	1	3	5	7	9	Feasibility

Maximum PT	1/9	1/7	1/5	1/3	1	3	5	7	9	Maximum BL
Maximum PT	1/9	1/7	1/5	1/3	1	3	5	7	9	Maximum BH
Maximum PT	1/9	1/7	1/5	1/3	1	3	5	7	9	Minimum BS
Maximum BL	1/9	1/7	1/5	1/3	1	3	5	7	9	Maximum BH
Maximum BL	1/9	1/7	1/5	1/3	1	3	5	7	9	Minimum BS
Maximum BH	1/9	1/7	1/5	1/3	1	3	5	7	9	Minimum BS

The fourth and last decision maker that was asked about his perception is the chief operational officer. His preferences are visible in the table below.

Quality	1/9	1/7	1/5	1/3	1	3	5	7	9	Costs
Quality	1/9	1/7	1/5	1/3	1	3	5	7	9	Speed
Quality	1/9	1/7	1/5	1/3	1	3	5	7	9	Layout
Quality	1/9	1/7	1/5	1/3	1	3	5	7	9	Flexibility
Costs	1/9	1/7	1/5	1/3	1	3	5	7	9	Speed
Costs	1/9	1/7	1/5	1/3	1	3	5	7	9	Layout
Costs	1/9	1/7	1/5	1/3	1	3	5	7	9	Flexibility
Speed	1/9	1/7	1/5	1/3	1	3	5	7	9	Layout
Speed	1/9	1/7	1/5	1/3	1	3	5	7	9	Flexibility
Layout	1/9	1/7	1/5	1/3	1	3	5	7	9	Flexibility

Sheet dimensions	1/9	1/7	1/5	1/3	1	3	5	7	9	Feasibility

Maximum PT	1/9	1/7	1/5	1/3	1	3	5	7	9	Maximum BL
Maximum PT	1/9	1/7	1/5	1/3	1	3	5	7	9	Maximum BH
Maximum PT	1/9	1/7	1/5	1/3	1	3	5	7	9	Minimum BS

Maximum BL	1/9	1/7	1/5	1/3	1	3	5	7	9	Maximum BH
Maximum BL	1/9	1/7	1/5	1/3	1	3	5	7	9	Minimum BS
Maximum BH	1/9	1/7	1/5	1/3	1	3	5	7	9	Minimum BS

During the pairwise comparisons, the COO and the process specialist made good choices about their preferences and took the consistency into account. As shown in the tables, there is nothing changed at these two decision makers. The metal department manager and operational manager had a bit higher inconsistency, which means that an additional moment was taken to look over the results. The initial values are marked in yellow, and the revised preferences are marked in green. Below, an overview is given about the changes that are made:

For the Operational Manager:

Criterion 1	Criterion 2	Modification
Quality	Costs	From 6 to 3
Costs	Speed	From 1/5 to 1/2
Speed	Flexibility	From 1 to 1/5
Sheet dimensions	Feasibility	From 4 to 1/4
Maximum PL	Maximum BL	From 1/5 to 1/3
Maximum BL	Maximum BH	From 1/6 to 1/5
Maximum BH	Minimum BS	From 1/6 to 1/3

For the Metal Department Manager:

Criterion 1	Criterion 2	Modification
Quality	Costs	From 7 to 4
Quality	Layout	From 3 to 6
Costs	Layout	From 3 to 5
Costs	Flexibility	From 3 to 1/3 (wrong way around)
Sheet dimensions	Feasibility	From 5 to 1/5 (wrong way around)
Maximum PT	Maximum BL	From 1/7 to 1/5
Maximum PT	Maximum BH	From 1/7 to 1/5
Maximum PT	Maximum BS	From 1/7 to 1/5

