



Workload Prediction For the V310

An application of linear regression and time study to make an estimation on required man hours.

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STEEL GROUP

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Management Summary

Problem context

The research for this thesis is conducted at Voortman Steel Machinery in the Part Manufacturing (VPM-1) department. The parts required are cut out of metal sheets on the V310, a plasma and oxyfuel cutting and drilling machine. VPM-1 presented the problem of having no insight on how many manhours are required at the machine to produce the demand. This results in the late notice of when the planning is infeasible, when it is not possible to outsource anymore. The action problem and research question are formulated as follows:

Action problem: The late notice of infeasible planning occurring resulting in a backlog on the Voortman V310 and a delay in the cutting planning.

Research question: How can Voortman Parts Manufacturing use order data to predict the upcoming workload for the V310 at least three weeks prior to cutting?

The goal is to provide VPM-1 with a tool that takes order data as input and then provides an estimation on the required man hours. This is done through two main steps, a linear regression model and a time study.

Processes involved

To address the research question effectively, it is essential to understand the various processes involved in the cutting operation, as well as the specific tasks performed by the operators and the time required for each task.

Before the actual cutting process, several preliminary steps are involved. Job preparation is conducted by the job preparators, who create a production plan for the construction halls that utilize the parts. This planning includes determining the demand for the parts. Once the weekly demand is established, the parts are nested, which refers to the process of optimizing the placement of parts on a sheet to minimize scrap. Nesting typically occurs approximately one week before the cutting process begins.

During the cutting process itself, the operators play a crucial role. They are responsible for picking up the metal sheet and transporting it to the cutting Table. They weld the sheet to the Table and then measure the sheet to ensure accurate positioning on the machine. If necessary, they perform a tool change before starting the cutting machine. Throughout the cutting process, operators conduct quality checks on measurements and tapholes.

After the parts have been cut, they undergo cleaning and sorting procedures. This involves removing any slack and sorting the parts based on the order number. Subsequently, the parts leave the cutting department and are transferred to other production halls for further construction.

For a comprehensive list of operator tasks involved with in this study see Figure B.

Linear regression

To estimate the required man-hours, it is crucial to determine the number of nestings that will be cut during the week, as most tasks are performed per nesting. This estimation is accomplished by developing

linear regression models for the various thicknesses present in the dataset. The nestings cut in 2022 serve as the training set, while those from 2021 serve as the validation set.

The dependent variable chosen for the regression models is the required area, which can be used to calculate the number of sheets. Among the potential independent variables, two variables, namely part area and rectangle area, satisfy the assumptions of linear regression. However, due to collinearity, only one of these variables can be selected. During the training set, total part area was found to be the best fitting variable for most thicknesses. Both variables showed a significant influence on the required area, as indicated by the F-value.

For thicknesses of 35mm, 50mm, and 60mm, rectangle area initially appeared to be a better fit considering the training set. However, during the validation process, these thicknesses exhibited lower R^2 values compared to part area, measuring that part area is thus a better fit. Consequently, the decision was made to use total part area as the independent variable for all thicknesses. The Table provided below presents the corresponding R^2 values obtained from the validation, along with the intercept and coefficient used to calculate the required area and, subsequently, the number of sheets per thickness.

Thickness	R^2	Intercept	Coefficient
5mm	0.915	101454.81	1.41
6mm	0.920	269842.16	1.06
8mm	0.984	363244.33	1.24
10mm	0.972	430179.42	1.22
12mm	0.959	56856.19	1.50
15mm	0.971	276017.32	1.34
20mm	0.934	409661.05	1.36
25mm	0.982	832549.71	1.20
30mm	0.979	350785.02	1.30
35mm	0.894	136895.92	1.25
40mm	0.972	544726.98	1.26
50mm	0.922	153270.29	1.34
60mm	0.944	80180.42	1.71

Figure A Table containing the used intercept, coefficient and corresponding R-values

Task division

To make an estimation on how many man hours are required you need to know how the tasks correspond to the differences on the sheet. The Table below describes the occurrence of the tasks involved.

Task	Occurance
Picking up the sheet from the plate centre	Every nesting
Placing the sheet on the machine	Every nesting
Welding the sheet to the table	Every nesting
Measuring the sheet	Every nesting
Cutting the grid loose	Every nesting
Cutting the grid for disposal	Every nesting
Disposing of the grid	Every nesting
Tool change	5x every nesting
Take out small parts	Number of small parts
Place small parts on the conveyor	Number of small parts
Take out meadium parts	Number of medium parts
Take out large parts	Numbe rof large parts
Measurement check	First and afterwards every 75th apt
Writing ordernumbers	Every part, if more then 10 parts in batch then every 10th part
Tap hole check	On average evey 2 pats has a tap hole, every 25th is checked
Immeadte sheets	6 a week with 40 small p[arts and 9 medium parts (avergae)
Magnet change	one a day, 5 times a week

Figure B Operator tasks and number of occurrences

Tool

To meet the requirements of VPM-1, the tool has been designed to be user-friendly and provide a quick and comprehensive overview of the outcome. This is achieved by minimizing manual steps and incorporating a dashboard that displays relevant graphs and information. The tool's functionality encompasses all aspects of the research conducted.

The tool takes various inputs, including a parts list, an export with the required part-IDs, planning data, the results of the linear regression model, and the findings from the time study. With this data, the tool performs calculations to determine the number of nestings required. By considering the nestings and part characteristics, the tool further estimates the time required for each task. The results are then presented on the dashboard, offering a clear and concise summary. Note that the dashboard is in Dutch as this allows for a better integration within the company.



Figure C Dashboard

Conclusion

In conclusion, it is feasible to estimate the required man-hours by utilizing a linear regression model that considers the total part area, an analysis of task occurrence, and a time study. The integrated tool incorporates these factors to perform the necessary calculations and generate the output displayed on the dashboard. To enhance the tool's efficiency, it is recommended to expand the data storage capabilities to include additional part characteristics such as the presence and length of bevels, the number of drill holes, and whether tapping is required.

Furthermore, conducting a study to determine the actual time operators require to complete a week's worth of nestings is advised. The current tool assumes smooth machine operation and only accounts for the primary tasks, disregarding the irregularity of additional operator responsibilities. Investigating the real-time availability will enable a more effective estimation of the hours that can be reliably planned.

Lastly, in the event of changes in the nesting methodology, it is recommended to repeat the linear regression analysis using a substantial sample of nestings (e.g., after one year). Alterations in the nesting approach will impact the model's parameters. By repeating the study and implementing the new coefficients and intercepts, more accurate predictions aligned with the updated nesting method can be obtained.

Preface

Dear reader,

In front of you lies my bachelor thesis entitled "Workload Prediction for the V310: An Application of Linear Regression and Time Study to Estimate Required Man-Hours." This thesis serves as the final assignment of the bachelor's program in Industrial Engineering and Management, representing my work on behalf of Voortman Steel Machinery in Rijssen.

To begin, I would like to express my deep gratitude to Voortman Steel Machinery and Voortman Part Manufacturing, particularly for providing me with the invaluable opportunity to learn and gain professional experience within their organization. I extend my appreciation to all my colleagues at Voortman for their approachability, assistance, and support. I am especially grateful to my supervisor, René Klein Nagelvoort, for his guidance and feedback, as well as the gentlemen at Voortman Part Manufacturing for creating a welcoming and pleasant work atmosphere.

Furthermore, I wish to express my sincere appreciation to my first supervisor, Leo van der Wegen, for his benevolence in assisting me, and to my second supervisor, Derya Demirtas. Both supervisors provided incredibly helpful feedback, which significantly enhanced the quality of this report.

Finally, I would like to extend my thanks to my family and friends for their unwavering support and understanding throughout the process of writing this thesis, as well as during my time at the UT. And lastly, I would like to express my gratitude to you, my reader: I hope you enjoy reading this thesis.

Mirjam Bakker

Rijssen, June 2023

Table of Contents

Preface	3
Management Summary	3
Problem context.....	3
Processes involved	3
Linear regression	3
Task division	4
Tool	5
Conclusion	5
Table of Contents	8
List of Figures.....	11
List of Tables	12
Glossary	13
1 Problem Identification	14
1.1 Introduction.....	14
1.2 Problem Context.....	15
1.3 Problem identification.....	16
1.3.1 Action problem	16
1.3.2 Problem Cluster	16
1.3.3 Core Problem	17
1.3.4 Research question.....	17
1.3.5 The norm and the reality.....	17
1.3.6 Scope.....	18
1.4 Deliverables	18
1.5 Conceptual framework	18
1.6 Research design.....	18
2 Processes for running the V310	21
2.1 Interviews and observations	21
2.2 Job preparation	21
2.2.1 VPM-2.....	21
2.2.2 Handling.....	22
2.3 Nesting	22

2.4	Management	23
2.5	Cutting	23
2.6	Cleaning and sorting	24
2.7	Cutting Operator tasks	24
2.7.1	Loading the machine	25
2.7.2	Starting the machine.....	25
2.7.3	Quality checks	26
2.7.4	Unloading	26
2.7.5	While running.....	27
2.7.6	Other tasks.....	27
2.7.7	Total list	28
2.8	Time required.....	29
2.8.1	Structured observation.....	29
2.8.2	Sample Selection	29
2.8.3	Data	30
2.9	Conclusion	31
2.10	Discussion.....	31
2.10.1	Operations.....	31
2.10.2	Time study	32
3	Linear regression.....	33
3.1	Linear regression	33
3.2	Data and theory	34
3.3	Specify the model	34
3.4	Estimating parameters.....	35
3.5	Test of significance	36
3.5.1	F- test.....	36
3.5.2	R ² and adjusted R ²	36
3.6	Check of validity	37
3.6.1	Analysis	37
3.6.2	Data splitting.....	37
3.6.3	Fresh data.....	37
3.7	ANOVA Table	38
3.8	Conclusion	39

4	Model for VPM-1	40
4.1	Data	40
4.2	Dependent variable and categorization	41
4.3	Assumptions check.....	42
4.4	Variable selection.....	43
4.5	Model building	43
4.5.1	Total part area	43
4.5.2	Total rectangle area	44
4.5.3	Comparison.....	45
4.6	Validation	46
4.7	Conclusion	47
4.8	Discussion.....	48
5	Influential factors	49
5.1	Number of Nestings	49
5.2	Tool change	49
5.3	Part characteristics	50
5.4	Measurement check and writing	50
5.5	Tap holes	51
5.6	Bevel cutting.....	51
5.7	Immediate sheets	52
5.8	Magnet exchange	52
5.9	Conclusion	53
5.10	Discussion.....	54
6	Tool.....	55
6.1	Tool requirements	55
6.1.1	Ease of use	55
6.1.2	Visual representation.....	56
6.2	Input data	57
6.3	Conceptual model.....	57
6.4	Calculations	58
6.4.1	Number of sheets.....	58
6.4.2	Time calculations	59
6.5	Tool implementation.....	60

6.6	Conclusion	60
6.7	Discussion.....	61
7	Conclusion	62
7.1	Research questions	62
7.1.1	What processes are involved with running the V310?	62
7.1.2	What factors influence the primary tasks of operators?	62
7.1.3	How to make a linear regression model?.....	62
7.1.4	What does a linear regression model to estimate the required nestings look like?.....	63
7.1.5	How to make a tool that can be implemented in VPM-1	63
7.2	How can Voortman Parts Manufacturing use order data to predict the upcoming workload for the V310 at least three weeks prior to cutting?.....	63
7.3	Discussion.....	63
7.3.1	Time study.....	63
7.3.2	Linear regression.....	64
7.3.3	Estimations on occurrence.....	64
7.3.4	Bevel cutting.....	64
7.4	Recommendations.....	64
	Bibliography.....	65
	Appendix A observation studies	67
	Appendix B Systematic literature review	70
	Appendix C data description	74
	Appendix D example of a nesting.....	76
	Appendix E Scatter plots	78
	Appendix F Correlation matrices	91
	Appendix G ANOVA Tables	96

List of Figures

Figure 1	V310	14
Figure 2	V320	15
Figure 3	V630	15
Figure 4	Process flow in VPM-1 (a larger version can be found in Appendix 1)	15
Figure 5	Figure with number of weeks planning was not finished in time.	15
Figure 6	Problem cluster	16
Figure 7	Conceptual framework tool.....	18

Figure 8 Timeline nesting to cutting.	23
Figure 9 Timeline nesting to cutting when outsourcing is involved.	23
Figure 10 Floorplan of the cutting department.....	24
Figure 11 BPM of loading the machine, either using rest sheet or new sheet.	25
Figure 12 BPM of starting the machine.	25
Figure 13 BPM for quality checks.	26
Figure 14 BPM unloading the machine.	26
Figure 15 BPM of the full process in the cutting department.....	31
Figure 16 Steps in making a linear regression model obtained from (Montgomery, Peck, & Vining, 2012) 34	34
Figure 17 Example of an ANOVA Table, the boxes correspond to a explanation in Section 3.7.....	39
Figure 18 Coloured part drawing to help illustrates data type, on part level.	41
Figure 19 Coloured nesting to help illustrate data types, on nesting level.	41
Figure 20 scatterplot for total part area, total part weight and total rectangle area for 5mm	42
Figure 21 ANOVA Table for 5mm when using part area.....	44
Figure 22 ANOVA Table for 5mm using rectangle area.	45
Figure 23 Example of a part with a bevelled edge.....	51
Figure 24 Dashboard as designed for VPM-1	57
Figure 25 Conceptual model of the black box.....	58

List of Tables

Table 1 Table with operator tasks, category and description	28
Table 2 The primary tasks measured with the corresponding number of observations and mean time....	30
Table 3 Data with the number of nestings of each thickness in the dataset.....	40
Table 4 Correlation matrix for 5mm.....	43
Table 5 Required values for all thicknesses using part area	44
Table 6 required values for rectangle area for all thicknesses	45
Table 7 Intercept and coefficient corresponding to best predictor in Table 7	46
Table 8 Best fitting variable based on R^2 for all thicknesses	46
Table 9 entities in validation set and r-squared per thickness	47
Table 10 Intercept and coefficient that provides the best predictions.	47
Table 11 Number of tap holes per week, ratio and average.....	51
Table 12 Number of bevel parts for 5 weeks	52

Glossary

BPM	Business process model
Cutting plate	Synonym for a nesting
Handling	Part of VPM-1 where transportation lines are welded.
Nesting	A schematic drawing of how the parts that need to be cut are located on a steel sheet.
Primary tasks	Tasks that are required on a day-to-day basis for running the machine.
Rest sheet	Metal plate that has been used before to cut parts, the surface area varies.
Sheet	18m ² metal plate
Secondary tasks	Non-primary tasks that operators conduct.
SigmaNest	The software used to make nestings.
V310	A plasma cutting and drilling machine.
VPM	Voortman Parts Manufacturing, divided into two manufacturing halls.
VPM-1	Voortman Parts Manufacturing one where the V310 is located.
VPM-2	Voortman Parts Manufacturing two where the machines are welded and assembled.
VSC	Voortman Steel Construction
VSG	Voortman Steel Group, consists of VSC and VSM
VSM	Voortman Steel Machinery
Weldment	Part of the final product consists of several parts that need to be cut.

1 Problem Identification

The first chapter will provide some background information on the Voortman Steel Group and Voortman Parts Manufacturing (Section 1.1). Next is the problem context and identification (Sections 1.2 and 1.3), this is where the stakeholders and norm and reality are determined. Section 1.4 describes the intended deliverables. And afterwards, Section 1.5 Presents the conceptual framework. Finally, Section 1.6 contains the research design with the sub research questions.

1.1 Introduction

Voortman Steel Group (VSG) is a Dutch company that used to be divided into two divisions, Voortman Steel Machinery (VSM) and Voortman Steel Construction (VSC). However, VSC is sold to a British company on April first, 2023, but remains mostly located within the facilities of VSG. VSC designs and builds steel projects and VSM specializes in the production of steel processing machinery. The company was founded in 1968 by the Brothers Voortman. It has its main headquarters in Rijssen but also has locations in countries such as the United States, Germany, and Australia.

Voortman Steel Machinery (VSM) develops and manufactures computer numerical controlled (CNC) machines for the steel fabrication processing industry. Their product range is applicable for various purposes. Among their extensive product lines are three notable machines: the V320, capable of cutting through 75mm of steel, drilling through 40mm, and milling (as shown in Figure 2); the V630, equipped with three independent drill heads for drilling, milling, and tapping (as shown in Figure 3); and the Voortman VP range, designed for spray painting. Additionally, Voortman offers adjustable transportation lines, which make it easy to integrate different Voortman machines into a client's production line.

The focus of this research is on the V310 machine (Figure 1). The Voortman V310 is a plasma cutting and drilling machine able to cut and drill through 200 mm thick steel. The machine is located in the cutting department of Voortman Parts Manufacturing 1 (VPM-1). At VPM the machine is 30 meters long and has two independently moving toolheads which both can change their own tools and work unmanned.

Operators load, unload and start the machine and then the machine cuts and drills based on the nesting provided. A nesting is a schematic drawing where all the parts are efficiently placed so the least amount of material is wasted. To make these nestings the software SigmaNest is used. Once a nesting is completed and sent to the machine it is also called a cutting plate.



Figure 1 V310



Figure 2 V320



Figure 3 V630

1.2 Problem Context

VPM-1 is a large manufacturing hall divided into cutting and handling. The cutting department cuts the parts for handling, VPM-2 and VSC. Handling welds the cross transports and roller conveyors and VPM-2 welds and assembles the machine frames. This research takes place in the cutting department where three different types of machines are located: Twice the V310 which produce for VSM and the V320 and V330, which produce for VSC based on the incoming orders. Within this thesis only the V310 will be taken into account due to the large number of differences between the planning processes for VSC and VSM. The process flow below depicts the general process of an order coming into the cutting department of VPM-1 to the moment it is sent away.

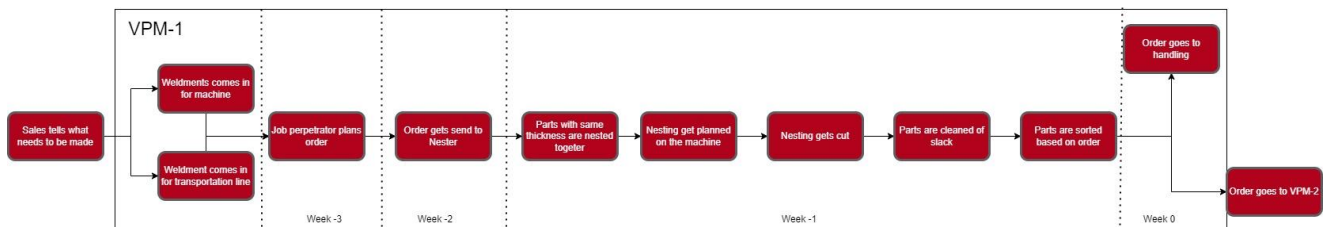


Figure 4 Process flow in VPM-1 (a larger version can be found in Appendix 1)

In general, three levels of planning apply to or influence the cutting process in VPM-1. First there is the tactical planning, this planning flows throughout the whole company and tells which machine needs to be finished at which time. Plus, it tells when which department needs to be finished with their part of the production process, this planning is made based on when machines need to be delivered to customers. Second there is the VPM-1 planning, this planning tells which orders need to be finished when within the department, and this planning gets made by the job preparator about three weeks prior to the required date of the parts. Finally, there is the cutting planning made by the nester, this planning is made a week prior to cutting and tells which nestings need to be cut during the next week. Currently there is a problem with an infeasible cutting planning

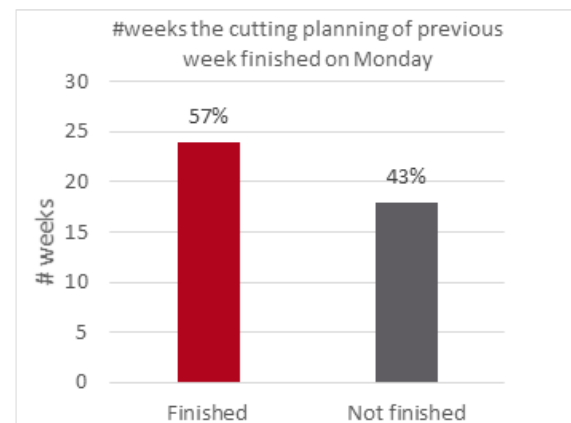


Figure 5 Figure with number of weeks planning was not finished in time.

because it is not certain how much work is coming up. The only moment when a clear calculation of required time can be made is after the nesting process, so a week before cutting and when it is not possible to make changes to the VPM-1 planning or make the decision outsource anymore. It would be beneficial to know earlier in the process when there is too much work coming up, the goal of this research is to find a method to estimate the man hours of the cutting planning during a week based on the information of the VPM-1 planning.

1.3 Problem identification

This section is about problem identification, first the definition of the action problem (Section 1.3.1), followed by the problem cluster (Section 1.3.2). In Section 1.3.3 the core problem is selected and explained. Next in Section 1.3.4, the research question can be found. In Section 1.3.5 the norm and reality are explained followed by an elaboration on the stakeholders (Section 1.3.6). The chapter is concluded with the scope (Section 1.3.7).

1.3.1 Action problem

“An action problem is a discrepancy between the norm and the reality, as perceived by the problem owner.” (Heerkens & van Winden, 2017). So, the action problem describes the problem that has to be solved. My action problem is formulated as follows:

The late notice of infeasible planning occurring resulting in a backlog on the Voortman V310 and a delay in the cutting planning.

1.3.2 Problem Cluster

A problem cluster is constructed beginning with the action problem. A problem cluster is a diagram that depicts all the connections between smaller problems that lead to the action problem. It is a tool that can be used to order the context of the problem and find the core problem. It is nearly impossible to focus on all problems at once, a problem cluster helps you identify the problems with the most impact on the problem context and how they are related. The arrows show the causal relationships between problems. This problem cluster was built after an interview with the manager of the cutting department, he is responsible for the parts being finished in time.

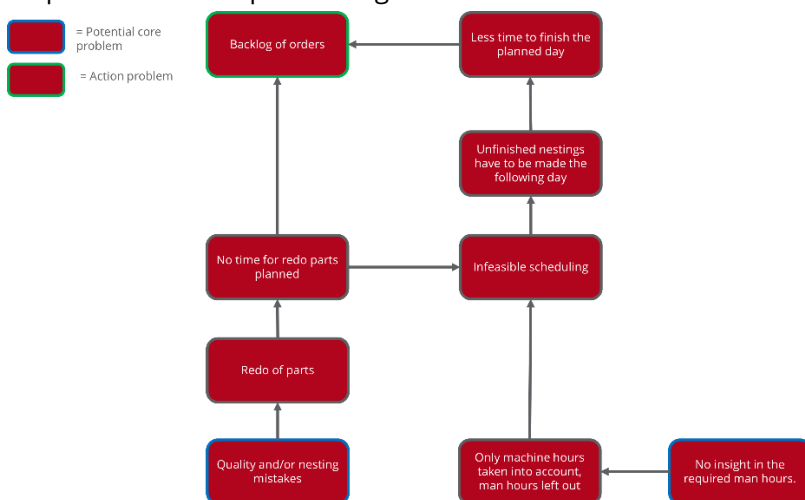


Figure 6 Problem cluster

1.3.3 Core Problem

From this problem cluster the core problem can be selected; two core problems can be found.

1. *Quality and/or nesting mistakes.* When an operator finds out that there are parts of an order missing or not of sufficient quality when most of the order is already completed, he reports the issue to the planner/nester who nests and schedules it again as soon as possible. However this could very well be next week resulting in less time in the planning.
2. *There is no insight into the required man hours.* The operators are in charge of loading and unloading the V310 and starting the machine when it is ready, but neither SigmaNest nor the planner takes the man hours (operator workload) required into account. Only the machine hours are accounted for, which results in a discrepancy in the planning.

Multiple factors should be considered when selecting the core problem(s) to address. First, you must ensure that there is a relationship with your action problem and that you can influence the problem. If more than one problem remains, a cost-benefit analysis may help you choose the problem with the most effective result. (Heerkens & van Winden, 2017)

The prevention of quality mistakes appears to be outside the ability of influence since the required knowledge and capabilities are not present. Plus, on average, about 3.7% of cut out parts must be redone due to issues and often with little cutting time required, therefore this does not seem to be the most beneficial to address. Therefore, the lack of insight into required man hours is chosen to be the core problem. During the continuation of this report man hours and workload will be used interchangeably.

1.3.4 Research question

In order to address the lack of insight into upcoming workloads, it is necessary to analyse the production data associated with incoming orders. This includes order details such as the number of holes that need to be drilled, the length that needs to be cut, the required thickness, the number of parts required, and the sizes of these parts. To facilitate outsourcing, it is necessary to have this information at least three weeks before the order is due to be handled. The research question will combine the order data with workload predictions to achieve the following goal:

How can Voortman Parts Manufacturing use order data to predict the upcoming workload for the V310 at least three weeks prior to cutting?

The sub-research questions can be found in Section 1.5.

1.3.5 The norm and the reality

Currently, the only moment a clear estimate of the workload can be made is after the nesting process, which happens the week prior to cutting, not earlier. At this point it is not possible anymore to outsource orders when the planning turns out to be infeasible and VPM-2 and handling will miss required parts. So there is currently no method to predict the upcoming workload. VPM-1 requires a method that can help predict the workload during a week before the nesting process happens. To be able to outsource orders VPM-1 needs to know at least three weeks prior to the due date that, during the week of the order, there is too much workload and outsourcing is required. The norm is then that there is a method to predict the upcoming at least three weeks prior.

1.3.6 Scope

During the cutting process research, operational efficiency will not be considered. Likewise, when collecting production time data, differences in operator performance will not be evaluated or factored into the analysis. However, the planning procedures will play a significant role in this thesis. It is important to note that the time frame in which the planning occurs will not be modified. Then it is

1.4 Deliverables

The problem owner, VPM, wants insight into the upcoming workload for operators based on the data of the incoming orders. Currently, there is no insight into the workload and tasks at all and no way of predicting the upcoming workload. Because the upcoming workload is dependent on multiple parameters in orders a tool is required to be able to evaluate the right variables. Therefore, the list of intended deliverables contains the following:

- A clear overview of all the tasks operators perform around the V310 separated into primary and secondary tasks.
- A tool that will help predict the upcoming workload.
- Recommendations on how to use and implement the tool.
- A written report containing the conducted research and findings.

1.5 Conceptual framework

The final product is a tool that utilizes the work order information (part-IDs) as input to provide estimations of the required man hours and the number of nestings. The tool operates through a series of calculations within its black box. To generate an accurate estimation, the tool follows three key steps.

The first step involves estimating the required number of nestings based on the input data. This estimation takes the part IDs and uses their corresponding variables.

Once the number of nestings is determined, the tool proceeds to calculate the required number of man hours. This estimation is based on the specific tasks assigned to operators for the given number of nestings.

These calculations occur in the tool, which combines various factors and data to make the estimations. The visual representation of the tool's setup is depicted in Figure 7.

Ultimately, the output of the tool is the estimation of the required man hours based on the provided work orders and associated part IDs.

1.6 Research design

Within this research, the MPSM cycle will be used to come to a solution for the lack of insight into the upcoming workload. Below the sub-research questions are formulated:

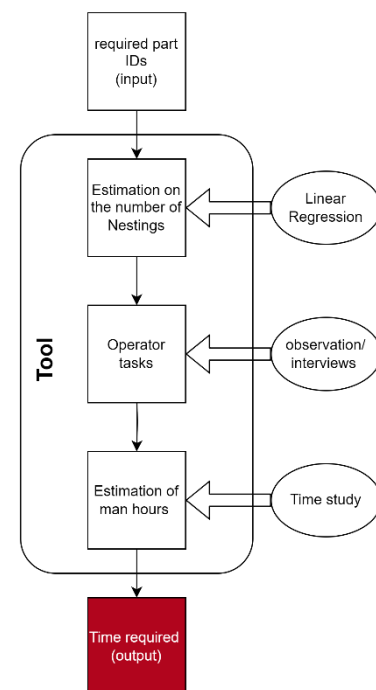


Figure 7 Conceptual framework tool

Research question 1: *What processes are involved with running the V310?*

- 1a. *What processes are required to run the V310 prior to cutting?*
- 1b. *What are the tasks of an operator?*
- 1c. *What time does an operator require to fulfil the assigned tasks?*

The first question aims to gather comprehensive insights into the overall process and flow of materials within VPM-1, including a detailed understanding of the planning procedure and the decisions made in this regard. The information obtained will be used to develop a flowchart depicting the material flow through VPM-1 and to create a clear overview of the planning procedure, which will subsequently be incorporated into the tool. To acquire this information, interviews will be conducted with key stakeholders such as the manager of the plate centre, the planner, and the operators. Additionally, observations will be conducted along the machine to supplement the interview data.

The second question focuses on creating a comprehensive list of tasks performed by the operators, which will be categorized into primary tasks (essential for machine operation) and secondary tasks (other non-essential tasks). This information is vital for the development of the tool. Additionally, question 1c addresses the data set required for time calculations in the tool to estimate the required man hours. To gather this data, structured observations of the operators will be conducted. This method involves systematically quantifying the occurrence of specific actions or behaviours. Through the use of an observation protocol that defines the observable actions and provides guidance during the observation process, it will be possible to measure time data and quantify the frequency of occurrences. (Saunders, Lewis, & Thornhill, 2019)

Research question 2: *What factors influence the primary tasks of operators?*

- 2a. *What factors influence the primary task of operators?*
- 2b. *How to make an estimation on required man hours for these factors?*

The objective of this research question is to identify the factors that impact the tasks and, consequently, the required man hours at the machine. To gather this information, semi-structured interviews will be conducted with both operators and management. The interviews will follow a flexible format, beginning with a predefined list of themes to be discussed. The main emphasis is on allowing participants to freely share their knowledge and insights, while also facilitating the comparison of answers across different interviewees. Additionally, if any interesting or noteworthy information arises during the interviews, further exploration and follow-up discussions can be pursued. (Schindler, 2019).

Research question 3: *How to make a linear regression model?*

The goal of this question is to research how linear regression models are build and validated in literature. In future questions this theory will be used to make a model for VMP-1 to calculate the number of nestings.

Research question 4 *What does a linear regression model to estimate the required nestings look like?*

The goal is to research how linear regression models are built specifically for the estimation for the number of nestings. Through the knowledge gained in research question 3 a model will be made that will be used in the tool.

Research question 5: *How to make a tool that can be implemented in VPM-1*

5a. What are the requirements for a tool?

5b. How to make a tool that uses the linear regression model and time data to make an estimation on the required man hours.

This is where all the previous chapters come together in a tool. Based on the requirements of management decisions are made on the design and functionality of the tool. This question will be answered via semi-structured interviews with the manager of the plate centre and the job preparator. Their answers together with the results of the previous questions will result in a tool that can be implemented in VPM-1.

2 Processes for running the V310

This chapter aims to answer the question: *"What processes are involved in running the V310?"*. Section 2.1 will provide a brief explanation of the methodologies used. Sections 2.2 to 2.6 present a chronological list of all the steps a part goes through within VPM-1 to answer the sub question: *"What processes are required to run the V310 prior to cutting?"*. Section 2.7 will delve into more detail on the operator tasks, which followed by the time study done in Section 2.8, these sections go into sub questions: *"What are the tasks of an operator?"* and *"What time does an operator require to fulfil the assigned tasks?"*. The chapter concluded with a conclusion and discussion in Sections 2.9 and 2.10, respectively.

2.1 Interviews and observations

The process flow has been mapped through a combination of interviews and observations. Interviews were conducted with the job preparators, the nester, and management. These semi-structured interviews covered topics such as process flow, task descriptions, choices made in the process and their impact, and the differences between handling and VPM-2. Follow-up questions were asked to gain more detailed insights based on the answers provided. All participants had full knowledge of the goals of my research and the purpose of the interviews.

The first set of observations was carried out to gain insight into the tasks performed by operators. For a period of two days, an operator was followed during their day-to-day activities at the machine, and they were asked questions regarding the rationale behind certain actions. The operator was well-informed about the goals of the observation and research, as well as the presence of the observer. The protocol for this observation can be found in Appendix 1.

2.2 Job preparation

The cutting department operates based on a pull system, where VPM-2 and handling request parts for the required weldments during a specific week. The two job preparators are responsible for creating the production schedule for VPM-2 and handling, each job preparation is responsible for one department. Based on this schedule, the required parts are automatically sent to the nester when they begin nesting for the corresponding weeks. There is a difference in the demand requests between VPM-2 and handling, and the nature of this difference will be explained below.

2.2.1 VPM-2

VPM-2 is responsible for assembling the weldments and subsequently constructing the machines. Once a month, a decision is made on which machines to initiate production based on the offers sent out and offers confirmed. The job preparator of VPM-2 utilizes this information to start creating the planning. In this planning, they aim to distribute the required man-hours in VPM-2 evenly across the weeks. Subsequently, based on this planning, the cutting department receives its demand.

Two weeks before the parts are needed at VPM-2, the nester receives the demand and proceeds to nest the required parts. This ensures that the parts are ready in time, with an additional week allocated as a buffer to account for potential delays or incidents.

2.2.2 Handling

Handling produces the transportation systems that can be used in conjunction with Voortman Machines, such as cross transports and roller conveyors. These systems consist of the nearly the same components in different quantities, with the customer demand often known at a later stage. In this case, the parts for these systems are produced in larger batch sizes and stocked. Only when the stock is insufficient to meet the demand, an order is placed with the cutting department to produce a whole new batch, which is then added to the stock.

The planning for handling is made as late as possible due to frequent changes that occur. The objective is to distribute the workload as evenly as possible. The planning for handling is typically done about two weeks prior to the week of welding. During the same week of planning, the parts that do not have sufficient stock are also sent to the nester for nesting.

2.3 Nesting

Ideally, the nester works one week ahead of the cutting process and two weeks ahead of the due date. For instance, if a part is scheduled for week 20, it will be nested in week 18 and cut in week 19. When the nester begins the nesting process, the first step is to check if he has the orders for both handling and VPM-2. If any orders are missing, he contacts the responsible job preparer to ensure the required orders are entered into the system for the upcoming nesting week. Figure 8 shows the timeline for nesting to cutting in weeks.

Once the total quantity of parts to be cut is complete, the data is loaded into SigmaNest, and the software automatically selects the required part IDs based on the orders. In some cases, certain parts may not be loaded automatically due to version differences, so those parts are manually loaded. The parts are then sorted based on thickness and further sorted within each thickness category based on length.

The actual nesting process begins by filling the available rest sheets. Starting with the longest part, the nester manually places all the parts onto the available sheets. Once the longest parts are nested, the remaining space is filled with the smaller parts. The primary objective during nesting is to minimize the scrap percentage, which refers to the wasted material. The goal is to keep the scrap percentage below 20% so the aim is to fill the space as efficiently as possible. The software takes into account the specifications of each part, including its dimensions, additional space for clean cutting, hole positions, drilling or cutting requirements, and estimated nesting time.

Once all the parts of a particular thickness are nested, the cutting lines are automatically determined, and the nesting report is saved. The nester then proceeds to work on the next thickness. After completing the nesting process, the nestings are scheduled in a way that ensures approximately 18 hours of cutting time per day, which aligns with the total number of working hours for operators.

If an operator or sorter discovers a mistake in a part, they record the part number, and these issues are reported back to the nester once a week. The nester then re-nests those parts on different sheets, separate from the regular nestings. These parts are given priority and will be cut first during the following

week.

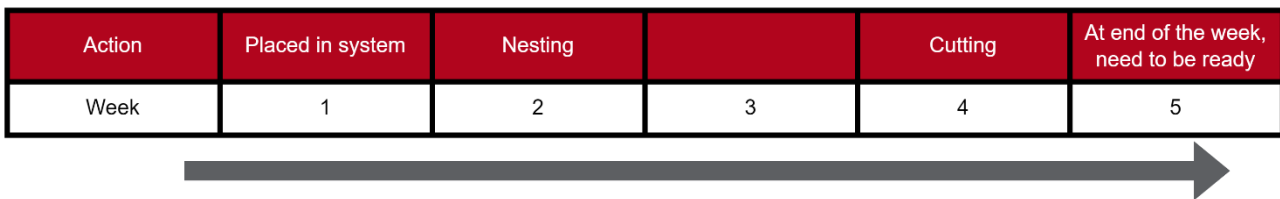


Figure 8 Timeline nesting to cutting.