C. Selected products that are used in the feasibility studies

ItemID	Dimensions	Setup time	Processing time
BE12Z504	514.99 x 1066.24	Low	Medium
BF20Z664	230 x 645.69	Low	Medium
BO12Z518	628.69 x 1103.31	Low	Medium
BO20Z033	238.62 x 250	Low	Low
BS12Z526	495.49 x 1338.12	High	High
CA20Z055	222.43 x 300	Low	High
EF12Z551	340.38 x 505.45	Medium	Medium
ET12Z559	644.97 x 816.75	Low	Medium
FI12Z506	175.99 x 487.5	Low	Low
FI15Z537	673.31 x 1048.81	Low	Medium
FL12Z510	251 x 516	Low	Low
GL12Z649	297.12 x 328.54	Medium	Low
NE10L096	558.74 x 441.87	Low	Medium
NG10L120	427.74 x 546.87	Medium	Medium
NG10L504	598.62 x 848.74	High	High
NG12Z006	476.89 x 1000.03	Medium	High
NG12Z014	577.29 x 700.9	High	Medium
NG12Z242	213.52 x 495.07	High	High
NG12Z538	430.84 x 488.42	Low	Medium
NG20Z507	179.68 x 518.5	Low	Low
NG20Z696	754.02 x 891.83	High	High
PB12Z170SH	347.4 x 377.89	Low	Medium
PB12Z232SH	263.89 x 430.69	Medium	Low
PB12Z745	430.84 x 511.63	Low	Medium
PB12Z766	189.92 x 569.59	High	Low
PB12Z972	271.34 x 307.46	Medium	Medium
SO10L546	463.52 x 626.02	High	High
SP12Z140	435.79 x 874.27	Medium	Medium
SP12Z238SH	713.74 x 1967.19	High	Medium
SP12Z601	577.84 x 1946.92	Medium	Medium
SP20Z037	249.14 x 390	Low	Low
SP20Z531	716.34 x 832.48	Medium	Medium
TD12Z803	577.84 x 2159.69	Medium	High
TN12Z569	238.79 x 287.62	Medium	Medium
ZU12Z847	643.87 x 430	Medium	High

Table 30: *The 35 selected products with corresponding categories*

D. Revised set of products that are used in the feasibility studies

ItemID	Dimensions	Setup time	Processing time
BE12Z504	514,99 x 1066,24	High	High
BF20Z664	230 x 645,69	Low	High
CA20Z055	222,43 x 300	Low	High
ET12Z559	644,97 x 816,75	Low	High
FI12Z506	175,99 x 487,5	Low	High
FI15Z537	673,31 x 1048,81	Low	Low
FL12Z510	251 x 516	Low	High
NE10L096	558,74 x 441,87	Low	Low
NG12Z014	577,29 x 700,9	Low	High
NG12Z538	430,84 x 488,42	Low	High
NG20Z696	754,02 x 891,83	High	High
PB12Z170SH	347,4 x 377,89	Low	High
PB12Z232SH	263,89 x 430,69	Low	Low
PB12Z745	430,84 x 511,63	Low	High
PB12Z766	189,92 x 569,59	High	Low
SP12Z140	435,79 x 874,27	High	High
SP12Z601	577,84 x 1946,92	Low	High
SP20Z037	249,14 x 390	Low	Low
SP20Z531	716,34 x 832,48	Low	High
TN12Z569	238,79 x 287,62	Low	High

Table 31: *Revised set of products that is used to assess the performances of the machines*

E. Total score calculations for each decision maker

In this section, we provide all the calculations for each decision maker. The results are already presented in **Table 19**. The first decision maker is the Process Specialist. The calculations for this decision maker are used as an example in Section 6.6. The second decision maker is the Manager Operations. The calculations for this decision maker are discussed next.

Manager Operations:

Prima Power FBe2220 = (0.0786 x 100) + (0.1194 x 63.99) + (0.0343 x 100) + (0.2439 x 100) + (0.5238 x 0.8 x 100) + (0.5238 x 0.2 x 0.0556 x 100) + (0.5238 x 0.2 x 0.1101 x 100) + (0.5238 x 0.2 x 0.2950 x 20) + (0.5238 x 0.2 x 0.5393 x 38.5) = 89.7560

Prima Power EBe2220 = (0.0786 x 62.5) + (0.1194 x 64.81) + (0.0343 x 50) + (0.2439 x 100) + (0.5238 x 0.8 x 95) + (0.5238 x 0.2 x 0.0556 x 100) + (0.5238 x 0.2 x 0.1101 x 100) + (0.5238 x 0.2 x 0.2950 x 20) + (0.5238 x 0.2 x 0.5393 x 38.5) = 83.0933

Salvagnini P4L-2120 = (0.0786 x 37.5) + (0.1194 x 63.5) + (0.0343 x 50) + (0.2439 x 100) + (0.5238 x 0.8 x 95) + (0.5238 x 0.2 x 0.0556 x 100) + (0.5238 x 0.2 x 0.1101 x 72) + (0.5238 x 0.2 x 0.2950 x 20) + (0.5238 x 0.2 x 0.5393 x 84) = 83.2188

Salvagnini P4L-2225 = (0.0786 x 0) + (0.1194 x 63.5) + (0.0343 x 50) + (0.2439 x 100) + (0.5238 x 0.8 x 95) + (0.5238 x 0.2 x 0.0556 x 100) + (0.5238 x 0.2 x 0.1101 x 80) + (0.5238 x 0.2 x 0.2950 x 70) + (0.5238 x 0.2 x 0.5393 x 10) = 77.7276

Salvagnini P2L-2225 = (0.0786 x 33.5) + (0.1194 x 58.5) + (0.0343 x 100) + (0.2439 x 100) + (0.5238 x 0.8 x 95) + (0.5238 x 0.2 x 0.0556 x 100) + (0.5238 x 0.2 x 0.1101 x 80) + (0.5238 x 0.2 x 0.2950 x 70) + (0.5238 x 0.2 x 0.5393 x 10) = 81.4819

Trumpf 7020 = (0.0786 x 100) + (0.1194 x 61.45) + (0.0343 x 100) + (0.2439 x 100) + (0.5238 x 0.8 x 95) + (0.5238 x 0.2 x 0.0556 x 100) + (0.5238 x 0.2 x 0.1101 x 65) + (0.5238 x 0.2 x 0.2950 x 100) + (0.5238 x 0.2 x 0.5393 x 85) = 90.2444

Metal Department Manager:

Prima Power FBe2220 = (0.1783 x 100) + (0.0925 x 63.99) + (0.0438 x 100) + (0.2479 x 100) + (0.4375 x 0.8333 x 100) + (0.4375 x 0.1667 x 0.0619 x 100) + (0.4375 x 0.1667 x 0.1563 x 100) + (0.4375 x 0.1667 x 0.3909 x 20) + (0.4375 x 0.1667 x 0.3909 x 38.5) = 92.6350

Prima Power EBe2220 = (0.1783 x 62.5) + (0.0925 x 64.81) + (0.0438 x 50) + (0.2479 x 100) + (0.4375 x 0.8333 x 95) + (0.4375 x 0.1667 x 0.0619 x 100) + (0.4375 x 0.1667 x 0.1563 x 100) + (0.4375 x 0.1667 x 0.3909 x 20) + (0.4375 x 0.1667 x 0.3909 x 38.5) = 82.0118

Salvagnini P4L-2120 = (0.1783 x 37.5) + (0.0925 x 63.5) + (0.0438 x 50) + (0.2479 x 100) + (0.4375 x 0.8333 x 95) + (0.4375 x 0.1667 x 0.0619 x 100) + (0.4375 x 0.1667 x 0.1563 x 72) + (0.4375 x 0.1667 x 0.3909 x 20) + (0.4375 x 0.1667 x 0.3909 x 84) = 78.4101

Salvagnini P4L-2225 = (0.1783 x 0) + (0.0925 x 63.5) + (0.0438 x 50) + (0.2479 x 100) + (0.4375 x 0.8333 x 95) + (0.4375 x 0.1667 x 0.0619 x 100) + (0.4375 x 0.1667 x 0.1563 x 80) + (0.4375 x 0.1667 x 0.3909 x 70) + (0.4375 x 0.1667 x 0.3909 x 10) = 71.1297