2.4 Management

Management does not directly engage in regular actions within the product flow, but they hold the responsibility to ensure that all parts are completed on time. If they receive a signal indicating a tight schedule, they make the decision to outsource certain tasks. This signal is provided by the nester, who identifies if the nestings for a particular week will exceed the available time.

During the day-to-day planning, the nester evaluates the schedule and determines if more than 1.5 weeks are required to cut the parts for a given week. If, by Wednesday, there are still nestings from the previous week that have not been completed, the nester notifies management. Management then consults with job preparation to assess the upcoming workload and determine if the tight schedule can be accommodated. If it cannot, the decision is made to outsource the parts for handling that are due two weeks later. By doing so, more time is allocated to address the week with excessive workload.

The choice to outsource handling parts is made because any delays in their production have less impact. Since handling parts are made to stock and the stock level is usually not completely depleted, production can continue even if there is a delay. On the other hand, at VPM-2, production would come to an immediate halt in such a scenario. Additionally, parts scheduled for two weeks in advance are outsourced to create additional time and provide some flexibility in the planning to accommodate the increased workload.

The Figure below presents a schematic timeline/overview of this process.

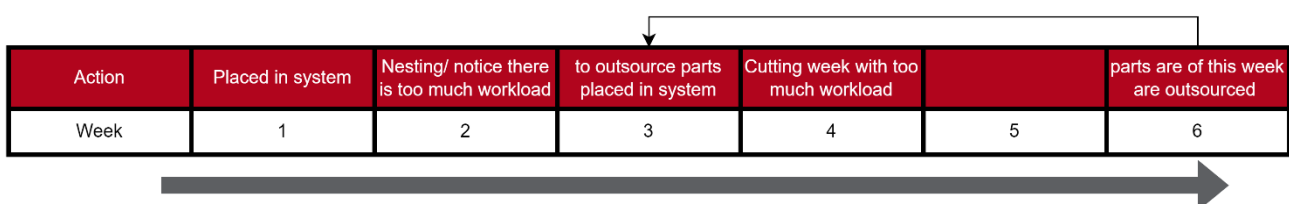


Figure 9 Timeline nesting to cutting when outsourcing is involved.

2.5 Cutting

This step is what it is all about, cutting out the parts from the metal sheets. The V310 machine uses the nestings to determine the precise cutting or drilling locations, tool selection, and movement pattern to follow. The cutting process begins with drilling the holes and tapholes, starting with one size at a time before changing the drill head and continuing. After drilling, the machine proceeds to cutting, using either

plasma or oxyfuel depending on the thickness of the sheet. Oxyfuel is used for sheets over 30 mm thick, while plasma is used for thinner sheets.

The operators at the V310 play a key role in ensuring minimal downtime for the machine. They are responsible for loading, starting, and unloading the machine, as well as responding to any notifications or incidents that may occur. The operators follow the daily planning provided by the nester. Based on the available space on the cutting Table and cutting time, they make decisions on which nesting to start next. Once the machine completes cutting, the operators remove the parts and place the small parts on a roller conveyor while stacking the larger parts for the cleaner/sorter to collect. More detailed information on the tasks of an operator and the cutting process steps can be found in Section 2.7.

2.6 Cleaning and sorting

The cleaning step is the final stage in the parts production process. Although it is not mandatory for running the V310, for the sake of completeness, it is included. The sorter receives the small parts through a conveyor belt and places them in a machine known as the time safer. This machine cleans the parts, removing any excess material. The larger parts are cleaned manually using a grinder. Once the cleaning process is complete, the sorter sorts the parts based on their order numbers and places them into different containers. After this step, the parts are ready to be sent to either VPM-2 or Handling for further use.

2.7 Cutting Operator tasks

In general, the tasks of operators at the machine are about ensuring the machine runs smoothly. However, if we delve deeper, these tasks can be categorized based on the timing of their execution. There are actions that need to be performed during the loading phase, starting the machine, conducting quality checks, responding to machine notifications, and unloading the machine (Sections 2.7.1 to 2.7.4). These actions are conducted for each nesting. Additionally, there are other actions that are not specific to a particular nesting but are part of the overall responsibilities of an operator (Sections 2.7.5 and 2.7.6). Finally, Section

2.7.7 shows a Table of all the actions of an operator. The layout of the cutting department, depicted in Figure 10, might help with understanding where every action takes place, the dotted line divides to halls and crane (for the magnet)

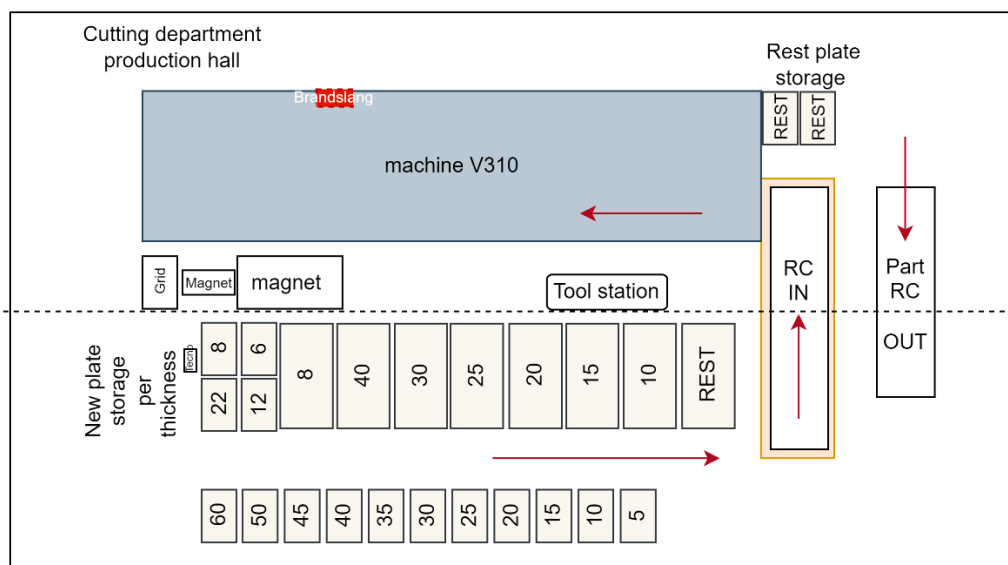


Figure 10 Floorplan of the cutting department

areas, RC stands for roller conveyor, the arrows depict the material flow in the cutting department. The Figures provide the Business Process Models (BPM) of the sequence of tasks.

2.7.1 Loading the machine

The whole cutting process begins with loading all the nestings that are currently scheduled. These nestings provide the operator with information regarding the sheet that is required, order numbers of the parts on the sheet, and whether oxy-fuel cutting is required. There are two options for sheet selection: using a new sheet or utilizing a rest sheet.

When a rest sheet is chosen for nesting, the operator searches for the specific sheet within a pile of rest sheets, hoping it is not at the bottom. The operator uses a magnet to pick up the sheet, removing any sheets on top if necessary. Once the correct sheet is secured on the magnet, it is carefully positioned along a strip on the cutting Table.

In the case of a new sheet, the operator follows a slightly different process. The required sheet is obtained from the plate centre, where all the new sheets are stored. As the magnets around the machine cannot reach this area, the operator uses a different magnet to pick up the sheet from the plate centre and places it on a conveyor. The conveyor transports the sheet approximately 15 meters to an area where the machine area magnet can access it. Here, the sheet is picked up, rotated 90 degrees, and placed in the designated area of the cutting Table, precisely along the strip.

To ensure stability during cutting, the loaded sheet is welded to the strip at several points, preventing any movement. It's important to note that these loading steps don't have to be performed consecutively. An operator may place a sheet on the conveyor without immediately placing it on the machine. This flexibility is taken into account in the observation protocol for time measurements. (Figure 11 provides the BPM)

2.7.2 Starting the machine

Once the sheet is securely welded onto the cutting Table, it is ready to commence the cutting process. When a machine becomes available, the sheet undergoes measurement. A laser point is moved along one edge of the sheet, allowing the machine to determine its precise location. At this stage, the machine may require a tool change.

There are eight available positions for tool changes, and an additional 19 positions where the machine can automatically change its tools. However, at the beginning of a new nesting, the first required

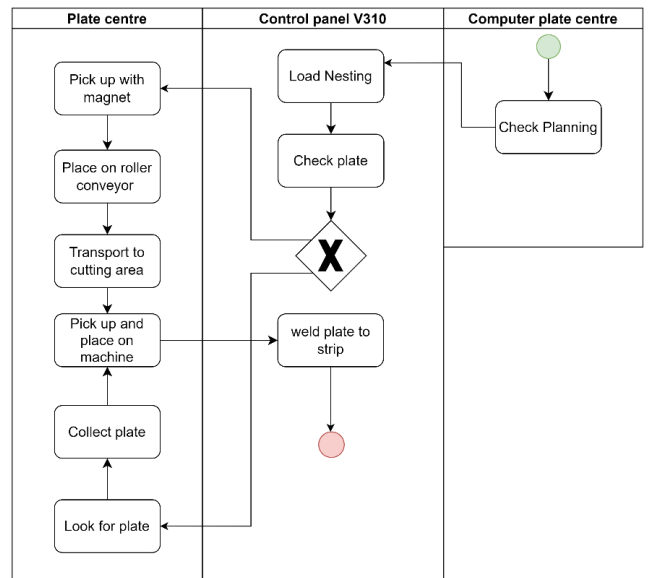


Figure 11 BPM of loading the machine, either using rest sheet or new sheet.

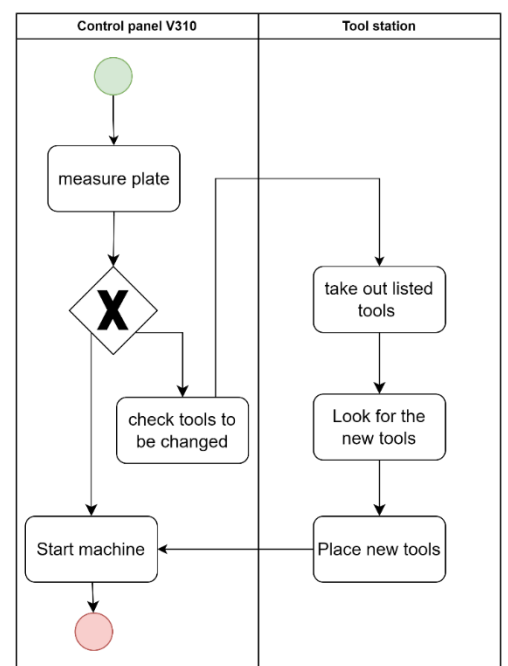


Figure 12 BPM of starting the machine.

drills must be in one of the first eight positions. The machine will indicate which drills need to be replaced and the exact position where each drill should be placed. If a new drill bit is needed, the operator must log the requirement, collect the drill from the nearby cabinet, and assemble it. Once the tool change is completed, the machine is ready to proceed.

For thicker sheets that require oxy-fuel cutting, the oxy-fuel head may need to be replaced based on the sheet thickness. There are four different size intervals, each with its own corresponding head. Similar to the tool change process, the machine will signal when a replacement is necessary. The operator then removes the current head, takes it to the tool station, retrieves the appropriate replacement head, and stores the old head. Logging is not required for this particular operation. (See Figure 12 for the BPM)

2.7.3 Quality checks

A quality check is conducted after the first tap hole is made, and subsequently, every 75 to 100 actions performed by the machine. This check involves the operator verifying if the tap hole has been drilled fully through and ensuring the measurements of the piece are accurate. For tap holes, the procedure is as follows: the operator screws a bolt with the required thickness into the hole and checks if it goes all the way through. If the hole is not fully drilled, the tap drill is inspected and replaced if necessary. The operator then reports this to the nester, indicating that the part needs to be re-nested.

After tracing, additional measurements are checked to ensure the machine's placement accuracy. The operator examines the piece for symmetry (if applicable) or refers to the drawing for specific measurements. If the measurements are found to be incorrect, the operator adjusts the toolhead slightly using the computer control. After making the necessary adjustment, the operator performs another check. If a misalignment or deviation is discovered after the part has already been cut, it is also reported back to the nester for further action. Figure 13 provides the BPM for both possible quality checks.

2.7.4 Unloading

After completing the cutting process for one nesting, the machine proceeds to the next nesting. The operator retrieve the Tablet that contain the colour overlay of the nesting, which provides information about the parts and their respective locations. The operator then writes down the order numbers on the corresponding parts to maintain the linkage with the order.

Next, all the parts are removed from the grid. Depending on their size, the parts are either transported to the conveyor belt for small parts or stacked in a designated area on-site for larger parts. From here, the parts are sent for the cleaning process.

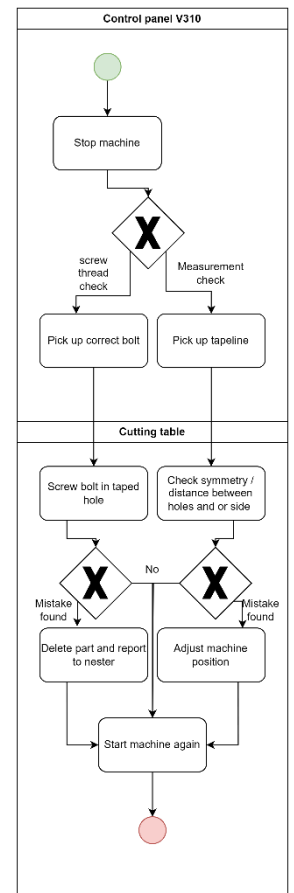


Figure 13 BPM for quality checks.

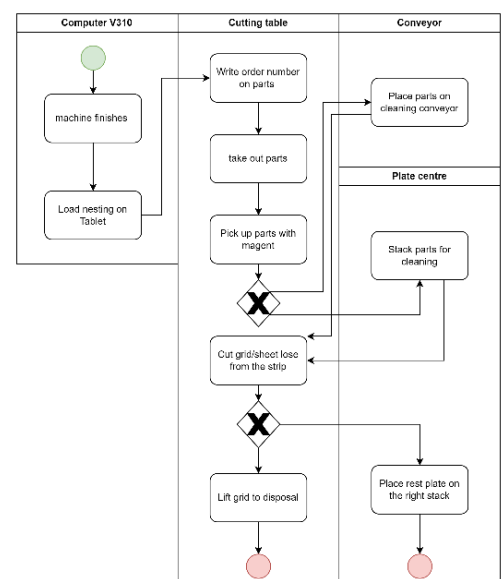


Figure 14 BPM of unloading the machine.

Once the parts have been taken care of, the operator removes the grid from the machine. Using a lifting hook, the grid is transported to a disposal pile. If there is any remaining rest material that can be used for future nestings, it is transported to a rest pile using a magnet. (See Figure 14)

2.7.5 While running

Apart from the regular process steps, there are various other actions that may be required during the operation of the machine. These actions can vary depending on the specific notifications and requirements from the machine. It is challenging to provide an exhaustive list due to the large number of possible notifications. However, I can provide some examples of situations where the machine may stop and require attention.

One common action is brooming the sheet, which typically occurs during or after the drilling process. The machine will stop and signal a blue light instead of the usual green light, indicating the need for an action. Brooming involves removing the chips and debris from the sheet to ensure a clean working surface.

Other instances where the machine may stop and require attention include:

- Drill bit malfunction: If a drill bit becomes worn out or breaks during the drilling process, it will need to be replaced. The machine will indicate the need for a drill bit replacement, and the operator will attend to it accordingly.
- Toolhead proximity: If the toolheads of the machine get too close to each other, the machine will stop to prevent any collisions or damage. The operator will need to adjust the toolhead positions to ensure proper spacing.

These are the most occurrent, there may be additional situations where the machine notifies the operator to address specific issues or perform necessary actions.

2.7.6 Other tasks

In addition to the machine-related tasks, operators also have responsibilities that involve handling equipment and maintaining a well-organized work floor. These tasks contribute to maintaining a smooth workflow, efficient equipment operation, and a safe working environment.

1. Changing the magnet on the lifting system: There may be instances where the operator needs to change the magnet used in the lifting system. This can be due to weight limitations, limitations in the magnet's turning capability, or when only the lifting system is required for a specific task.
2. Transporting disposal grids: The operator is responsible for transporting the pile of disposal grids to the designated container outside. This task typically occurs once a day to ensure proper disposal of the used grids.
3. Maintaining organization: Operators play a role in keeping the work floor organized. This includes ensuring that the pile of rest sheets is neat and orderly, allowing for easy access and identification when needed. They may also tidy up the workstation to ensure all the required tools are readily available for use.
4. Stock the plate centre: When a new load of sheets arrive, the operators transport these sheets of the truck and to the designated stock location in the plate centre. While doing this they register the sheets into the ERP-system so SigmaNest can use them.

5. Redrill erroneous holes: It occurs that cut parts come back because the holes are drilled incorrectly, for example the hole is not completely through, or the tap malfunctioned during drilling. When this goes unnoticed during cutting these parts come back later and have to be redrilled by hand.

2.7.7 Total list

The Table below provides a list with all the tasks of an operator with their category and a short description. The task type describes whether the task is required for V310 to run (primary) or whether the tasks is not necessary for the machine to run (secondary).

Table 1 Operator tasks, category and description

Task	Number (if included)	Category	Type	Description
Pick up sheet	3-4	Loading	Primary	Placing a sheet on the cutting Table, either a rest sheet (which needs to be searched) or a new sheet (which needs to be transported)
Weld sheet to Table	5	Loading	Primary	Weld the sheet to a strip on the cutting Table to prevent it from moving
Look for rest sheet	-	Loading	Primary	A rest sheet has to be found from a pile of other rest sheets, sometimes this requires piles to be moved.
Transport new sheet	-	Loading	Primary	A new sheet has to be transported by a roller conveyor which needs to be started
Measure sheet to machine	9	Starting	Primary	Move the toolhead with laser pointer via the control panel along one edge of the sheet.
Tool change drills	2	Starting	Primary	See which drill heads need to be exchanged and switch those out, if needed place a new bit into a drill head.
Tool change oxy head	2	Starting	Primary	Take of oxy head, store it in the tool station and pick up the required head and place it.
Check tap holes	8	Quality check	Primary	Screw are bolt into the hole to see if it is done fully through
Check measurements	7	Quality check	Primary	Measure some distances or symmetry to see if the placement of the machine is off
Respond and solve machine notifications	-	Running	Primary	There are quite a large number of possible notifications the machine can give; the operator has to resolve these notification
Broom sheet	1	Running	Primary	After drilling the chips and debris is broomed of the sheet.
Write order numbers	17	Writing	Primary	Write the last 3 digits of an order number on the part using colour overlay
Take out parts	13-14-15-16	Unloading	Primary	Take the parts out of the grid and place them on the roller conveyor or the cleaning pile

Cut loose the grid	11	Unloading	Primary	Grind the grid loose of the strip on the cutting Table
Cut grid to pieces for disposal	10	Unloading	Primary	Grind the grid into at maximum 2x2m pieces
Take off the grid	12	Unloading	Primary	Lift the grid of the cutting Table and transport it to the disposal pile
Take off the rest sheet	-	Unloading	Primary	Lift the rest sheet of the Table and transport it to the rest sheet piles
Dispose grids	-	Extra	Secondary	Take all the grids to the bin outside with the forklift
Prevent possible mistakes	-	Extra	Secondary	Operators can do some things that might help preventing machine malfunctions or mistakes,
Magnet exchange	6	Extra	Primary	There are different magnets, there is none that can be used for all tasks, sometimes it needs exchanging
Redrill wrong drilled parts	-	Extra	Secondary	It can occur that the drilling on the machine goes wrong than these holes need to be redrilled by hand.
Refill oil	-	Extra	Secondary	The machine requires oil for drilling and tapping which needs to be refilled occasionally.
Stock plate centre	-	Extra	Secondary	When new sheets arrive by truck, take them off and place them in the right location in plate centre
Bevel cutting	-	Running	Primary	Bevel cutting (cutting under an edge) requires extra caution by the operators as goes wrong easily. To prevent this the watch the machine closely.

2.8 Time required

The following section is about collecting time data, the aim is to answer the question *What are the tasks of an operator and what time does an operator require to fulfil the assigned tasks?* The tasks of operators are explained in Section 2.7, this section will dive onto the time study.

2.8.1 Structured observation

The data is collected through a structured observation, after two shadow days with an operator, the observation protocol was made, this can be found in Appendix A.2. The collection of time data was done using this observation protocol. The focus is on the primary tasks of the operators as described in Table 1, the secondary tasks are removed due to their irregular occurrence and being mandatory for running the machine.

2.8.2 Sample Selection

When collecting data, it is important to select the right sample population for the study. Within this observation studies it is important to have operators with experience, skill with the machine and knowledge on the operations but perform on an average level. Within Voortman there are several very

skilled operators who fit these criteria. The chosen sample were the two operators of the morning shift during the time measuring week.

To select the right moment for the time study it is required to select a moment that is representative. The week of time measurements was chosen because it was a whole work week, other weeks during the research period often had several days off. So, the data collected during this study happened during the office hours of the morning shift.

During the week of time measuring a total of 136 useful time entities were collected that can be spread out over 21 categories as seen in the observation protocols in Appendix A.2. Due to time constraints, it was not possible to collect more entities, because of this constraint the choice is made to have at least 5 entities in each category. This is not sufficient to calculate a sample mean with a 95% level of confidence following the formula as presented by (Pang & Li, 2014) (1). Which calculated that at least number of observations as depending on the category in the range 42 to 408 for a 95% accurate sample mean. Which is unrealistic to measure in the in the time frame of a week or several weeks. Table 2 shows the number of observations included in each category.

$$N = \left(\frac{40 \sqrt{n \sum_{i=1}^n X_i^2 - \left(\sum_{i=1}^n X_i \right)^2}}{\sum_{i=1}^n X_i} \right)^2 \quad (1)$$

Within this formula N is the number of observations required, n the number of observations included and X the value of the ith observation.

2.8.3 Data

The Table below shows primary tasks measured with their corresponding number of observations and mean duration. Secondary tasks are excluded due to their irregular frequency, further elaborated upon in Chapter 5.

Table 2 The primary tasks measured with the corresponding number of observations and mean time in seconds.

Number	Description	Code	Number of observations	Mean time in seconds	Standard deviation	Comment
1	Brooming plate	DCB	5	116	49.627	
2	Change drill	DCDM	8	205	93.181	
3	Place plate on the machine	LPM	14	186	79.451	
4	Pick up new plate	LPN	6	96	24.114	
5	Weld plate to table	LWT	5	158	49.147	
6	Magnet exchange	MW	5	194	47.655	
7	Check measurements	QCM	19	77	37.293	Happens at the first piece and then every 75 pieces
8	Check tapholes	QCT	5	54	10.670	Happen for the first and every 25th taphole
9	Measure plate to machine	SMM	5	48	18.584	
10	Cut grid in pieces for disposal	UCD	5	223	76.058	
11	Cut grid / plate lose	UCL	5	92	40.118	
12	Dispose of grid	UDG	17	137	55.716	
13	Place parts on conveyor	UPB	9	32	5.159	Measured per 10 for category small
14	Pick up parts	UPP	10	76	16.189	Measured per 10 for category small
15	Take out big parts	UTB	8	158	41.632	Measured per 3
16	Take out large parts	UTL	5	144	15.770	
17	Writing down part numbers	UWN	7	43	15.127	measured per 10

2.9 Conclusion

In VPM-1, the production process follows a sequential flow consisting of job preparation, nesting, cutting, and cleaning. Here is a summary of the steps involved:

1. Job Preparation: Orders are planned and prepared in the handling and VPM-2 departments. Job preparation determines the required parts for each order and sends them to the nester.

2. Nesting: The nester receives the orders and designs the nestings, arranging the parts on metal sheets for efficient cutting. Nesting involves optimizing the use of materials and minimizing waste.

3. Cutting: Operators operate the V310 machine, which cuts the parts according to the nestings designed by the nester. The operators perform various tasks during cutting, such as loading the sheets, performing tool changes, monitoring the machine, and conducting quality checks. For a full list of all the operator tasks see Table 1.

4. Cleaning: After cutting, the parts are sent to the cleaning area. Small parts are cleaned using a time-saver machine, while larger parts are manually cleaned with a grinder. The sorter then organizes and sorts the cleaned parts based on their order numbers.

The described steps represent the general flow of the product through the cutting department of VPM-1. Figure 15 provides a visual representation of the production flow described within this chapter, it illustrates general overview of the steps of as described in Sections 7.2 to 7.7 and the connections between the various stages.

Regarding the time study the times used for further calculations are as presented in Table 1.

2.10 Discussion

2.10.1 Operations

Most of the knowledge gained in this chapter is obtained via semi- structured interviews with the involved parties. During these interviews the aim has always been to create an open environment where the interviewee would not hesitate to tell or explain anything regarding the subjects discussed. To do this all interviewees were fully updated on the subject and intended impact of this thesis and the aim of the interview, and after the interview everyone had the possibility to react on the reporting regarding their interview.

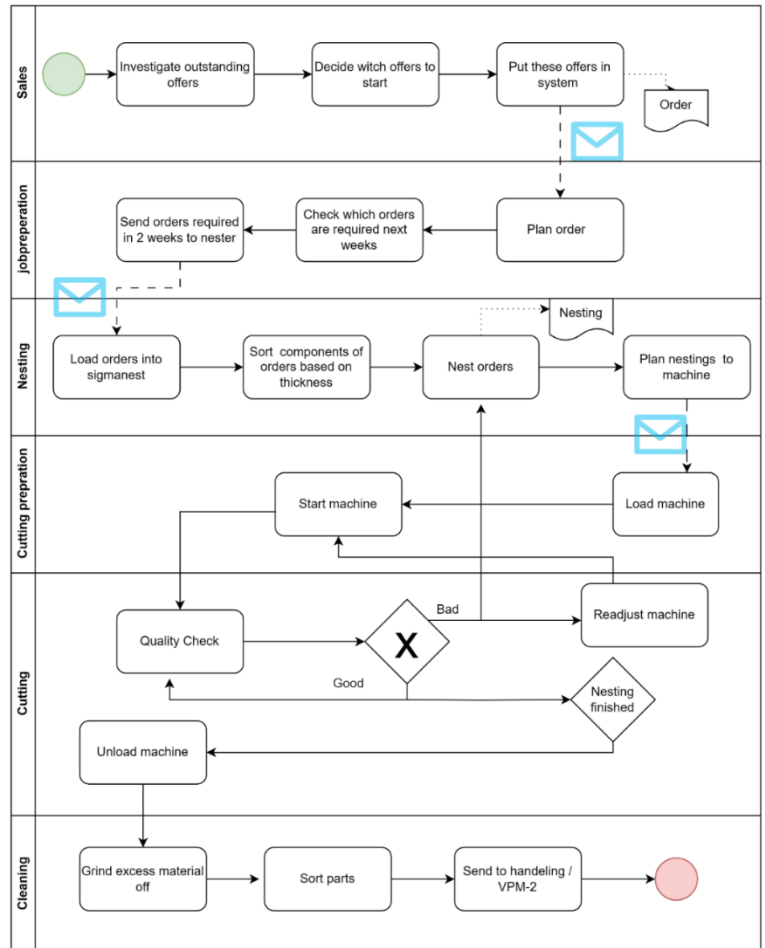


Figure 15 BPM of the full process in the cutting department

Regarding the operator tasks the semi-structured interviews were verified via observations, during these observations a lot more minor tasks surfaced that did not come up during the interviews because they occur infrequently and do not consume a significant part of the workday, an example of this is the oil change of the machine. All of these tasks that surfaced during a week of observations were added, however if you would do more or longer observations more of these minor tasks could come up. These minor tasks missing in not a problem as only the primary tasks, thus tasks required to run the machine on day-to-day basis, are included when making an estimation on the required manhours, all primary tasks are included as they are mandatory for running the machine. Secondary tasks occur irregularly, making their measurement and estimation challenging, and thus they are excluded.

2.10.2 Time study

The time study conducted during the research process encountered certain difficulties that affected the reliability of the measurements. Approximately 50 data points had to be removed from the dataset due to small interferences during the task execution, rendering those measurements invalid, examples of these interferences are: a quick conversation between operators or quitting the task temporarily and respond to a machine notification. To address this issue and ensure more reliable measurements, explicit instructions could be given to finish one task before starting another or to delay questions until a task is completed. This approach would result in more useful data points for analysis.

Additionally, the measured times exhibited a significant variation, primarily attributed to the varying lifting distances on the work floor. For future measurements, it is suggested to exclude the lifting time from the overall measurement and record it separately. This approach would require fewer data points to obtain an accurate sample mean, while allowing for a more precise consideration of the lifting time as a separate factor.

3 Linear regression

Within this chapter the question: "How to make and validate a linear regression model?" will be answered through a systematic literature review, the method can be found in Appendix B. This chapter will elaborate on how to build and check a linear regression model. Section 3.1 provides a general introduction and overview of all the steps and the following sections will describe each step into more detail, with Section 3.2 discussing data and theory before you start making the model, Section 3.3 is about specifying the model, followed by estimating the parameters in section 3.4. Section 3.5 and 3.6 discuss the significance and validity of the model, followed by 3.7 that provides an explanation and the ANOVA Table. Finally, Section 3.8 provides a short conclusion.

3.1 Linear regression

For prediction the number of cutting plates several statistical methods could be used to come to a solution, the two most used being machine learning or linear regression. Here the choice for a linear regression is made because of the nature of the solution, the goal is to make a tool that based on the production variables gives an estimate of the required machine hours and man hours. Using a linear regression model seems to be the best fit since it nicely identifies the correlation between dependent and independent variables which can be used to make predictions. Other methods that could be used but are less fitting to this problem are for example machine learning; which is more fitting when predicting a future full of unknowns, and the Bayesian method used to calculate conditional probabilities to predict a certain outcome (van de Schoot, et al., 2014).

Linear regression is a statistical method to make a model that includes different variables. (Baždarić, Šverko, Salarić, & Martinović, 2021). Via analysing the correlation between the different independent variables it aims to estimate a dependent variable. In this research the dependent variable will be the required area of a nesting and the independent variables come from the order data. In general, the formula for a multiple linear regression model looks as follows (Montgomery, Peck, & Vining, 2012):

$$y = \beta_0 + \beta_1x_1 + \beta_2x_2 + \dots + \beta_kx_k + \varepsilon$$

Here y is the dependent variable, x_i (1 to k) are the independent variables with k the number of independent variables, β_0 is the intercept (the mean for when all the independent variables are 0 (Montgomery, Peck, & Vining, 2012)), the regression coefficient β_i (1 to k) and ε the error between the observed value and the line. The regression coefficients will be determined through a process of fitting the model to the data.

Building a multi-linear regression model is a difficult process that involves several steps and can be seen as an iterative process meaning that it involves a lot of improvement and updating before it can be used (Montgomery, Peck, & Vining, 2012). Figure 7 depicts a general flowchart of the steps that need to be followed to make a well working linear regression model. In the remainder of this chapter all these steps will be explained and followed.

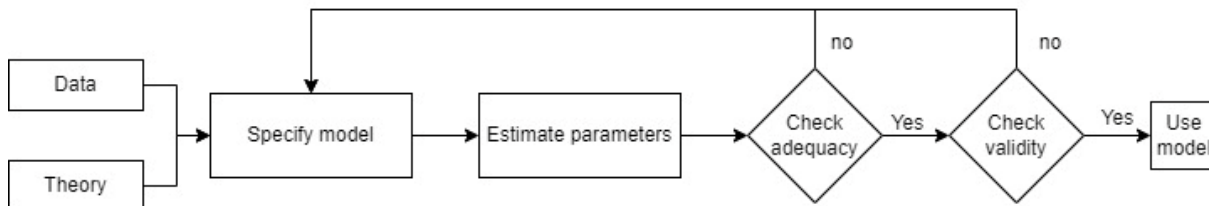


Figure 16 Steps in making a linear regression model obtained from (Montgomery, Peck, & Vining, 2012)

3.2 Data and theory

Both data and theory form the basis of the model. There are several assumptions that apply to linear regression and the used data has to fit those assumptions for a model to be valid. The first one is linearity, which means that “continuous independent variables and the dependent variable are linearly related” (Casson & Farmer, 2014). This can be tested by making a plot of the variables with the dependent variable, and seeing whether this shows a linear relation. Next is the assumption of the errors of conditionality being normally distributed with a mean of zero and variance σ^2 . This variance has to be constant (homoscedasticity). This can also be tested with the scatterplot, if the points are randomly located around the zero-line the scatterplot ensures that this assumption is not violated. The third assumption is the assumption of continuity, the outcome can take any value within a certain range. Then there is the assumption that there are no random components and multicollinearity to the variables x (1 to k), and there are no measurement errors. This is violated when there is a correlation between the error and the dependent variable, tested with a Q-Q plot. The last assumption is that there are no significant outliers (Casson & Farmer, 2014) (Bazdaric, Sverko, Salaric, Martinovic, & Lucijanac, 2021)

3.3 Specify the model

As mentioned earlier, the formula for linear regression is depicted in Eq(1). The goal of this formula is to calculate the expected outcome of a dependent variable, y , based on the regression variables. The mathematical formulation of this equation is represented by Eq(2).

$$y = \beta_0 + \beta_1x_1 + \beta_2x_2 + \dots + \beta_kx_k + \varepsilon . (1)$$

$$E(Y|x) = \beta_0 + \sum_{k=1}^k \beta_k x_k + E(\varepsilon|x) (2)$$

Within this step, the regression variables, denoted as x_i (1 to k), that will be included in the model are determined. The goal is to achieve the best possible explanatory power for the model, which is tested through accuracy and validity checks. Therefore, this step is highly iterative, often performed alongside parameter estimation. Whenever adequacy or validity tests yield negative results, adjustments need to be made, requiring a return to these steps. Ideally, all possible combinations of variables should be tested, and the combination with the best results in the tests should be selected. However, when the number of variables is very large (over 50), this becomes impractical due to time and complexity constraints (Andersen & Bro, 2010).

There is also the risk of overfitting the data, which occurs when more variables are selected than there are samples available (Andersen & Bro, 2010). When validating the model, it is important to check for signs of overfitting.

Another crucial criterion for selecting regression variables may seem obvious: there should be a reasonable belief that the dependent variable, y , is influenced by the independent variables, x . It is important to note that this is not an assumption specific to linear regression models (Casson & Farmer, 2014). However, it is possible to find correlations between dependent and independent variables that are not necessarily causally linked. Thi

3.4 Estimating parameters

There are several methods available to estimate the regression coefficients, and one commonly used method is the least squares method. This method aims to minimize the sum of squared errors between the observed data and the predicted values. In order to apply this method, two assumptions are typically made: there are more observations than regression variables, and the regression variables are independent. The least squares function to be minimized is represented by Eq(3) (Montgomery, Peck, & Vining, 2012). Here i represents the observation and j the independent variable.

$$S(\beta_0, \beta_1, \dots, \beta_k) = \sum_{i=1}^n \epsilon_i^2 = \sum_{i=1}^n (y_i - \beta_0 - \sum_{j=1}^k \beta_j x_{ij})^2 \quad (3)$$

From this point on it is easier to work with matrices which will allow for a more compact display of the model and results (Montgomery, Peck, & Vining, 2012). So Eq(1) will translate to Eq(4) and Eq(3) to Eq(5) :

$$y = X\beta + \epsilon \quad (4)$$

$$S(\beta) = (y - X\beta)'(y - X\beta) \quad (5)$$

with:

$$y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}, \quad X = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1k} \\ 1 & x_{21} & x_{22} & \cdots & x_{2k} \\ \vdots & \vdots & \vdots & & \vdots \\ 1 & x_{n1} & x_{n2} & \cdots & x_{nk} \end{bmatrix}$$

$$\beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_k \end{bmatrix}, \quad \epsilon = \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \vdots \\ \epsilon_n \end{bmatrix}$$

Now taking the derivative of Eq(5) and setting it to zero to minimize will result in Eq(6) which simplifies to Eq(7) which are the least-squared normal equations. By multiplication on both sides with $(X'X)^{-1}$ you obtain the formula to calculate the regression coefficients Eq(8), X' is the transpose of X . (Montgomery, Peck, & Vining, 2012)

$$\frac{\partial S}{\partial \beta} |_{\hat{\beta}} = -2X'y + 2X'X\hat{\beta} = 0 \quad (6)$$

$$X'X\hat{\beta} = X'y \quad (7)$$

$$\hat{\beta} = (X'X)^{-1}X'y \quad (8)$$

3.5 Test of significance

Again, there are several methods for testing the adequacy of the linear regression model, the following three will be discussed: the partial F-test (Section 3.5.1), the R^2 -test and the adjusted R^2 -test (Section 3.5.2).

3.5.1 F- test

The F-test tests the relevance of your model, it tests whether there is a linear relationship in the model by testing if the regression coefficient β_i is zero. Thus, whether the regression variable has influence on the dependent variable. (Chaurasia & Harel, 2015). It takes the null-hypotheses that $\beta_1 = \beta_2 = \dots = \beta_k = 0$, meaning none of the regression values influence the independent variable and thus the model is useless. The null hypotheses gets rejected when the following is true: (Montgomery, Peck, & Vining, 2012)

$$F_0 > F_{\alpha, k, n-k-1} \quad (9)$$

Here F_0 follows from Eq10, $F_{\alpha, k, n-k-1}$ is the P-value. This P-value tests if it the probability of obtaining the data when the null-hypothesis is true. When the P-value > 0.05 it is rejected (Bazdaric, Sverko, Salaric, Martinovic, & Lucijanac, 2021). F_0 can be calculated via the following formula's (Montgomery, Peck, & Vining, 2012):

$$F_0 = \frac{SS_r/k}{SS_{res}/n-k-1} = (10)$$

with $SS_r = \hat{\beta}'X'y - \frac{(\sum_{i=1}^n y_i)^2}{n}$ (11) and $SS_{res} = y'y - \hat{\beta}'X'y$ (12) (note that y , X and β are the matrices shown in Eq(5)). n is the number of observations and k the degrees of freedom of regression (equal to the number of independent variables). SS stands for sum of squares, SS_{res} is the sum of the squared difference between the observed and the predicted value. SS_r is the squared difference between the predicted value and the mean value of the data points. (Montgomery, Peck, & Vining, 2012)

This tests linear relationships; however, this does not mean that the relationship in the model is appropriate for prediction (Montgomery, Peck, & Vining, 2012), it is required to do more tests in order to assess the accuracy.

3.5.2 R^2 and adjusted R^2

The R^2 value shows how well the independent variables perform in predicting the independent variable. When all the data points lie exactly on the model R^2 will have a maximum value of 1 which is the largest value it can obtain (Quinino & Reis, 2013), so the closer the R^2 is to one the better the model is. The R^2 -value is also calculated via sum of squares and the sum of squares due to regression, with the formula (Quinino & Reis, 2013):

$$R^2 = 1 - \frac{SS_{res}}{SS_{total}} \quad (13)$$

where the total sum of squares (SS_t) is the sum of SS_r and SS_{res} . The flaw with this method is that it will always increase when an extra regression variable is added (Montgomery, Peck, & Vining, 2012), and thus is selecting the optimal variables to include impossible. To solve this adjusted R^2 can be seen as more preferable, this method adds another fraction to penalize when a regression variable is added that does not significantly contribute to the increase of the R^2 -value and therefore prevents overfitting as it will decrease when too many insignificant values are added. (Montgomery, Peck, & Vining, 2012). The new formula becomes:

$$R_{adjusted}^2 = 1 - \frac{n-1}{n-k-1} * \frac{SS_{res}}{SS_{total}} \quad (14)$$

where k is the number of independent variables that are included.

3.6 Check of validity

There are three often used techniques to validate a linear regression model (Montgomery, Peck, & Vining, 2012). First, the analysis of the coefficients and predicted value, in Section 3.6.1. Second the validation through data splitting is explained in Section 3.6.2. And finally using fresh data, this is discussed in Section 3.6.3.

3.6.1 Analysis

Determining the validity of the model via analysis can be done via calculating the variance inflation factors (VIF). The formula for calculating the VIF is as follows: (Cheng, Sun, Yao, & Cao, 2022) (García, García, López Martín, & Salmerón, 2015)

$$VIF = \frac{1}{1-R_i^2} \quad (15)$$

R_i^2 measures the coefficient of determination of x_i . The VIF measures to which degree there is correlation between the regression variables. For a model to be considered valid the VIF has to be smaller than 10 (Cheng, Sun, Yao, & Cao, 2022). Otherwise, that coefficient is incorrect or unstable. (Montgomery, Peck, & Vining, 2012). If possible, the stability can also be checked by making multiple models for smaller fractions of the data set and check whether the outcome is similar. For example, if there is weekly data from the past couple of years make a model for each year and compare the coefficients, if they are similar the coefficient is stable. (Montgomery, Peck, & Vining, 2012).

3.6.2 Data splitting

This method is similar to the previous one, the only difference is that you do not collect new data, you split the existing data into two parts. The model gets build following the first data set and afterwards you check the model with second set. Afterwards you calculate the R^2 of your predictors using the press statistic which takes the leverage of the datapoint into account. (Montgomery, Peck, & Vining, 2012).

$$PRESS = \sum_{i=1}^n \left(\frac{e_i}{1-h_{ii}} \right)^2 \quad (16)$$

where e_i is the error between the observed value and the predicted value and h_{ii} the leverage of datapoint i . Next you calculate the R^2 using the following formula (Montgomery, Peck, & Vining, 2012):

$$R^2 = 1 - \frac{PRESS}{SS_{total}} \quad (17)$$

For predictive studies it is favourable to have the R^2 - value as close to one as possible, however literature is not clear on what on value of R^2 is acceptable, within other similar predictive linear regression studies the range between 0.8733 and 1 is deemed acceptable. (Lee, Seo, & Kwak, 2022).

3.6.3 Fresh data

This method can be seen as the most effective to evaluate the model. You collect a new set of data and directly evaluate your model against it, if the predictions are close to the measured data your model can be seen as valid, this is done via the same method as described for data splitting. To evaluate the model via this method you would need at least 15 to 20 observations and if the predictions of these

observations are accurate it will give the user a lot more confidence in the model. (Montgomery, Peck, & Vining, 2012)

3.7 ANOVA Table

During this research the linear regression model will be build using Excel, which gives the output in two different Tables, the regression statistics, and the Analysis of Variance Table (ANOVA). The choice for Excel is made as it easily interpreTable in VPM-1. Figure 17 provides an example of an ANOVA Table, the colour boxes highlight the following:

- The intercept, indicated by the orange square in Figure 17. This is the β_0 values in Eq1. The amount of area on the sheet you require independent of the independent variable. When all the independent variables are 0 this is the area required.
- The coefficients (blue squares), the β values in Eq1. Indicating how many square meters you require per unit of the corresponding independent variable.
- The F-value in the green square, calculated by mean squared errors (Eq11 and Eq12) in the black squares).
- P-Value, light blue square, and test for the likelihood of there being a significant linear relationship between the dependent and independent variables.
- The R- values in the red square. Testing degree of variation. As calculated by Eq13 and Eq14. The adjusted R- value penalizes for adding to much variables preventing overfitting.
- The number of observations, pink square, the amount of observation included in the regression.

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.96117							
R Square	0.923848							
Adjusted R Square	0.922309							
Standard Error	473608.5							
Observations	102							
ANOVA								
	df	SS	MS	F	Significance F			
Regression	2	2.69E+14	1.35E+14	600.5125	4.4E-56			
Residual	99	2.22E+13	2.24E+11					
Total	101	2.92E+14						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	220909	64653.07	3.416837	0.00092	92623.29	349194.7	92623.29004	349194.7
total parts area	1.278085	0.044551	28.68781	9.06E-50	1.189685	1.366485	1.189684849	1.366485
total loss area	-0.70832	0.10164	-6.96889	3.59E-10	-0.90999	-0.50664	-0.909991877	-0.50664

Figure 17 Example of an ANOVA Table, the boxes correspond to a explanation in Section 3.7

3.8 Conclusion

In conclusion, constructing a multi-linear regression model and calculating the regression coefficients involves several complex calculations. The steps required for creating a multi-linear regression model are as follows:

1. Data collection and assessment: Ensure that the dataset is clean and meets the assumptions of the regression analysis.
2. Model specification: Select the variables to be included in the model and revisit this step if any unusual findings arise later in the process.
3. Calculation of the F-value and significance: Determine the F-value to assess the overall significance of the model and test the null hypothesis that the regression coefficients are all zero.
4. Model validation: Perform one or more validation steps to assess the validity of the model, such as checking for overfitting or assessing the model's predictive performance on new data.

These steps are crucial for building a reliable and effective multi-linear regression model.

4 Model for VPM-1

This chapter aims to answer question 4: "What does a linear regression model to estimate the required nestings look like?". It will follow the method described in Chapter 4 and aims to make an estimation on the number of nestings. Section 4.1 will discuss the dataset used for this linear regression model and the adjustments made to make it workable. Section 4.2 provides an explanation of the dependent variable and the choice for categorizing the dataset. Afterwards, the clustered data is tested against the assumptions of linear regression in Section 4.3. This is followed by variable selection and model building in Sections 4.4 and 4.5. Section 4.6 examines the validity test for the model. The chapter concludes with a conclusion and discussion in Sections 4.7 and 4.8, respectively. Please note that all Tables/Figures in this chapter related to the specific category of 5mm, while Tables and Figures for other thicknesses can be found in the Appendices E, F and G.

4.1 Data

The data used to construct this linear regression model was obtained from SigmaNest and exported to an Excel file. The raw dataset includes the following information for the time period between 2021 and 2022:

- All the parts that were cut
- All the nestings that were cut

For a comprehensive list of the information contained in each dataset, including the respective units and explanations for each data point, please refer to the Appendix. It is important to note that data elements related to naming parts within VMS were omitted as they are not relevant to the linear regression model.

By utilizing the nesting names, it was possible to determine the machine on which each entity was cut. Consequently, the data was filtered to include only the V310 machine while excluding the V320 machine, as it falls outside the scope of this analysis since it produces for VSC. Next, the data was divided into two sets based on the respective years, with 2022 serving as the training set for the model and 2021 being allocated for validation purposes. This approach is used as the data set for 2022 was earlier available. The remaining nestings were sorted based on thickness, resulting in the following number of nestings for each thickness; please refer to Table 2.

Thickness	Number of nestings
5mm	153
6mm	102
8mm	180
10mm	386
12mm	101
15mm	261
18mm	2
20mm	280
22mm	5
25mm	180
30mm	192
35mm	16
40mm	102
45mm	2
50mm	54
60mm	37
Total	2053

Table 3 Data with the number of nestings of each thickness in the dataset

By linking the data, a new file was created containing all the unique nestings, with the following information appended to each nesting: (Figure 18 explains some of the variables on part level)

- Thickness in millimetres
- Number of parts
- Total part area in square millimetres (indicated by the white area in Figure 18)
- Total rectangle area in square millimetres (indicated by the grey border in Figure 18)
- Total loss area in square millimetres (rectangle area - part area, indicated by the red area in Figure 18)

- Total part weight in kilograms
- Total cutting length in millimetres (circumference of the parts plus the circumference of the inner cut-outs of the parts)
- Total cutting time in seconds
- Pierce quantity (number of times the plasma head pierces the sheet)

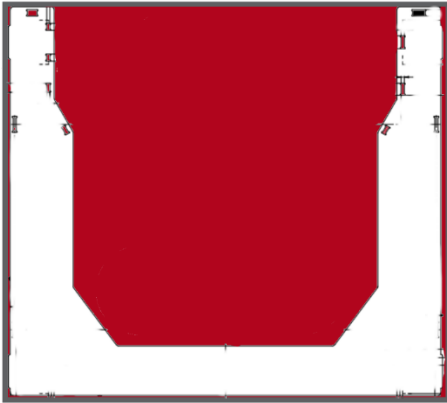


Figure 18 Coloured part drawing to help illustrates data type, on part level.

On a nesting level it looks as in Figure 19, the red area is the required area, and the grey part is the not used area and becomes a rest sheet.



Figure 19 Coloured nesting to help illustrate data types, on nesting level.

4.2 Dependent variable and categorization

The primary objective of this linear regression model is to estimate the number of nestings that need to be cut. However, this number is heavily influenced by the availability of rest sheets, which is not known at the time of estimation. Therefore, using the number of nestings as the dependent variable would not be suitable.

Fortunately, there is a new nesting method being implemented in VPM-1 where only fully filled nestings are cut. This change significantly reduces the number of rest sheets needed, almost eliminating them entirely. Under this new method, we can assume that a new sheet will always be chosen, providing approximately 18m² of available area. By using the "required area" as the dependent variable in the regression model, we can account for the area occupied by previously cut nestings while still making estimations based on the scenario of cutting only full sheets.

By estimating the required area for new nestings using the "required area" variable and considering the availability of 18m² per sheet, we can determine the number of nestings needed. If the required area exceeds 18m², a second sheet will be required. This approach allows us to make informed predictions while considering the constraints of the new nesting method.

To create an accurate model, it is necessary to categorize all the nestings. Thickness is an important constraint, as parts that are 10mm thick cannot be nested on a 50mm thick sheet, resulting in unusable parts. Therefore, it is necessary to develop an individual model for each thickness. In the following sections of this chapter, all the examples provided will be for the 5mm model. Tables and Figures for other thicknesses can be found in the Appendix.

For thicknesses 18mm, 22mm, 35mm, and 45mm, there is insufficient data available to create an accurate model. Starting from 2023, 18mm, 22mm, and 45mm thicknesses are always outsourced due to the very low number of parts required in these thicknesses. Therefore, they do not need to be modelled as they will no longer be cut in-house. As for the 35mm thickness, later on in the process, it will be determined what the best fitting model is for this specific thickness.

4.3 Assumptions check

The data needs to be examined based on several assumptions, including linearity, multivariate normality, multicollinearity, homoscedasticity, the absence of significant outliers, and continuity. However, homoscedasticity, multivariate normality, and outliers can only be assessed once the model is built and evaluated.

Linearity refers to the existence of a linear relationship between the dependent variable (required area) and independent variables. To test for linearity, scatterplots are investigated to determine if a linear relationship exists. The scatterplots for each thickness and variable can be found in the Appendix E. Upon investigating the scatterplots, you can observe that only total rectangle area, total part weight and total part area show a linear relationship with the used area. (See Figure 20)

Multicollinearity focuses on the presence of correlation between variables. It is expected that there will be correlations between variables in the dataset. For example, there may be a correlation between rectangle area and part area, as well as between pierce quantity and the number of parts since each part requires at least one pierce. A correlation matrix for the 5mm thickness is provided in Table 4, while the matrices for other thicknesses can be found in the Appendix. According to Rekha (2023), a correlation coefficient above 0.7 indicates multicollinearity, rendering the variable combination unsuitable for use

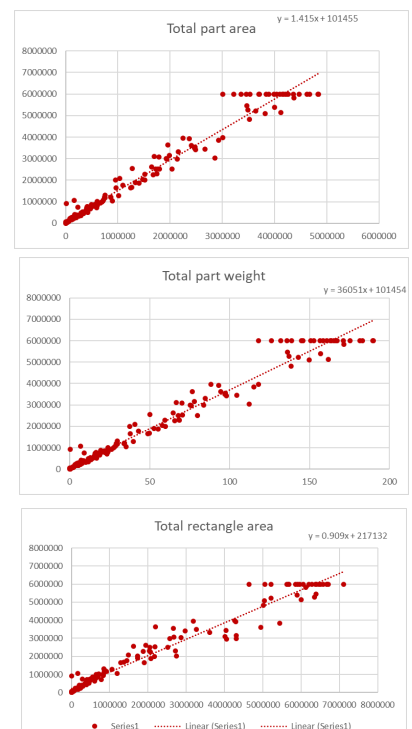


Figure 20 Scatterplot for total part area, total part weight and total rectangle area for 5mm

in the model. As for the multicollinearity matrix below, all the red entities are deemed unfit as a combination for linear regression.

variable	# parts	total parts area	total loss area	pierce quantity	total cutting time	total part weight	total rectangle area	total cutting length
# parts	1.0000	0.1860	0.1023	0.8796	0.8900	0.1860	0.1599	0.8305
total parts area	0.1860	1.0000	0.8564	0.2719	0.2734	1.0000	0.9794	0.5218
total loss area	0.1023	0.8564	1.0000	0.1427	0.1748	0.8564	0.9430	0.4194
pierce quantity	0.8796	0.2719	0.1427	1.0000	0.7979	0.2719	0.2311	0.8322
total cutting time	0.8900	0.2734	0.1748	0.7979	1.0000	0.2734	0.2446	0.8979
total part weight	0.1860	1.0000	0.8564	0.2719	0.2734	1.0000	0.9794	0.5218
total rectangle area	0.1599	0.9794	0.9430	0.2311	0.2446	0.9794	1.0000	0.5003
total cutting length	0.8305	0.5218	0.4194	0.8322	0.8979	0.5218	0.5003	1.0000

*Table 4
Correlation
matrix for 5mm*

4.4 Variable selection

Upon examining the scatterplots, it is observed that only three variables meet the linearity assumption: total part area, total part weight, and total rectangle area. This holds true for all thicknesses. However, when analysing the multicollinearity matrix, these variables are found to be highly correlated. For total part weight and total part area, the correlation coefficient is equal to 1, which is logical since the dataset is sorted based on thickness, and the weight is solely dependent on the part area. For part area and rectangle area, the correlation coefficient consistently falls within the range of 0.96 to 0.99, independent of thickness. Consequently, it is not possible to include these variables together in the regression model.

However, it is possible to select one variable, which would result in a simple linear regression model rather than a multi-variable regression model. Making the new regression formula:

$$y = \beta_0 + \beta_1 x_1 \quad (1)$$

where y is the required part area, β_0 the intercept, area you always require independent of the part you want to cut, β_1 the coefficient for the independent variable and x_1 the value for the independent variable.

To determine the best variable for the regression model, it is necessary to assess which one yields the most significant model. Based on the outcomes of the subsequent steps, the appropriate variable can be selected. Additionally, due to the utilization of a single predictor variable, it is feasible to create a separate model for the 35mm thickness instead of attempting to fit it within another thickness category.

4.5 Model building

In order to determine the significance of each possible variable, two values will be tested using the methods described in Chapter 3.6. First, the significance of total part area will be examined in Section 4.5.1, followed by the examination of total rectangle area in Section 4.5.2. A comparison between the two will then be made in Section 4.5.3. All tests will be conducted using the data analysis tool pack of Excel, utilizing regression statistics and the Analysis of Variance (ANOVA) Table. Please note that the output provided here pertains to the 5mm thickness; the information for other thicknesses can be found in the Appendix E, F and G.

4.5.1 Total part area

Figure 21 depicts the ANOVA Table for the linear regression model using total part area as the independent variable. It should be noted that the variables in the dependent variable are measured in square millimetres within the dataset, which explains the relatively large values.

Starting with the F-test (formula 3.8), you test the F-value to the P-value when the P-value is below 0.05 you can reject the null hypothesis, suggesting that the variable is a good predictor for estimation.

Moving on to the adjusted R-squared test (indicated by the red square), the Table shows an adjusted R-squared value of 0.97 (rounded), which indicates that the dataset fits well to the model. This means that only 3% (1 - 0.97) of the data in the training set cannot be explained by the predictor variable. This is a very high score, indicating a strong relationship between the independent variable and the dependent variable. As discussed in Section 3.6.3 a R-squared value above 0.7 will be deemed acceptable.

Table 5 displays the most important values from the ANOVA Tables for all the thicknesses. Here, we can observe that the reasoning discussed above holds true for all thicknesses. However, it is worth noting that for 6mm, 25mm, and 50mm thicknesses, the adjusted R-squared value drops below 90%. Despite this, these thicknesses still pass the F-test significantly, suggesting that it is a not bad predictor. Overall, the analysis indicates that using total part area as the independent variable yields favourable results for estimation in the linear regression model across different thicknesses.

Regression Statistics								
Multiple R	0.98491231							
R Square	0.970052258							
Adjusted R Square	0.969853929							
Standard Error	373480.0828							
Observations	153							
ANOVA								
	df	SS	MS	F	Significance F			
Regression	1	6.82249E+14	6.82E+14	4891.116	6.0776E-117			
Residual	151	2.10626E+13	1.39E+11					
Total	152	7.03312E+14						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	101454.813	41659.66599	2.435325	0.016043	19143.68981	183765.9	19143.69	183765.9363
Total part area	1.414989315	0.020232482	69.93652	6.1E-117	1.375013999	1.454965	1.375014	1.454964631

Figure 21 ANOVA Table for 5mm when using part area.

Thickness	P-value	F-value	Adjusted R	Std. Error
5mm	6.0776E-117	4891.12	0.970	373480
6mm	4.76565E-49	780.98	0.885	575323
8mm	2.21162E-78	3298.21	0.970	765995
10mm	1.6264E-301	13538.87	0.972	1132490
12mm	3.20717E-85	4692.93	0.979	307924
15mm	2.6036E-216	11436.08	0.978	873001
20mm	2.6727E-214	9077.96	0.970	1115322
25mm	4.40516E-88	1475.76	0.892	1889656
30mm	3.8684E-189	17553.34	0.989	668777
35mm	6.67149E-16	1635.47	0.991	38114
40mm	5.05319E-52	910.16	0.900	1201247
50mm	2.03293E-27	456.89	0.896	255877
60mm	2.13309E-27	1008.83	0.966	318448

Table 5 Required values for all thicknesses using part area.

4.5.2 Total rectangle area

Figure 22 presents the ANOVA Table for the linear regression model with total rectangle area as the independent variable for the 5mm thickness. It can be observed that the independent variable has a

substantial impact on the dependent variable, as indicated by the very small P-value. This pattern holds true for all thicknesses, suggesting that total rectangle area is a strong indicator of the total used area.

The adjusted R-squared value for the 5mm thickness is 0.96 (rounded), which is a highly favourable score. It signifies that approximately 96% of the data in the dataset can be explained using total rectangle area as the independent variable. However, it is worth noting that for the 6mm, 25mm, and 40mm thicknesses, the adjusted R-squared values fall below 90%. Particularly for the 6mm thickness, the value of 76% is considered unacceptable. This discrepancy may be attributed to the fact that 6mm parts often have large rectangles but smaller net areas, resulting in a significant amount of unused area that could be filled with other pieces. Overall, the analysis demonstrates that total rectangle area is a strong indicator of the total used area in the linear regression model, with Table 6 displaying the predictive power across various thicknesses.

Regression Statistics								
Multiple R	0.981318097							
R Square	0.962985207							
Adjusted R Square	0.962740076							
Standard Error	415215.0338							
Observations	153							
ANOVA								
	df	SS	MS	F	gnificance F			
Regression	1	6.77279E+14	6.77E+14	3928.45	5.4E-110			
Residual	151	2.60329E+13	1.72E+11					
Total	152	7.03312E+14						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	217131.9267	45141.30783	4.81005	3.62E-06	127941.8	306322.1	127941.8	306322.1
total rectangle area	0.908979116	0.014502514	62.67735	5.4E-110	0.880325	0.937633	0.880325	0.937633

Figure 22 ANOVA Table for 5mm using rectangle area.

Thickness	P-value	F-value	Adjusted R	Std. Error
5mm	5.397E-110	3928.45	0.963	415215
6mm	5.62834E-33	320.88	0.760	832367
8mm	2.8405E-130	4746.22	0.964	839941
10mm	3.5135E-249	7049.29	0.948	1549916
12mm	4.57323E-74	2753.58	0.965	399098
15mm	2.3686E-182	6135.46	0.959	1180631
20mm	9.1771E-185	5458.29	0.951	1424390
25mm	1.03156E-87	1460.03	0.891	1898704
30mm	2.9937E-188	17175.27	0.989	676018
35mm	5.64639E-16	1675.24	0.9911202	37663
40mm	4.67735E-46	667.73	0.868	1377913
50mm	9.98058E-30	572.12	0.915	231053
60mm	8.19093E-32	1830.41	0.981	238213

Table 6 required values for rectangle area for all thicknesses.

4.5.3 Comparison

As previously mentioned, both total part area and total rectangle area are effective predictors of the used area. However, for the final model, only one of these variables can be included. To determine which variable to use for each model, the adjusted R-squared. The F-value is excluded from the comparison because, regardless of the thickness, it indicates that either variable is a good predictor. The goal is to maximise the R-squared value as it tests how well the model fits to the data set, therefore for each

thickness the model and accompanying independent variable with the highest R-squared value are chosen.

By comparing both variables in Tables 5 and 6, column 4 based on these criteria, we obtain Table 8. From this Table, we can conclude that for thicknesses 5mm to 30mm and 40mm, total part area is the best-fitting independent variable. On the other hand, for thicknesses 35mm, 50mm, and 60mm, total rectangle area is the preferred choice. Table 7 displays the corresponding intercept and coefficient that will be used for validating the model. The intercept gives the square millimetres that are always required when you would cut a sheet, independent of the parts that are placed on the sheet, in the formula for regression this value would be the β_0 . The coefficients provide the estimation on how many extra square millimetres you require per square millimetre of the parts (either part area of rectangle area depending on the thickness) you want to cut, it is the β_1 value of Formula 5.1.

thickness	Best R-value
5mm	part area
6mm	part area
8mm	part area
10mm	part area
12mm	part area
15mm	part area
20mm	part area
25mm	part area
30mm	part area
35mm	rectangle area
40mm	part area
50mm	rectangle area
60mm	rectangle area

Thickness	Intercept	Coefficient
5mm	101454.813	1.414989315
6mm	269842.158	1.055774245
8mm	363244.329	1.240123796
10mm	430179.416	1.21977707
12mm	56856.1934	1.498061476
15mm	276017.324	1.336057077
20mm	409661.053	1.363662163
25mm	832549.71	1.198465837
30mm	350785.019	1.298975476
35mm	136895.921	1.165475841
40mm	544726.983	1.261223419
50mm	183565.932	1.159687618
60mm	713020.581	1.43992632

4.6 Assumption check

The assumptions multivariate normality and homoscedasticity have to be checked after the model building step. Multivariate normality must be checked according to a Q-Q plot. You want to have your data points to follow a straight line, which is the case for 5mm as you can see in Figure 24. To test homoscedasticity, you look at the scatterplot and want you points to be randomly distributed without a pattern showing up, this is also the case for all thicknesses. Therefore, you can see that the chosen variable is a reliable predictor.

Table 8 Best fitting variable based on R^2 for all thicknesses.

Table 7 Intercept and coefficient corresponding to best predictor in Table 8

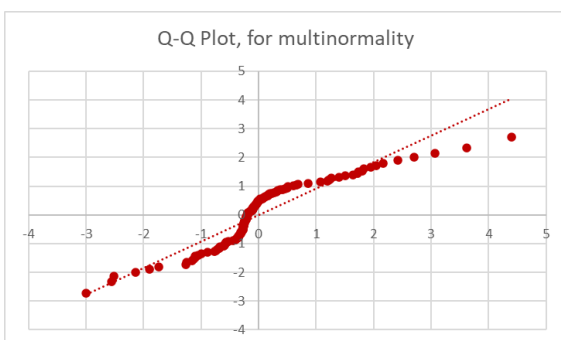


Figure 24 Q-Q plot to test multivariate normality for 5mm

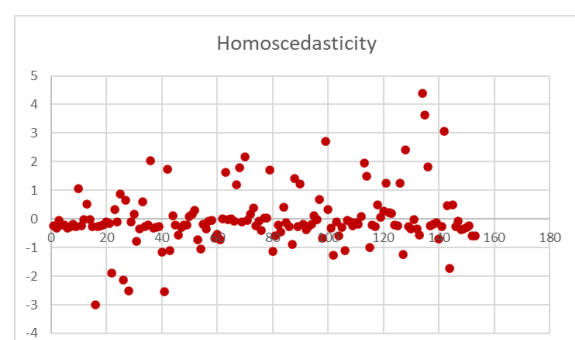


Figure 23 scatterplot for homoscedasticity 5mm

4.7 Validation

The model validation is performed using the technique of data splitting, as the variance inflation factor (VIF) cannot be used due to the inclusion of only one variable. The model is constructed using the 2022

dataset, and its performance is tested on the 2021 dataset. This approach is valid because the years 2021 and 2022 exhibit similarities in terms of the number of nestings cut and the used area, with a difference of only -9% and 1% respectively.

To validate the model, the coefficient of determination (R-squared) is calculated for the predictions. The R-squared value indicates the percentage of the dataset that can be explained by the predictor variable (Montgomery, Peck, & Vining, 2012). Table 9 displays the R-squared values for the predictions, which generally appear favourable. However, there are concerns for the 35mm, 50mm, and 60mm thicknesses as their R-squared values fall below 90%. This discrepancy may be attributed to the fact that rectangle area is a less precise measurement of the required area, resulting in a larger sum of squares.

Thickness	Number of nestings	R ²
5mm	194	0.915314
6mm	120	0.919855
8mm	194	0.984169
10mm	360	0.972111
12mm	101	0.959002
15mm	239	0.970572
20mm	314	0.934473
25mm	169	0.981564
30mm	232	0.978896
35mm	41	0.852303
40mm	150	0.971708
50mm	76	0.865303
60mm	46	0.724134
Total	2236	

Table 9 entities in validation set and r-squared per

As the R-squared values for 35mm, 50mm, and 60mm are unacceptably low, a revaluation of the variable selection step is necessary. By using total part area as the predictor variable along with their corresponding intercepts and coefficients, the predictor R-squared values for 35mm, 50mm, and 60mm increase to 0.894, 0.922, and 0.944 respectively. This suggests that total part area provides better predictions of the required area compared to rectangle area within the validation set. Therefore, a switch is made from rectangle area to part area as the predictor variable for the 50mm and 60mm thicknesses.

Although the R-squared value for 35mm remains below 87%, total part area and total rectangle area were the only two variables that exhibited a linear relationship. However, they cannot be selected together due to multicollinearity. Hence, total part area is deemed the best option for the independent variable, despite not meeting the conditions set.

4.8 Conclusion

To summarize, it is generally possible to create a linear regression model that meets the criteria set by VPM-1 using the total part area as the dependent variable. So all the thicknesses have the same variable. Total part area is the best fitting independent variable as the other variables either fail to satisfy the

Thickness	Intercept	Coefficient
5mm	101454.81	1.41
6mm	269842.16	1.06
8mm	363244.33	1.24
10mm	430179.42	1.22
12mm	56856.19	1.50
15mm	276017.32	1.34
20mm	409661.05	1.36
25mm	832549.71	1.20
30mm	350785.02	1.30
35mm	136895.92	1.25
40mm	544726.98	1.26
50mm	153270.29	1.34
60mm	80180.42	1.71

Table 10 Intercept and coefficient that provides the best predictions.

linearity assumptions or perform worse as independent variable. The coefficients and intercepts resulting from the linear regression model are presented in Table 10. Where the intercept gives the square millimetres that are always required when you would cut a sheet, independent of the parts that are placed on the nesting. The coefficients provide the estimation on how many extra square millimetres you require per square millimetre of the parts you want to cut.

4.9 Discussion

The presence of a flaw within the dataset could have impacted the outcome of the linear regression model. Up until mid-2022, parts that were rejected after cutting due to quality issues were not properly reported in SigmaNest, resulting in a discrepancy between the actual total part area and the reported total part area. Approximately 1.3% of the total number of parts cut in the training set were affected by this issue. It is difficult to identify the specific nestings that were affected, except for the fully rejected nestings, which were excluded from the training dataset. Consequently, the actual intercept and coefficients may be smaller than the calculated values, potentially explaining some outliers in the model. Using the actual intercept and coefficients would likely yield a lower mean squared error and a higher R-squared value. Nonetheless, the calculated values still resulted in acceptable models for all thicknesses, and therefore, these flaws do not lead to major discrepancies, and the models can still be used for predicting the required sheet area.

Another factor that causes a discrepancy between the real values and the calculated values in the correlation matrices is the datatype "pierce quantity." Pierce quantity represents the number of times the machine has to pierce the sheet, either through drilling or plasma cutting. Changes in the requirement for predrilling on certain thicknesses during 2022 may have increased the pierce quantity for some thicknesses within the dataset. However, pierce quantity is not involved in the linear regression model as there is no linear relationship, and it does not affect the outcome of the model.

To address these flaws in future analyses and accurately calculate real values, it is important to avoid such changes or clearly document any changes made to data storage, so they can be adjusted for in the training and validation datasets.

Regarding the low R-squared value for 35mm, it is worth noting that 88% of the training dataset for this thickness comprised similar nestings, with each nesting containing the same part replicated eight times. As a result, these nestings had the same total part area, limiting the variation in the independent variables and making it challenging to estimate the required area accurately, as required area differs based on how the parts are nested and the shape of the sheet available. The low number of observations and lack of diversity in the independent variables contribute to the lower R-squared value for 35mm.

5 Influential factors

In order to estimate the required man hours, it is necessary to understand the factors that affect this. This chapter addresses the questions: *"What factors influence the primary tasks of operators?"* and *"How to make an estimation on required man hours for these factors?"*. The objective is to determine how tasks are related to the required man hours and how to estimate the need for these tasks. By combining this information with the time study in Chapter 2, it becomes possible to estimate the required man hours.

Through semi-structured interviews and observations, the following two questions are answered: "What factors influence the primary tasks of operators?" and "How can we estimate the required man hours for these factors?" The sections below describe each factor that emerged from the interviews, along with its corresponding task(s), and how these tasks can be included in the time estimation. Please refer to Table 1 in Section 2.7.7 for a comprehensive list of operator tasks. If estimations are required, historical data is utilized. Section 5.1 goes into detail on the tasks that need to happen for each nesting, Section 5.2 discusses the need for a tool change. Section 5.4 describes how the estimation is made for tap hole checks and measurement checks, followed by Section 5.4 about the taphole checks. Section 5.6 provides more information about bevel cutting and Section 5.7 explains how immediate sheets are taken into account. Finally the chapter concludes with an explanation on the magnet exchange and the discussion and conclusion. See Section 6.4.2 for the calculations of the time estimations for these tasks.

5.1 Number of Nestings

Several tasks need to be performed for each nesting, referred to as standard tasks. These tasks are independent of the number or characteristics of the parts in the nesting. The tasks corresponding to this section include, (the numbers in brackets describe the tasks number):

- Picking up the sheet from the plate centre (3)
- Placing the sheet on the machine (4)
- Welding the sheet to the Table (5)
- Measuring the sheet (9)
- Cutting the grid loose (11)
- Cutting the grid for disposal (10)
- Disposing of the grid (12)

Estimating the required number of nestings is accomplished through a linear regression model. Further details can be found in Chapters 3 and 4.

5.2 Tool change

Tool changes occur at the beginning of cutting a sheet and sometimes during the cutting process. When cutting starts, the machine indicates which drills or cutting heads are needed, and these tools must be replaced. Additionally, if a tool malfunctions during cutting, it also needs to be replaced. The frequency of tool changes depends greatly on the sequence in which sheets are cut. If you cut sheets of the same thickness consecutively, fewer tool changes are required compared to when switching between thicknesses. Since the required tools are unknown prior to nesting, an estimation of the number of tool changes is necessary.

Based on observations and interviews, it has been determined that an average of five tool changes per sheet to be cut is expected. (task 2)

5.3 Part characteristics

The handling time after cutting is mainly influenced by the characteristics of the parts. Depending on the size and weight of the part, it is transported to one of three locations, each corresponding to different tasks.