Salvagnini P2L-2225 = (0.1783 x 33.5) + (0.0925 x 58.5) + (0.0438 x 100) + (0.2479 x 100) + (0.4375 x 0.8333 x 95) + (0.4375 x 0.1667 x 0.0619 x 100) + (0.4375 x 0.1667 x 0.1563 x 80) + (0.4375 x 0.1667 x 0.3909 x 70) + (0.4375 x 0.1667 x 0.3909 x 10) = 78.8299

Trumpf 7020 = (0.1783 x 100) + (0.0925 x 61.45) + (0.0438 x 100) + (0.2479 x 100) + (0.4375 x 0.8333 x 95) + (0.4375 x 0.1667 x 0.0619 x 100) + (0.4375 x

0.1667 x 0.1563 x 65) + (0.4375 x 0.1667 x 0.3909 x 100) + (0.4375 x 0.1667 x 0.3909 x 85) = 89.6822

COO:

Prima Power FBe2220 = (0.2975 x 100) + (0.2975 x 63.99) + (0.0353 x 100) + (0.0721 x 100) + (0.2975 x 0.875 x 100) + (0.2975 x 0.125 x 0.0446 x 100) + (0.2975 x 0.125 x 0.1930 x 100) + (0.2975 x 0.125 x 0.2129 x 20) + (0.2975 x 0.125 x 0.5495 x 38.5) = 87.3959

Prima Power EBe2220 = (0.2975 x 62.5) + (0.2975 x 64.81) + (0.0353 x 50) + (0.0721 x 100) + (0.2975 x 0.875 x 95) + (0.2975 x 0.125 x 0.0446 x 100) + (0.2975 x 0.125 x 0.1930 x 100) + (0.2975 x 0.125 x 0.2129 x 20) + (0.2975 x 0.125 x 0.5495 x 38.5) = 73.4163

Salvagnini P4L-2120 = (0.2975 x 37.5) + (0.2975 x 63.5) + (0.0353 x 50) + (0.0721 x 100) + (0.2975 x 0.875 x 95) + (0.2975 x 0.125 x 0.0446 x 100) + (0.2975 x 0.125 x 0.1930 x 72) + (0.2975 x 0.125 x 0.2129 x 20) + (0.2975 x 0.125 x 0.5495 x 84) = 66.3174

Salvagnini P4L-2225 = (0.2975 x 0) + (0.2975 x 63.5) + (0.0353 x 50) + (0.0721 x 100) + (0.2975 x 0.875 x 95) + (0.2975 x 0.125 x 0.0446 x 100) + (0.2975 x 0.125 x 0.1930 x 80) + (0.2975 x 0.125 x 0.2129 x 70) + (0.2975 x 0.125 x 0.5495 x 10) = 54.1012

Salvagnini P2L-2225 = (0.2975 x 33.5) + (0.2975 x 58.5) + (0.0353 x 100) + (0.0721 x 100) + (0.2975 x 0.875 x 95) + (0.2975 x 0.125 x 0.0446 x 100) + (0.2975 x 0.125 x 0.1930 x 80) + (0.2975 x 0.125 x 0.2129 x 70) + (0.2975 x 0.125 x 0.5495 x 10) = 64.3454

Trumpf 7020 = (0.2975 x 100) + (0.2975 x 61.45) + (0.0353 x 100) + (0.0721 x 100) + (0.2975 x 0.875 x 95) + (0.2975 x 0.125 x 0.0446 x 100) + (0.2975 x 0.125 x 0.1930 x 65) + (0.2975 x 0.125 x 0.2129 x 100) + (0.2975 x 0.125 x 0.5495 x 85) = 79.2880

Overview of the final scores per decision maker:

	Prima Power		**Salvagnini**			**Trumpf**
	FBe2220	EBe2220	P4L-2120	P4L-2225	P2L-2225	7020
Process Specialist	89,7234	82,6957	81,6779	75,4641	80,1641	89,2028
Manager Operations	89,7560	83,0933	83,2188	77,7276	81,4819	90,2444
Department Manager	92,6350	82,0118	78,4101	71,1297	78,8299	89,6822
COO	87,3959	73,4163	66,3174	54,1012	64,3454	79,8280

Table 32: *Overview of the final scores per decision maker*