1. Small Parts:

These are parts smaller than 0.4m² and weigh below 7 kilograms. They are taken out of the grid and loaded into a basket. The basket is connected to a lifting system and can hold a large quantity of parts. Once the basket is filled, it is transported to a roller conveyor that carries the parts to the cleaning and sorting area. At the roller conveyor, the parts are removed from the basket and placed close to each other. The tasks involved are:

- Take parts out of the grid and load them into the basket. (14)
- Remove the parts from the basket and place them on the roller conveyor. (13)

2. Medium Parts:

These parts fall between the small and large categories. They are larger than 0.4m² and heavier than 7 kilograms but smaller than 2 meters in length. These parts are taken out of the grid using a magnet, often handling 3 to 5 parts at once, and transported to the roller conveyor for cleaning and sorting.

- Take the parts out of the grid and transport them to the roller conveyor. (15)

3. Large Parts:

These are parts with a side length exceeding 2 meters. They are taken out of the grid and immediately stacked to the side of the cutting as this is more practical in the cleaning stage. The responsibility for cleaning and sorting these parts lies with the designated operator who picks them up from the stack.

- Take the parts out of the grid and transport them to the designated spot. (16)

5.4 Measurement check and writing

The frequency of these tasks depends on the number of parts present on the sheet.

Measurement Check (7):

The operator performs a measurement check on the first part of the sheet, ensuring the measurements are accurate. If adjustments are needed, the toolhead location is slightly modified. This process is conducted for every first part on the sheet and subsequently for every 75th part.

Writing the Order Number (17):

Before transporting each part to the cleaning and sorting area, the order number is recorded. For individual parts, the order number is written for every part. However, if a batch of the same parts (consisting of over 10 parts) is being produced, the order number is written on every 10th part.

To estimate the frequency of these tasks, you can count the number of parts falling into each category (e.g., unique parts, parts in a batch) and multiply it by the corresponding frequency for each task. This will provide an estimation of how often these tasks are performed based on the total number of parts on the sheet.

5.5 Tap holes

Tap holes require additional quality checks by the operators (task 8). The operator verifies if the hole is correctly tapped by screwing a bolt into the hole and ensuring that it fits properly and extends through the entire hole. Based on the time study conducted in Section 2.8, it was determined that checking a tap hole takes approximately 55 seconds.

# tap holes during the week	# parts	ratio tap holes/parts
514	1805	0.2848
1373	3194	0.4299
1328	2423	0.5481
2410	4958	0.4861
654	910	0.7187
Average		0.4935

Table 11 Number of tap holes per week, ratio, and average

To estimate the number of tap holes per week, an analysis of five representative weeks is conducted. These weeks provide a reliable sample for determining the number of tap holes. Additionally, it is important to consider the correlation between the number of tap holes and the number of parts, which has a correlation coefficient of 0.95 for the counted weeks. This correlation should be considered during estimation and therefore you can say that the number of tapholes is dependent on the number of sheets.

Table 11 provides the values for each of the selected weeks. From this Table, it can be inferred that, on average, 49% of the parts contain a tap hole. Operators check the first tap hole of a nesting and subsequently check every twenty-fifth tap hole on the sheet. These factors should also be considered in the estimation process.

5.6 Bevel cutting

Bevel cutting involves tilting the cutting head to create a bevelled edge on the part, as shown in Figure 25 for reference. This task is time-consuming for operators and can easily go wrong. For instance, the plasma head may fail to pierce the sheet at the beginning of the cut, or the machine location may be displaced, resulting in the rejection of the part(s) (or multiple parts if the issue goes unnoticed), leading to waste. To prevent such errors, operators closely monitor the machine during bevel cutting and cannot perform other tasks simultaneously. (task 18)

When operators identify that a nesting about to be cut includes bevels, they introduce a pause on the machine before reaching the bevel. When the machine reaches the bevel side of the parts, it stops, and operators manually restart it. From that point onward, they closely monitor the cutting process until the bevel sides are completed.



Figure 25 Example of a part with a bevelled edge

Unfortunately, the information regarding which parts require bevels is not included in the part data. As bevel cutting is time-consuming, it is essential to account for it when estimating the required man hours. By examining five representative weeks and counting the number of bevels during those weeks (refer to Table 12 for the results), it becomes evident that there is high variability. Due to practical constraints, obtaining this information for more weeks was not feasible. The outlier in week 4 may be attributed to the requirement of a "made to stock" part, where bevel parts were identical throughout the week. However, because of the substantial variability and the inability to trace the parts in the ERP system, it is impossible to estimate the time required by operators for these parts. The time for bevel cutting is highly dependent on the length of the bevel side, which is unknown. Moreover, considering the very low proportion of parts that contain a bevel (on average 1.7%), it can be neglected during the time estimation process.

# bevel parts	# parts	ratio bevel/ parts
20	1061	0.0189
4	1884	0.0021
36	4958	0.0073
120	2423	0.0495
16	1805	0.0089
Average		0.0173

Table 12 Number of bevel parts for 5 weeks

5.7 Immediate sheets

Every week, there are immediate nestings that consist of parts rejected in the previous week due to quality issues. Since the deadline for these parts is approaching or has already passed, these nestings need to be prioritized. To ensure their separation from the current week's nestings, they are placed on separate sheets. Estimating the number of hours spent on these nestings requires an estimation of the number of immediate nestings per week and the corresponding man hours.

By analysing the data from 2022, it was found that a total of 328 immediate sheets were cut throughout the year. On average, this translates to approximately 6 immediate sheets per week. These sheets consisted of an average of 40 small parts, 9 medium parts, and 0 large parts, distributed across 6 different thicknesses. These factors need to be considered when calculating the time required.

On average, it was determined that an immediate sheet requires 14 minutes and 5 seconds (or 845 seconds) to cut. This average time will be taken into account on a weekly basis.

By considering the number of immediate nestings and the average cutting time for each, it becomes possible to estimate the man hours required for these nestings every week.

5.8 Magnet exchange

Within the production hall, there are two magnets available for different purposes. The first magnet is the same size as the sheets and is primarily used to turn the sheets by 90 degrees as they enter the cutting hall from the plate storage. When a sheet arrives from the roller conveyor, it needs to be turned to fit onto the cutting Table. This particular magnet is specifically designed for this turning operation and cannot be used for other tasks. For a visual reference, please refer to Figure 10 in Section 2.7

The second magnet consists of two beams and is capable of lifting full sheets, but it is not designed for turning them. This magnet is utilized more frequently throughout the entire production hall, including other machines besides the V310.

To ensure that the lifting system is not occupied too often by the first magnet, a process is in place. Once a day, the sheets scheduled for that day are transported to the cutting hall, turned using the first magnet,

and placed on the ground. When a sheet is needed, it is picked up from the ground and placed on the machine using the second magnet.(task 6)

Based on the time study conducted in Section 2.8, it is observed that it takes a little over three minutes to exchange the first magnet. Therefore, to facilitate efficient operations, the magnet is changed twice a day during a regular week, amounting to a total of 10 magnet changes.

5.9 Conclusion

In conclusion, the primary tasks can be categorized into three types: standard tasks, handling tasks, and regular tasks.

Standard tasks are tasks that need to be performed for every nesting during the cutting process. When estimating the time required, the durations for these tasks will be summed together; Handling tasks are tasks that depend on the type and number of parts required. These tasks involve the transportation, sorting, and handling of parts based on their characteristics. The time estimation for handling tasks will take into account the specific requirements associated with different part types and quantities. And regular tasks are tasks that need to be performed every week, regardless of the specific parts required. These tasks may include maintenance, setup, or other routine activities necessary for the operation of the machine.

By categorizing the tasks into these three types, a more comprehensive and accurate time estimation can be made, considering the unique requirements and variations in each task category.

Standard tasks

- Picking up the sheet from the plate centre (3)
- Placing the sheet on the machine (4)
- Welding the sheet to the Table (5)
- Measuring the sheet (9)
- Cutting the grid loose (11)
- Cutting the grid for disposal (10)
- Disposing of the grid (12)

Handling tasks, for estimating the number of parts in each category is counted and taken into account corresponding to their category

All parts

- Measurement check (7)
- Writing part numbers (17)
- Tap hole check (8)

Small parts

- Take out parts and place them in the basket (14)
- Place parts on the roller conveyor (13)

Medium parts

- Pick with three at the time and transport to the roller conveyor (15)

Large parts

- Pick up parts individually and transport to designated spot (16)

Regular tasks, these will always be added when making a time estimation.

- Magnet exchange (17)
- Immediate sheets

5.10 Discussion

In this Chapter many values are used to make an estimation in the occurrence of the tasks. These values have been obtained using various methods, including normative standards, observations, analysis of historical data, and manual counting. It is important to acknowledge that manual counting, especially for bevels and tap holes, may introduce the possibility of errors or missed entities. However, the impact of such errors is not significant given the large quantity of parts involved. The calculated averages would not change significantly if there was an additional part cut during a week or an additional tap hole to be checked.

Although it is unfortunate that accurate information about bevels could not be obtained because of their low occurrence rate (1.7% per week), it does not significantly affect the time estimations. Since bevels are a relatively rare occurrence, their exclusion from the estimations does not have a substantial impact.

It is worth noting that due to the manual nature of data collection, it was not possible to gather more data beyond the available weeks. However, if more weeks were included in the analysis, the average values would likely provide a more accurate representation.

Another aspect that needs attention is the categorization of tasks, as described in section 5.3. These categories are highly dependent on the operators and the specific situations encountered. There is no universally defined standard regarding the appropriate handling of magnets or the specific methods to be employed. The categorization was developed based on interviews with multiple operators to ensure a realistic and practical classification system.

6 Tool

This chapter aims to bring together the theories and methods described in previous chapters to develop a tool that can be implemented in VPM-1. The research question guiding this development is: *"How to create a tool that can be implemented in VPM-1?"* This question is further divided into two sub-questions: *"What are the requirements of the tool?"* and *"How to develop a tool that utilizes the linear regression model and time data to estimate the required man hours?"*

Section 6.1 will delve into the first sub-question by discussing the requirements of the tool. This section will outline the necessary criteria and specifications that the tool needs to meet. The subsequent sections will provide a detailed explanation of the tool. Section 6.2 will focus on the input data required for the tool's operation, discussing the specific information and variables needed to perform accurate estimations. In Section 6.3, a conceptual model for the tool, represented as a black box, will be presented, illustrating its internal functioning and logic. Section 6.4 will delve into the calculations and algorithms employed by the tool. It will explain how the linear regression model and time data are utilized to estimate the required man hours for different tasks and factors. The chapter will conclude with practical guidance on implementing the tool in VPM-1 (Section 6.5), a summary of the findings and conclusions drawn from its development (Section 6.6) and a discussion regarding this conclusion in Section 6.7.

By addressing the research question and its sub-questions, this chapter aims to provide a comprehensive understanding of the requirements and development process of the tool, enabling its effective integration into VPM-1 for accurate time estimations.

6.1 Tool requirements

The objective of this research is to equip VPM-1 with a methodology for estimating the required man hours at the V310. To achieve this, interviews were conducted with both management and end users to gather their perspectives and insights. The purpose of these interviews was to identify the requirements and explore the possibilities of the tool. The outcomes of these interviews will now be discussed, along with how they have been incorporated into the development and design process of the tool. By engaging with management and end users, valuable input regarding the specific needs and expectations for the tool is obtained. This input serves as a foundation for the construction and design of the tool, ensuring that it addresses the identified requirements effectively. The insights gathered from the interviews have guided the development process, enabling the tool to cater to the unique context and challenges faced by VPM-1. By incorporating the feedback and suggestions provided by both management and end users, the tool aims to provide a practical and tailored solution for estimating man hours at the V310.

6.1.1 Ease of use

To ensure easy integration and user-friendliness, the chosen approach for the tool is to develop it using Microsoft Excel VBA. This decision is based on the familiarity of VPM-1 with Microsoft Excel, making it easier for users to adopt and integrate the tool into their existing workflow. Additionally, using Excel VBA allows for flexibility and customization if needed.

The goal is to minimize manual handling within the tool and make it as user-friendly as possible. Although it was challenging to completely eliminate manual actions due to the difficulties in program communication, the tool has been designed to streamline the process and guide the user through the necessary steps. There are three manual actions required: pasting the Table from the planning software onto the tool's provided sheet, uploading the order numbers to the ERP system, and requesting document links. The tool provides clear instructions on how and where to obtain the required information, reducing the likelihood of errors and simplifying the overall process.

In terms of speed, once the tool has the necessary data from the manual actions, its runtime is approximately 5 seconds, depending on the number of orders being processed. With the inclusion of the manual steps, the total runtime for a familiar user is approximately 1 minute and 30 seconds, excluding the time required for logging into the ERP and planning systems.

The tool also takes into consideration the importance of updating the parts list for future use. As the parts list does not include parts that have never been cut before, an extra button and user form are provided in the tool. This allows users to input the location of the file containing the updated parts list, ensuring that new parts can be included in future calculations. The tool also provides a dashboard that lists any parts that could not be found in the parts list, allowing users to identify and handle them separately.

6.1.2 Visual representation

One of the requirements for the tool is to provide a clear and easily understandable overview of the calculation results. The output should effectively indicate instances where the workload exceeds capacity and quantify the excessive number of hours. To address this requirement, the tool incorporates a dashboard that presents the following information. The number correspond to a number or Figure in Figure 26.

1. Graph that shows the required hours. (1)
2. The number of sheets for each thickness. (2)
3. The area required for each thickness. (3)
4. An overview of in what category (standard, regular and handling) most time is spent. (4)
5. Times required per thickness. (5)
6. Material weight per thickness required (6)
7. A list of parts that could not be found and are not taken into account for the calculations. (7)
8. A written representation of hour required both cutting hours and man hours. (8)
9. Two buttons for starting the calculations. (9)



Figure 26 Dashboard as designed for VPM-1

6.2 Input data

The tool requires several files as input data. Below a description of each input data type required is given,

1. Hours available
The number of man hours you have available during the given week. In a regular week this would be 80. However, if needed this can be adjusted on the dashboard.
2. Planning form
For the time period you want to calculate the hours for you load in the order number and the quantity required. This data will be used to find the part-IDs in the ERP-system and how often these parts are ordered.
3. ERP export
This export provides the part-IDs that are needed for each order.
4. Parts list
The parts list provides all the data on which the cutting time and number of sheets are based, this file is obtained from SigmaNest and via the part-IDs all the required data can be found.

6.3 Conceptual model

The Figure below depicts the black box of the tool, all the steps made for the calculation.

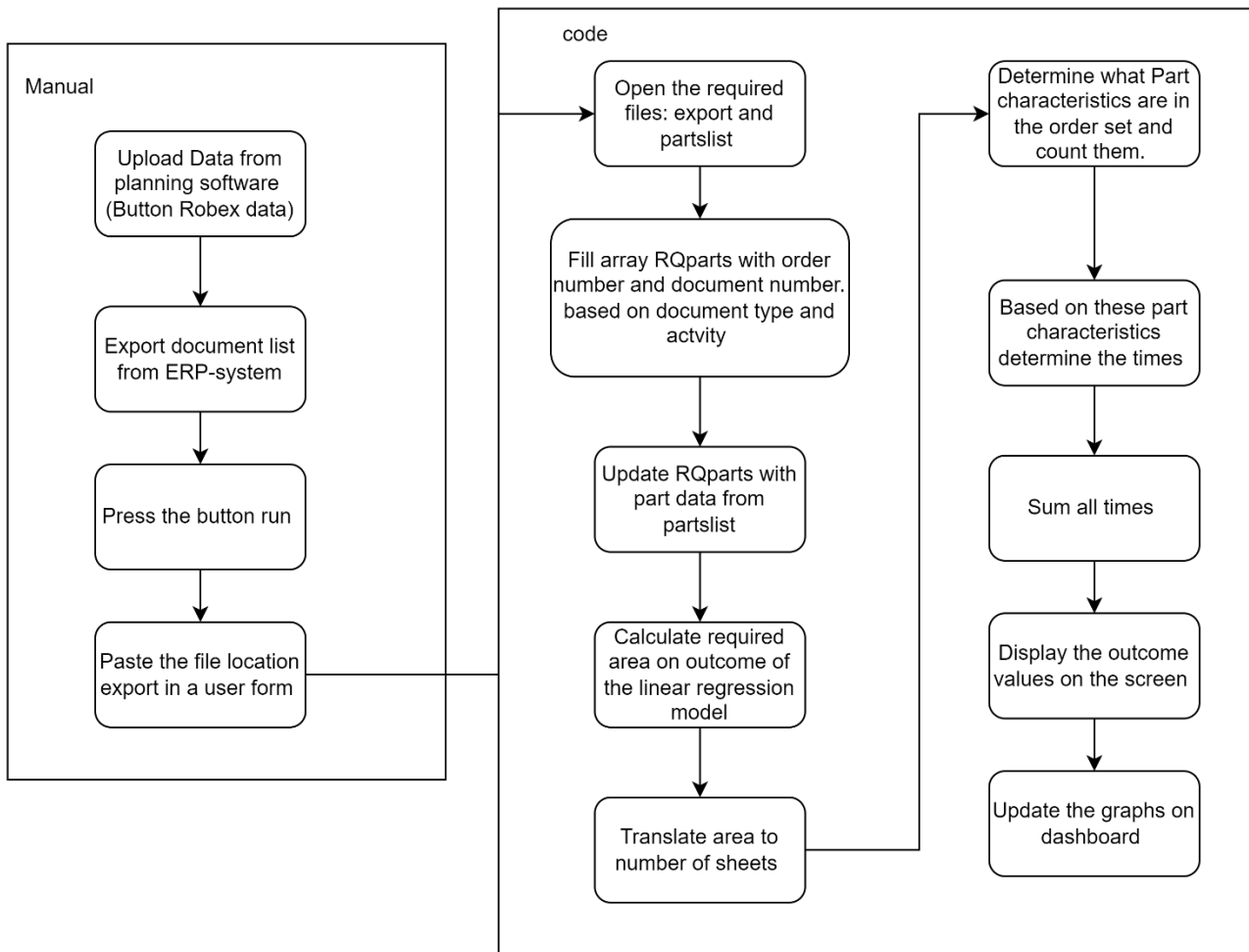


Figure 27 Conceptual model of the tool

6.4 Calculations

The tool incorporates multiple calculation steps, starting with the estimation of the number of sheets, followed by the calculation of corresponding times. In Section 6.4.1, the calculation method for determining the number of sheets is explained, utilizing the principles of Linear regression as discussed in Chapters 3 and 4. Section 6.4.2 further elaborates on the calculations involved in estimating the time required, taking into account the results of the time study and the categorization process outlined in Chapters 2 and 5.

6.4.1 Number of sheets

To calculate the number of nestings required, all the parts were sorted based on thickness. Then for each thickness the following formulas are used to calculate the required area and the number of nestings. These formula's take the output of the linear regression model as intercept and coefficient and gives the required area per thickness as output (y).

$$y = \beta_0 + \sum_{i=1}^n \beta_q x_i \quad (1)$$

$$c = \text{roundup}(y / 18) \quad (2)$$

$$\begin{cases} y = y, & \text{if } c = 1 \\ y = y + (c - 1)\beta_0, & \text{if } c > 1 \end{cases} \quad (3)$$

The calculation for the number of nestings involves using formulas based on the thickness of the parts. The intercept (β_0) corresponds to the given thickness, the coefficient (β_q) relates to the thickness, and x_i represents the part area of the i th part in the dataset, where i is the number of parts of the same thickness. The variable c denotes the number of nestings. y stand for the area required on these nestings. The values for β_0 and β_q are as calculated in Chapter 5. The 18m² follows the assumption of always having a full sheet available / always cutting a full sheet. Both equation 2 and 3 come in to play as the intercepts needs to be added for each sheet cut. For example you the outcome is that you require three nestings then you need to add the intercept 2 times more as it intercept needs to be added for every sheet you cut.

6.4.2 Time calculations

It is possible to distinguish 3 different "types" of time, standard time T_S : time that is required for every sheet; Handling time T_H : time that is dependent on the variables on the sheet and regular time T_R : time that independent on the number of nestings or part characteristics.

Standard time

For that tasks that you always have to carry out for each nesting you cut. These tasks are as described in Chapter 3.

$$T_S = c * \sum_{l=1}^n T_l \quad (4)$$

c is again the number of cutting plates and T_l the time in seconds required for the l th standard task. n is the number of standard tasks.

Handling time

This is done by counting the number of parts in each thickness in the dataset that satisfy the different criteria as set in chapter 3 and by counting the total number of parts for each thickness.

$$T_H = T_P + T_W + T_c \quad (5)$$

T_P is the time needed for handling the parts depending on the category of the part, T_W the time it takes to write the order number of the parts and T_c the time it takes to check for possible quality issues in the in the sheets.

$$T_P = \sum_{j=1}^3 \text{roundup}\left(\frac{d_j}{r_j}\right) T_j \quad (6)$$

Where d_j the number of parts that fall in category j . r_j is the number of parts that of category j that are measured at once, and T_j the time needed to handle r_j parts. For writing the order number on the part the following formula applies:

$$T_W = \text{roundup}\left(\left(\frac{p-g}{10} + \frac{g}{100}\right)\right) * T_{writing} \quad (7)$$

Here p is the total number of parts of the thickness, g is the quantity of part where there more than 10 of. If there are more than 10 pieces the numbers are written on one in ten pieces that is why these done separately. $T_{writing}$ is the time it takes to write the numbers on 10 parts.

$$T_c = \text{roundup}\left(\left(\frac{p}{75} + 1\right)\right) * T_m + \text{roundup}\left(\left(\frac{p*0.49}{25} + 1\right)\right) * T_l \quad (8)$$

This is the formula for checking for quality issues, p is again the total number of parts, here the first parts gets checked and afterwards every 75th, T_m is the time it takes to check the measurements of a part. T_t is the time it takes to check for a tap hole, about 49% of the parts have a tap hole (see Section 5.5 for a full explanation), after the first one every 25th is checked.

Regular times

These times are included every week, they consist of the time immediate sheets T_m , on average 6 per week consisting of 40 small parts and 9 medium parts, and the magnet exchange T_e .

$$T_R = T_m + T_e$$

Total

Then the total time the sum of the times for regular tasks, standard tasks, and the handling tasks for each thickness, z is the number of thicknesses included.

$$T_{total} = T_R + T_S + \sum_{z=1}^q T_{Hz}$$

6.5 Tool implementation

The intended use of this tool will be in the transition between the job preparation and nesting stages, as discussed in Chapter 2. However, neither of these stages directly bears the responsibility for ensuring that the parts are cut on time. This responsibility falls on the management team, which becomes actively involved after the nestings are prepared. Although management is the logical end user of the tool, there is a possibility to assign the tool's usage to the job preparators. By doing so, certain communication lines regarding the decision to outsource can be eliminated, as the job preparators can use the tool to signal when outsourcing is necessary. Additionally, the job preparators have knowledge of when all the orders are placed in the system, ensuring that the estimation is complete. Therefore, if feasible, it is advisable to incorporate the use of this tool into the job responsibilities of the job preparation team.

6.6 Conclusion

In this chapter, the culmination of knowledge from previous chapters is presented in the form of a tool. The tool addresses the key requirements of VPM-1, namely ease of use and providing a quick and clear overview. To achieve this, the tool minimizes manual steps and incorporates a dashboard that displays relevant Figures for VPM-1, as depicted in Figure 24.

The input data for the tool includes a parts list, an export of the ERP system containing part IDs, and the required quantities per order number. Using this data, the tool performs calculations within the black box, utilizing the insights from the linear regression model discussed in Chapter 4, the task descriptions and time study from Chapter 2, and the task division outlined in Chapter 5.

The recommended approach for implementing the tool is to assign the responsibility of using it to the job preparation team. This decision aims to streamline communication lines regarding outsourcing and ensure a comprehensive estimation process. By integrating the tool into the job preparation responsibilities, VPM-1 can benefit from improved efficiency and accuracy in estimating required resources.

6.7 Discussion

Evaluating the accuracy of the tool presents some challenges, mainly because of the lack of accurate data on the time operators spend on completing weekly nestings complicates the assessment of the tool's accuracy, to test the tool, gather this data and then proceed to compare it. Also, the tool focuses on the primary tasks of operators, tasks involved with running the machine, where the full job responsibilities entail more (see Section 2.8 for more explanation).

Moreover, the tool does not account for bevel cutting, as explained in Section 5.6. This omission overlooks the time and tasks associated with bevel cutting (see Chapter 5), which can impact the overall estimation. Furthermore, the tool assumes the availability of full sheets for cutting, which aligns with VPM-1's future perspective. However, in the current reality, the use of rest sheets may necessitate additional nestings and involve additional tasks that are not considered in the existing model.

7 Conclusion

This chapter presents a summarized answer to all the sub-research questions and the main research question. A discussion is provided regarding the outcomes, along with some recommendations for future utilization of the tool.

7.1 Research questions

Each sub-heading below shortly answers one of the sub research questions as defined in Section 1.6.

7.1.1 What processes are involved with running the V310?

1a. What processes are required to run the V310 prior to cutting?

1b. What are the tasks of an operator?

1c. What time does an operator require to fulfil the assigned tasks?

The steps that a part goes through within the cutting department are as follows:

- Job preparation, where production planning for handling and VPM-2 is carried out, based on which the parts are requested in VPM-1.
- Nesting, which involves placing the parts on a sheet in preparation for cutting.
- Cutting, where the actual cutting of the parts on the machine takes place, with involvement from the operators
- Cleaning and sorting, which includes removing slack from the parts and sorting them based on their order number.

During the cutting process, the operators perform the following tasks: Loading the machine, which entails placing a sheet on the machine and welding it to the Table. Starting the machine, measuring the sheet, and performing any necessary tool changes. They also conduct quality checks for both tapholes and part measurements. Unloading involves taking out the cut parts and transporting them to the appropriate location, while the remaining material is properly stored. For a comprehensive list of operator tasks, please refer to Table 1. The required times for these tasks can be found in Table 2.

7.1.2 What factors influence the primary tasks of operators?

2a. What factors influence the primary task of operators?

2b. How to make an estimation on required man hours for these factors?

The primary tasks of operators are influenced by several factors, including the number of nestings, the number of parts and their characteristics, tap holes, bevel cutting, the number of immediate sheets, and the need for a magnet exchange. By analysing historical data and conducting observations, it is possible to estimate how these factors impact specific tasks performed by operators. This information is crucial in accurately estimating the required man-hours for a given job, as these factors need to be taken into account during the estimation process.

7.1.3 How to make a linear regression model?

To build a linear regression model, follow these steps: check assumptions, assess linearity and collinearity, specify the model, and select variables, estimate coefficients, test model significance using the F-test and the R-squared test, validate the model using analysis and new data. If any invalid values arise during testing or validation, revise the model specification.

7.1.4 What does a linear regression model to estimate the required nestings look like?

To estimate the number of nestings, the dependent variable is the required area, and the data is sorted based on thickness. Two potential independent variables that meet the assumptions are part area and rectangle area. However, due to collinearity, only part area is selected based on performance, resulting in a simple linear regression model. This approach allows for the creation of a model for all thicknesses cut in VPM-1. During model specification and validation, part area showed better fit based on the F-test and R-squared. Data splitting is used for validation, resulting in R-squared acceptable values. Table 10 displays the intercepts and coefficients used for predicting the required area. Dividing the outcome by 18m² provides the number of sheets required.

7.1.5 How to make a tool that can be implemented in VPM-1?

5a. What are the requirements of a tool?

5b. How to make a tool that uses the linear regression model and time data to make an estimation on the required man hours.

The tool should prioritize ease of use by minimizing manual actions and ensuring fast calculations. Additionally, it should offer a clear and comprehensive output, which can be achieved through the design of a dashboard (refer to Figure 27). By utilizing the parts list, planning data exports, and time study data as inputs, the tool performs all necessary calculations within its black box. For implementation, it is recommended to assign responsibility for the tool to the job preparators.

7.2 How can Voortman Parts Manufacturing use order data to predict the upcoming workload for the V310 at least three weeks prior to cutting?

After addressing the five sub-research questions, the main research question can be answered. The answer is straightforward: By utilizing the output of the linear regression model, which uses total part area as an independent variable, VPM can estimate the number of nestings required for each thickness. This output can then be combined with the time study data in Section 2.8 and the occurrence of tasks described in Chapter 5 to estimate the required man-hours. All of these components are integrated into a tool that takes order data as input and performs the necessary calculations. This tool provides Voortman Parts Manufacturing with a method to predict the upcoming workload three weeks prior to cutting.

7.3 Discussion

The accuracy of the answer is influenced by several factors, which have been discussed in their respective chapters. These factors include data quality and assumptions, model specification, model validation, and tool implementation. By carefully considering and addressing these factors, we can enhance the accuracy of the final outcome.

7.3.1 Time study

The time study shows two mayor parts that affect the outcome, lack of datapoints and the high variability in the datapoints. First the lack of data, due to the time constraint it was not possible to collect enough datapoints to calculate an accurate sample mean. The accuracy of the sample mean is also affected by the high variability in the data points. This variability can be explained by the large differences of lifting distance in some observation (when lifting is required). Depending on where on the cutting Table a

nesting is located the lifting distance varies. As it is random where on the cutting Table a specific nesting gets placed it should not affect the outcome as much as the average lifting distance should then be the same.

7.3.2 Linear regression

In the training dataset of the linear regression model, approximately 1.3% of the data was affected by errors in reporting part area. Resolving this error would lead to a smaller intercept and coefficients, resulting in a more accurate linear regression model. By addressing this issue and ensuring accurate reporting of part area, the model's predictive capability can be improved.

7.3.3 Estimations on occurrence

To estimate the occurrence rate of certain tasks, historical data or observations are used. For tasks like tap holes, the data is manually counted, but there is a possibility that some entities were missed during the counting process. This could result in a smaller average occurrence rate being calculated, leading to less time being allocated for these tasks. Additionally, the handling of different parts and the frequency of quality checks can vary among individual operators. The values currently used for calculations are based on the norms set by VPM-1, but it is important to acknowledge that individual operators may have their own approaches, which can result in variations in time calculations.

7.3.4 Bevel cutting

Bevel cutting is excluded from the estimation process due to the challenges in accurately estimating its occurrence and the required time. Operators closely monitor the cutting of bevelled edges due to the high possibility of quality errors. When a bevelled edge is cut, an operator cannot perform other tasks simultaneously. Therefore, the time required for bevel cutting is currently excluded from the calculations.

On average, only 1.7% of the weekly parts contain a bevelled edge, which is a relatively low proportion. Estimating the time required for bevels is difficult as it also depends on the length of the bevel. As a result, the actual time required for the primary tasks is slightly higher than the estimation provided by the tool.

7.4 Recommendations

To enable VPM-1 to make more accurate time estimations, the following actions would be beneficial so VPM-1 can enhance the accuracy of time estimations, improve operational efficiency, and align with its future goals and objectives.

First is use the model, the job preparator has to use the model and act when he sees that too much man hours are required for the schedules amount on work. This allows for an early recognition of planning infeasibility and results in less backlog.

Enhance data collection: Include more detailed information about part characteristics, such as the presence of bevels, number of holes, and tap holes. This additional data would allow for better estimations of occurrence rates and improve the accuracy of time estimations for these specific tasks. When you would implement this data in the tool it allows for a better estimation.

Conduct a comprehensive time study: Extend the time study to gather a larger sample size, ensuring a more accurate calculation of the sample mean. It would be helpful to separate and estimate the lifting

time separately, as it is a major contributor to the high variability observed. Doing this will make your time study more complex however it will result in a better estimation when integrating the new parts in the tool.

Investigate real-time operator performance: Identify areas where time is lost, or inefficiencies occur and develop strategies to address these time losses. This research will be valuable in improving overall time estimations and identifying opportunities for optimization within VPM-1.

Repeat the linear regression study, it is recommended to repeat the linear regression study when you have a large sample of nestings (after one year for example). When the method of nestings changes this will affect the parameters, repeating the study and implementing the new coefficient and intercept will allow for a more accurate prediction corresponding the method of nesting. For example, when a new method of nesting is implanted that reduces the scrap factor, this will result in less nesting required and thus less time on the machine than that is currently accounted for.

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Appendix A observation studies

This appendix provides the observation protocols for both observation 1 and 2.

A.1 Observation study 1

Getting familiar with the tasks of operators

Goal: Gaining the start information to make an observation protocol for observation study 2

Observation type: observer as participant, observer shadows operator and acts as a spectator. Ask questions is required.

Motivation: For my research I require time data of the operator tasks. Currently I have a vague understanding of all the tasks the operators perform however for performing the time observation data I require more detailed information of the sub tasks. Aside from this the current knowledge I have is obtained from management, I would like to test this knowledge to the reality.

Duration: two days

Prior knowledge operator: goal and motivation of the total research, goal and motivation observation study. Possibility not to participate.

Focus areas: Write down all the handlings and other remarks in the boxes

- Loading machine
- Starting machine
- Quality checks
- Tool change
- Unloading
- Tidying up
- Other handling that are not listed / unknown

A.2 Observation study 2

Collecting time data

Goal: Gaining time data of the actions of operators at the V310

Observation type: Structured observation – observations from a distance

Motivation: The goal of my research is to make a tool that can estimate the manhours / cutting hours required. Currently there is little to no data on the time it takes for operators to complete their tasks. To be able to make the calculations I need time data.

Duration: Several days to a week.

Prior knowledge operator: Goal and motivation of the total research, goal and motivation observation study. Possibility not to participate.

Observation protocol

category	Action	Comment:
Loading	Pick up new sheet	Happens in the plate centre
Start: Walk towards residual sheet location Finish: conveyor belt is turned on.		
Loading	Place sheet on the machine	
Start: Walk towards sheet location Finish: Move magnet lose of sheet		
Loading	Look for rest sheet	This is difficult to measure, this might occur in intervals
Start: Walk towards residual sheet location Finish: Move magnet to sheet location for pick up (not for moving other sheets then stop when last sheet is removed)		
Loading	Weld sheet to Table	
Start: Pick up welding cart Finish: Put away welding cart		
Starting	Measure sheet to machine	Probably a very short process
Start: Operator at computer to measure sheet Finish: Red light for measuring is off		
Starting	Drill change	Highly dependent on the amount of tools to change, of a drill needs to be reassembled
Start: Machine requires tool change Finish: Operator back at machine to start machine		
Starting	Plasma head change	Highly dependent if head needs to be reassembled
Start: Machine requires tool change Finish: Operator back at machine to start machine		
Quality check	Check tapholes	
Start: Stop machine to check Finish: Start machine again		
Quality check	Check measurements	
Start: Stop machine to check Finish: Start machine again		
Respond to machine notifications	Brooming sheet	
Start: Operator reads notification Finish: Operator dismisses notifications		
Respond to machine notifications	Change Tool	
Start: Read machine notification Finish: Start machine again		
Unloading	Writing down part numbers	Measure per 10 numbers
Start: Pick up Tablet Finish: Place Tablet back		

Unloading	Take out medium parts	For parts heavier then 7kg, measure per 3
Start: Start moving magnet to location Finish: part is where it is supposed to be		
Unloading	Take out small parts	Happens in larger batches, measure per 10
Start: Start moving magnet to location Finish: Pat is placed in basket		
Unloading	Take out largest parts	Go to different location, part with rectangle area larger then 2m ²
Start: Start moving magnet to location Finish: part is where it is supposed to be		
Unloading	Place small parts on conveyor	Happens in larger batches, measure per 10
Start: magnet at conveyor Finish: 10nth part is placed		
Unloading	Cut grid for disposal	
Start: Pick up grinder Finish: Put grinder away		
Unloading	Put away rest sheet	
Start: Start to move magnet towards sheet Finish: Magnet is loose of the rest sheet		

Appendix B Systematic literature review

B.1 Research goal

The goal is to find the required steps to make a linear regression model and the requirements for each steps to be finished.

B.2 Databases

The following three databases will be used, Scopus and Web of Science because of their large coverage and easy usability. The UT library was used to find a book on the topic that will help a lot with the basics of linear regression.

- Scopus
- Web of science
- UT- Library

B.3 General search

This is a rather general question and while trying some search queries I found a lot of results, often over a thousand and really specific applications. So I started with a general search with broader search terms to get me with a familiar with the concept of linear regression. From a couple of sources form these search I selected my keywords so a could do a better systematic literature review based on topics that were more valuable to me.

Search string	Date	Date rang	scope	entities
Scopus				
"linear regression" AND prediction AND statistics	13-apr	All	tilt -key - abstract	810
UT find				
Linear regression	11-apr	All	Books	1500

From these outcomes the following two sources were selected I help provide a general introduction to linear regression.

Montgomery, D., Peck, E. A., & Vining, G. (2012). *Introduction to Linear Regression Analysis (Wiley Series in Probability and Statistics) 5th edition*. Hoboken, New Jersey: John Wiley & Sons, Inc.,.

Bazdaric, K., Sverko, D., Salaric, I., Martinovic, A., & Lucijanac, M. (2021). The ABC of linear regression analysis: What every author and editor should know. *europaean science editing* 47.

B.4 Key concepts

Key concepts

Related terms

Narrower terms

Broader terms

1 Multi-Linear Regression	Linear regression analysis	Regression models, Variable estimation	Regression models, prediction
2 Significance	Importance, reachability	F-test, R^2 -test	Goodness of fit
3 Validity	correctness	variance check	Test , check
4 Variable selection	Parameter choice	Regression variables	Parameters
5 Assumptions	Presumptions	Data set	expectations

B.5 Criteria

Inclusion criteria

multi- variable linear regression – This research is focussed on linear regression and how to build a linear regression model, this is a really broad term but there is some large differences between simple linear regression and multi- variable linear regression. Therefore it is important that the article discusses multi variable linear regression.

Clear explanation of the theory – A lot of articles are about applying linear regression and less focussed on the theory behind it, I want articles that explain the theory.

Articles have to be visible for me – If I cannot reach the theory I cannot use it.

Exclusion criteria

Machine learning – Bayesian – non-linear regression – during the general search I found that a lot of sources discuss either one of these which are closely related to multi- variable linear regression. During this research I do not want any of them included.

Fuzzy Linear regression – This is another regression technique the will not be applicable for me so left out.

Reaction – Some of the articles I found where reactions to other articles and did not contain new theory themselves. Those will be excluded.

B.6 Search log

Search string	Date	Date range	scope	entities
Scopus				
"linear regression" AND assumptions	14-apr	1980-now	Title	17
"linear regression" AND "variable selection" NOT Bayesian (all fields)	14-apr	1980-now	Title	72
"linear regression " AND "f-test"	14-apr	1980-now	Title	6
"variance inflation factors" AND "Linear regression"	14-apr	1980-now	Keywords	14
Web of science				

linear regression AND assumptions	14-apr	1980-now	Title	19
linear regression AND "variable selection" NOT Bayesian (all fields)	14-apr	1980-now	Title	108
linear regression AND "f-test"	14-apr	1980-now	Title	7
linear regression AND variance inflation factors	14-apr	1980-now	Topic	13
Total				256
Duplicates				88
Unique				168
Excluded				146
Total left				22

B.7 Articles to use

From the 22 articles that are left the following will be used:

1. Andersen, C. M., & Bro, R. (2010). Variable selection in regression—a tutorial. *Journal of Chemometrics*, 728-737.
2. Bazdaric, K., Sverko, D., Salaric, I., Martinovic, A., & Lucijanac, M. (2021). The ABC of linear regression analysis: What every author and editor should know. *European Science Editing* 47.
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9. Quinino, R. C., & Reis, E. A. (2013). Using the coefficient of determination R² to test the significance of multiple linear regression. *Teaching Statistics* 35(2), 84-88.

	Assumptions	significance	validity	variable selection	variable estimation
(Andersen & Bro, 2010)		X		X	

(Bazdaric, Sverko, Salaric, Martinovic, & Lucijanic, 2021)	X	X			
(Casson & Farmer, 2014)	X		X		X
(Chaurasia & Harel, 2015).				X	
(Cheng, Sun, Yao, & Cao, 2022)				X	
(García, García, López Martín, & Salmerón, 2015)			X		
(Jamshidiana, Jennrichb, & Liuc, 2017)		X			
(Montgomery, Peck, & Vining, 2012)	X	X	X	X	X
(Quinino & Reis, 2013)		X		X	

Appendix C data description

Name	Unit	Example	Description
Part Level Contains all the parts cut			
Archive date	Date	29-11-2022 15:24	Moment at which the nesting the part was on is stored.
Program name	-	20mm1 2022- 47-00	Name of the nesting. Consists of thickness of the sheet (20mm), index number sheet of that week (1) and the year and week number the nesting has to be finished.
Work order	-	2050823	The workorder the part belongs to.
Part name	-	10007658	With this number the drawing + material of the part can be found in the ERP-system.
Material	-	S355JR	Name of the material used.
Thickness	Mm	20	Thickness of the part or sheet.
Quantity order	-	35	Amount order of this part in the workorder.
Quantity programmed	-	6	Number of parts with that part Id on the nesting.
Drawing number	-	005-9849	Drawing ID.
Due date	Date	26-9-2022	Date the part has to be finished.
Part length	mm	275 40	The largest length of the piece.
Part width	mm	275 40	The largest width of the piece.
Area	Mm ²	80327.5536	Surface area of the part.
Rectangle area	Mm ²	42550	The area of the part if it would be placed in a rectangle. The largest length multiplied by the largest width
Part weight	Kg	3.7009	Weight of the part after it is cut
Rectangle weight	Kg	31.9709	The weight of the part if it would be placed in a rectangle.
Nested area	Mm ²	224484.5689	Area on the nesting used for this part. Differs on every nesting.
Cutting time	Seconds	31.5893	Time it takes the machine to cut out the part
Cutting length	Mm	1190	The circumference of a part, including possible inner areas that need to be cut away
Pierce quantity	-	4	The number of times the machine has to pierce the sheet to cut out the part, this includes drilled holes in the part and the amount of time the machine pierces the sheet to start cutting.
Nesting Level contains all the nestings cut			
Program name	-	20mm1 2022- 47-00	Name of the nesting. Consists of thickness of the sheet (20mm), index number sheet of that

			week (1) and the year and week number the nesting has to be finished.
Archive date	Date	29-11-2022 15:24	Moment at which the nesting is stored.
Task Name	-	S355JR- 10	Name of the task at the machine
Used area	Mm ²	18000000	Area of the sheet that is used to cut the nesting
Scrap fraction	-	0.2731	Fraction of the sheet that is thrown out for disposal
Machine name	-	Voortman_V31 0_XPR300_L2R	The name of the machine the nesting was cut on, in this case the V310
Pierce quantity	-	255	The number of times the machine has to pierce the sheet, this includes drilled holes in the part and the amount of time the machine pierces the sheet to start cutting.
Sheet level	Contains all the sheets cut		
Program name	-	20mm1 2022- 47-00	Name of the nesting. Consists of thickness of the sheet (20mm), index number sheet of that week (1) and the year and week number the nesting has to be finished.
Sheet Name	-	006- 5089_8500008 003-60-06 V310	Name of the sheet at which the nesting is placed
Archive date	Date	29-11-2022 15:24	Moment at which the nesting on this plate was stored
Task Name	-	S355JR- 10	Name of the task at the machine
Used area	Mm ²	18000000	Area of the sheet that is used to cut the nesting
Scrap fraction	-	0.2731	Fraction of the sheet that is thrown out for disposal
Material	-	S355JR	Name of the material used.
Sheet length	Mm	40 2000	The largest length of the sheet
Sheet width	Mm	40 2000	The largest width of the sheet
Sheet area	Mm ²	550983.5	Surface area of the sheet

Appendix D example of a nesting



Machine: Voortman_V310_XPR300_L2R

2-12-2022 10:05:03

Programma naam : 15mm2 2022-49-00									
Nesting:		2 van 2		Netto Afval: 20,50%		Gewicht gebruikte plaat: 301 kg			
Aantal platen		1		Th. lengte gebruikte plaat: 837 mm		Gebruikte plaat: 2,560 m ²			
Materiaal S355JR		Heat Nr. B2197809DD--A		Lengte plaat		2000		Lengte nesting	
Dikte		15mm		Breedte plaat		3000		Breedte nesting	
Plaatnaam				Snijtijd		00:52:11		Tot gewicht ond.: 239,64kg	
Reststuk naam				Gewicht reststuk:		405,05kg			
Boor		Aantal		Tijd		Boor		Aantal	
Boor 14		16				Boor 18		68	
Totaal aantal Boorgaten 84 stuks									
ID		Ond. naam		Aantal nodig		Aantal genest		Netto gewicht	
11		10000816		21		17		2,56 kg	
ID		Ond. naam		Aantal nodig		Aantal genest		Netto gewicht	
12		10041060		21		4		2,61 kg	
ID		Ond. naam		Aantal nodig		Aantal genest		Netto gewicht	
18		10043276		40		33		5,62 kg	



Machine: Voortman_V310_XPR300_L2R

12-1-2023 11:10:19

Programma naam : 40mm2 2023-02-00

Nesting:

2 van 3

Netto Afval: 42,87%

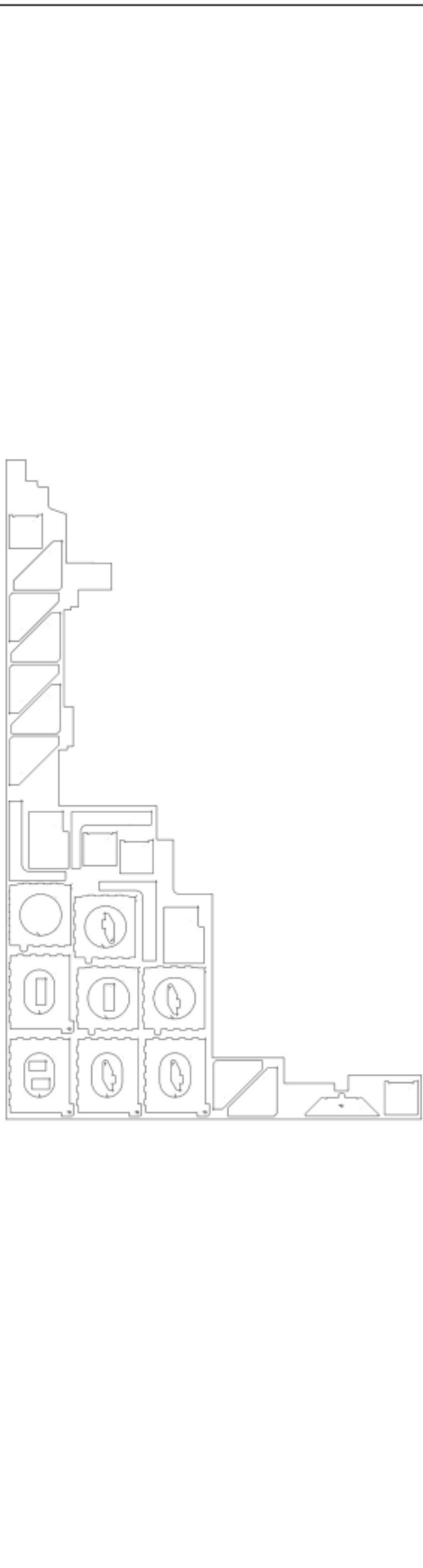
Gewicht gebruikte plaat: 1494 kg

Aantal platen

1

Th. lengte gebruikte plaat: 1556 mm

Gebruikte plaat: 4,759 m²



Material S355JR	Heat Nr. A2201909B0--C	Lengte plaat	4777	Lengte nesting	4757
Dikte	40mm	Breedte plaat	3000	Breedte nesting	2980
Plaatnaam	006-5088_8500013171-40-02 V310	Snijtijd	01:59:45	Tot gewicht ond.:	853,70kg

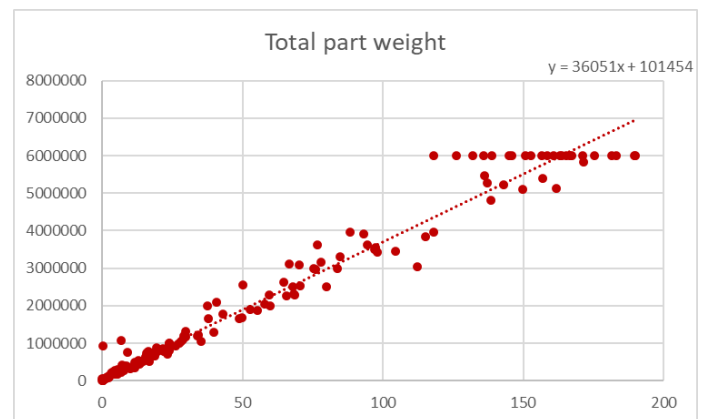
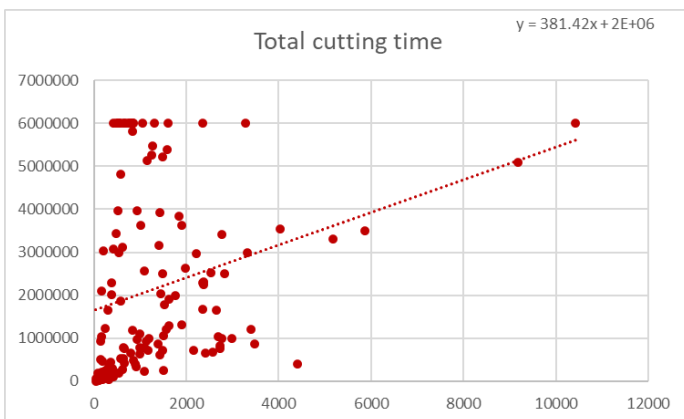
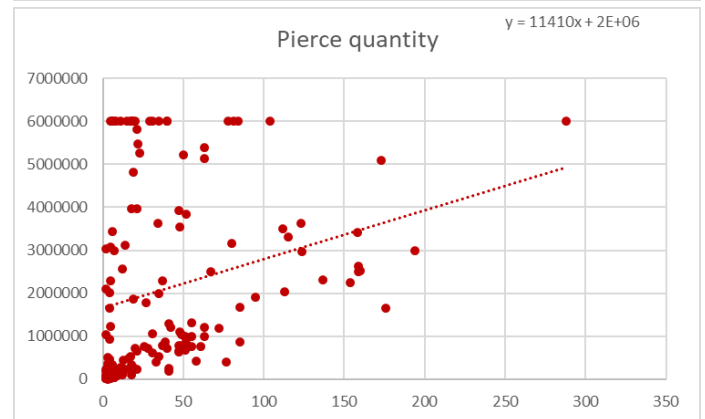
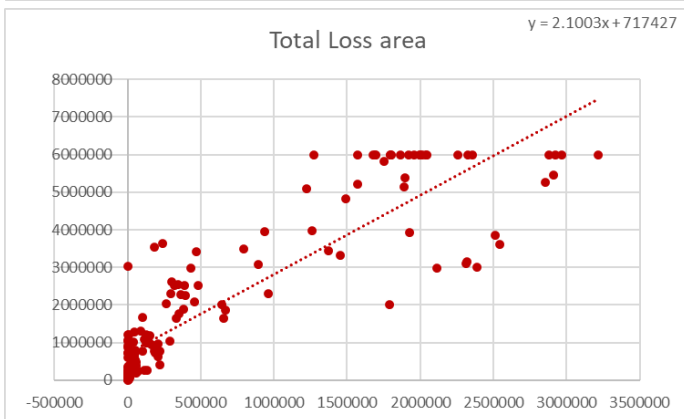
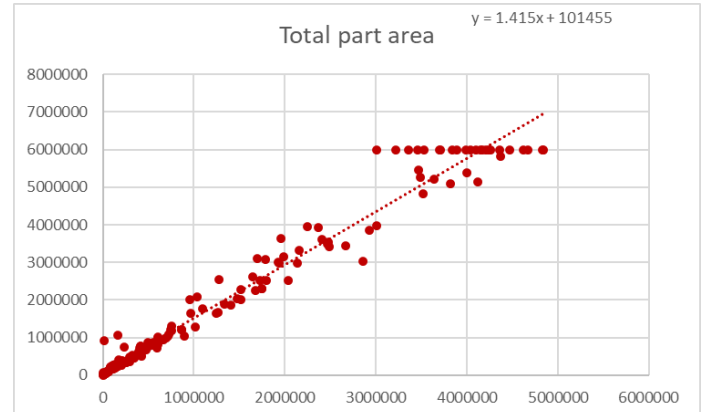
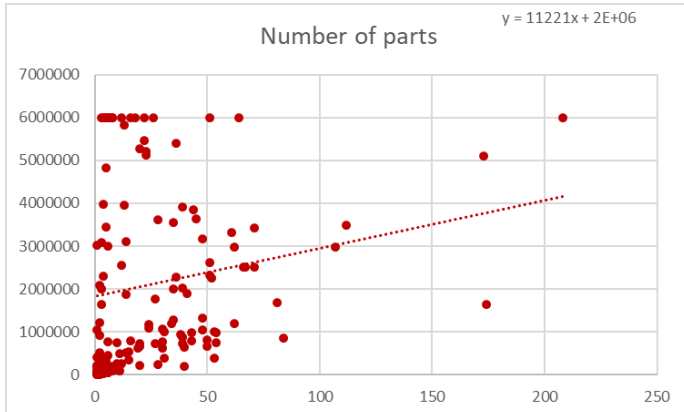
Boor	Aantal	Tijd	Boor	Aantal	Tijd
Rapid	0		Boor 6.8	4	
Boor 18	1		Tap M20	1	
Boor	Aantal	Tijd	Boor	Aantal	Tijd
Rapid	0		Boor 17.5	4	
Boor 18	1		Tap M20	4	

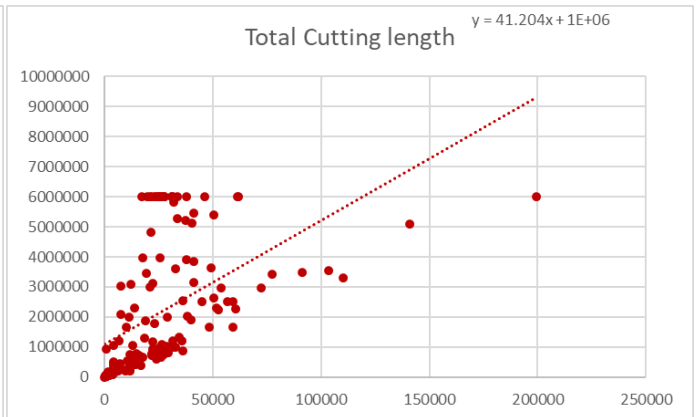
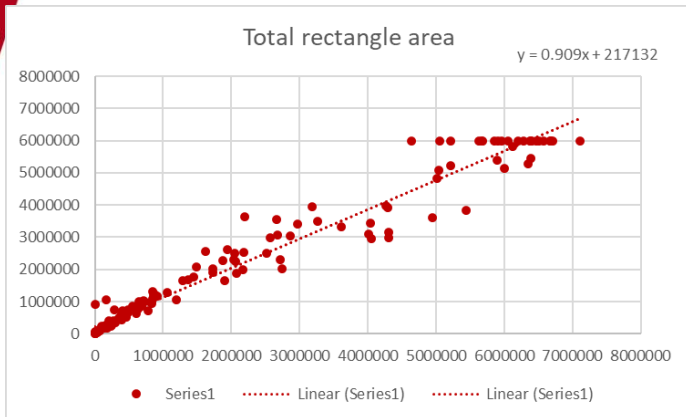
Totaal aantal Boorgaten 14 stuks

ID	Ond. naam	Aantal nodig	Aantal genest	Netto gewicht	ID	Ond. naam	Aantal nodig	Aantal genest	Netto gewicht	ID	Ond. naam	Aantal nodig	Aantal genest	Netto gewicht
1	10048735	2	2	35,15 kg	3	10057469	8	8	25,91 kg	4	10057771	8	1	17,97 kg
5	10057775	12	4	17,81 kg	6	10008024	4	3	23,75 kg	7	10066319	1	1	2,64 kg
8	10066978	4	4	4,12 kg	9	10083015	4	4	55,28 kg	10	10066543	2	2	4,30 kg

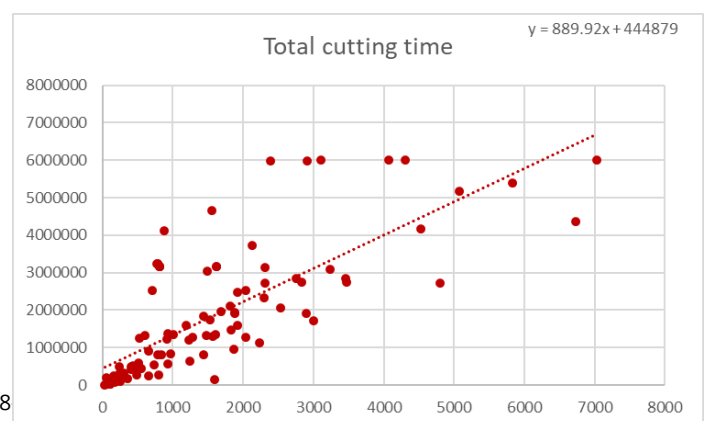
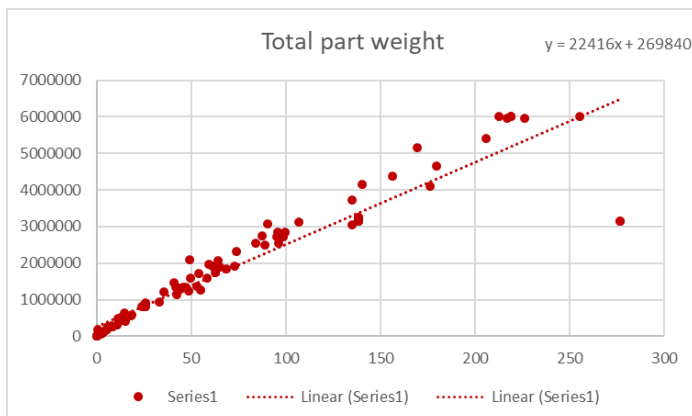
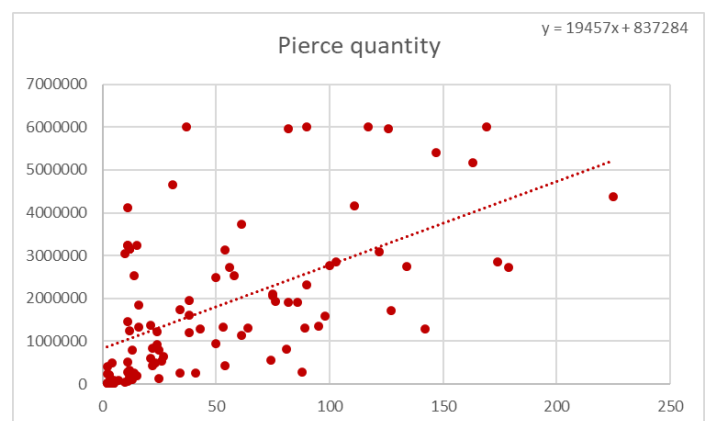
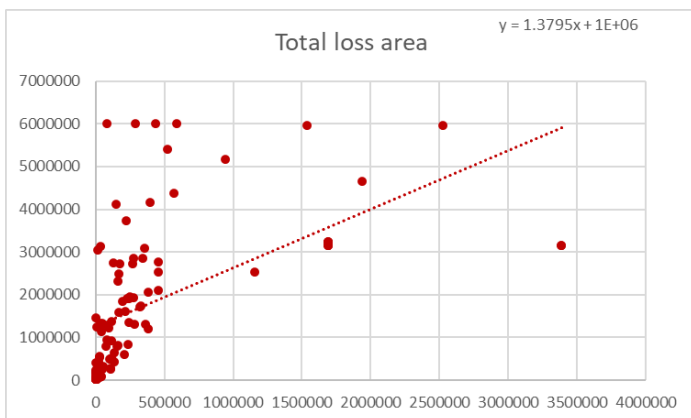
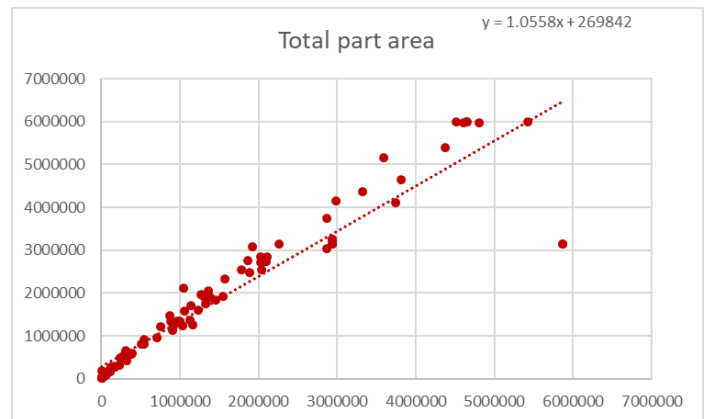
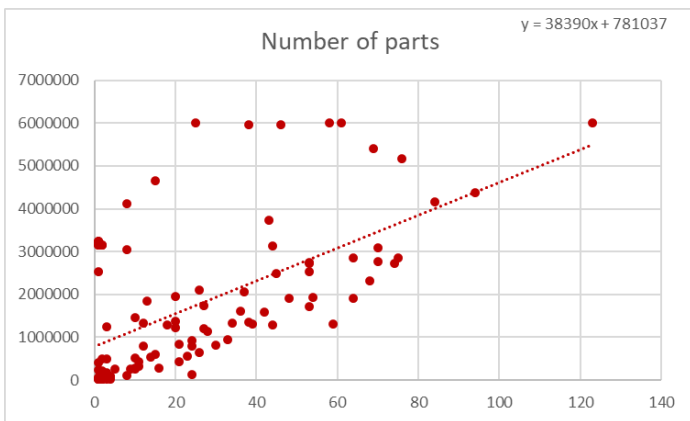
Appendix E Scatter plots

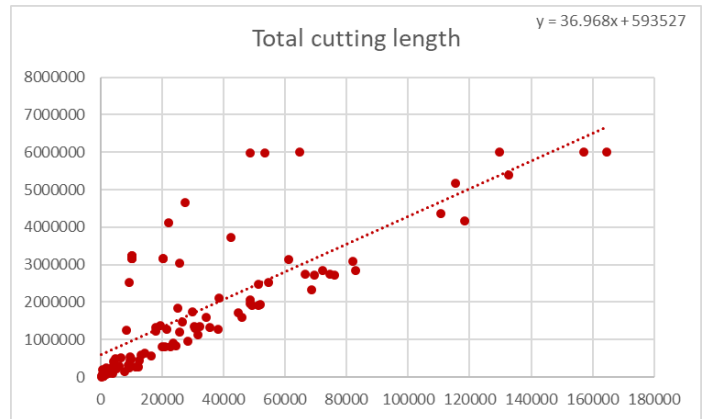
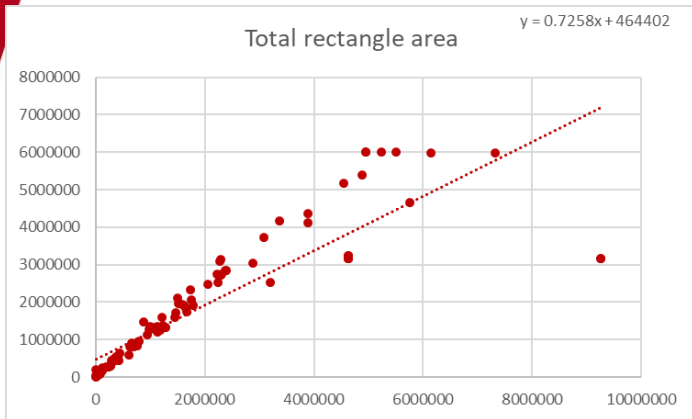
5mm



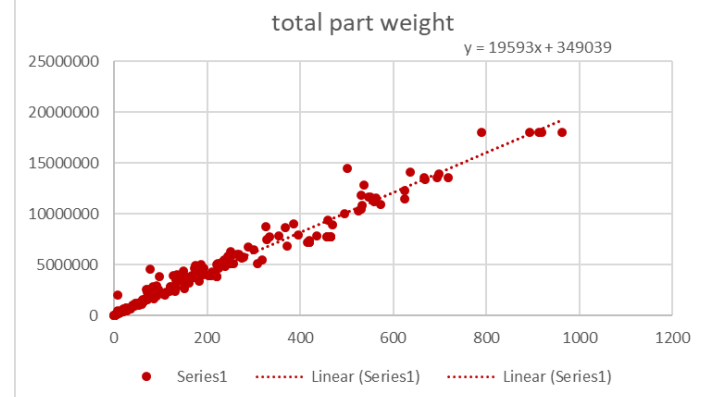
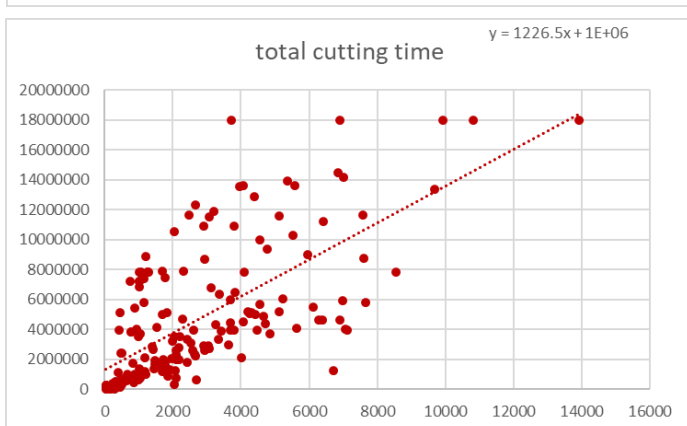
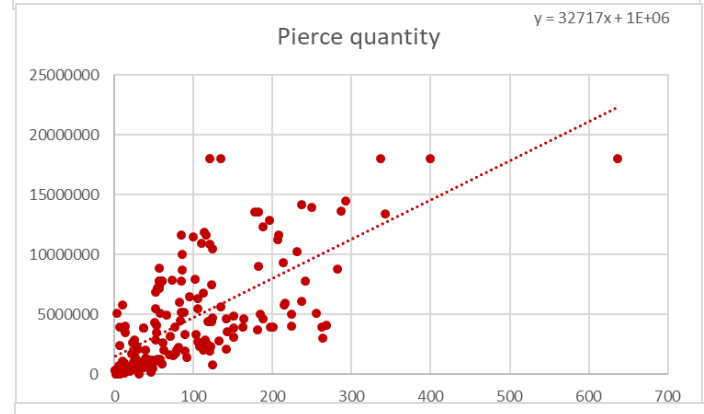
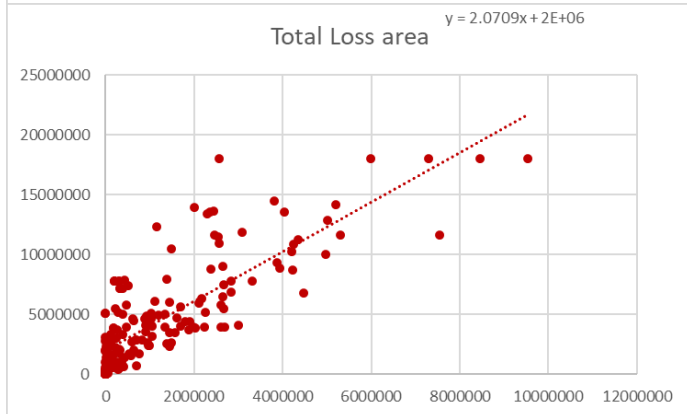
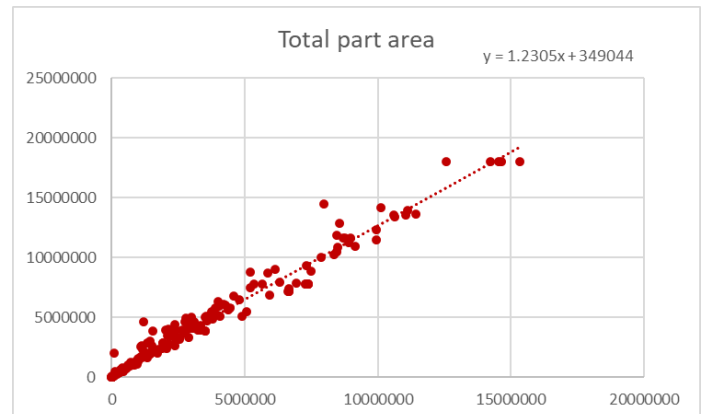
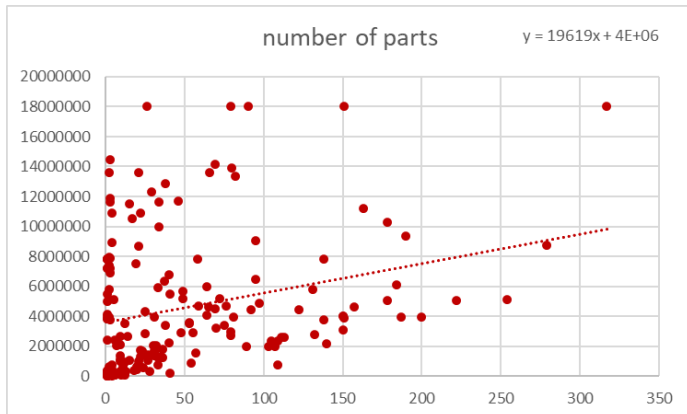


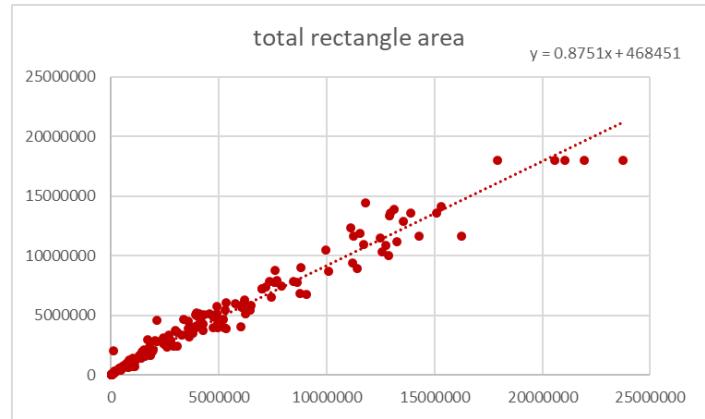
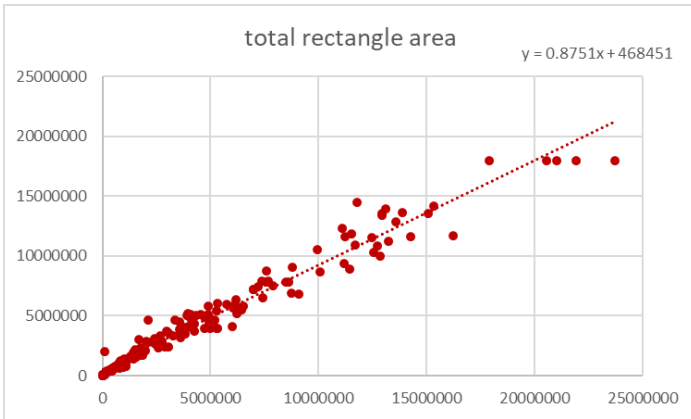
6mm



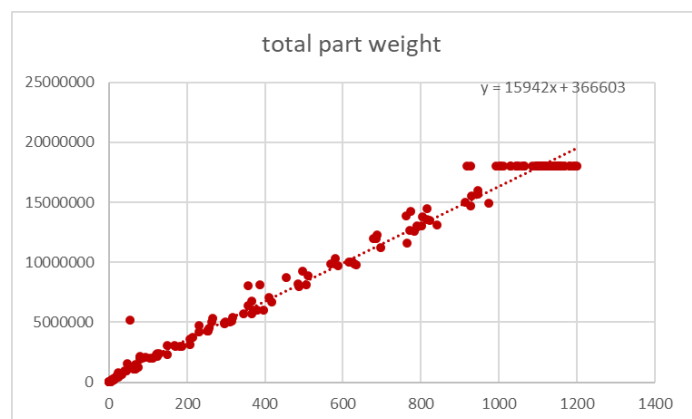
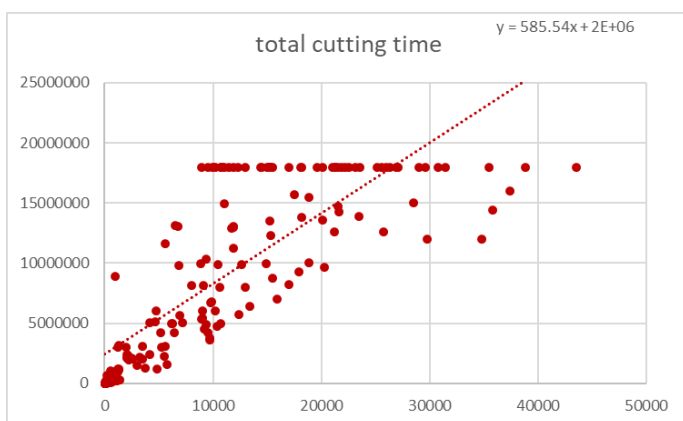
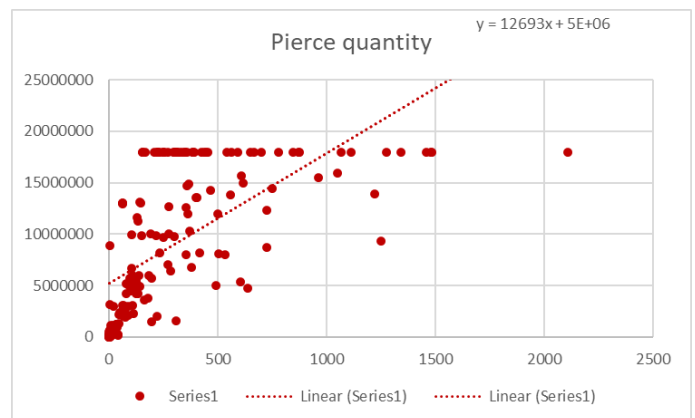
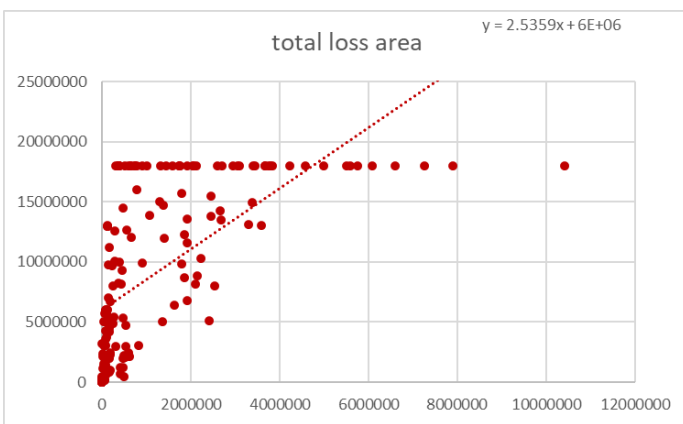
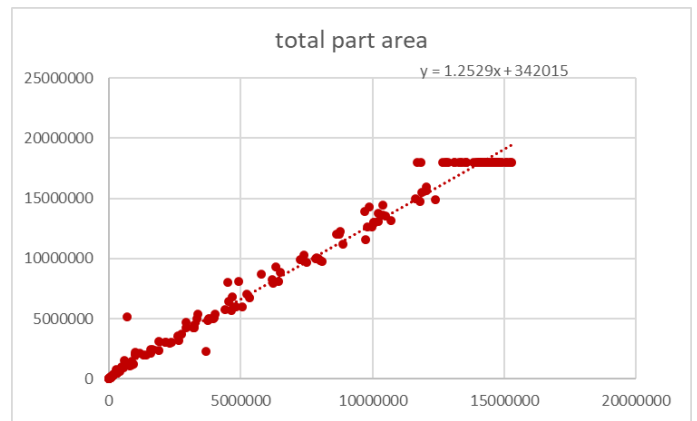
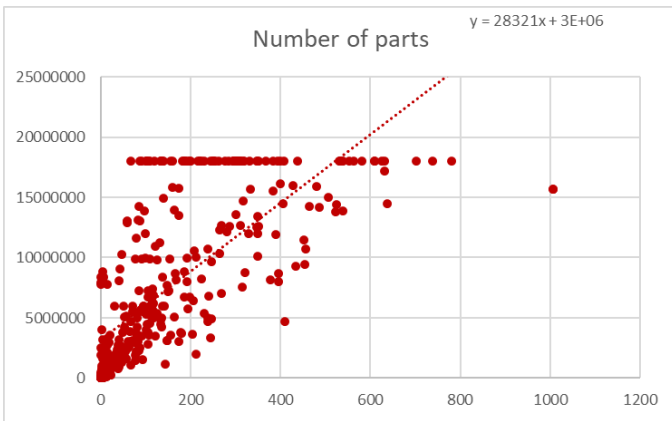


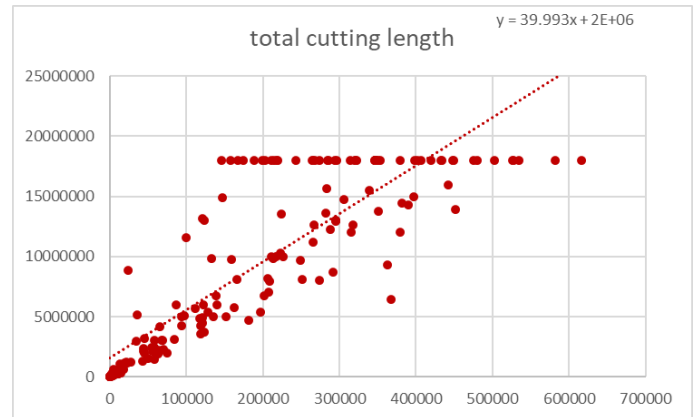
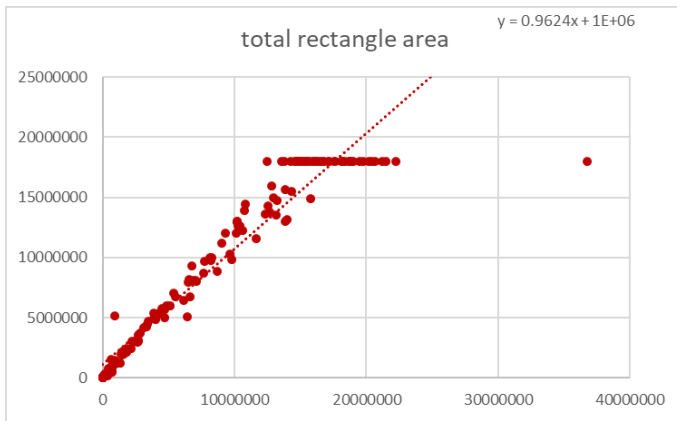
8mm



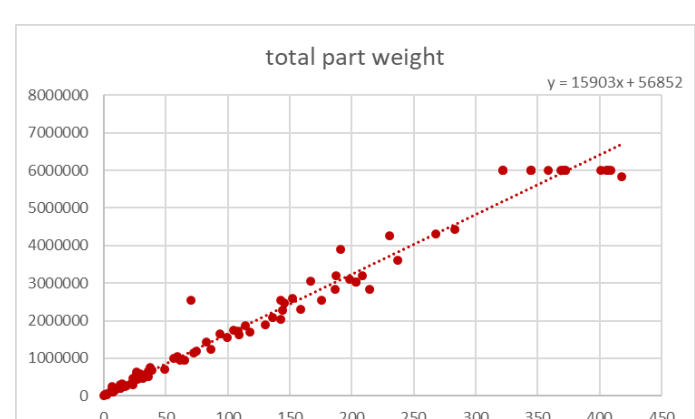
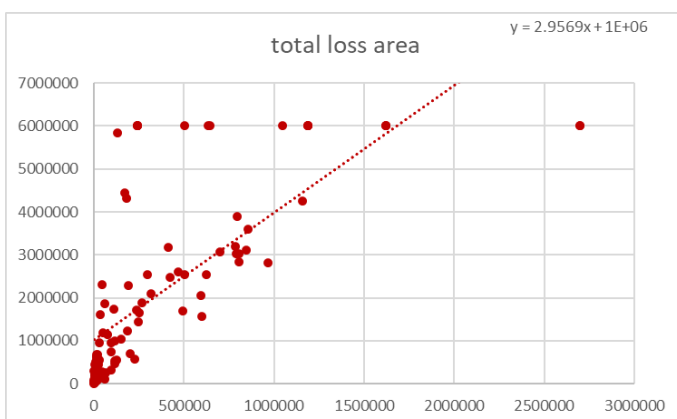
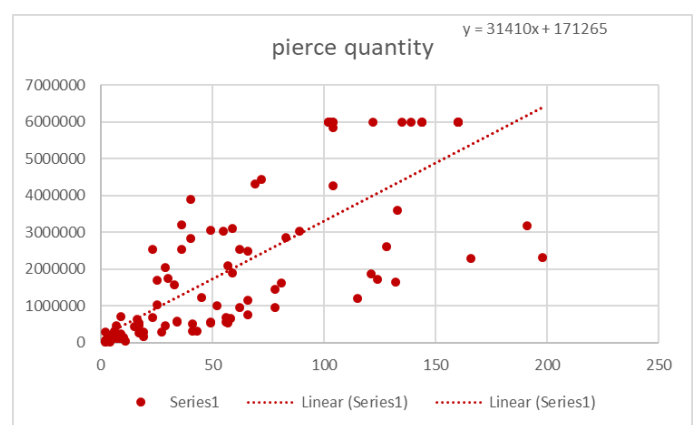
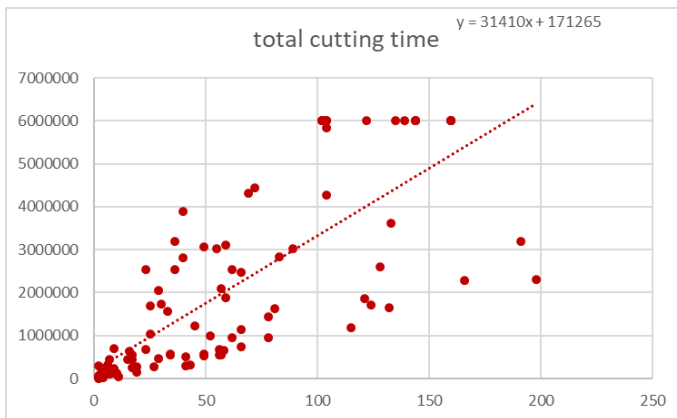
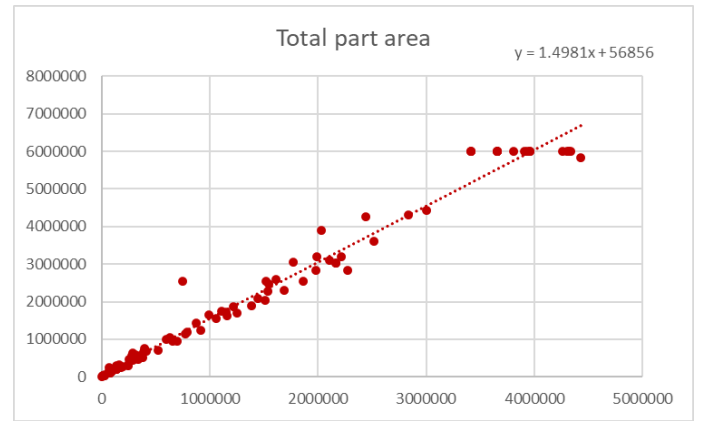
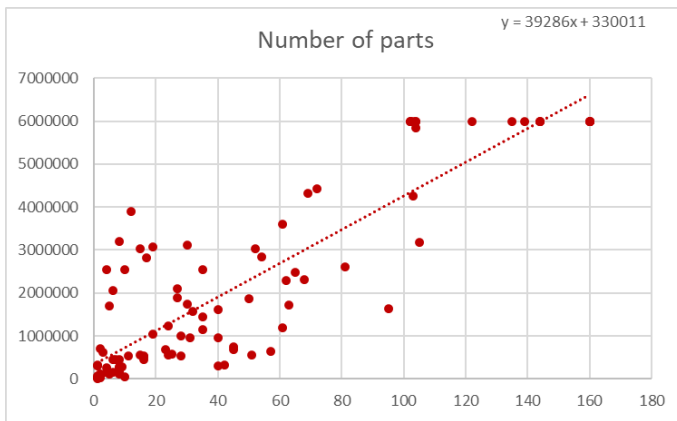


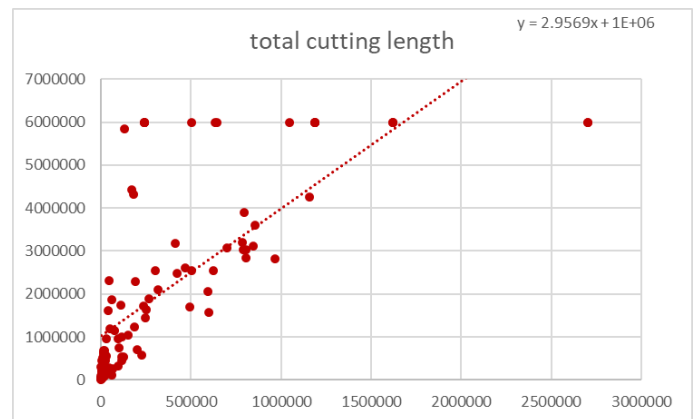
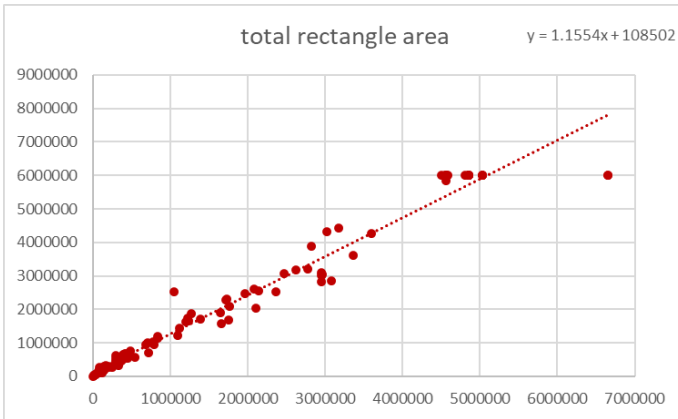
10mm



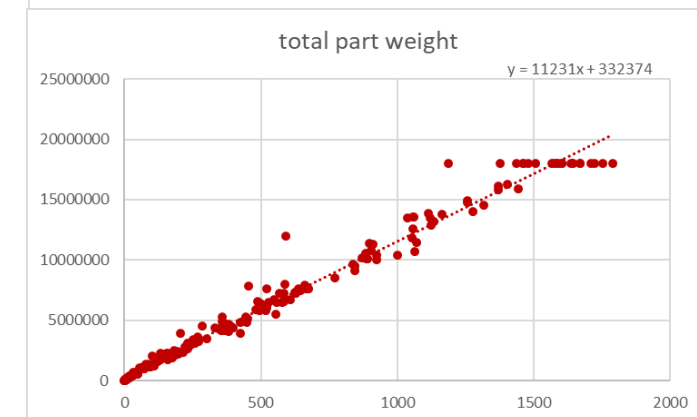
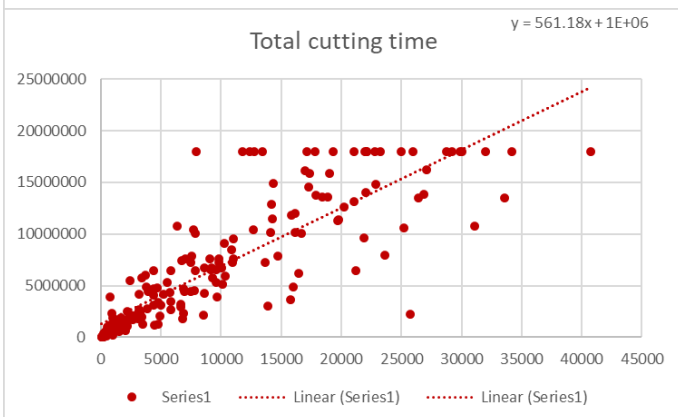
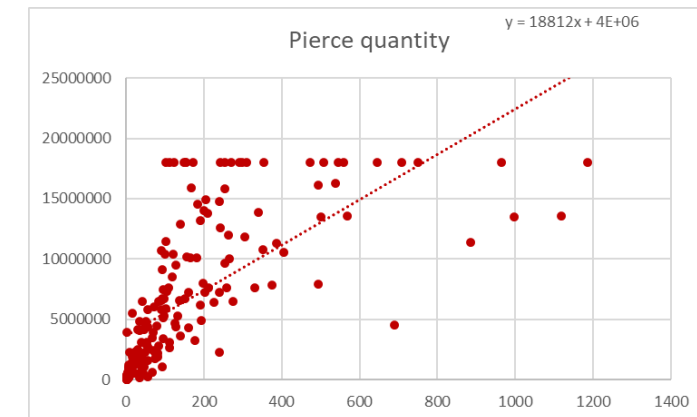
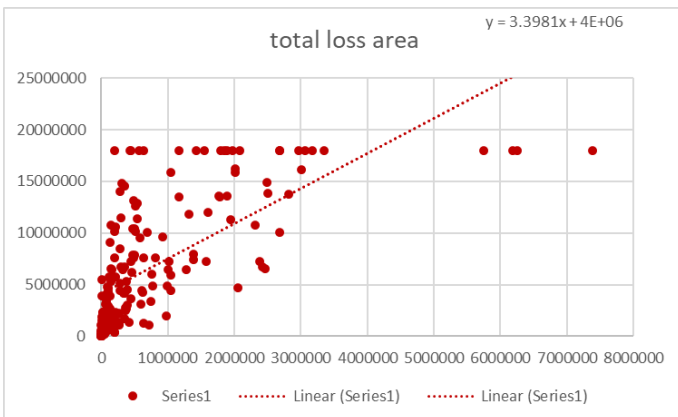
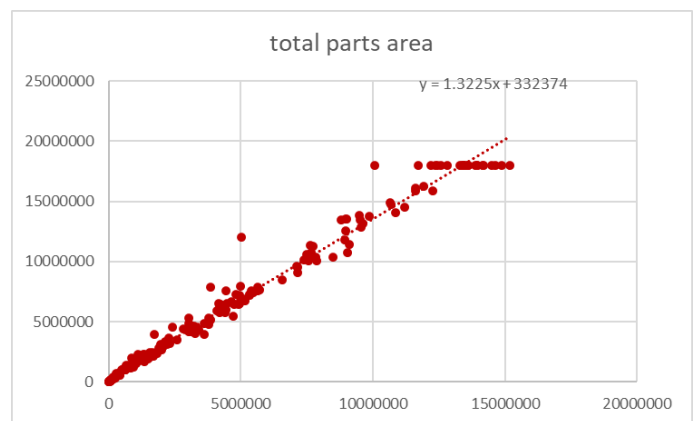
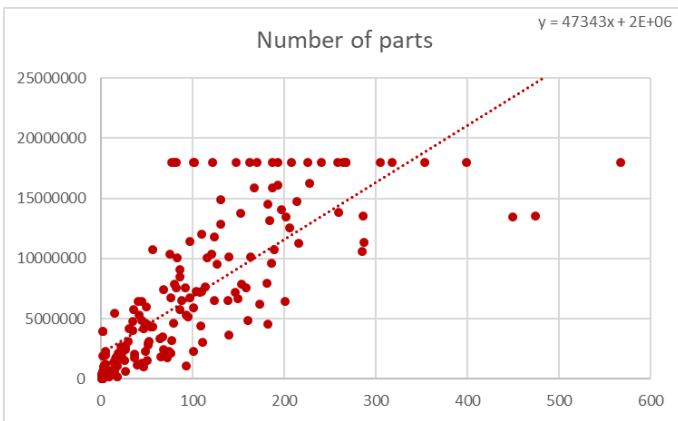


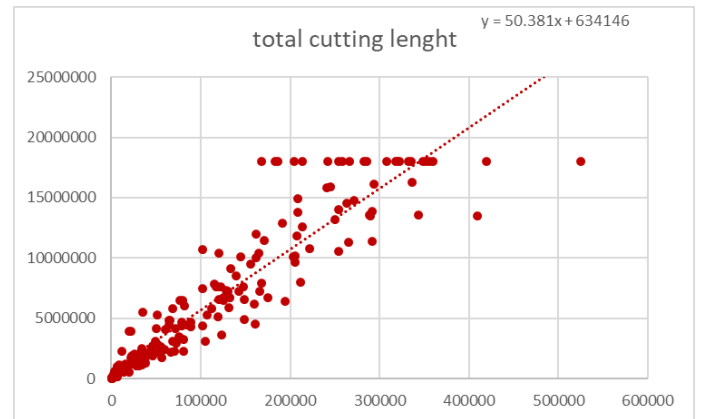
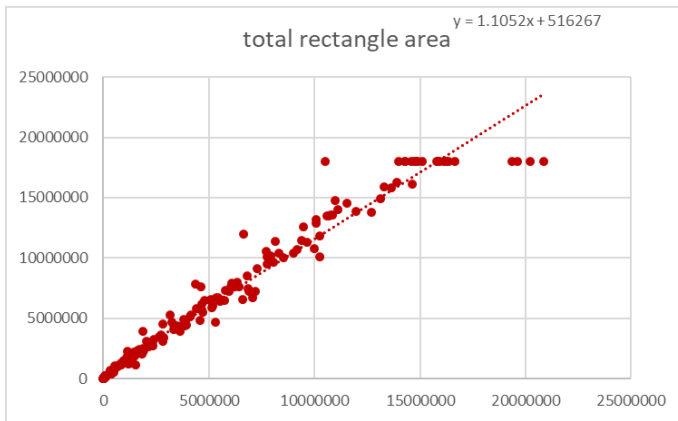
12mm



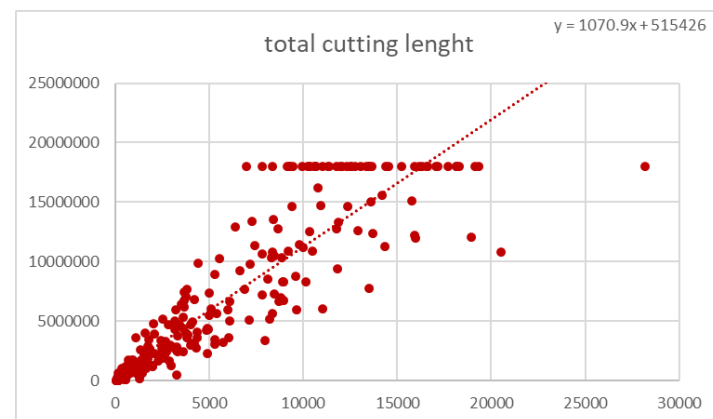
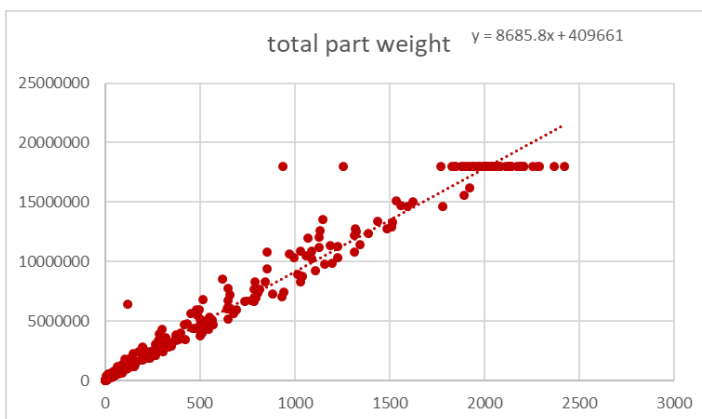
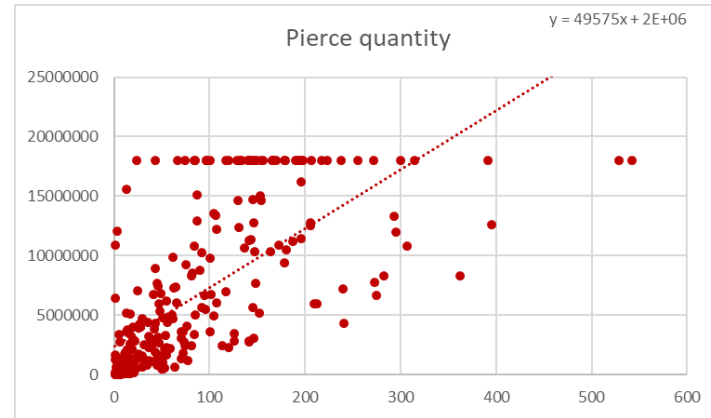
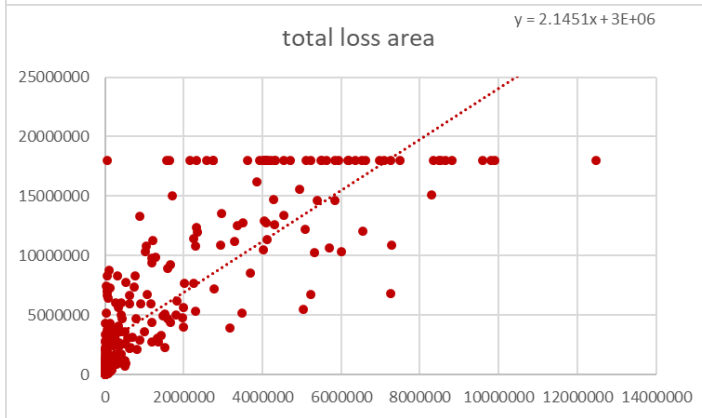
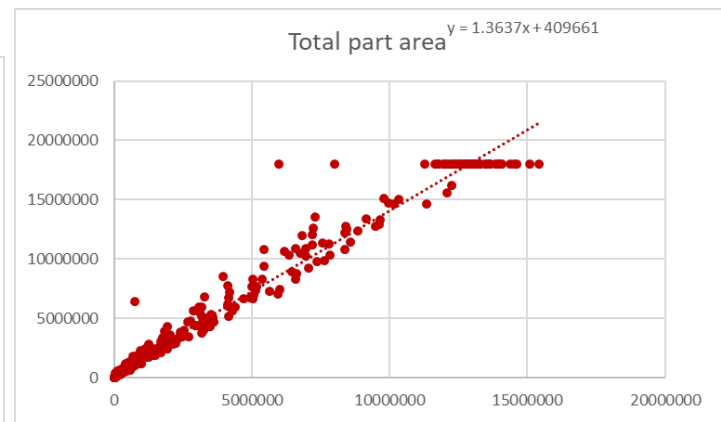
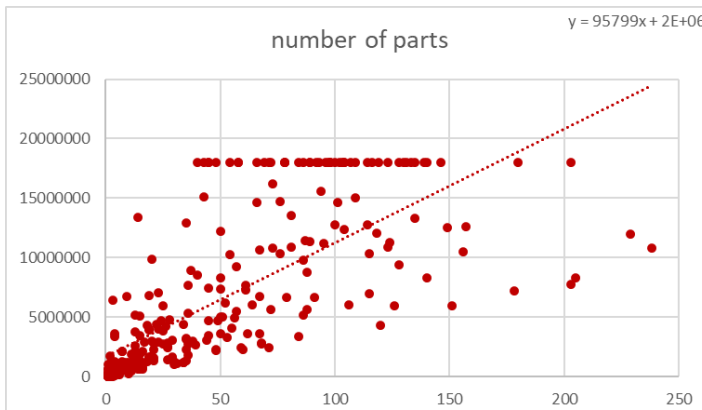


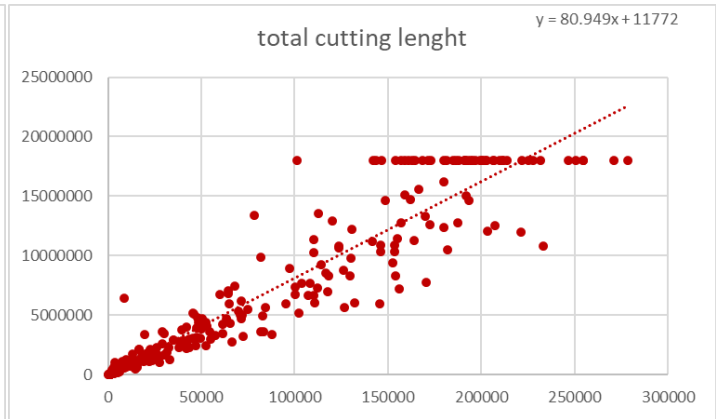
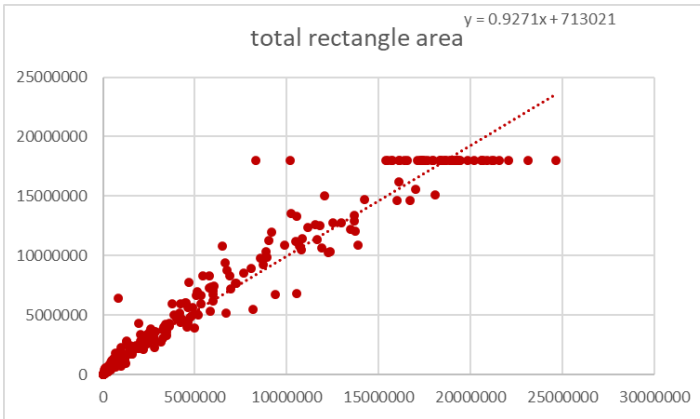
15mm



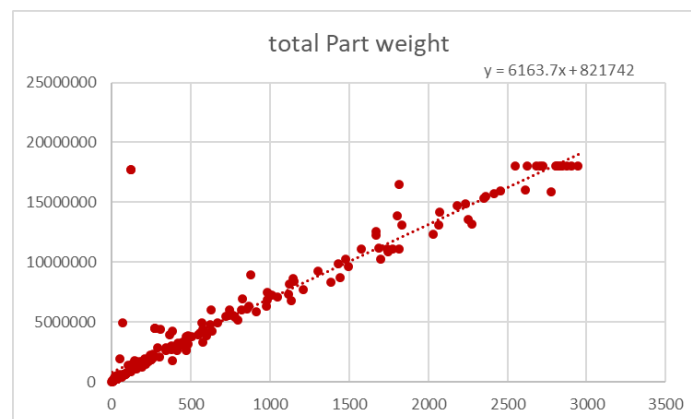
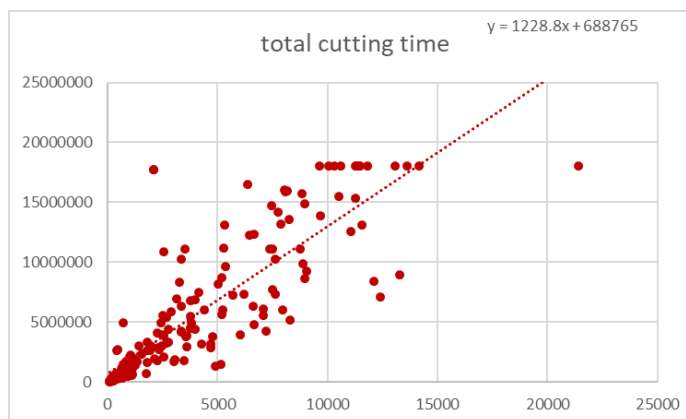
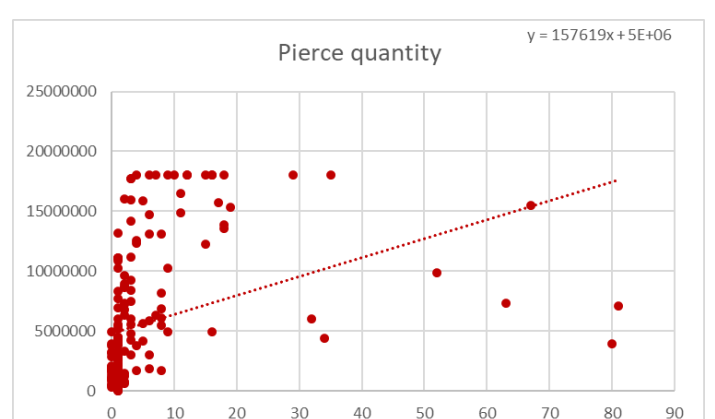
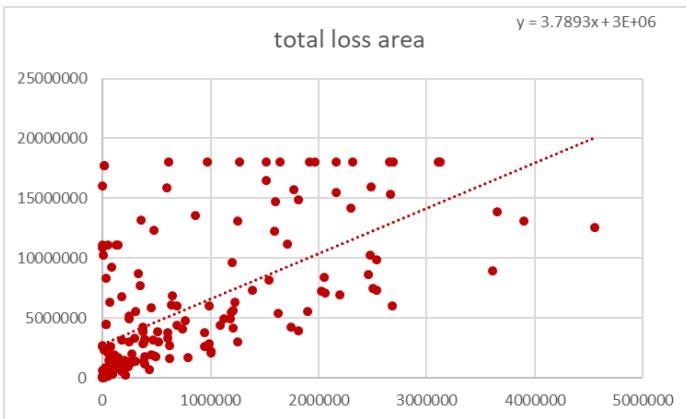
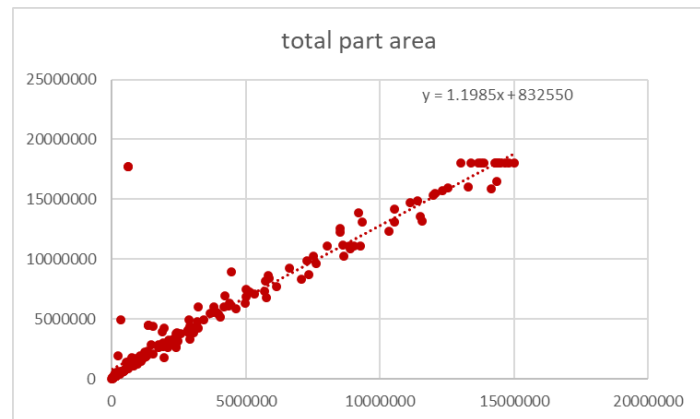
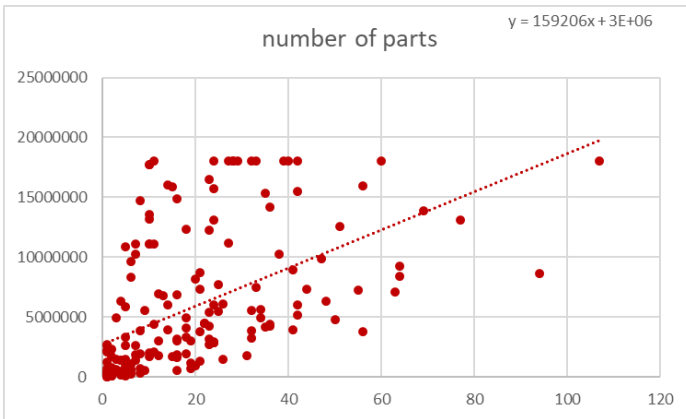


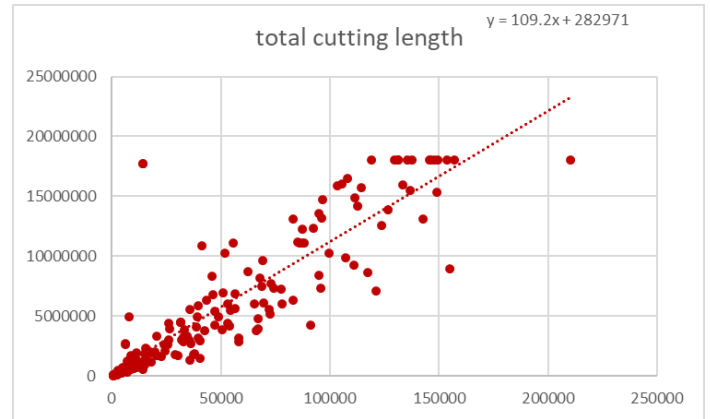
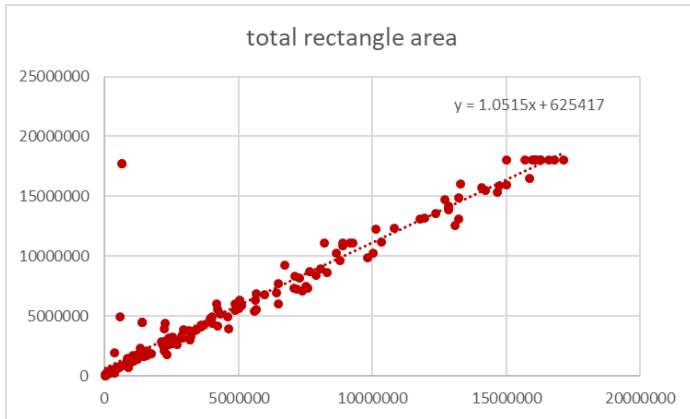
20mm



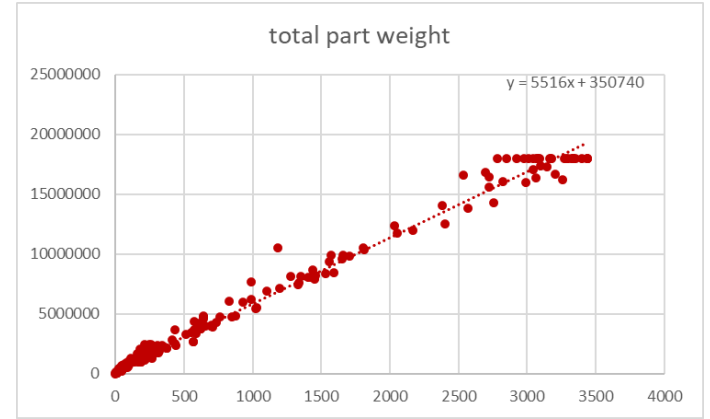
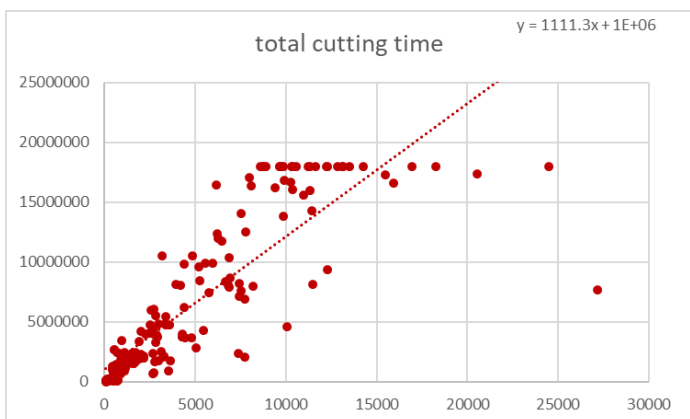
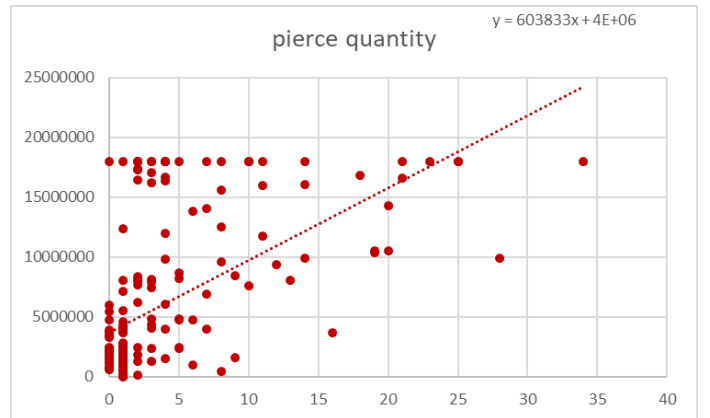
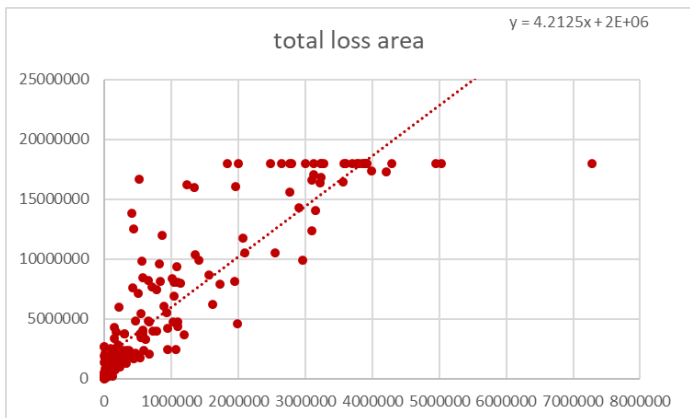
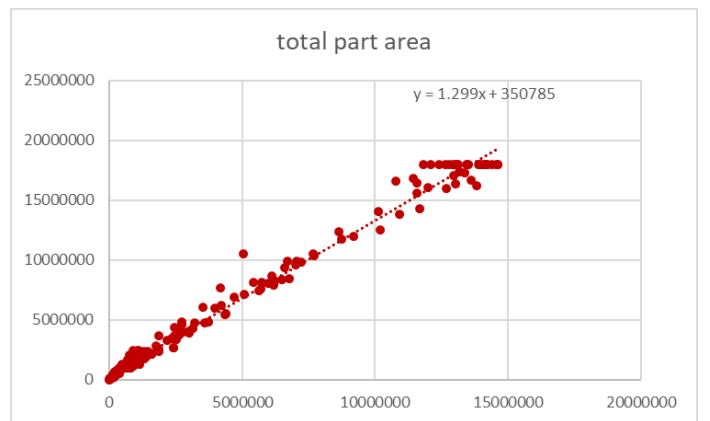
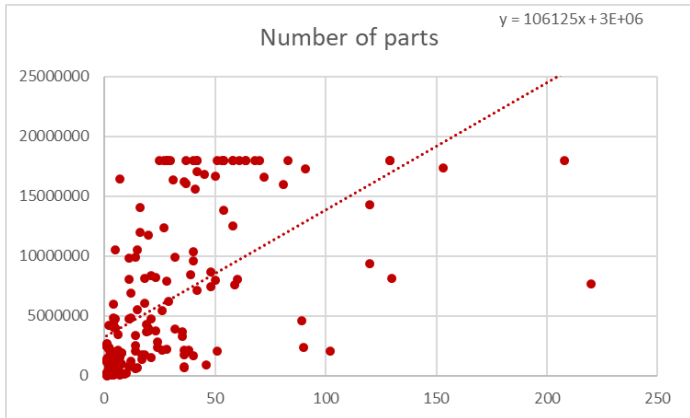


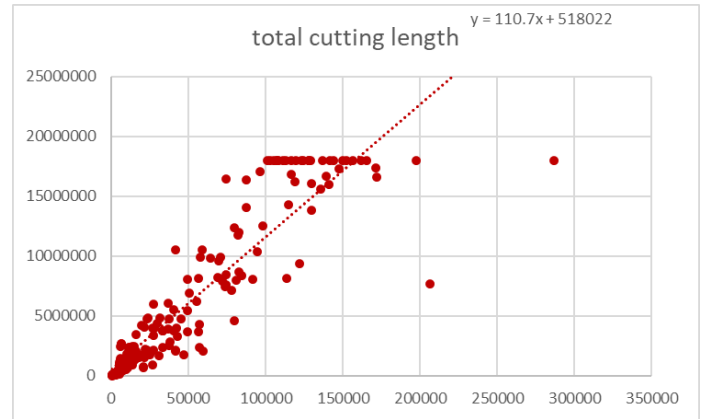
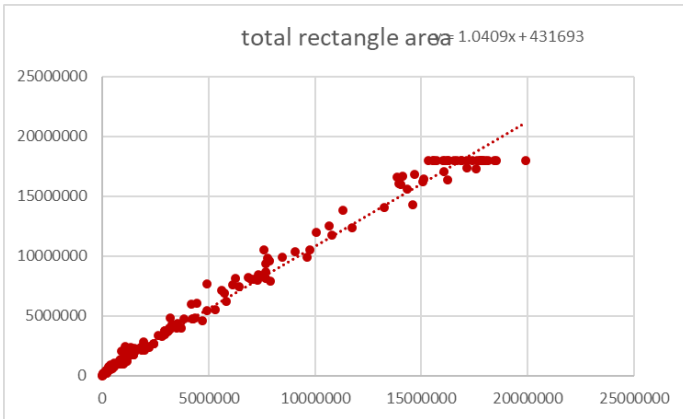
25mm



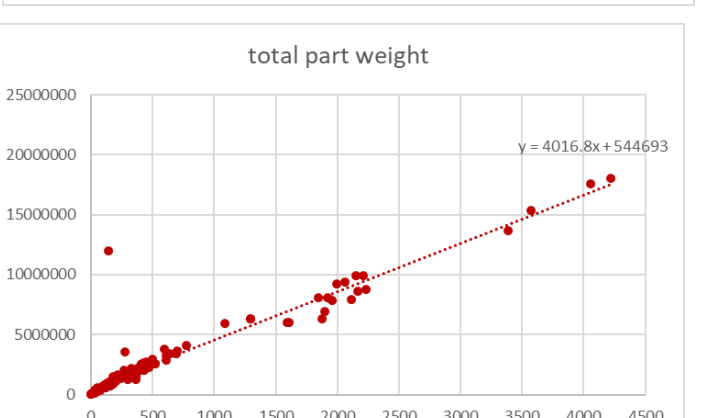
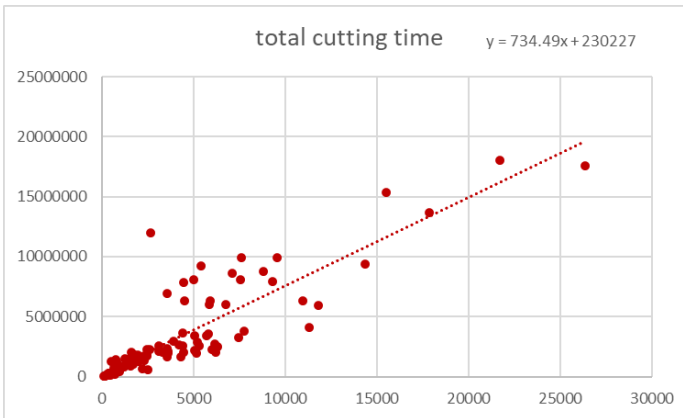
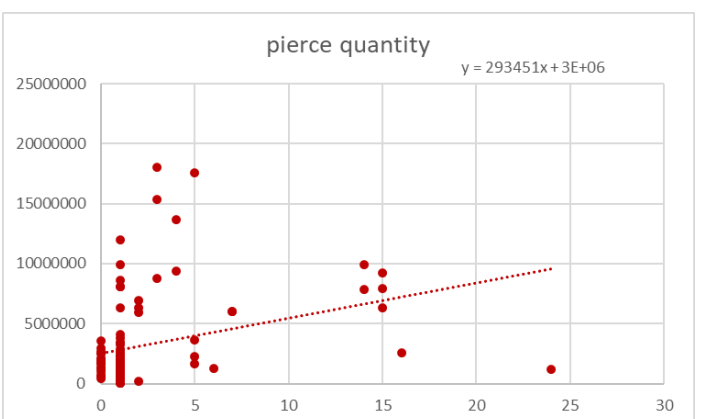
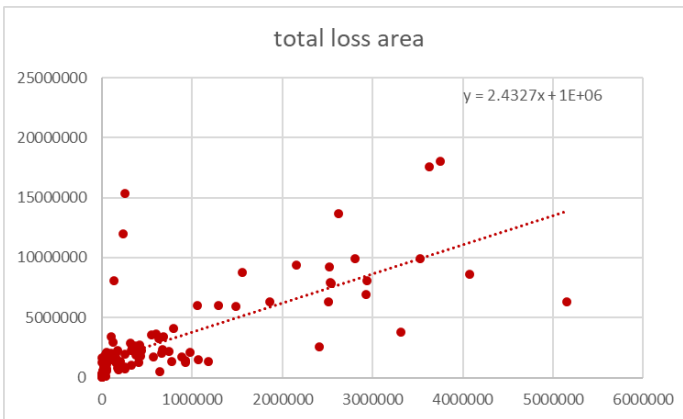
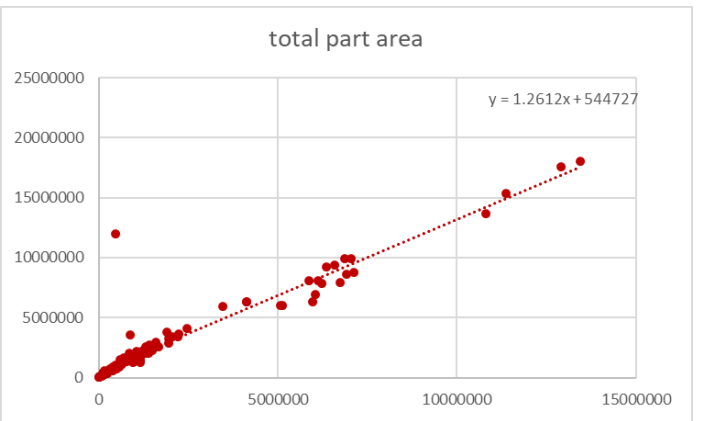
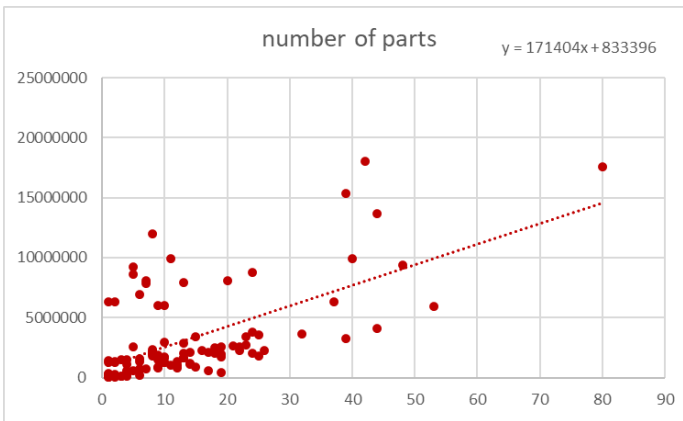


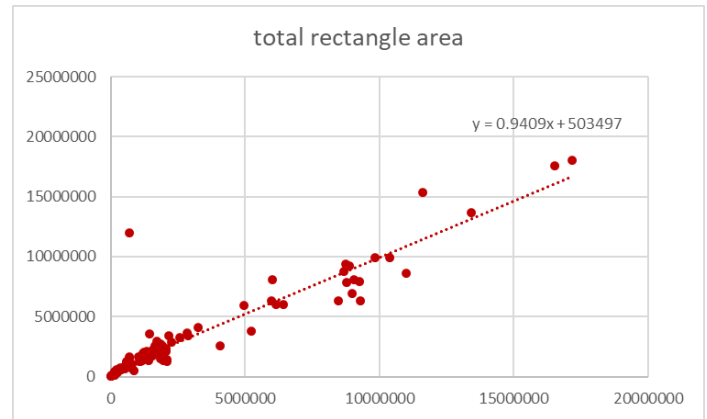
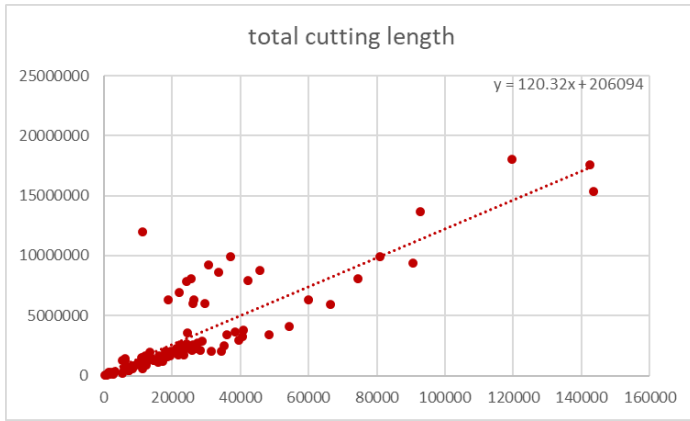
30mm



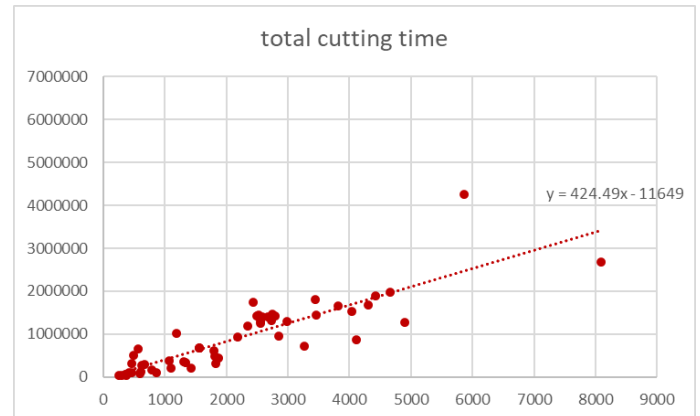
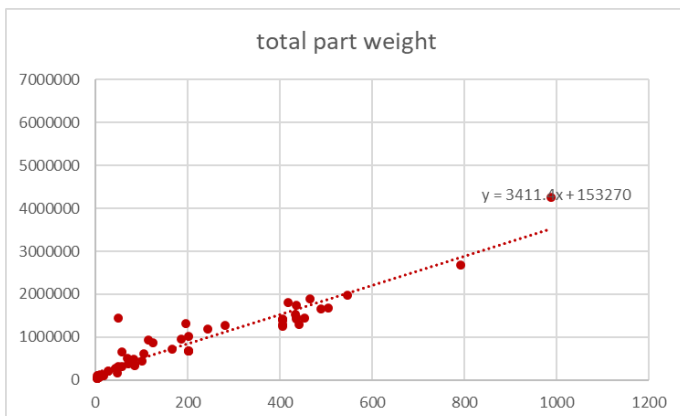
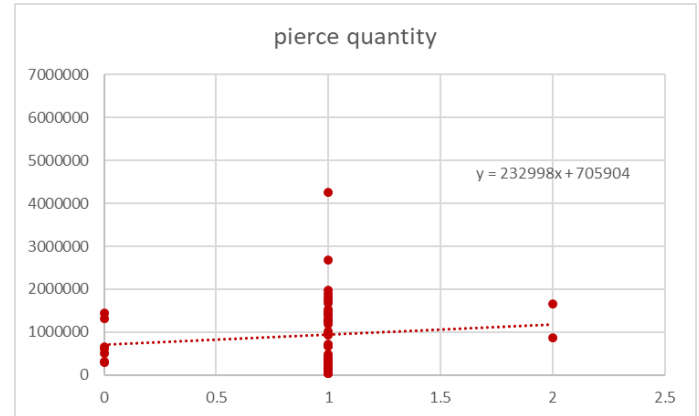
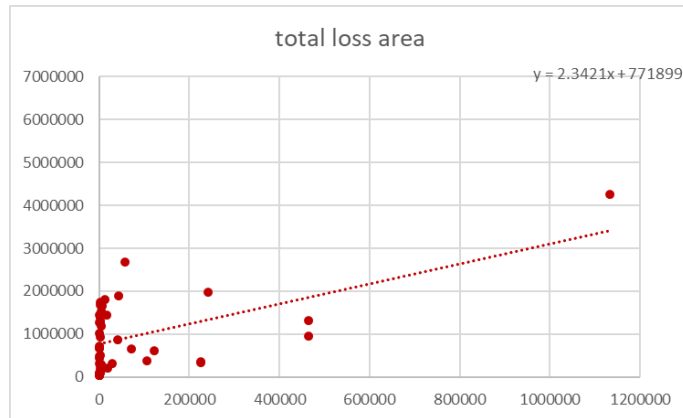
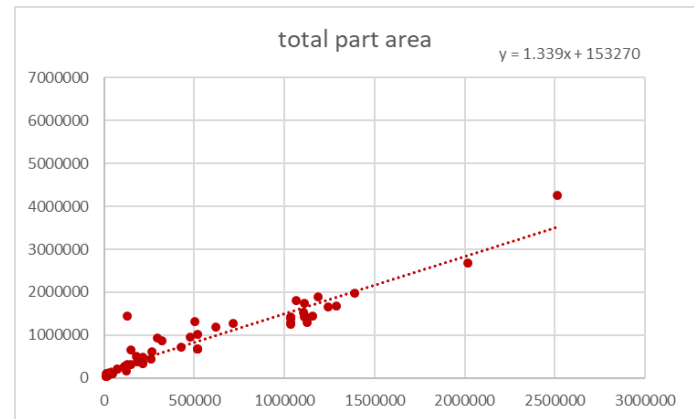
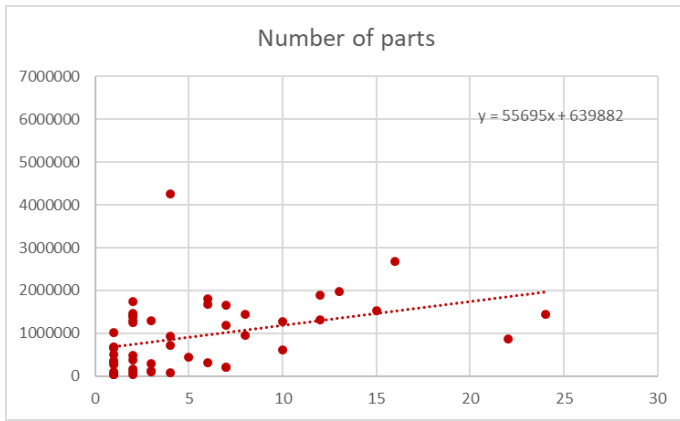


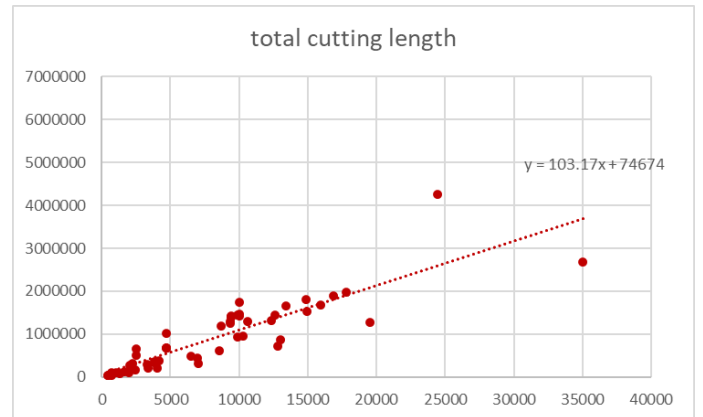
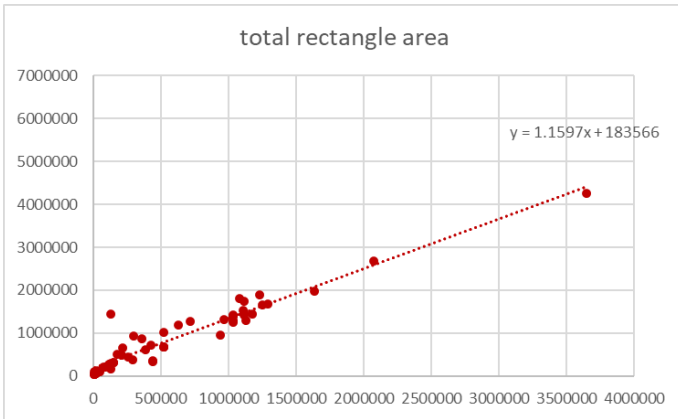
40mm



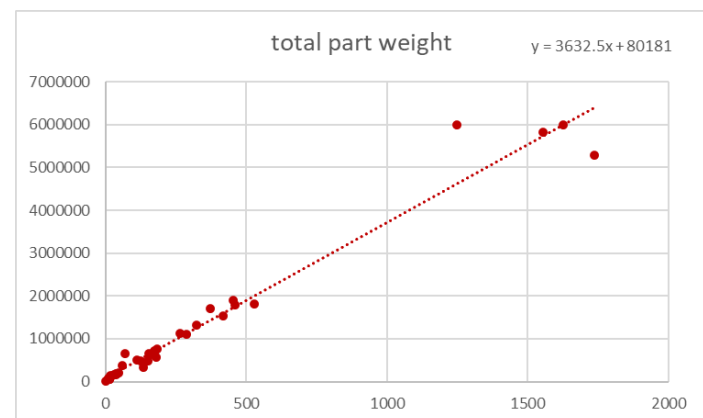
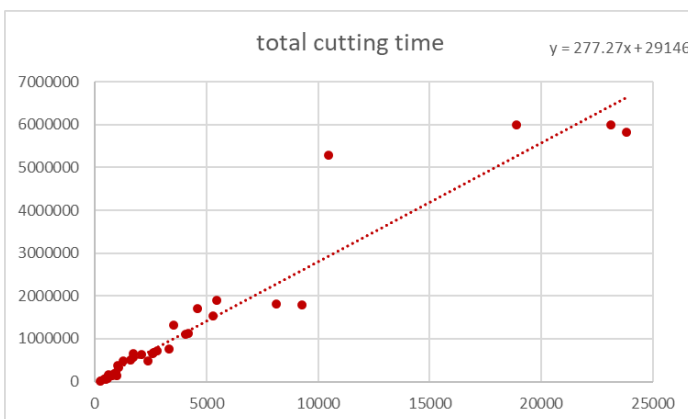
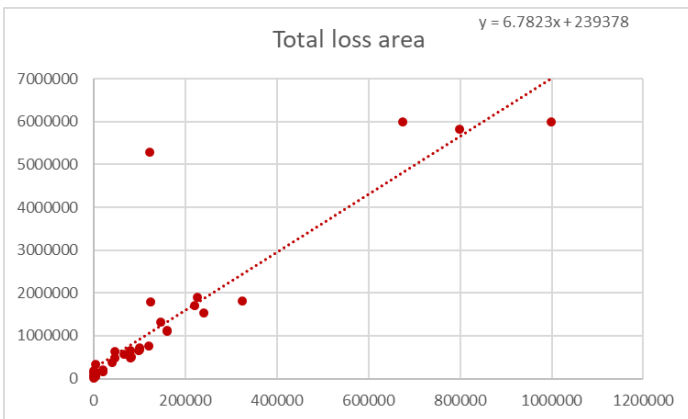
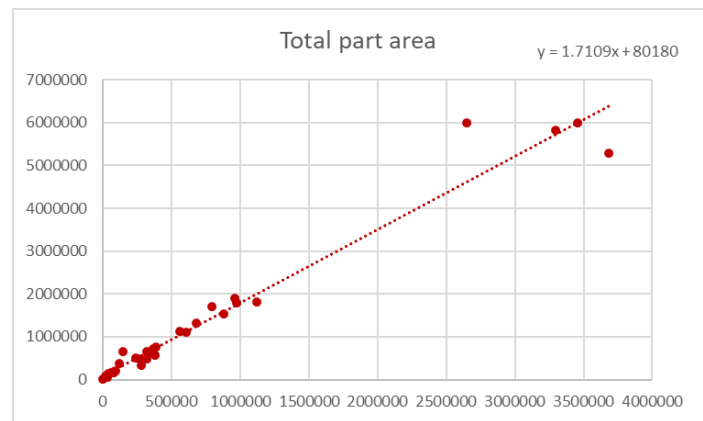
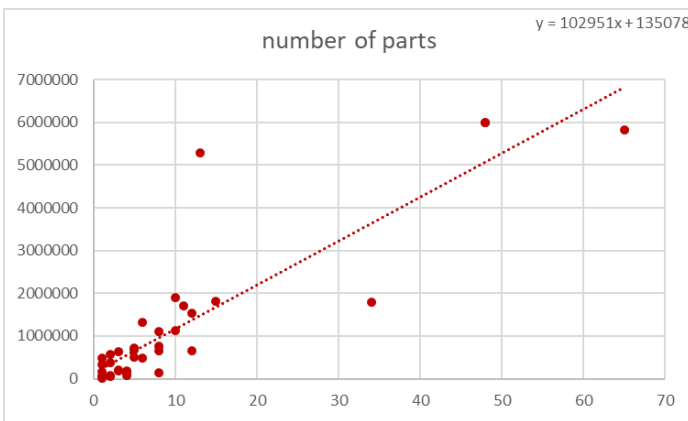


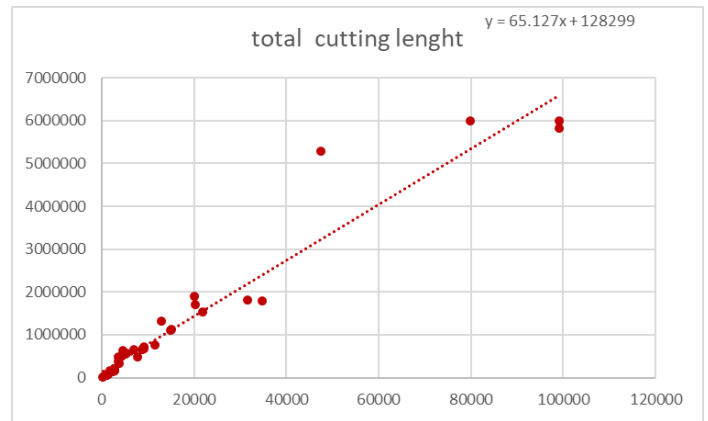
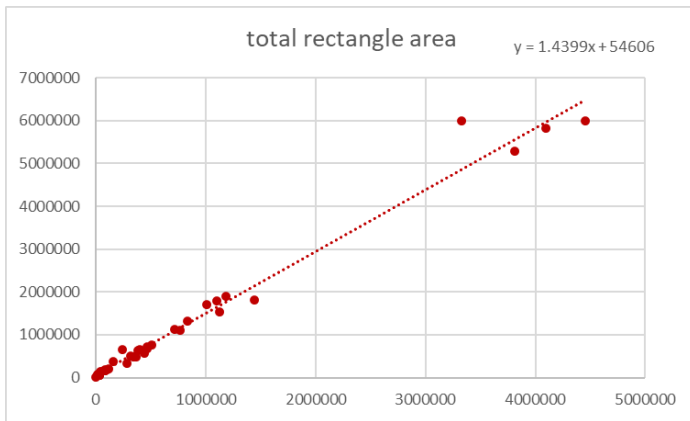
50mm





60mm





Appendix F Correlation matrices

5mm

variable	# parts	total parts area	total loss area	pierce quantity	total cutting time	total part weight	total rectangle area	total cutting length
# parts	1.0000	0.1860	0.1023	0.8796	0.8900	0.1860	0.1599	0.8305
total parts area	0.1860	1.0000	0.8564	0.2719	0.2734	1.0000	0.9794	0.5218
total loss area	0.1023	0.8564	1.0000	0.1427	0.1748	0.8564	0.9430	0.4194
pierce quantity	0.8796	0.2719	0.1427	1.0000	0.7979	0.2719	0.2311	0.8322
total cutting time	0.8900	0.2734	0.1748	0.7979	1.0000	0.2734	0.2446	0.8979
total part weight	0.1860	1.0000	0.8564	0.2719	0.2734	1.0000	0.9794	0.5218
total rectangle area	0.1599	0.9794	0.9430	0.2311	0.2446	0.9794	1.0000	0.5003
total cutting length	0.8305	0.5218	0.4194	0.8322	0.8979	0.5218	0.5003	1.0000

6mm

variable	# parts	total parts area	total loss area	pierce quantity	total cutting time	total part weight	total rectangle area	total cutting length
# parts	1.0000	0.4221	-0.0267	0.9034	0.8997	0.4221	0.3042	0.8920
total parts area	0.4221	1.0000	0.7160	0.4155	0.6499	1.0000	0.9739	0.6301
total loss area	-0.0267	0.7160	1.0000	0.0530	0.1692	0.7160	0.8557	0.0886
pierce quantity	0.9034	0.4155	0.0530	1.0000	0.8830	0.4156	0.3253	0.8144
total cutting time	0.8997	0.6499	0.1692	0.8830	1.0000	0.6499	0.5367	0.9400
total part weight	0.4221	1.0000	0.7160	0.4156	0.6499	1.0000	0.9739	0.6301
total rectangle area	0.3042	0.9739	0.8557	0.3253	0.5367	0.9739	1.0000	0.4959
total cutting length	0.8920	0.6301	0.0886	0.8144	0.9400	0.6301	0.4959	1.0000

8mm

variable	# parts	total parts area	total loss area	pierce quantity	total cutting time	total part weight	total rectangle area	total cutting length
# parts	1.0000	0.2241	0.2400	0.7488	0.6618	0.2241	0.2430	0.8108
total parts area	0.2241	1.0000	0.7498	0.6394	0.6213	1.0000	0.9733	0.6094
total loss area	0.2400	0.7498	1.0000	0.5221	0.6283	0.7498	0.8816	0.6371
pierce quantity	0.7488	0.6394	0.5221	1.0000	0.8687	0.6394	0.6371	0.8585
total cutting time	0.6618	0.6213	0.6283	0.8687	1.0000	0.6213	0.6611	0.8985
total part weight	0.2241	1.0000	0.7498	0.6394	0.6213	1.0000	0.9733	0.6094
total rectangle area	0.2430	0.9733	0.8816	0.6371	0.6611	0.9733	1.0000	0.6556
total cutting length	0.8108	0.6094	0.6371	0.8585	0.8985	0.6094	0.6556	1.0000

10mm

variable	# parts	total parts area	total loss area	ierce quantity	total cutting time	total part weight	total rectangle area	total cutting length
# parts	1.0000	0.7098	0.4951	0.8521	0.8673	0.7109	0.7066	0.9362
total parts area	0.7098	1.0000	0.6317	0.5714	0.7898	0.9995	0.9597	0.8486
total loss area	0.4951	0.6317	1.0000	0.4288	0.4117	0.6316	0.7349	0.4985
ierce quantity	0.8521	0.5714	0.4288	1.0000	0.7187	0.5739	0.5986	0.8051
total cutting time	0.8673	0.7898	0.4117	0.7187	1.0000	0.7901	0.7469	0.9249
total part weight	0.7109	0.9995	0.6316	0.5739	0.7901	1.0000	0.9595	0.8492
total rectangle area	0.7066	0.9597	0.7349	0.5986	0.7469	0.9595	1.0000	0.8201
total cutting length	0.9362	0.8486	0.4985	0.8051	0.9249	0.8492	0.8201	1.0000

12mm

variable	# parts	total parts area	total loss area	ierce quantity	total cutting time	total part weight	total rectangle area	total cutting length
# parts	1.0000	0.8564	0.6226	0.8943	0.8505	0.8564	0.8468	0.9711
total parts area	0.8564	1.0000	0.6876	0.7606	0.7722	1.0000	0.9773	0.9417
total loss area	0.6226	0.6876	1.0000	0.5315	0.5774	0.6876	0.8257	0.6994
ierce quantity	0.8943	0.7606	0.5315	1.0000	0.8832	0.7606	0.7458	0.8623
total cutting time	0.8505	0.7722	0.5774	0.8832	1.0000	0.7722	0.7682	0.8443
total part weight	0.8564	1.0000	0.6876	0.7606	0.7722	1.0000	0.9773	0.9417
total rectangle area	0.8468	0.9773	0.8257	0.7458	0.7682	0.9773	1.0000	0.9355
total cutting length	0.9711	0.9417	0.6994	0.8623	0.8443	0.9417	0.9355	1.0000

15mm

variable	# parts	total parts area	total loss area	ierce quantity	total cutting time	total part weight	total rectangle area	total cutting length
# parts	1.0000	0.7390	0.5733	0.8922	0.9000	0.7390	0.7508	0.9412
total parts area	0.7390	1.0000	0.6372	0.6234	0.8008	1.0000	0.9869	0.8917
total loss area	0.5733	0.6372	1.0000	0.5120	0.5757	0.6372	0.7532	0.6435
ierce quantity	0.8922	0.6234	0.5120	1.0000	0.7729	0.6234	0.6392	0.8280
total cutting time	0.9000	0.8008	0.5757	0.7729	1.0000	0.8008	0.8040	0.9312
total part weight	0.7390	1.0000	0.6372	0.6234	0.8008	1.0000	0.9869	0.8917
total rectangle area	0.7508	0.9869	0.7532	0.6392	0.8040	0.9869	1.0000	0.8958
total cutting length	0.9412	0.8917	0.6435	0.8280	0.9312	0.8917	0.8958	1.0000

20mm

variable	# parts	total parts area	total loss area	pierce quantity	total cutting time	total part weight	total rectangle area	total cutting length
# parts	1.0000	0.6888	0.5411	0.8768	0.8276	0.6888	0.6699	0.8759
total parts area	0.6888	1.0000	0.7923	0.6509	0.8637	1.0000	0.9750	0.9257
total loss area	0.5411	0.7923	1.0000	0.4907	0.7396	0.7923	0.9081	0.7860
pierce quantity	0.8768	0.6509	0.4907	1.0000	0.7683	0.6509	0.6255	0.8022
total cutting time	0.8276	0.8637	0.7396	0.7683	1.0000	0.8637	0.8622	0.9435
total part weight	0.6888	1.0000	0.7923	0.6509	0.8637	1.0000	0.9750	0.9257
total rectangle area	0.6699	0.9750	0.9081	0.6255	0.8622	0.9750	1.0000	0.9217
total cutting length	0.8759	0.9257	0.7860	0.8022	0.9435	0.9257	0.9217	1.0000

25mm

variable	# parts	total parts area	total loss area	pierce quantity	total cutting time	total part weight	total rectangle area	total cutting length
# parts	1.0000	0.4940	0.7272	0.4296	0.7814	0.4979	0.5672	0.7630
total parts area	0.4940	1.0000	0.6063	0.3386	0.8462	0.9965	0.9893	0.9040
total loss area	0.7272	0.6063	1.0000	0.4546	0.7471	0.6079	0.7160	0.7898
pierce quantity	0.4296	0.3386	0.4546	1.0000	0.4673	0.3394	0.3807	0.4529
total cutting time	0.7814	0.8462	0.7471	0.4673	1.0000	0.8518	0.8801	0.9757
total part weight	0.4979	0.9965	0.6079	0.3394	0.8518	1.0000	0.9865	0.9060
total rectangle area	0.5672	0.9893	0.7160	0.3807	0.8801	0.9865	1.0000	0.9387
total cutting length	0.7630	0.9040	0.7898	0.4529	0.9757	0.9060	0.9387	1.0000

30mm

variable	# parts	total parts area	total loss area	pierce quantity	total cutting time	total part weight	total rectangle area	total cutting length
# parts	1.0000	0.5550	0.5526	0.2952	0.8777	0.5550	0.5672	0.8221
total parts area	0.5550	1.0000	0.8697	0.5484	0.8270	1.0000	0.9940	0.8920
total loss area	0.5526	0.8697	1.0000	0.5531	0.7831	0.8697	0.9184	0.8102
pierce quantity	0.2952	0.5484	0.5531	1.0000	0.4420	0.5484	0.5620	0.4805
total cutting time	0.8777	0.8270	0.7831	0.4420	1.0000	0.8270	0.8362	0.9746
total part weight	0.5550	1.0000	0.8697	0.5484	0.8270	1.0000	0.9940	0.8920
total rectangle area	0.5672	0.9940	0.9184	0.5620	0.8362	0.9940	1.0000	0.8943
total cutting length	0.8221	0.8920	0.8102	0.4805	0.9746	0.8920	0.8943	1.0000

35mm

variable	# parts	total parts area	total loss area	pierce quantity	total cutting time	total part weight	total rectangle area	total cutting length
# parts	1.0000	-0.6547	-0.5269	0.8925	-0.4544	-0.6547	-0.6468	-0.5547
total parts area	-0.6547	1.0000	0.9761	-0.9228	0.9616	1.0000	0.9999	0.9842
total loss area	-0.5269	0.9761	1.0000	-0.8355	0.9598	0.9761	0.9793	0.9575
pierce quantity	0.8925	-0.9228	-0.8355	1.0000	-0.8034	-0.9228	-0.9181	-0.8701
total cutting time	-0.4544	0.9616	0.9598	-0.8034	1.0000	0.9616	0.9630	0.9848
total part weight	-0.6547	1.0000	0.9761	-0.9228	0.9616	1.0000	0.9999	0.9842
total rectangle area	-0.6468	0.9999	0.9793	-0.9181	0.9630	0.9999	1.0000	0.9839
total cutting length	-0.5547	0.9842	0.9575	-0.8701	0.9848	0.9842	0.9839	1.0000

40mm

variable	# parts	total parts area	total loss area	pierce quantity	total cutting time	total part weight	total rectangle area	total cutting length
# parts	1.0000	0.5783	0.3889	0.1110	0.8394	0.5783	0.5544	0.8378
total parts area	0.5783	1.0000	0.7455	0.3660	0.8693	1.0000	0.9803	0.8528
total loss area	0.3889	0.7455	1.0000	0.2982	0.6506	0.7455	0.8625	0.5436
pierce quantity	0.1110	0.3660	0.2982	1.0000	0.2019	0.3659	0.3663	0.1993
total cutting time	0.8394	0.8693	0.6506	0.2019	1.0000	0.8693	0.8529	0.9439
total part weight	0.5783	1.0000	0.7455	0.3659	0.8693	1.0000	0.9803	0.8528
total rectangle area	0.5544	0.9803	0.8625	0.3663	0.8529	0.9803	1.0000	0.8086
total cutting length	0.8378	0.8528	0.5436	0.1993	0.9439	0.8528	0.8086	1.0000

50mm

variable	# parts	total parts area	total loss area	pierce quantity	total cutting time	total part weight	total rectangle area	total cutting length
# parts	1.0000	0.2238	0.1069	0.0170	0.5980	0.2238	0.2212	0.5821
total parts area	0.2238	1.0000	0.4048	0.2451	0.8534	1.0000	0.9681	0.8469
total loss area	0.1069	0.4048	1.0000	-0.0808	0.3371	0.4048	0.6210	0.3612
pierce quantity	0.0170	0.2451	-0.0808	1.0000	0.2812	0.2451	0.1879	0.1817
total cutting time	0.5980	0.8534	0.3371	0.2812	1.0000	0.8534	0.8239	0.9892
total part weight	0.2238	1.0000	0.4048	0.2451	0.8534	1.0000	0.9681	0.8469
total rectangle area	0.2212	0.9681	0.6210	0.1879	0.8239	0.9681	1.0000	0.8250
total cutting length	0.5821	0.8469	0.3612	0.1817	0.9892	0.8469	0.8250	1.0000

60mm

variable	# parts	total parts area	total loss area	ierce quantity	total cutting time	total part weight	total rectangle area	total cutting length
# parts	1.0000	0.8204	0.9071	-0.6026	0.9612	0.8204	0.8581	0.9540
total parts area	0.8204	1.0000	0.8357	-0.6734	0.9267	1.0000	0.9945	0.9373
total loss area	0.9071	0.8357	1.0000	-0.5918	0.9567	0.8357	0.8886	0.9551
ierce quantity	-0.6026	-0.6734	-0.5918	1.0000	-0.6328	-0.6734	-0.6752	-0.6565
total cutting time	0.9612	0.9267	0.9567	-0.6328	1.0000	0.9267	0.9563	0.9986
total part weight	0.8204	1.0000	0.8357	-0.6734	0.9267	1.0000	0.9945	0.9373
total rectangle area	0.8581	0.9945	0.8886	-0.6752	0.9563	0.9945	1.0000	0.9649
total cutting length	0.9540	0.9373	0.9551	-0.6565	0.9986	0.9373	0.9649	1.0000

Appendix G ANOVA Tables

5mm

<i>Regression Statistics</i>									
Multiple R	0.98491231								
R Square	0.970052258								
Adjusted R Square	0.969853929								
Standard Error	373480.0828								
Observations	153								
ANOVA									
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>				
Regression	1	6.82249E+14	6.82E+14	4891.116	6.0776E-117				
Residual	151	2.10626E+13	1.39E+11						
Total	152	7.03312E+14							
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>ower 95.0%</i>	<i>Upper 95.0%</i>	
Intercept	101454.813	41659.66599	2.435325	0.016043	19143.68981	183765.9	19143.69	183765.9363	
Total part area	1.414989315	0.020232482	69.93652	6.1E-117	1.375013999	1.454965	1.375014	1.454964631	

6mm

<i>Regression Statistics</i>									
Multiple R	0.94153614								
R Square	0.886490303								
Adjusted R Square	0.885355206								
Standard Error	575323.1239								
Observations	102								
ANOVA									
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>				
Regression	1	2.58502E+14	2.59E+14	780.982	4.76565E-49				
Residual	100	3.30997E+13	3.31E+11						
Total	101	2.91602E+14							
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>ower 95.0%</i>	<i>Upper 95.0%</i>	
Intercept	269842.1584	78073.74912	3.456247	0.000805	114946.0639	424738.3	114946.1	424738.253	
total parts area	1.055774245	0.037779008	27.94606	4.77E-49	0.980821769	1.130727	0.980822	1.130726721	

8mm

Regression Statistics								
Multiple R	0.985176497							
R Square	0.97057273							
Adjusted R Square	0.970278457							
Standard Error	765994.9263							
Observations	102							
ANOVA								
	df	SS	MS	F	Significance F			
Regression	1	1.93522E+15	1.94E+15	3298.208	2.21162E-78			
Residual	100	5.86748E+13	5.87E+11					
Total	101	1.99389E+15						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	363244.329	103792.559	3.499715	0.000697	157322.8481	569165.8	157322.8	569165.8098
total parts area	1.240123796	0.021593647	57.43003	2.21E-78	1.197282616	1.282965	1.197283	1.282964976

10mm

Regression Statistics								
Multiple R	0.986113317							
R Square	0.972419475							
Adjusted R Square	0.97234765							
Standard Error	1132490.477							
Observations	386							
ANOVA								
	df	SS	MS	F	Significance F			
Regression	1	1.73641E+16	1.74E+16	13538.87	1.6264E-301			
Residual	384	4.92493E+14	1.28E+12					
Total	385	1.78566E+16						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	430179.4163	84324.8422	5.101455	5.31E-07	264383.2035	595975.6	264383.2	595975.629
total parts area	1.21977707	0.01048309	116.3566	1.6E-301	1.199165629	1.240389	1.199166	1.240388512

12mm

Regression Statistics								
Multiple R	0.989616232							
R Square	0.979340286							
Adjusted R Square	0.979131602							
Standard Error	307923.5521							
Observations	101							
ANOVA								
	df	SS	MS	F	Significance F			
Regression	1	4.4497E+14	4.45E+14	4692.935	3.20717E-85			
Residual	99	9.38687E+12	9.48E+10					
Total	100	4.54356E+14						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	56856.19337	42689.47419	1.331855	0.185966	-27848.98497	141561.4	-27849	141561.3717
total parts area	1.498061476	0.021867915	68.505	3.21E-85	1.454670787	1.541452	1.454671	1.541452164

15mm

Regression Statistics								
Multiple R	0.988864977							
R Square	0.977853943							
Adjusted R Square	0.977768437							
Standard Error	873000.5383							
Observations	261							
ANOVA								
	df	SS	MS	F	Significance F			
Regression	1	8.71578E+15	8.72E+15	11436.08	2.6036E-216			
Residual	259	1.97392E+14	7.62E+11					
Total	260	8.91317E+15						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	276017.3244	77692.77628	3.552677	0.000453	123027.3854	429007.3	123027.4	429007.2635
total parts area	1.336057077	0.012493564	106.9396	2.6E-216	1.311455181	1.360659	1.311455	1.360658972

20mm

<i>Regression Statistics</i>								
Multiple R	0.985031132							
R Square	0.970286332							
Adjusted R Square	0.970179448							
Standard Error	1115322.196							
Observations	280							
ANOVA								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	1	1.12925E+16	1.13E+16	9077.964	2.6727E-214			
Residual	278	3.45816E+14	1.24E+12					
Total	279	1.16383E+16						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	409661.0531	90808.16291	4.51128	9.52E-06	230902.0993	588420	230902.1	588420.007
total parts area	1.363662163	0.014312403	95.27835	2.7E-214	1.335487711	1.391837	1.335488	1.391836616

25mm

<i>Regression Statistics</i>								
Multiple R	0.944651406							
R Square	0.892366279							
Adjusted R Square	0.891761595							
Standard Error	1889655.89							
Observations	180							
ANOVA								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	1	5.26963E+15	5.27E+15	1475.757	4.40516E-88			
Residual	178	6.35602E+14	3.57E+12					
Total	179	5.90523E+15						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	832549.7101	189234.8949	4.399557	1.86E-05	459117.1851	1205982	459117.2	1205982.235
total parts area	1.198465837	0.03119739	38.41558	4.41E-88	1.136901504	1.26003	1.136902	1.26003017

30mm

Regression Statistics								
Multiple R	0.994631469							
R Square	0.989291759							
Adjusted R Square	0.9892354							
Standard Error	668776.9395							
Observations	192							
ANOVA								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	1	7.85095E+15	7.85E+15	17553.34	3.8684E-189			
Residual	190	8.49799E+13	4.47E+11					
Total	191	7.93593E+15						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	350785.019	64843.15885	5.409746	1.88E-07	222880.0607	478690	222880.1	478689.9772
total parts area	1.298975476	0.0098044	132.489	3.9E-189	1.279636021	1.318315	1.279636	1.318314931

35mm

Regression Statistics								
Multiple R	0.995747							
R Square	0.991512							
Adjusted R Square	0.990906							
Standard Error	38114.4							
Observations	16							
ANOVA								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	1	2.38E+12	2.38E+12	1635.475	6.67E-16			
Residual	14	2.03E+10	1.45E+09					
Total	15	2.4E+12						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	129274.7	11513.43	11.22817	2.19E-08	104580.9	153968.5	104580.9	153968.5
X Variable 1	1.25105	0.030935	40.441	6.67E-16	1.184701	1.317399	1.184701	1.317399

40mm

<i>Regression Statistics</i>								
Multiple R	0.949213124							
R Square	0.901005555							
Adjusted R Square	0.900015611							
Standard Error	1201247.331							
Observations	102							
<i>ANOVA</i>								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	1	1.31335E+15	1.31E+15	910.1577	5.05319E-52			
Residual	100	1.443E+14	1.44E+12					
Total	101	1.45765E+15						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	544726.983	148385.2234	3.671033	0.00039	250334.9261	839119	250334.9	839119.04
total parts area	1.261223419	0.041805527	30.16882	5.05E-52	1.178282444	1.344164	1.178282	1.344164395

50mm

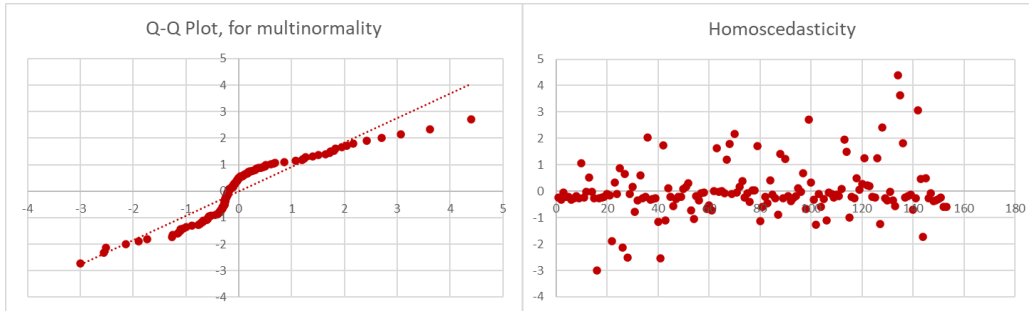
<i>Regression Statistics</i>								
Multiple R	0.947532386							
R Square	0.897817622							
Adjusted R Square	0.895852576							
Standard Error	255877.0587							
Observations	54							
<i>ANOVA</i>								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	1	2.99143E+13	2.99E+13	456.894	2.03293E-27			
Residual	52	3.4046E+12	6.55E+10					
Total	53	3.33189E+13						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	153270.2941	49901.77251	3.07144	0.003385	53135.06177	253405.5	53135.06	253405.5265
total parts area	1.33896822	0.062641556	21.37508	2.03E-27	1.213268742	1.464668	1.213269	1.464667698

60mm

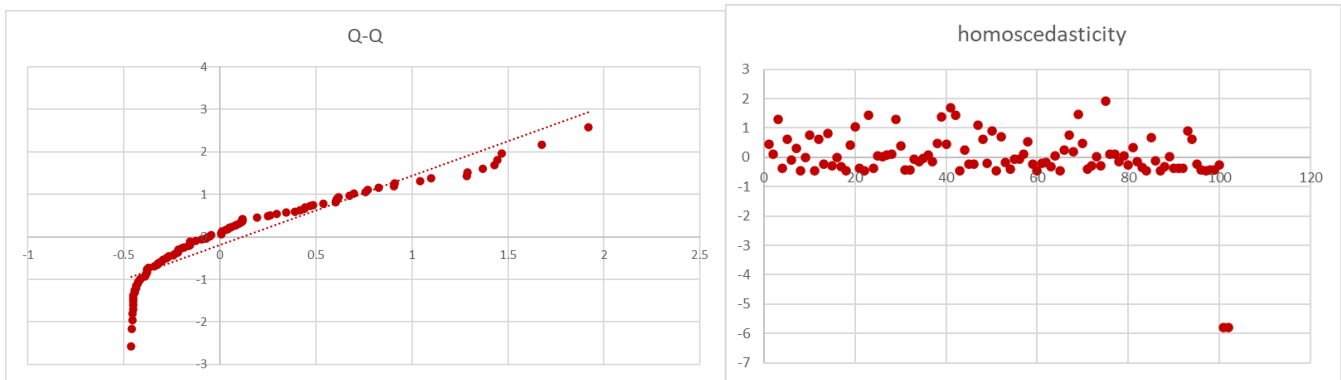
<i>Regression Statistics</i>								
Multiple R	0.983091794							
R Square	0.966469476							
Adjusted R Square	0.965511461							
Standard Error	318448.1719							
Observations	37							
ANOVA								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	1	1.02304E+14	1.02E+14	1008.825	2.13309E-27			
Residual	35	3.54932E+12	1.01E+11					
Total	36	1.05854E+14						
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	80180.41614	62790.26843	1.276956	0.210025	-47290.60561	207651.4	-47290.6	207651.4379
total parts area	1.710908801	0.053866522	31.76201	2.13E-27	1.601553947	1.820264	1.601554	1.820263654

Appendix H Q-Q plots and homoscedasticity plots

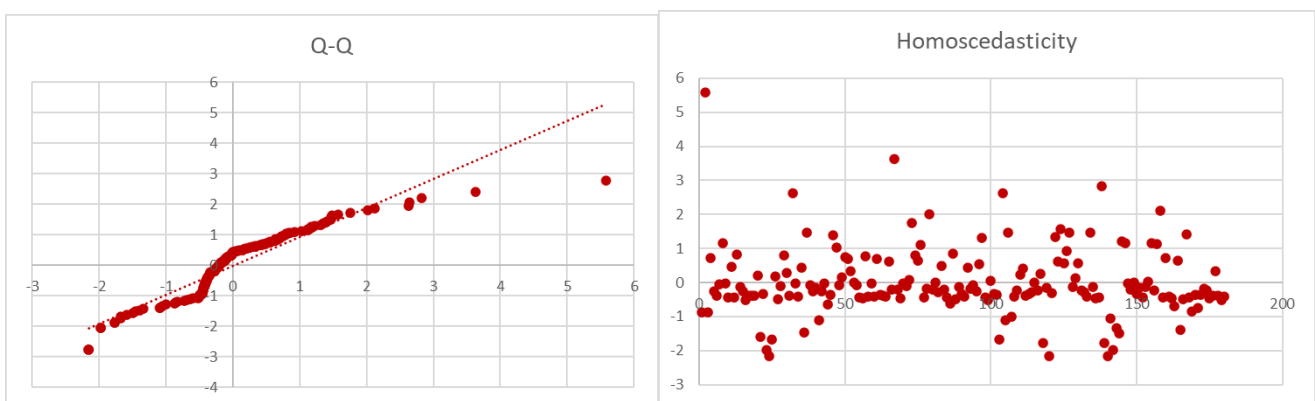
5mm



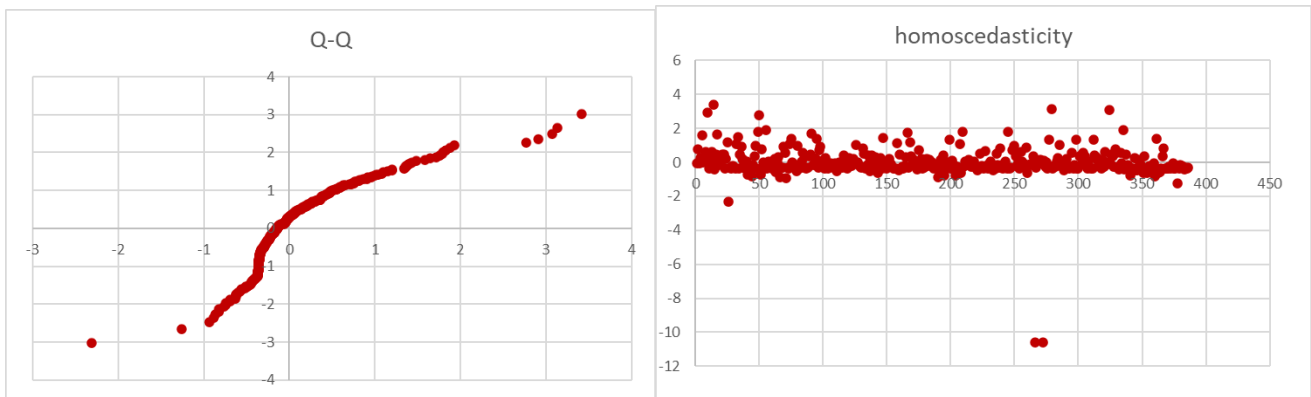
6mm



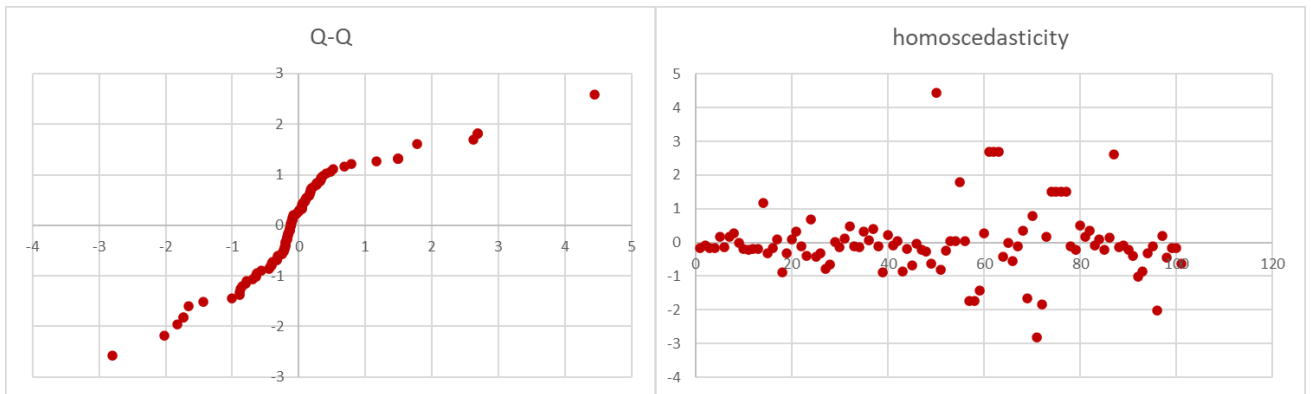
8mm



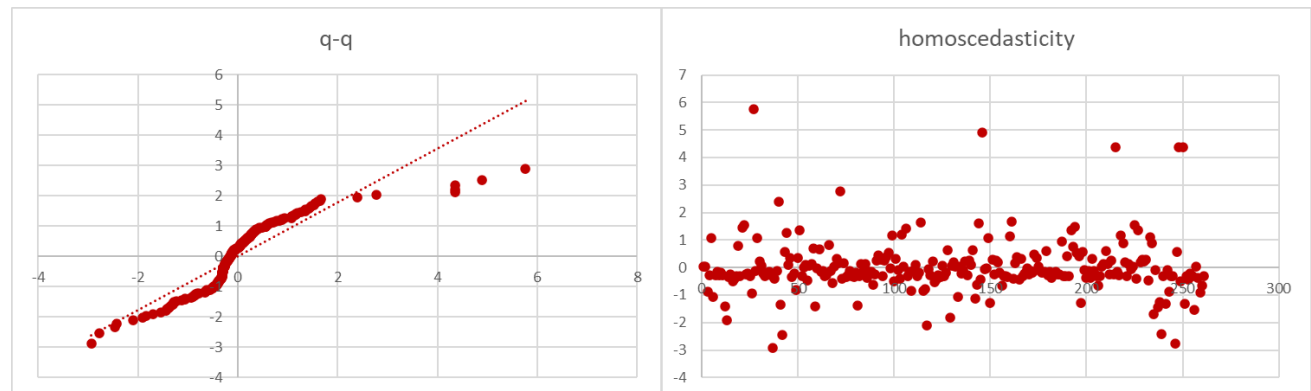
10mm



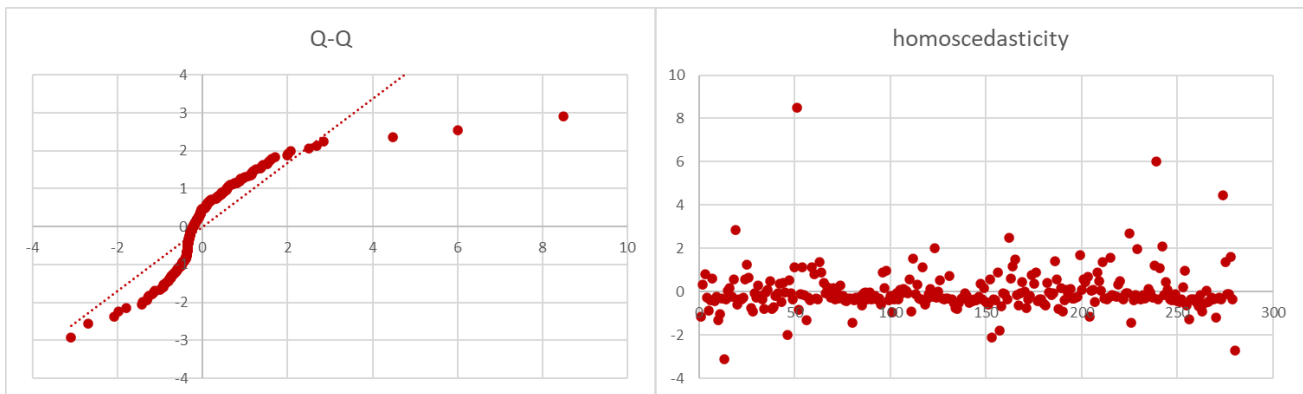
12mm



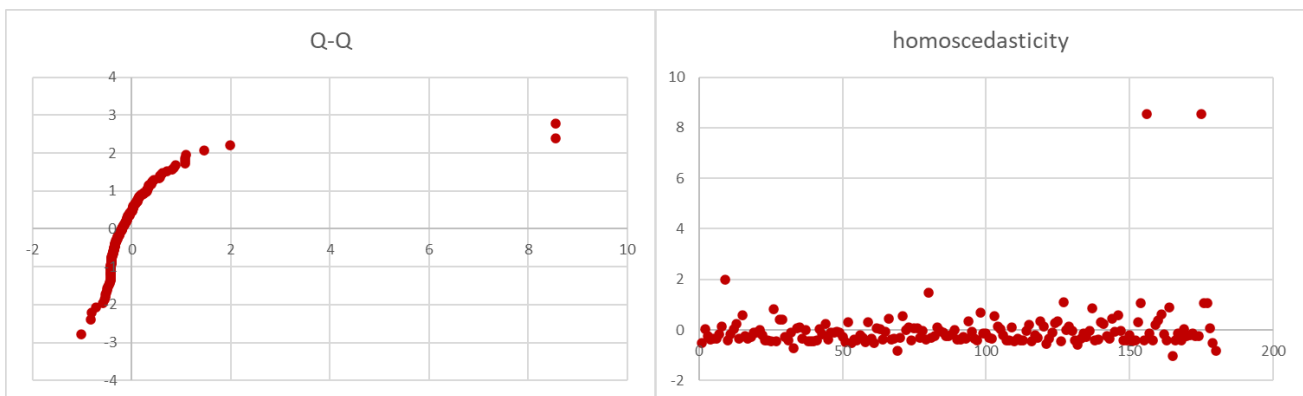
15mm



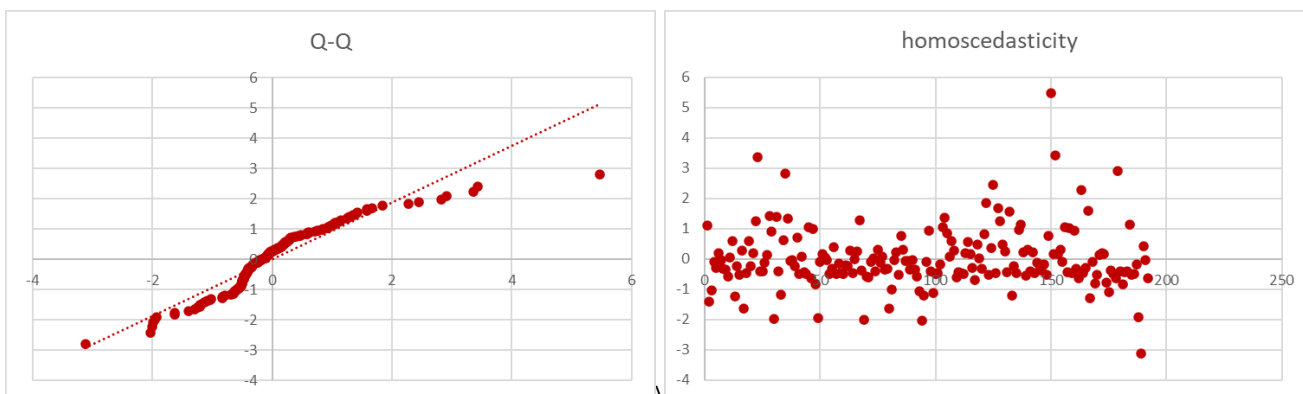
20mm



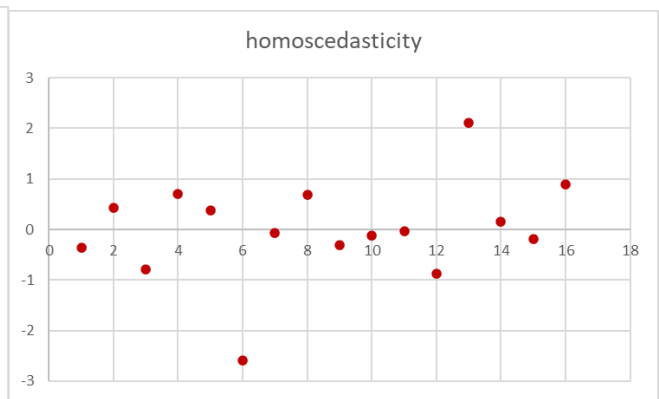
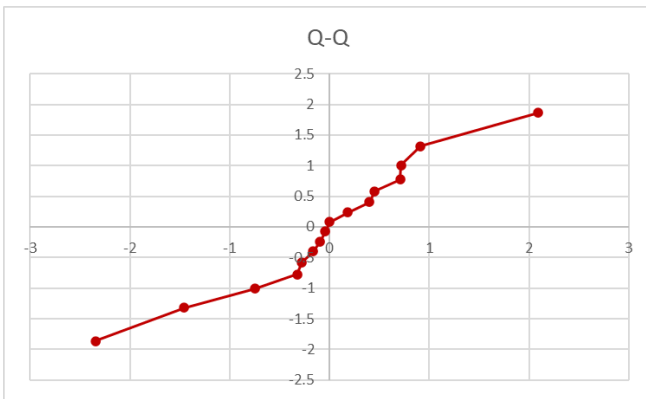
25mm



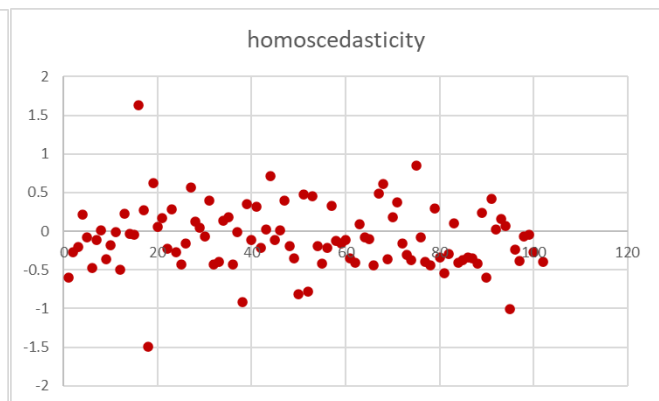
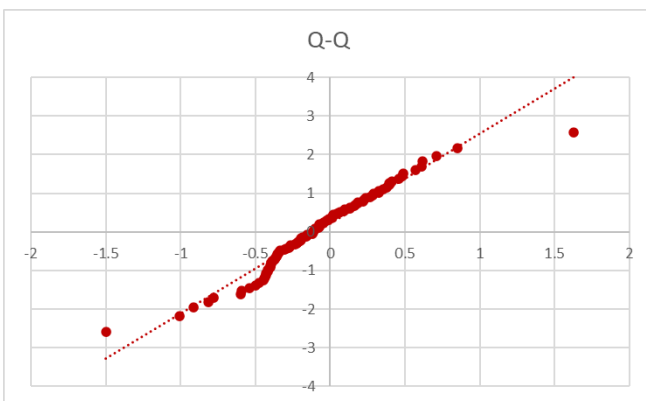
30mm



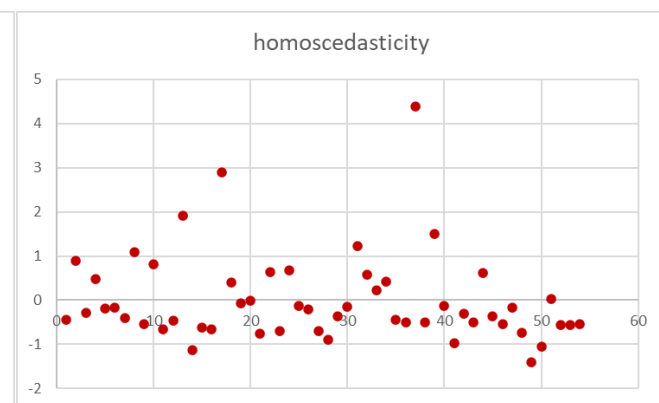
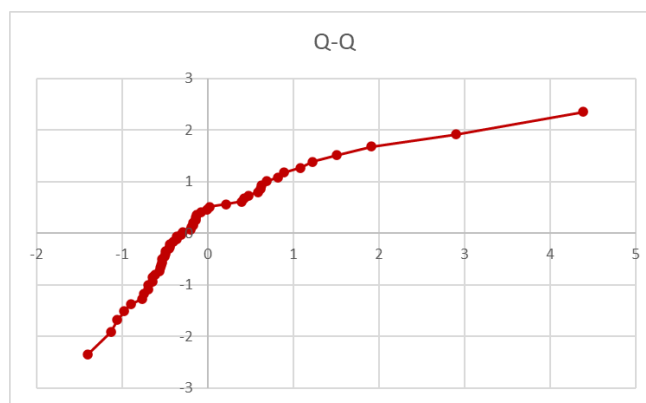
35mm



40mm



50mm



60mm

